ISSN 2759-0399
Research Journal of SDGs and Circular Economy Partnership Institute
Volume 4, March 31, 2025
SDGs and Circular Economy Partnership Research Institute,
Aoyama Gakuin University, Japan

2024 (3rd Year) International Trend Research Report on Circular Economy (CE) Policy/Standard and Case Studies of Advanced CE Companies

Grant-in-aid for Scientific Research, Basic Research (B), Japan
"Development, Empirical Research and Dissemination of New Theories and System Techniques for Circular Economy (CE) to Meet SDGs Goal 12; Producer and Consumer Responsibility"
Academic period: from 2022 to 2025 (4 years)
Research project number: 22H01717

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Acknowledgements

This research was conducted as part of the Grant-in-Aid for Scientific Research Activity in Japan (2022–2025), which aimed to contribute to the "development, empirical research, dissemination of new theories and system techniques for the circular economy to meet the responsibility for the production and consumption of SDGs". It was further supported by a research grant from the Global Business Research Institute at Aoyama Gakuin University.

Research Framework of
This Grant-in-aid for Scientific Research

2024 (3rd Year of Research Period)
The Latest Trends in EU and Japanese Policies and International Standard Regulations Related to the Circular Economy

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Abstract
Our Circular Economy (CE) research themes were selected as “Development, empirical research, and dissemination of new theories and system techniques of the circular economy (CE) to meet the SDGs Goal 12: Producer and consumer responsibility" (Research period: 2022-2025, Principal investigator: Kin'ya Tamaki, for Grant-in-aid for Scientific Research, Basic Research (B), Japan). The first CE research theme is to delineate the research framework and to develop five research topics as new methodologies and system techniques as described below: (1) Multi-generational CE value chain management and business model, (2) Cyclical resource collection, recovery, and supply, (3) CE product planning, digital marketing, and customer engagement, (4) Lifecycle design for smart products and services, and (5) Sharing platform and application software. The second CE research theme is to explore how to proceed international trend surveys concerning CE policies in each area and country, and international standards. Based on the results of these trend surveys, comparative case studies of advanced CE companies are conducted in each industry. The purpose of this research paper is to focus on the aforementioned second CE research theme. The first research topic examines the new regulations on CE policies announced by the European Commission in 2024. The second research topic reviews the current progress of the compilation of regulations for CE international standards. The third research topic investigates emerging CE policy trends in Japan and the development status of CE-related laws and regulations.

Keywords: Circular economy (CE), CE methodologies, CE system techniques, CE policy, CE international standard, CE-related laws and regulations.

1. Introduction

"Target 12.3: Food loss reduction" and "Target 12.5: Waste reduction" included in " SDGs Goal 12: Producer and consumer responsibility" are related to the circular economy (CE); Target 12.5 stipulates that the targeted social issues should be resolved on a global scale by 2030. The European Union (EU) Commission [2016] had defined CE as follows: "CE is an economic policy that will enhance new competitiveness by creating new business opportunities and innovative and efficient production methods and consumption styles, protecting companies from resource depletion and price volatility”.

Our CE research themes were selected as “Development, empirical research, and dissemination of new theories and system techniques of the circular economy (CE) to meet the SDGs Goal 12: Producer and consumer responsibility" (Research period: 2022-2025, Principal investigator: Kin'ya Tamaki, for Grant-in-aid for Scientific Research, Basic Research (B), Japan).

The first CE research theme is to delineate the research framework and to develop five research topics as new methodologies and system techniques as described below [Tamaki, 2024]:

(1) Multi-generational CE value chain management and business model,
(2) Cyclical resource collection, recovery, and supply,
(3) CE product planning, digital marketing, and customer engagement,
(4) Lifecycle design for smart products and services, and
(5) Sharing platform and application software.

The second CE research theme is to explore how to proceed international trend surveys concerning CE policies in each area and country (Japan, EU: Germany and Italy, USA), and CE international standards [Tamaki, 2023]. Based on the results of these trend surveys, comparative case studies of advanced CE companies are conducted in each industry such as automobiles, electronics and devices, construction, food and agriculture, and software and platforms.

The purpose of this research paper is to focus on the aforementioned second CE research theme. The first research topic examines the new regulations on CE policies announced by the European Commission in 2024. The second research topic reviews the current progress of the compilation of regulations for CE international standards. The third research topic investigates emerging CE policy trends in Japan and the development status of CE-related laws and regulations.

The following chapters and sections present the content of this paper, which incorporates new research findings as stated in its objective, in addition to the research results published in the “International Trend Researches on CE Policy/Standard” investigation report from the first year of the research period under this Grant-in-Aid for Scientific Research [Tamaki, 2023]. The latest trends of CE policies and regulations in each chapter are described as follows:

Chapter 3 covers content that was already investigated in a research report from two years ago [Tamaki, 2023] and includes the following descriptions: the trend researches on CE policies, master plans, regulations in the EU: Ecodesign Working Plan, the EU Action Plan for Circular Economy (CE Package), and New Circular Economy Action Plan.

Chapter 4 explores new regulations related to “Ecodesign Requirements for Sustainable Products”. This Regulation also includes “Digital Product Passport (DPP)” regulations, provides for the setting of mandatory green public procurement requirements and creates a framework to prevent unsold consumer products from being destroyed.

Chapter 5 reviews the current progress of the compilation of the international standards (ISO 59000 series) of CE documents still under development by ISO/TC (Technical Committee) 323 Secretariat.

Based on Chapter 6 shown the CE policy regarding “Circular Economy Vision 2020” compiled by the Ministry of Economy, Trade and Industry (METI) in Japan, Chapter 7 reports the “Growth－Oriented, Resource-Autonomous Circular Economy Strategy” by the METI.

Chapter 8 reviews the new 2025 edition of the “Noteworthy Cases” such as CE industry case studies selected by the Japan Partnership for Circular Economy (J4CE) which was founded on March 2021 by Japan Business Federation (Keidanren).

Chapter 9 investigates evolution of CE legislations in Japan: Basic Law on Resources, the 6th Basic Environmental Plan, the Advanced Resource Recycling Act, and the Fifth Fundamental Plan for Establishing a Robust Material-Cycle Society.

2. Historical Progression and Transformation toward Circular Economy

2.1 Transformation of Supply Chains Evolving Toward CE

This section discusses the trends in the evolution of the economic model of the supply chain, which follows the sequence of "raw materials → manufacturing → use → disposal → collection → resource reuse or recycling," from a linear economy to a recycling economy, and further to a circular economy.

(1) Linear Economy

Since the Industrial Revolution, technological advancements had brought a comfortable and prosperous lifestyle. However, this prosperity had been built upon an economic model that relied on mass production and mass consumption. This model extracted resources and energy from the earth and disposed of them once they were used. Such a model was referred to as the "**linear economy**."

The linear economy relied on companies servicing to sell more: they tried to cut costs, to encourage customers to buy the latest version, or persuade them to buy products with a short life-cycle.

(2) Recycle Economy

As the next economic model, the process of collecting used products and then applying the **3Rs** (**Reduce**, **Reuse**, **Recycle**) became known as the "**Recycle Economy**." This model aimed to reduce the generation of waste and utilize valuable materials within the waste as circulating resources. By properly managing waste disposal, it contributed to reducing the consumption of natural resources and minimizing environmental impact as much as possible. However, the disadvantage of this model lay in the fact that it was based on a supply chain that assumed "waste would be generated." This led to the creation of resources that could not be reused or recycled.

(3) Circular Economy

In contrast to the "Recycling Economy," which was based on the premise of generating waste, the “**Circular Economy**” model operates on the principle that "waste and pollution should not be created." In other words, the key feature of the CE model is its focus on reducing the potential for resource waste from the beginning of processes such as formulating business strategies, planning new ventures, and even designing products. The aim is to establish a social system where resources continuously circulate within a closed-loop supply chain. Particularly with regard to scarce natural resources, the goal is to recover used products whenever possible, regenerate those resources, and reuse them in the production of new products.

The EU Commission defined the economic policy aimed at the Circular Economy (CE) as follows: "An economic policy that protected businesses from resource depletion and price fluctuations, while creating new business opportunities and innovative, efficient production methods and consumption styles, thereby enhancing new competitiveness (hereinafter referred to as '**CE policy**')." The core of this "CE policy" lay in identifying product sectors with high circularity potential and creating a framework for specific rules and legislative proposals that aimed to design product services that reduced waste and avoided pollution.

Governments, business large and small, NGOs and consultancies are recognizing these circular problems and risks. They set the potential to redesign the products and services that depended on unsustainable consumption and are investing in CE approaches.

2.2 Historical Progression of Circular Economy in European Commission

In 2011, the EU Commission published a Communication on “Roadmap for Resource-Efficient Europe”. On the basis of this roadmap, the European Resource Efficiency Platform – a group of high-leveled economic and environmental experts – developed a report by 2014 containing a series of economic recommendations for actions [EREP 2014]. This report was the basis for further consideration by the EU of how these general recommendations could be transformed into practical implementation proposals.

At the same time, the Ellen MacArthur Foundation was also working intensively on the concept of a transition to a circular economy. In a series of studies, the challenges and opportunities of the transition were examined and presented, not least in a study from 2013 [Ellen MacArthur Foundation 2015]. These and other studies have had a storing influence on the policy debate.

In 2014, the EU Commission adapted a first CE package. This package consisted of a communication on the transition to a CE, with a legislative proposal to revise the objectives of a number of waste management directives and several communications.

After intensive work, the EU Commission adopted a new EU action plan for the transition to a CE on 2nd December 2015 [European Commission, 2015]. This action plan included legislative proposals to revise European waste legislation, as well a list 54 measure covering the whole life cycle products and materials. The full implementation of this plan is one of EU’s proprieties and is an essential contribution to the EU’s comprehensive agenda for Grothe and jobs.

As a part of 2015 package, the EU has committed itself to producing a comprehensive implementation report five years after the adoption of the 2015 Action Plan. This report “New Circular Economy Action Plan in in March 2020” provided an opportunity to take stock of developments since 2015 and provided a basis for further reflection on measures for transition to a CE [European Commission, 2020].

3. CE Policy Trends in European Commission

3.1 Eco-Design Working Plan

The “Eco-design working plan (2016-2019)” was issued in November 2016, with the purpose of identifying working commissions’ priorities under eco-design and energy labelling [European Commission, 2016]. In Europe, the eco-design and energy labelling directive are framework directives; therefore, they should be transposed by Member States, which establish binding requirements that are specific to each product group. Working plans are designed to help identify categories of products to be investigated in depth in the upcoming three years and for which new measures can be prepared.

Eco-design directive and energy labelling measures have been then modified, including new material efficiency requirements, such as ease of repair and the facilitation of end-of-life treatment. Beyond these mandatory aspects, voluntary tools have been developed such as the EU Ecolabel and the Green Public Procurement criteria. In October 2019, 10 eco-design implementing regulations were adopted specially concerning household appliances such as refrigerators, washing machines, dishwashers and televisions.

3.2 EU Action Plan for Circular Economy (CE Package)

Starting in 2015, the first “circular economy action plan” was adopted in previous initiatives promoted by the European Commission. This initial plan included measures stimulating the Europe’s transition towards a circular economy while fostering sustainable economic growth and the generation of new jobs [European Commission, 2015]. Fifty-four actions were included in the plan, and after three years of implementation, all of them had been achieved, even if the work continues beyond 2019 for some actions. Actions were related to the entire life cycle and included details of different phases of the production and consumption process. The actions were divided according to the topic they mainly refer to and thus included the following: production, consumption, waste management, market for secondary raw materials, and sectorial actions concerning some on strategic sectors (e.g., plastic, food waste, critical raw materials, construction and demolition, biomass and bio-based materials, innovation and investments, and monitoring).

3.3 New Circular Economy Action Plan

As one of the main pillars of the European Green Deal, in March 2020, the European Commission adopted the “New Circular Economy Action Plan” [European Commission, 2020]. The new action plan is composed of thirty-five actions to be implemented in the timeframe 2020-2023; it focuses on different areas from the previous action plan. The key actions are listed under seven macro-areas that correspond to as many overall goals and targets: a sustainable product policy framework; key product value chains; “less waste more value;” making the circular economy work for people, regions, and cities; crosscutting actions; leading efforts at a global level; and monitoring progress.

The design of sustainable products is intended to help broaden the eco-design directive beyond energy-related products, thereby improving product durability, reusability, upgradability and reparability and increasing the amount of recycled content. Prioritized areas of intervention include electronics, textiles and ICT (Information and Communication Technology).

In the three years since the adoption of the circular economy action plan, many results have been achieved. The Commission adopted a proposal for a new regulation regarding sustainable batteries (2020); a Global Alliance on Circular Economy and Resource Efficiency (GACERE) was launched in 2021; and new proposals about organic pollutants in wase and waste shipments were adopted.

4. Impact of New CE Regulations for Ecodesign and Digital Product Passport in European Commission

CHAPTER I GENERAL PROVISIONS: Article 1 Subject matter and scope

This Regulation (EU) 2024/178 (13 June, 2024) for the setting of "**ecodesign requirements for sustainable products**" establishes a framework for the setting of **ecodesign requirements** that products have to comply with to be placed on the market or put into service, with the aim of improving the environmental sustainability of products in order to make sustainable products the norm and to reduce the overall carbon footprint and environmental footprint of products over their life cycle, and of ensuring the free movement of sustainable products within the internal market [European Parliament and of the Council, 2024].

This Regulation also establishes a **digital product passport (DPP)**, provides for the setting of mandatory green public procurement requirements and creates a framework to prevent unsold consumer products from being destroyed.

4.1 Regulations Related to Ecodesign Requirements for Sustainable Products

Ecodesign requirements should include, as appropriate, <u>performance requirements</u> or <u>information requirements</u>, or both. Those requirements should be used to improve product aspects relevant for environmental sustainability, such as durability, reusability, repairability, energy efficiency, recyclability, and carbon and environmental footprints. Ecodesign requirements should be transparent, objective, proportionate and in compliance with international trade rules.

The ecodesign requirements shall be such as to improve the following product aspects ('**product aspects**') where necessary supplemented by others, be used, individually or in combination, as a basis for improving the product aspects:

(1) durability;
(2) reliability;
(3) reusability;
(4) upgradability;
(5) repairability;
(6) the possibility of maintenance and refurbishment;
(7) the presence of substances of concern;

(8) energy use and energy efficiency;
(9) water use and water efficiency;
(10) resource use and resource efficiency;
(11) recycled content;
(12) the possibility of remanufacturing;
(13) recyclability;
(14) the possibility of the recovery of materials;
(15) environmental impacts, including carbon footprint and environmental footprint;
(16) expected generation of waste.

4.2 Regulations related to Digital Product Passport for Verification of Product Information

Where a "**Digital Product Passport**" is available, the required information shall be provided therein and shall, where necessary, also be provided in one or more of the following forms:
(1) on the product itself;
(2) on the product's packaging;
(3) on a label;
(4) in a user manual or other documentation accompanying the product;
(5) on a free access website or application.

Information that makes it possible to track substances of concern pursuant to paragraph 5 shall be given either on the product or be accessible through a data carrier included on the product.

The "**Digital Product Passport**" is scheduled to be gradually introduced based on the "2024 EU Sustainable Product Regulation (**ESPR**)" and will initially apply to specific product categories. According to the report, the initial stages will focus on categories such as electronic devices, textiles, and batteries, with potential expansion to other product categories under consideration.
The "Digital Product Passport" requires the inclusion of "**product information**" that covers various aspects throughout the product's entire lifecycle, from its basic characteristics to detailed technical specifications. The purpose of providing this information is to facilitate consumers and recyclers in understanding the environmental impact of products and to promote sustainable usage and proper disposal. The main categories of information required in the "product information" section are as follows.

(1) **Basic Product Information**

- Product Name and Model Number: The name, model, and number of the product.
- Manufacturer: Name of the manufacturer, location, and contact information (for customer support).
- Country of Origin: The country and region where the product was manufactured.

(2) **Information on Materials and Raw Materials**

- Types and Proportion of Materials Used: Proportion of recycled materials, types of materials used such as plastic, metal, and fiber, and their respective proportions.

- Presence of Hazardous Substances: Information on hazardous chemicals contained in the product (e.g., compliance with RoHS regulations).
- Sustainability of Raw Materials: Verification of sustainable sourcing, such as forest certification and use of recycled materials.

(3) **Product Performance and Function**

- Energy Efficiency: Energy consumption and efficiency of the product (with applicable certifications such as Energy Star or eco-labels).
- Functional Specifications: Overview of the primary functions, performance, and durability data of the product.

(4) **Information on Use and Maintenance**

- Product Lifespan: Recommended usage period and estimated lifespan of the product.
- Repairability and Maintenance: Feasibility of repair, repair methods, and availability of replaceable parts.
- Safety Guidelines: Instructions for use and safety precautions to prevent accidents.

(5) **End-of-Life and Recycling Information**

- Recycling Methods: Information on parts that require disassembly, recyclable components, and appropriate recycling facilities.
- Disposal Methods: Environmental impact of improper disposal and guidelines on proper disposal methods.

5. CE International Standards /TC 323

International Standardization in the field of "**Circular Economy**" to develop frameworks, guidance, supporting tools and requirements for the implementation of activities of all involved organizations, to maximize the contribution to Sustainable Development. International standards related to "**circular economy**" are still under development by ISO/TC (Technical Committee) 323 Secretariat. The **ISO 59000 series** of documents are designed to deepen the understanding of the circular economy and to support its implementation and measurement (**Figure 5.1**).

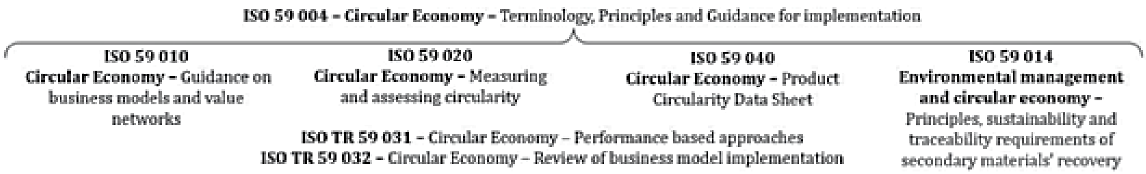

Figure 5.1 The ISO 59000 series of documents [ISO/CD 59004]

5.1 ISO/CD 59004 - Circular Economy – Terminology, Principles and Guidance for Implementation

This document defines key terminology, establishes a circular economy vision and principles for organizations, and provides guidance, including possible actions, for implementation [ISO/CD 59004].

It is applicable to organizations seeking to understand and commit or contribute to a circular economy while contributing to sustainable development. These organizations can be either private or public, acting individually or collectively, regardless of type or size, and located in any jurisdiction, or position within a specific value chain or value network.

This document gives guidance for any kind of organization. It describes the main terms and definitions, a circular economy vision, the circular economy principles, provides practical guidance on actions that contribute to a circular economy, and guidance to implement a circular economy in any kind of organization.

5.2 ISO/CD 59010 - Circular Economy - Guidance on the Transition of Business Models and Value Networks

Circular value creation models continuously improve their resource management practices and contributions to a circular economy and more sustainable business pathways [ISO/CD 59010]. Circular value creation models establish measurable indicators (see ISO 59020) which can track resource use and losses over time, and monitor their impacts on and benefits to society and the natural environment.

In addition to its potential environmental benefits, studies show that a CE offers opportunities worth trillions of United States dollars, including job creation, which builds resiliency in national and international economies. These findings have propelled momentum towards a global circular economy, and as a result, organizations have begun the transition to take advantage of these many opportunities.

However, transitioning from a linear to a circular value creation model can be challenging because it typically demands that an organization’s value creation models and value networks be restructured. Accordingly, this document gives guidance for organizations wishing to transition their linear value creation models and value networks to circular ones. This document is divided into eight clauses, of which Clauses 4 to 8, including their subclauses and interrelationships, are shown in **Figure 5.2**.

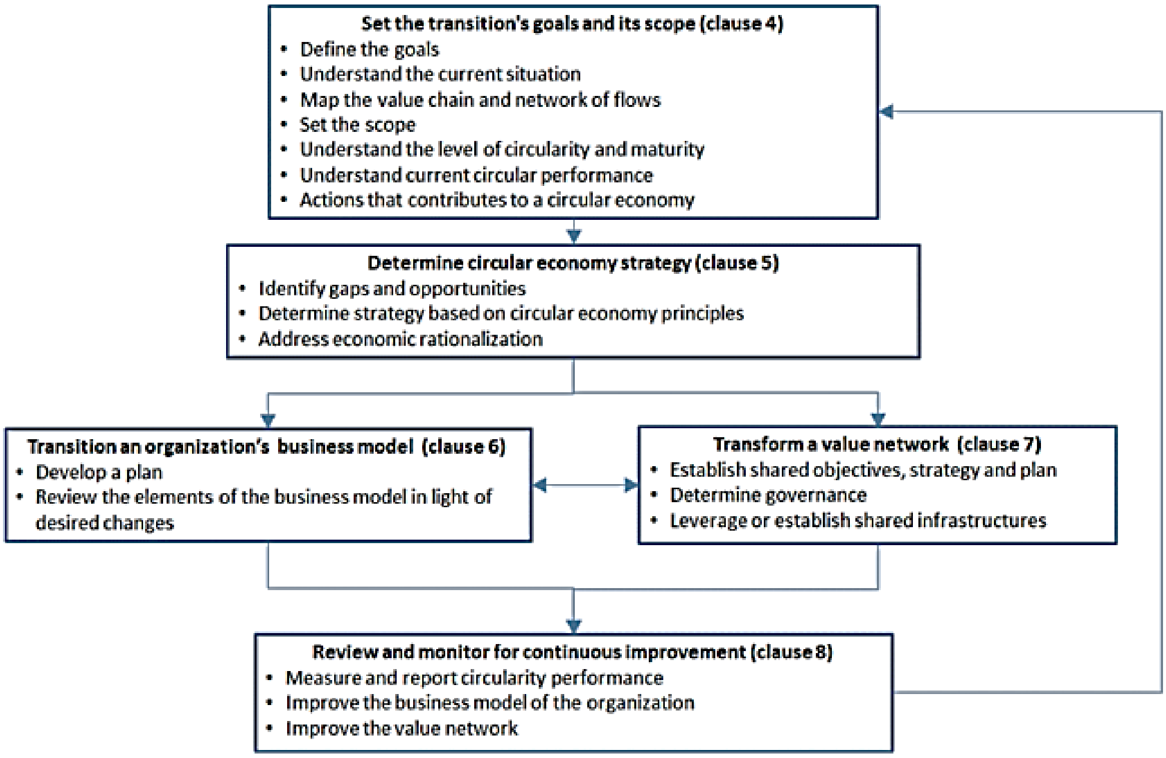

Figure 5.2 The structure of this document: "ISO/CD 59010: Guidance on the transition of business models and value networks" [ISO/CD 59010]

5.3 ISO/CD 59020 - Circular Economy - Measuring and Assessing Circularity

This document specifies requirements and gives guidance to organizations for measuring and assessing a defined economic system to determine their circularity performance at a specific time [ISO/CD 59020]. Measurement and assessment are performed by the collection and calculation of data with the help of mandatory and optional circularity indicators.

This document provides a framework to guide users within organizations of all types and sizes through the measurement and assessment process, including system boundary setting and choice of indicators, as well as processing and interpreting data in a consistent and reproducible manner to generate meaningful and verifiable results. The framework is applicable to multiple levels of an economic system, ranging from regional, interorganizational and organizational to the product level.

To measure and assess social, environmental and economic impacts that are caused by the actions of the organization to achieve circular goals and objectives, the document provides a list of complementary methods that can be used in addition to this document.

5.4 ISO/CD TR 59031 - Circular Economy – Performance-Based Approach – Analysis of Cases Studies

*Status: Under development [ISO/CD TR 59031].

5.5 ISO/CD TR 59032 - Circular Economy – Review of Existing Value Networks

ISO 59010 provides guidance on supporting an organization's business model and processes from linear to circular by transforming an organization's business ecosystem into a value network. The contents of this document support the users of ISO 59010 in providing further detail on the development of value networks in a circular economy. In the development of ISO 59010, a survey was conducted to review and analyze the examples of globally existing value networks.

This document provides an analysis of the survey results [ISO/CD 59032]. It reviews examples of value networks to illustrate their characteristics and structures and how they can accelerate a circular economy transition process, and therefore supports ISO 59010. This document investigates suitable examples of value networks to promote circular economy transition. ISO 59010 gives guidance on a critical aspect in transitioning an organization's business model and processes from linear to circular and transforming an organization's business ecosystem into a value network. This document complements ISO 59010 by providing further information on value networks.

The characteristics and structure of the value networks reflect multiple organization cooperation. The multiple organizations work together to advance their businesses and accelerate their CE transition process. A specific organization does not necessarily control the others. This document addresses the methods used to establish and organize a value network to meet the desired requirements.

This document collects and analyses existing relevant cases, examples of the creation of value networks, to demonstrate what is a value network in the context of the circular economy.

5.6 ISO/CD 59040 - Circular Economy – Product Circularity Data Sheet

*Status: Under development

The document provides a general methodology for improving the accuracy and completeness of circular economy-related information based on the usage of a "Product Circularity Data Sheet" when acquiring or supplying products [ISO/CD 59040].

This general methodology contains then a set of requirements that need to be established by an organization aiming to use the concerned data sheet when acquiring or supplying products, which also includes the trusted reporting and exchanging of circular economy-related information. The document also provides guidance regarding the definition and sharing of the Product Circularity Data Sheet in relation to the type, content and format of information to be provided. This guidance and these requirements are intended to be applicable to all organizations, regardless of type, size and nature.

These requirements implement a qualitative approach to business-to-business data exchange, to ensure inclusivity in relation to small and medium businesses or enterprises, and to protect confidential information.

6. "Circular Economy Vision 2020" Compiled by the Ministry of Economy, Trade and Industry (METI) in Japan

6.1 Background of "Circular Economy Vision 2020"

With the aim to present basic future directions of policies for a CE, the Ministry of Economy, Trade and Industry (METI) conducted surveys on the current state of challenges related to resource circulation at home and abroad, and analyzed the results. As part of this effort, the "Study Group on Circular Economy Vision" held repeated discussions since July 2018 and compiled the discussion results into a report titled "Circular Economy Vision 2020" [METI, 2020].

6.2 Outline of the Circular Economy Vision

In addition to the need to transform to a CE, Japan should consider development of digital technologies and growing demand for environmental considerations from markets and society as new drivers. All industries in Japan should regard this transformation as a new business opportunity that can guide their businesses to a "virtuous cycle of the environment and growth:" this should be considered as a marked shift from the existing 3Rs initiative as a measure for addressing waste and the environment, to new business models with higher circularity as management and business strategies.

With the aim to encourage Japanese companies to exercise their strengths related to mid to long-term industrial competitiveness by advancing their efforts in the 3Rs program, METI compiled the Circular Economy Vision 2020 with three different viewpoints in mind:
[i] shift to new business models with higher circularity,
[ii] acquire appropriate evaluation from the market and society: and
[iii] establish a resilient resource circulation system early to present Japan's basic policy directions for a CE.

In the following, the "[i] shift to new business models with higher circularity" is discussed in particular.

6.3 [i] Shift to new business models with higher circularity

To create a highly cyclical business, it is necessary to make various efforts beyond the traditional 3Rs. It is essential for companies to select appropriate recycling-oriented initiatives according to each industry at every stage of design, production, use, and disposal, and to design circularity throughout the entire product life cycle.

(1) **Artery industry**: Toward a recycling industry that ensures circularity and leads recycling and towards the shift to a CE within all arterial industries, including the manufacturing industry, the distribution industry, and even service platforms that utilize digital technology,

- In addition to the role of the generator of industrial waste (responsibility of the generator).
- It is necessary to design highly cyclical products and business models and build a circulation system that includes recycling.

As described above, it is important to place each used product on the most appropriate collection route and reuse or recycle it in the most appropriate manner, according to its value chain, properties, and emission sources.

- Distribution and collection while maintaining product ownership through leasing, sharing, subscription.
- Efforts should be made to circulate resources throughout the product lifecycle via voluntary collection of used products and the establishment of recycling routes in cooperation with venous industries.

(2) **Venous industry**: Shift from recycling industry to resourcing industry

For daily necessity products that are widely distributed among end consumers, it is difficult to predict collection times and discharge locations. For this reason, the venous industry should collect these various used products over a wide area, and stably supply high-quality recycled materials by actively utilizing automatic sorting technology.

It is important to expand the use of recycled materials by facilitating communication between the arteries and veins regarding the quality, origin, and product characteristics that are necessary when deciding, whether to buy or sell materials based on these quality standards and usage standards. Through these efforts, it is expected that the cost of recycled materials will decrease.

7. Growth－Oriented, Resource-Autonomous Circular Economy Strategy by the METI (2023)

The METI formulated a document titled "Growth－Oriented, Resource-Autonomous Circular Economy Strategy" in March 2023 [METI, 2023]. It is essential to carefully assess and enhance the adequacy of current policy measures from the following three perspectives:

(1) Enhancement of new policy instruments,

(2) Expansion of coverage for existing policies,

(3) Creating a Robust Market Environment.

7.1 Enhancement of New Policy Instruments (Challenge of Discontinuities: Fostering Competition in Competitive Domains)

In line with the objectives of the circular economy, appropriate goal-setting is essential. To avoid dissipation of policy resources, resources should be strategically allocated according to the established goals and their respective intensities.

- Understanding circulation realities (Macro/Micro) and setting targets (clarification of KPIs)
- Establishing obligations to make efforts toward KPIs (qualitative/quantitative)
- Support based on commitments to quantitative targets benefiting circulation

Through initiatives like GX upfront investment support, which includes about a two-trillion-yen investment over the next decade in the resource circulation sector, providing assistance via "Pledge & Support". These measures aim to streamline efforts and effectively allocate resources to achieve circular economy goals.

7.2 Expanding Coverage of Existing Policies (Raising the Baseline: Shifting from the 3Rs to Circular Economy Concepts)

To achieve a transformative, non-linear transition toward a CE, it is essential to shift the foundational approach from the 3Rs (Reduce, Reuse, Recycle) to a broader and more integrated CE framework. This requires elevating the baseline of the existing policy system.

- Deepening the 4Rs (Reduce, Reuse, Recycle, Renewable) Policies
  - Consideration of adding new items to the scope of the Act on the Promotion of Effective Utilization of Resources (3Rs Act), including solar panels, clothing, batteries, etc.
  - Expansion and enforcement of circularity-conscious design
  - Strengthening efficient collection of circular resources
  - Measures to enhance the value of circular resources, such as standardizing labeling
  - Development of the recommerce market, etc.
- Cross-cutting measures for efficient recovery of metal resources and others
- Establishment of cooperative relationships to promote international resource circulation with willing countries, especially in the Indo-Pacific region
- Enhancement of wide-area regional circulation

7.3 Creating a Robust Market Environment (Establishing a Nonlinear Foundation: Expansion of Cooperative Domains)

To achieve a nonlinear transition toward a CE, it is essential to expand cooperative domains through collaboration among relevant stakeholders, as individual corporate efforts alone cannot ensure economic viability. Therefore, industry, government, and academia should work together toward shared goals to develop the necessary market environment.

- Strengthening partnerships among industry, government, and academia
- Creating an environment for data sharing
- Attracting risk capital

Three Gears: Transmission for Growth-Oriented Resource-Autonomous Economy

To accelerate the commercialization of the circular economy in Japan and gain international competitiveness through the establishment of a growth-oriented, resource-autonomous economy, the CE policy framework outlined in "Deepening of 4R Policies" is organized into the following three "gear" packages:

- Gear I: Establishing a Competitive Environment (Regulations & Rules)
  Deepening of 4R Policies
  - Expanding and implementing circularity-conscious design
  - Increasing the supply of circular resources: strengthening efficient collection
  - Expanding demand for circular resources: implementing standardization and life cycle assessment (LCA)
  - Ensuring proper labeling: visualizing circular value
  - Developing the recommerce market: strengthening product safety, etc.

- Improving Collaboration with Overseas Partners
  - Securing critical minerals
  - Aligning regulations and rules (e.g., plastic pollution measures [UNEP], international standardization of circular economy [ISO], development of information-sharing platforms)

Gear II: Circular Economy Toolkit (Policy Support)

- Investment Support for the Circular Economy
  - Support for research and development, and proof of concept (PoC)
  - Support for capital investment, including investment in recommerce
- Support for Digital Transformation (DX)
  - Assistance in building architecture to ensure information traceability
  - Support for the development and implementation of digital systems
- Standardization Support
  - Assistance in establishing quality indicators
- Support for Startups and Ventures
  - Attracting risk capital (circular economy-focused investment)

Gear III: Circular Economy Partnership (Industry-Government-Academia Collaboration)

- Industry: Setting ambitious voluntary targets, committing to them, and managing progress
- Government: Establishing a competitive environment and allocating the Circular Economy Toolkit based on the ambition level of targets
- Developing a Vision and Roadmap
- Solving Issues in Cooperative Domains
  - Developing projects and creating use cases such as establishing a circular economy information platform, standardization, and promoting regional circularity on a wide scale
- Branding the Circular Economy
  - Promoting and embedding circular economy values, education, and corporate management policies

8. Japan Partnership for Circular Economy (J4CE) by Keidanren in Japan

The Japan Partnership for Circular Economy (J4CE) was founded on March 2021 by the Japanese Ministry of the Environment (MOE), Ministry of Economy, Trade and Industry (METI), and Japan Business Federation (Keidanren). J4CE works to strengthen public-private partnerships to foster understanding of the CE among a wide range of stakeholders, including companies in Japan, and to promote initiatives in response to the accelerating global trend toward a CE.

The launch of J4CE attracted wide attention and more than 150 companies and industrial organizations had joined J4CE as of September 2022. Approximately 160 cases and initiatives have been submitted by participating companies and organizations, and all these cases are introduced on the J4CE website. In September 2021, J4CE selected 28 noteworthy cases and initiatives and published a brochure entitled "Noteworthy Cases 2021 Edition." They were also actively involved in international outreach by distributing the brochure at a side event of COP26.

According to the UNEP International Resource Panel (IRP), the extraction and processing of natural resources into materials, fuels and food accounts for about half of all global GHG emissions (excluding climate impacts related to land use). In light of this, when preparing the 2022 and the 2025 edition of the "Noteworthy Cases," they selected cases related to and resource recycling in diverse industries, based on the recognition that promoting the circular economy is also important for advancing decarbonization [Keidanren, 2022 and 2025].

J4CE hopes that the cases will make it widely known inside and outside Japan, that Japanese companies are promoting the CE through their excellent technologies, ideas and collaborations; they also aim to help promote the CE in Japan and around the world by further disseminating these efforts. Below is a table of contents for CE Noteworthy Cases by industry:

[Noteworthy Cases in 2022 Edition]

Noteworthy Area 1: Steel

- Case 01; Steel is a Sustainable Material (Nippon Steel Corporation)
- Case 02; Effective Use of Steel Slag (Same as above)
- Case 03; Building a Recycling Scheme for Scrap Iron (Panasonic Corporation)

Noteworthy Area 2: Non-Ferrous Metals

- Case 04; Recovering Various Types of Valuable Metals Using a Large-scale Smelting and Recycling Complex (DOWA HOLDINGS CO., LTD.)
- Case 05; Processing of Recycled Materials in the Copper Smelting and Refining Business (JX Nippon Mining & Metals Corporation)
- Case 06; Closed Loop Recycle of Lithium-ion Batteries (LiBs) (ENVIPRO HOLDINGS Inc.)

Noteworthy Area 3: Cement

- Case 07; Waste Utilization by Cement Industry (TAIHEIYO CEMENT CORPORATION)
- Case 08; Recycling of Lithium-ion Batteries (Same as above)
- Case 09; Recovery and Recycle System for Precious Metals in Municipal Solid Waste Incineration Residue (Same as above)

Noteworthy Area 4: Paper and Woody Resources

- Case 10; Production and Circulation of Woody Resources (Nippon Paper Industries Co., Ltd.)
- Case 11; Initiatives for Resource Recycling Business: Promote Collection and Recycling of Used Paper Cup Containers – (Same as above)
- Case 12; Development of New Biomass Material: Cellulose Nanofibre – (Same as above)
- Case 13; Towels Made from Japanese Cedar (NEBA Forestry Union, Nagano Prefecture)

Noteworthy Area 5: Bioplastics

- Case 14; Renewable Plant-Based Engineering Bioplastic "DURABIO" (Mitsubishi Chemical Corporation)
- Case 15; Bio-Based and Biodegradable Plastic "BioPBS™" for Agriculture Film (Same as above)
- Case 16; Renewable Plastics from 100% Bio-Based Hydrocarbons (Mitsui Chemicals, Inc.)

Case 17; Eco-friendly Package “Biomass ECO CUP” (NISSIN FOODS HOLDINGS CO., LTD.)

Noteworthy Area 6: Collection and Recycling of Plastic

Case 18; Blockchain-Based Digital Platform for Plastic Traceability (Asahi Kasei Corporation)

Case 19; Collection of Used PET Bottles and Educative Activities for Bottle-to-Bottle Closed Loop Recycling (Japan Soft Drink Association (JSDA))

Case 20; Collaborative Plastic Recycling Program Promoted by Consumers, Local Governments and Companies (Veolia Japan Group, Unilever Japan, Kao Corporation, The Procter & Gamble Company of Japan Limited, Lion Corporation)

Noteworthy Area 7: Recycling Technologies (Home Appliances, Plastic, Textile)

Case 21; Automatic Picking System Using AI (Artificial Intelligence) (Association for Electric Home Appliances)

Case 22; SORPLAS™, Sony’s Proprietary Flame-Retardant Recycled Plastic with up to 99% Recycled Material Utilization Rate (Sony Group Corporation)

Case 23; Chemical Recycling Technology of Polyester (Teijin Ltd., JGC HOLDINGS CORPORATION, ITOCHU Corporation)

Noteworthy Area 8: Formulating a Recycling Loop (Plastic, Food Waste)

Case 24; Closed-Loop Recycling of Label Release Film (NEION Film Coatings Corp., TOYOBO CO., LTD., Shionogi Pharma Co., Ltd., TOPPAN INFOMEDIA CO., LTD., Mitsui Bussan Chemicals Co., Ltd.)

Case 25; Self-Contained Food Recycling Loop (AEON Co., Ltd., DAIEI KANKYO Co., Ltd., AEON AGRI CREATE CO., LTD., AEON RETAIL Co., Ltd. | The Daiei Inc.)

Case 26; Yokohama Food Recycle Project (JFE Engineering Corp., J&T Recycling Corp., Urban Energy Corp., East Japan Railway Company, JR East Environment Access Co., Ltd., J Bio Food Recycle Corp.)

[**Noteworthy Cases in 2025 Edition**]

- **Case 01 - Plastic packaging containers**: Collection of refill packs and horizontal recycling
- **Case 02 - Plastic**: Public-private partnership initiatives for plastic resource circulation
- **Case 03 - Plastic**: Acquisition and utilization of the Type 2 certification for resource recycling business plans under the Plastic Resource Circulation Promotion Act
- **Case 04 - Plastic**: Sustainable Plastics Initiative (SusPla): A dynamic-static collaboration organization aiming to expand the market for recycled plastics
- **Case 05 - Plastic packaging**: Achieving complete polystyrene recycling through the world's first dissolution-separation recycling technology and a four-party integrated recycling loop
- **Case 06 - Disposable diapers**: Establishment of a circular model throughout the product lifecycle by realizing a recycling system for used disposable diapers
- **Case 07 - Construction by-products**: Collection system utilizing the wide-area certification system

- **Case 08 - Construction plastic waste**: Accelerating resource circulation (3R) and decarbonization at construction sites using a digital platform
- **Case 09 - Construction flat glass waste**: Demonstration test on the recycling of waste flat glass from construction sites
- **Case 10 - Packaging materials**: Circular platform "De-Owarasenai PLATFORM" (Beyond Disposability PLATFORM)
- **Case 11 - Plastic**: Realizing "Car to Car" recycling through resource recovery of end-of-life vehicle plastics
- **Case 12 - Small household appliance plastic**: Accelerating the recycling of waste plastics derived from small household appliances
- **Case 13 - Disposable diapers**: Material recycling system for disposable diapers
- **Case 14 - Plastic**: Chemical recycling of acrylic resin – Circulating the beauty of transparent resin along with carbon
- **Case 15 - Household unwanted items**: "PASSTO" resource circulation service for seamless collection, sorting, and redistribution of unwanted goods toward a circular economy
- **Case 16 - Household unwanted items**: Demonstration experiment on reuse promotion by Mercari, Yakult Sanyo, Akitakata City, and Miyoshi City
- **Case 17 - Tires**: Contribution to resource efficiency through remote tire pressure monitoring service
- **Case 18 - Infrastructure**: Prolonging service life through maintenance of infrastructure structures

9 Evolution of CE Legislation in Japan

9.1 Basic Law on Resources

"**Basic Law on Resources**" (officially titled "Law for the Promotion of the Effective Utilization of Resources") was established by the Ministry of Economy, Trade and Industry (then called the Ministry of International Trade and Industry) in 1991 and plays a significant role as a policy foundation related to the CE. The core principles of this law are the sustainable use of resources and the decreasing of environmental burdens through waste reduction. Specifically, it aims to enhance overall resource efficiency in society by providing guidelines that promote 3Rs (reduce, recycling, and reuse), and it aims to improve resource efficiency for businesses and consumers.

Building on the Basic Law on Resources, Japan has enacted industry-specific recycling laws facilitating the efficient reuse of resources and the appropriate management of waste. Representative examples of these industry-specific recycling laws include:

- **Home Appliance Recycling Law** (enforced in 1998): Mandates the recycling of home appliances such as televisions, refrigerators, washing machines, and air conditioners, establishing a system where manufacturers and consumers share the costs of recycling.
- **Food Recycling Law** (enforced in 2001): Promotes the reuse of food waste with the aim of utilizing it for the production of animal feed and fertilizers.

- **Automobile Recycling Law** (enforced in 2005): Systematizes the dismantling and reuse of automobiles by mandating the proper disposal of airbags and fluorocarbons.
- **Small Appliance Recycling Law** (enforced in 2013): Promotes the reuse of precious metals and rare metals contained in small electronic devices, such as mobile phones and digital cameras.

However, there are several disadvantages and limitations associated with these industry-specific recycling laws:

- **Lack of consistency among industries**: Differences in standards across industries can lead to inefficiencies in resource circulation.
- **Increased expenses**: The rising costs of recycling may decrease economic rationality.
- **Vertical Structure**: Cooperation among different industries is difficult, making the recycling of composite products challenging.
- **Delayed response to new technologies**: Laws may not be able to keep up with the advancements in new materials and technologies.
- **Insufficient consumer participation**: The lack of awareness among consumers regarding recycling necessitates efforts to promote their participation.
- **Incompatibility with international standards**: Japan's unique regulations may act as a barrier in the international market.

9.2 The 6th Basic Environmental Plan

The "**6th Basic Environmental Plan**", established on May 21, 2024, introduces new measures aimed at realizing a sustainable society [Ministry of the Environment, 2024(1)]. This plan strengthens responses to environmental challenges and promotes the CE advancement. In particular, it emphasizes the importance of promoting recycling and efficient resource utilization with an expectation that these efforts will contribute to reducing environmental impact while ensuring consistency with existing regulations.

The 6th Basic Environmental Plan also sets forth policies to address a broad spectrum of environmental issues, including climate change countermeasures and biodiversity conservation. Furthermore, it emphasizes collaboration with industry and proposes specific targets and measures to provide guidance for local governments and businesses to engage actively. In this way, the revisions to regulations aim to deepen environmental policies and enhance sustainability efforts.

To advance environmental policies concretely, six priority measures have been outlined for key environmental fields, focusing on environmental, economic, and societal perspectives:

(1) Climate change countermeasures
(2) **Formation of a circular society**
(3) Securing biodiversity and harmonizing with nature
(4) Management of environmental risks, etc.
(5) Foundational measures for various policies

(6) Reconstruction and revitalization following the Great East Japan Earthquake, and preparedness and response to future major disasters

Focusing on "**(2) Formation of a Circular Society**", the following details outline the expansion of the CE activities.

Developing sustainable communities and societies through the CE transition for circular society formation

To enforce effective CE approaches for resource efficiency and for circularity improvements across the entire value chain, and to connect the CE with net-zero (aiming for zero waste) or with nature-positive initiatives, or by implementing integrated measures related all three.

Inter-enterprise collaboration for comprehensive resource circulation throughout the entire lifecycle

To accelerate resource circulation, a coordinated approach between "arterial industries" (e.g., manufacturing and retail) and "venous industries" (e.g., waste management and recycling) will be fostered. This collaboration will support the creation of a resilient resource circulation market over the medium-to-long term.

Establishing diverse regional circulation systems and implementing regional revitalization

To form sustainable regions and a circular society with high resource productivity, this plan will promote initiatives that will take into account the local natural capital and implement the appropriate circulation scale for each region and resource. Efforts will include the continuous use of renewable resources within regions, effective maintenance of regional stock to use as extensively and wisely as possible, and reduction of input resources and generated waste amounts, ultimately fostering sustainable and vibrant communities.

Strengthening resource circulation and waste management infrastructure, and implementing robust, appropriate disposal and environmental restoration

This plan aims to reinforce waste management infrastructure through utilizing digital technology, robotics, and traceability systems that will strengthen resource circulation and facilitate decarbonization in the sector by advancing recycling processes such as, dismantling, shredding, and sorting used products, promoting biomass and recycled material use, establishing 3R principles for the rapidly spreading new products and materials, and making environmental burdens visible. Additionally, data platforms will be developed to enhance resource circulation information and promote arterial-venous collaboration.

Establishing an appropriate international resource circulation framework and promoting overseas expansion of the circular industry

Through platforms such as the G7, G20, OECD, and ASEAN, as well as bilateral and multilateral collaborations, Japan will address the international agreements related to 3Rs including the CE, resource efficiency policies, and resource circulation. Japan will also lead the discussions on the responsible trade of recyclable waste, plastic pollution measures, and international resource circulation.

9.3 The Advanced Resource Recycling Act

The **Advanced Resource Recycling Act** (Act on the Advancement of Resource Recycling Businesses to Promote Resource Circulation) was enacted by the Ministry of the Environment on April 9, 2024 [Ministry of the Environment, 2024(2)] The purpose of the Act is to contribute to environmental protection by promoting efficient resource recycling practices and reducing greenhouse gas emissions through improved productivity in recycling processes. This act introduces measures to advance the technologies and facilities involved in waste collection, transportation, disposal, and recycling to achieve highly effective resource circulation. Through these actions, the Act seeks to enhance the efficiency and effectiveness of resource recycling systems, thereby supporting sustainable environmental management and economic growth.

The term "**advancement of resource recycling businesses**" in this act refers to measures that enhance greenhouse gas reduction in recycling processes through one of the following approaches:
Efficient Recycling for Demand-Driven Production: Conducting recycling operations (including collection, transportation, and disposal) to meet the needs of manufacturers, processors, or retailers, while focusing on efficient recycling practices.
Productivity Improvement: Advancing technologies for separating valuable materials from waste to increase the productivity of recycling.
Introduction of Equipment for Efficiency in Recycling: Measures to introduce equipment for streamlining the recycling process and other measures aimed at reducing the volume of greenhouse gas emissions generated from that process.
In addition to the measures listed above, other measures contributing to the reduction of **greenhouse gas emissions** associated with the implementation of recycling are

Businesses can create and submit an advanced resource recycling plan that corresponds to one of the four aforementioned measures. If the plan meets the specified criteria, the submitted company can receive "certification" from the Minister of the Ministry of the Environment as an Advanced Resource Recycling Operator. This certification acknowledges the company's commitment to high-efficiency recycling practices and contributes to overall environmental sustainability efforts.

9.4 The Fifth Fundamental Plan for Establishing a Robust Material Cycle Society

The **Basic Act for Establishing a Robust Material Cycle Society** was enacted in year 2000 under the jurisdiction of the Ministry of the Environment. Based on this law, the Fundamental Plan for Establishing a Robust Material Cycle Society has been formulated. This plan is reviewed approximately every five years. In 2023, the Minister of the Ministry of the Environment submitted an inquiry to the Central Environment Council regarding the plan's revision. Following deliberations,

the fifth fundamental plan was approved by the Cabinet on August 2, 2024 [Ministry of the Environment, 2024(3)].

Overview of the Fifth Fundamental Plan for Establishing a Robust Material Cycle Society

The transition to a CE is a critical national policy issue that should be addressed as a state strategy. It not only addresses environmental challenges such as climate change, biodiversity conservation, and pollution prevention, but also contributes to solving social issues like "strengthening industrial competitiveness", ensuring economic security, revitalizing local communities, and achieving a "high quality of life."

The key issues, policy responses, and envisioned future scenarios that are particularly closely related to CE within the context of "strengthening industrial competitiveness" and achieving a "high quality of life" are summarized in **Table 9.1.**

Table 9.1 Points of **CE Relevance** in "Strengthening Industrial Competitiveness" and Achieving a "High Quality of Life"

Key Issues / Background	Main Policy Responses	Future Achieving Goals
- Movement to strengthen the **use of recycled materials** in batteries, automobiles, packaging, etc.	- Expansion of the use and supply of **recycled materials** through **environmentally considerate designs** and **advanced resource recycling**. - Leading the formation of **international rules for value chain circularity**.	- Realization of thorough **resource circulation throughout the entire lifecycle**. - Establishment of **domestic and international resource circulation systems**. - Improvement of **product and service competitiveness**. - Enhancement of **Japan's international presence**.
- Increased global demand for resources leading to **competition for resource acquisition**. - Rising prices and supply concerns for **minerals and other resources**.	- Maximization of the recycling and utilization of **imported minerals, food, and other resources**. - Strengthening **domestic and international resource circulation for minerals** and other materials.	
- **Need to shift away** from a society characterized by **mass production, mass consumption, and mass disposal**.	- **Transitioning lifestyles** through the use of recycled materials in products, reuse and repair, and reduction of food and fashion waste.	- Achieving a high quality of life by **transforming behaviors and lifestyles from diverse choices**.

Resource Circulation Throughout the Entire Lifecycle through Inter-Enterprise Collaboration

In this fundamental plan, the CE transition is positioned as a national strategy, with **five key priority areas** established as important directions, aiming for the target year of 2030. For the realization of these priority areas, specific initiatives, along with evaluation indicators and numerical targets corresponding to these initiatives, have been set. The following are the five key priority areas:

- Developing sustainable communities and societies through the CE transition for circular society formation.
- Inter-enterprise collaboration for comprehensive resource circulation throughout the entire lifecycle.
- Establishing diverse regional circulation systems and implementing regional revitalization.
- Strengthening resource circulation and waste management infrastructure, and implementing robust, appropriate disposal and environmental restoration.
- Establishing an appropriate international resource circulation framework and promoting overseas expansion of the circular industry.

Among those five key priority areas, particularly relevant to "**CE business strategy and CE value chain management**" is "Inter-enterprise collaboration for comprehensive resource circulation throughout the entire lifecycle." This area emphasizes the importance of collaboration among companies and businesses to effectively implement resource circulation strategies.

[Background]

- Through inter-enterprise collaboration between the [**artery industries**], such as manufacturing and retail, and the [**vein industries**], such as waste management and recycling (known as [**artery-vein collaboration**]), advanced examples of circular economy (CE) are beginning to emerge, creating new value in the market.

[Medium-to-Long Term Direction]

- Through inter-enterprise collaboration, support the creation of a resilient resource circulation market in the medium-to-long term by expanding the use and ensuring the stable supply of recycled materials.
- Promote thorough resource circulation across the entire lifecycle for resources that are important from the perspectives of environmental impact, waste generation, and contributions to decarbonization:
  - Waste plastics and waste oils
  - Utilization of biomass technologies (including waste-derived biomass, underutilized resources, food waste, sewage sludge, wood, paper, and sustainable aviation fuel [SAF])
  - Improvement of recovery rates and recycling of used products containing base metals and rare metals
  - Promotion of construction recycling with an emphasis on "quality" for used earth, rocks, and construction materials

- Promote business models that maximize service offerings and added value while effectively utilizing stocks:
  - Containers and packaging
  - Buildings
  - Automobiles
  - Small home appliances and electronics
  - Textile products (fashion)
  - For products and materials that have become widespread due to global warming countermeasures, clarify the policy direction for each product.

10. Conclusion

Chapter 3 explained the development of various CE policies within the European Commission. The "New CE Regulations for Ecodesign and Digital Product Passport," discussed in Chapter 4, require particular attention because these regulations will enter the phase of developing concrete implementation plans for each industry in approximately a few years. Once these regulations will be enacted, they will not only impact businesses operating within the EU but also have significant implications for all companies that trade with the EU on a global scale.

Chapter 9 investigated evolution of circular economy legislations in Japan. “Basic Law on Resources” was established in 1991 and played a significant role as a policy foundation related to the circular economy. Building on the Basic Law on Resources, Japan had enacted industry-specific recycling laws, facilitating the efficient reuse of resources and the appropriate management of waste.

The “6th Basic Environmental Plan”, established on May 21, 2024, introduced new measures aimed at realizing a sustainable society. To advance environmental policies concretely, six priority measures had been outlined for key environmental fields, especially including “Establishment of a Circular Society.”

The “Advanced Resource Recycling Act” was enacted by Ministry of the Environment on April, 2024. Businesses can create and submit an advanced resource recycling plan that corresponds to one of the four aforementioned measures. If the plan meets the specified criteria, the submitted company can receive “certification” from the Minister of the Environment as an Advanced Resource Recycling Operator.

The “Fifth Fundamental Plan for Establishing a Robust Material-Cycle Society” was approved by the Cabinet on August, 2024. The descriptions of the “Future Vision for Resource Circulation and Circular Economy Business Models” regarding "Resource Circulation Throughout the Entire Lifecycle through Inter-Enterprise Collaboration" had been extracted from the basic plan report.

Acknowledgements

This research was conducted as part of the Grant-in-Aid for Scientific Research Activity in Japan (2022–2025), which aimed to contribute to the “development, empirical research, dissemination of new theories and system techniques for the circular economy to meet the responsibility for the production and consumption of SDGs". It was further supported by a research grant from the Global Business Research Institute at Aoyama Gakuin University.

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Automotive Sector

Business Models for Circular Value Creation: Advanced Case Studies in Automotive Industry

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Abstract

The automotive industry is at the forefront of adopting circular business models, demonstrating how sustainability and profitability can go hand-in-hand. These models contribute to a more sustainable future while creating new revenue streams, reducing waste, and extending the lifecycle of automotive products. In our study we use the circular business model classification frameworks by Accenture (2014) to study the most discussed circular economy business model archetypes in the literature and apply them to the practice. By applying these archetypes we analysed three main automobile manufacturing companies in Japan, such as Toyota, Honda and Nissan Motor Corporation to investigate their adopting business models and their best practices. This study provides some advanced case studies within the automotive industry that illustrate how circular business models are being implemented and how car manufacturers create a value-generating systems in CE context.

Keywords: Circular Economy (CE), archetypes of CE business models, automobile companies.

1. Introduction.

The linear take-make-waste industrial model is no longer viable in the face of rapid population growth, resource constraints, urbanization, water insecurity and other trends. It is time for new paradigm is giving way to the circular economy, a model that focuses on careful management of material flows through product design, reverse logistics, business model innovation and cross-sector collaboration.

As a business model innovation tool, literature categorizes business models for a circular economy from different perspectives. Scholars and practitioners proposed numbers of frameworks of business model in terms of CE. However, in our study we use the circular business model classification frameworks by Accenture (2014) to study the most discussed circular economy business model archetypes in the literature and apply them to the practice. By applying these archetypes we analyse three main automobile manufacturing companies in Japan, such as Toyota, Honda and Nissan Motor Corporation to investigate their adopting business models and their best practices. Accordingly, to conduct this study our research looks to answer the following questions:

What advanced CE business models are implemented in Japanese automobile companies? How mature are automotive organizations in implementing their circularity initiatives?

This report addresses these questions by drawing together insights from the existing literature on circular business models. The other part of our report as follows: Section 2 introduces the Circular business model definition and the typology of key circular business models; Section 3 explains the methodology of conducting the research process; Sections 4 and 5 provide the advanced case examples of business models adoption in Japanese auto industry and comparative analysis. The last sections conclude and give the main sources that are used for this study.

2. Background.

2.1. What is a circular business model?

The Circular economy (CE) is a system that is designed to be restorative and regenerative in order to transition current linear production and consumption patterns to cyclical ones that remove waste from the system. CE is increasingly seen as way to contribute to sustainable development. To contribute to redesign for the CE, we must all make changes in the way we produce, consume and manage waste. The business model is one of the main themes and building blocks of circular economy thinking in which business model innovation takes a crucial part in the success of a circular economy (Linder and Williander, 2017).

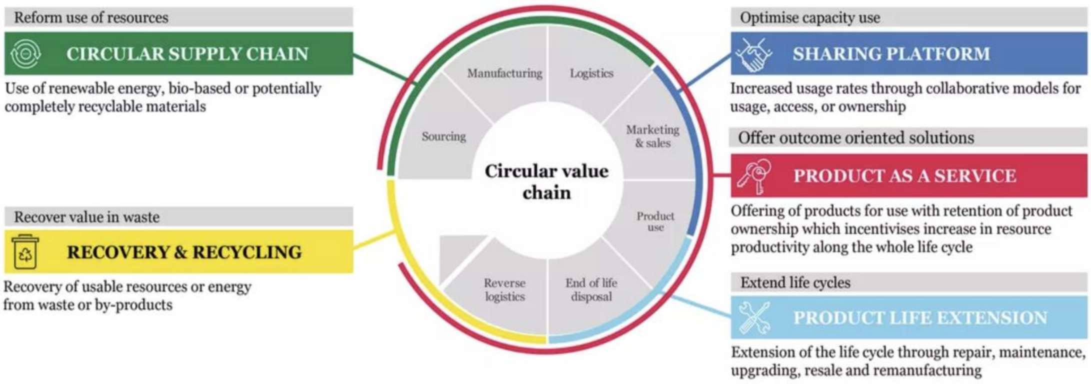
One way for organizations to contribute to the CE is through circular economy business models (CEBM). CEBMs work to reduce resource use and waste within production, but also to extend product life cycles and employ strategies that allow the consumer to do more than buy, use and dispose (NTNU, 2024).

A circular business model articulates the logic of how an organization creates, delivers, and captures value to its broader range of stakeholders while minimizing ecological and social costs (BOI, 2024).

2.2. What kind of circular business models are there?

The literature on circular business models is growing rapidly and contains a variety of models and frameworks. The categorization of circular business models made Accenture (2014) focuses on classifying business models according to their role within the circular economy and showing the product outcome of such a business model. In this report we adopted the business model archetypes created by Accenture (2014).

The five types of circular business models addressed in this report are: (i) circular supply models, (ii) resource recovery models, (iii) product life extension models, (iv) sharing models, and (v) product service system models.



Picture 1. Five business models for circular growth - Accenture (Accenture, 2014)

Tirufat et al., (2023) investigated and analysed frequency of usage the business models by Accenture (2014) (Figure 1).

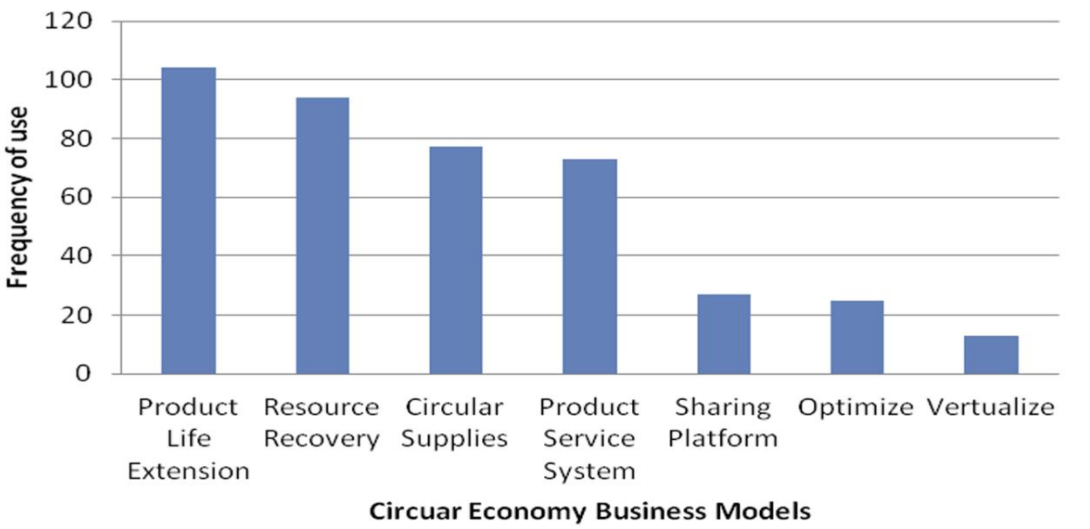


Figure 1. Most investigated business models in the circular economy literature (adapted from Tirufat et al, 2023)

From the analysis of Tirufat et al., we can see that majority of companies prefer to adopt CE strategies for **Extend their product life span** and **Recovery of resources**, where other models such as **Sharing platforms, Optimize and Virtualize** less popular. On the Table we provided the characteristics for the more preferable circular business models giving their key characteristics, resource efficiency driver and business model sub-types.

Table 1. Circular Business Models characteristics (Adopted by OECD, 2019)

	Circular supply	**Resource recovery**	**Product life extension**	**Sharing**	**Product service system**
Key characteristic	Replace traditional material inputs with renewable, bio based, recovered ones	Produce secondary raw materials from waste	Extend product lives	Increase utilisation of existing products and assets	Provision of services rather than products. Product ownership remains with supplier
Resource efficiency driver	Close material loops	Close material loops	Slow material loops	Narrow resource flows	Narrow resource flows
Business model sub-types	Cradle to cradle	Industrial symbiosis Recycling Upcycling Downcycling	Classic long life Direct reuse Repair Refurbishment Remanufacture	Co-ownership Co-access	Product-oriented User-oriented Result-oriented

Description of models.

1. *Circular Supply-Chain*

When a company needs resources that are scarce or environmentally destructive, it can either pay more or find alternative resources. The Circular Supply-Chain introduces fully renewable, recyclable or biodegradable materials that can be used in consecutive lifecycles to reduce costs and increase predictability and control. One example: CRAiLAR Technologies Inc., a company that produces renewable biomass resources using flax and hemp to create fibers as good as cotton without the environmental impact.

2. *Recovery & Recycling*

The Recovery & Recycling model creates production and consumption systems in which everything that used to be considered waste is revived for other uses. Companies either recover end-of-life products to recapture and reuse valuable material, energy and components or they reclaim waste and by-products from a production process. Like Procter & Gamble Company (P&G)—the company operates 45 facilities on a zero waste basis.

3. *Product Life-Extension*

Consumers discard products they no longer value—because the products are broken, out of fashion or no longer needed. But many of these products still hold considerable value, and the Product Life-Extension model seeks to recapture it. By maintaining and improving products through repairs, upgrades, remanufacturing or remarketing, companies can keep them economically useful for as long as possible. This means shifting from merely selling things to actively keeping them alive and relevant.

It also means moving customers from transactions to relationships, tailoring upgrades and alterations to specific needs. Through its refurbishment business, Dell Inc. Computers takes back old equipment and resells units when possible.

4. Sharing Platform

In developed economies, up to 80 percent of the things stored in a typical home are used only once a month.5 The Sharing Platform model—increasingly assisted by new forms of digital technology—forges new relationships and business opportunities for consumers, companies and micro-entrepreneurs, who rent, share, swap or lend their idle goods. Fewer resources go into making products that are infrequently used, and consumers have a new way to both make and save money. Examples include Uber Inc., Airbnb Inc. and Lyft Inc. among a growing field.

5. Product as a Service

What if manufacturers and retailers bore the "total cost of ownership?" Many would immediately adjust their focus to longevity, reliability and reusability. When consumers lease or pay for products by use through the Product as a Service model, the business model fundamentally shifts—in a good way. Performance trumps volume, durability tops disposability, and companies have an opportunity to build new relationships with consumers. (Lacy and Rutqvist, 2015)

3. Methodology.

The report employs a theoretical approach to examine literature related to circular business models by scholars and practitioners with the aim to analyse and determine automotive companies advanced cases in terms of CE. Three Japanese automotive companies, Toyota, Honda and Nissan, were used to investigate the best practices in the industry. In this regard, companies annual Sustainability Reports, Industrial Reports were reviewed to conduct the case study research. Moreover, the findings indicate the comparative analysis of companies in the context of implementation circular business strategies and their characteristics.

4. Findings.

Findings from the analysis reports of auto manufacturers illustrate great interest of companies in the Circular Economy practices adoption. To achieve the high circularity of resources and maximize the value creation they apply for different circular business models. Below Table describes business models adopted by automotive companies and their best practices directed to value creation.

Table 2. Analysis of companies' circularity business models

Automotive companies	Circular Business Models	Best practices
Toyota	*Circular Supply-Chain* *Recovery & Recycling* *Product Life-Extension*	Creation of a closed-loop battery ecosystem Establishing a Recycling-based Society (Reducing Waste by Reusing Coolant)
Honda	*Recovery & Recycling* *Product Life-Extension*	Achieving Horizontal Recycling by Maximizing the Use of End-of-Life Products Creating Economic Viability in Resource Circulation (5 principles of Resource Circulation Concept)
Nissan	*Circular Supply-Chain* *Product Life-Extension*	4R Business strategy Second life of EV batteries

Company 1: Toyota Motor Corporation

a) <u>Circular Supply-Chain</u>

Creation of a closed-loop battery ecosystem

Toyota is implementing a number of sustainable strategies aimed at the creation of a circular economy for its electric vehicles, including the reuse and recycling of lithium batteries under its Battery 3R initiative to reduce, rebuild/reuse and recycle.

On top of developing "resource-efficient and long-lasting" batteries to build in longevity and minimise waste, the carmaker is looking at finding a second life for batteries once their use in EVs is finished, either in automotive or non-automotive applications. In addition, once the batteries have reached end-of-life, Toyota said it is looking at recycling them in a sustainable way that cuts the amount of CO2 produced by the recycling process and allows as much material as possible to be reused for new battery production.

As part of its Seventh Toyota Environmental Action Plan the carmaker has targets to implement Battery 3R throughout China, Japan, and wider Asia, Europe and the US by 2025. It also aims to maximise the collection and detoxification of end-of-life batteries globally. In this regard, Toyota is working with a number of partners to realise these goals.

Toyota Motor North America (TMNA) is expanding on its collaboration with lithium battery recycler Redwood Materials for the reuse of end-of-life EV batteries. In November 2023 year it announced an agreement for Toyota to source cathode active material (CAM) and anode copper foil from Redwood's recycling activities for Toyota's future, new automotive battery production.

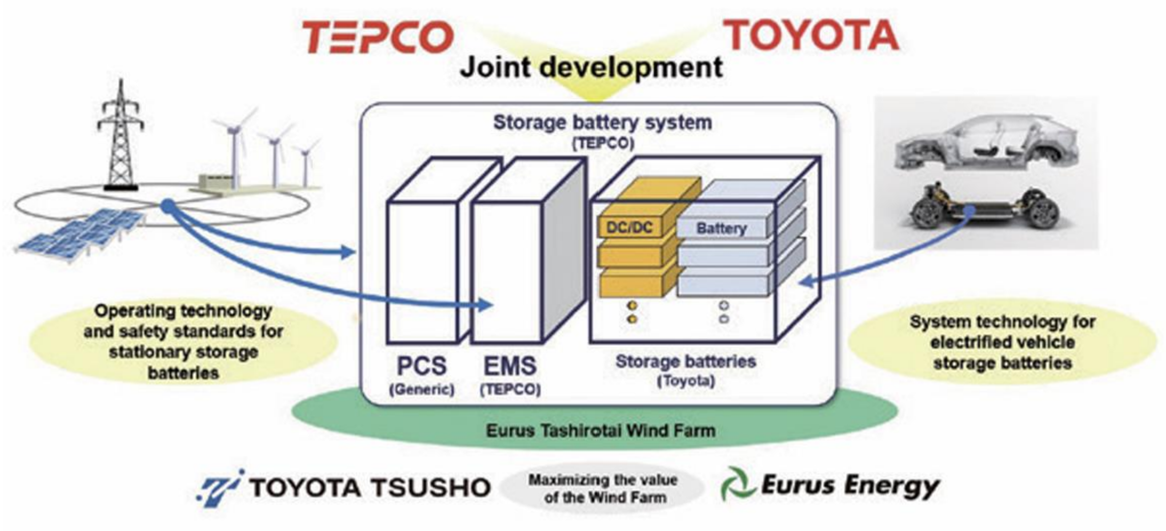
Picture 2. Battery 3R initiative

"Working with Redwood Materials, we are creating a circular supply chain to optimise logistics, expand refining, and ensure that the valuable metals recovered can be reintroduced into our future vehicles. Accelerating our recycling efforts and domestic component procurement gets us closer to our ultimate goal of creating a closed-loop battery ecosystem that will become increasingly important as we add more vehicles with batteries to roads across North America." said Christopher Yang, group vice-president of business development, TMNA (https://www.automotivelogistics, https://pressroom.toyota.com/).

Case: Development and verification of stationary storage battery systems

Tokyo Electric Power Company Holdings, Inc. (TEPCO HD) and Toyota developed a stationary storage battery system (1 MW output, 3 MWh capacity) that combines TEPCO's operating technology and safety standards for stationary storage batteries and Toyota's system technology for used electrified vehicle storage batteries.

Toyota Tsusho Corporation and Eurus Energy Holdings Corporation installed this system at the Eurus Tashirohira Wind Farm, with a demonstration test now underway (Toyota Sustainability Report, 2024).



Picture 3. Battery Reuse

b) ***<u>Recovery and Recycling</u>***

Establishing a Recycling-Based Society

To establish a recycling-based society, Toyota has been striving to reduce and recycle waste and minimize the usage of and environmental impact on water resources.

Toyota continues to use easy-to-recycle materials to promote resource recycling of end-of-life vehicles.

■ Having visited and surveyed dismantlers around the world since the launch of the Raum passenger car in 2003, Toyota actively adopts vehicle structures for new vehicles that make it easy to dismantle and separate parts to ensure safe and speedy dismantling operations.

■ Vehicle models released in 2023 with easy-to-dismantle designs Century (SUV), Crown series, Alphard, Vellfire, Lexus (RZ, LBX, LM).

■ Toyota's recyclability rate based on vehicle design values is 85% or more, and the recoverability rate including energy recovery is 95% or more.

■ Under the "Challenge of Establishing a Recycling-based Society and Systems", Toyota Motor Corporation regards the end-of-life stage as the start of the life cycle as they implement initiatives in development and design, production, and sales and services. At each stage, Toyota strives to reduce the amount of waste generated, and reuse waste and recycle end-of-life vehicles in order to improve resource efficiency (Toyota Sustainability Report, 2024)

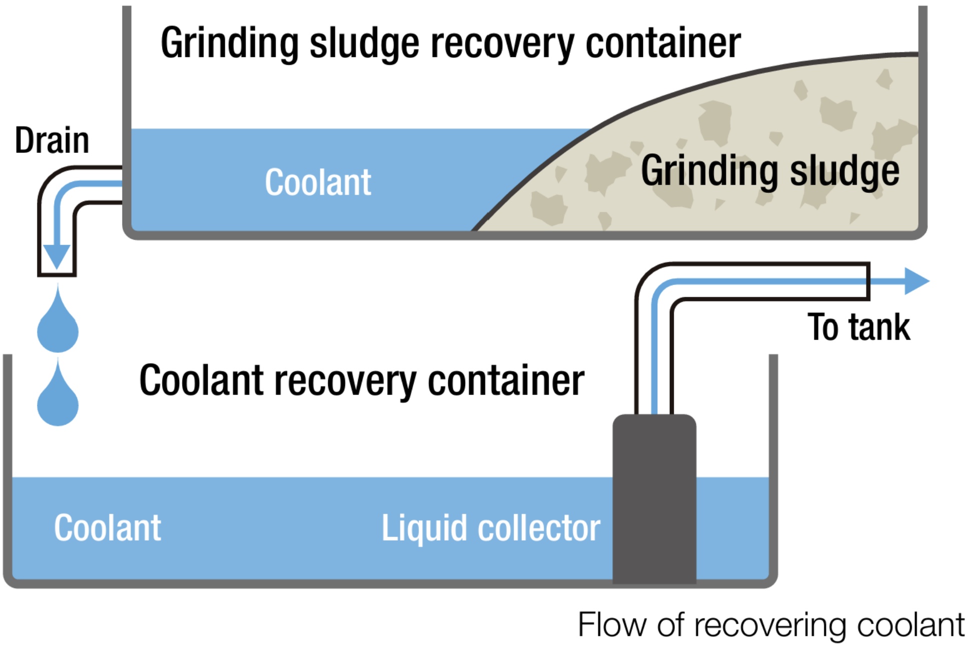
Case: Use of marine litter in products.

In an effort to help mitigate the worldwide issue of marine plastic litter, they are examining the potential of collecting PET drink bottles that have washed ashore on Japan's beautiful islands, cleaning and shredding them, and then using them as a component of the raw materials used to manufacture automobiles (Toyota Sustainability Report, 2024).

Picture 4. Use of marine litter in seat upholstery

Case: Reducing Waste by Reusing Coolant

The Higashiura Plant, a production base of car air conditioning compressors in Aichi Prefecture, has been proactively working to reduce its waste generation volume. Polishing, a process in the manufacture of compressor parts, generates a large volume of grinding sludge, which is a mixture of polishing dust and coolant (cooling liquid used to reduce thermal damage and abrasion). The plant examined the grinding sludge discharged into a recovery container and found that it contained about 1.4 kg/h of coolant. The plant accordingly launched a project based on the idea that reducing the discharge of the coolant might lead to less grinding sludge. In order to solely recover the coolant from the grinding sludge, the plant first added a coolant discharging drain and coolant recovery container to the grinding sludge recovery container. It then installed a liquid collector in the coolant recovery container so that the coolant, which had been discarded with the grinding sludge, would be returned to a tank for reuse. The liquid collector takes power from a coolant supply pump used in the existing equipment and does not need additional energy for air suction. As a result, the process was able to reduce its monthly waste by about 1.2 tons without increasing CO2 emissions (Toyota Sustainability Report, 2022).



Picture 5. The process of reducing the discharge of the coolant

Case: Reducing Use of Resources by Unifying Skids

Kirloskar Toyota Textile Machinery Pvt. Ltd. (KTTM), a textile machinery production subsidiary in India, has been promoting production activities to minimize its use of resources. KTTM uses skids, a type of pallet, to make it easy to handle and carry cargo by lift trucks when shipping products. Previously, it used a total of eight types of skids with different shapes and sizes, four metal ones for exporting and four wooden ones for transportation within India. Wooden skids are prone to defects during assembly. Compared to metal skids, they are also difficult to reuse, thus consuming a large amount of resources. Coupled with the need for a large space to store these multiple types of skids, KTTM started examining the possibility of integrating the eight types into one metal type. The results showed that the unification of the existing skids was difficult due to their structures and from the perspective of the efficiency of loading onto containers. KTTM thus decided to design a new, general-purpose metal skid for both export and domestic shipping. The company also asked its customers in India to switch from non-reusable wooden skids to the new metal skids. Consequently, KTTM abolished the use of wooden skids and reduced its annual use of wood materials by 13.7 tons, achieving less use of natural resources overall (Toyota Sustainability Report, 2023).

Picture 6. Newly designed metal skid

Case: Development and verification of battery recycling without incineration

Toyota Tsusho Corporation and Toyota Chemical Engineering Co., Ltd. have started a joint verification.

Lithium-ion batteries contain flammable electrolytes, since they have been traditionally processed in incinerators.

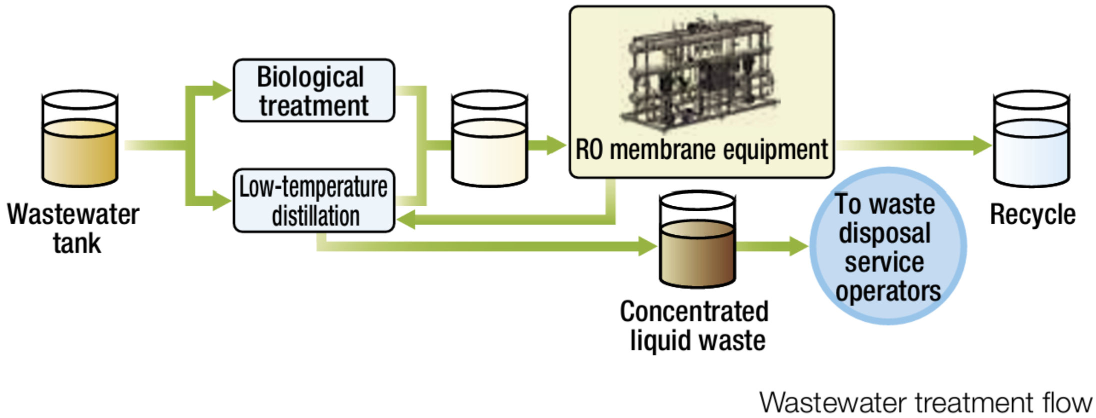
The new recycling method can reduce CO2 emissions and improves resource recovery rates by directly feeding the batteries into recycling facilities where they are crushed rather than incinerated.

This method makes it possible to sort and recover valuable materials, including rare metals, and extracted electrolytes, with the aim of promoting the circulation of resources (Toyota Sustainability Report, 2024).

Picture 7. Materials recovered from recycled batteries

Case: Achieving Zero Wastewater from Production Processes by Recycling Wastewater

In July 2023, TD Automotive Compressor Kunshan Co., Ltd. (TACK), a compressor production subsidiary in China, completed the construction of a new plant to increase its production capacity of electric compressors. The new plant has implemented a range of environmental measures to ensure legal compliance and reduce its environmental impact. One such measure is to promote the effective use of water resources. The plant's wastewater treatment system applies biological treatment or low-temperature distillation depending on the type of wastewater discharged from various production processes. The wastewater is then treated through a reverse osmosis (RO) membrane process for recycling in these processes. In this way, the plant achieved zero wastewater from production processes. TACK also applies the RO process to remove impurities from tap water and recycles wastewater from the process as supplementary water for a cooling tower, leveraging it to reduce the use of supplementary water. Through these efforts, TACK expects to reduce its annual water consumption by about 16,930 m3. In addition to reducing the use of water resources, these efforts have led to a lower risk of contaminating the local environment with wastewater from production processes.



Picture 8. Wastewater treatment flow process

Case: Reducing the Dependence on Local Water Resources by Increasing the Use of Rainwater

KTTM has also been promoting production activities that consider the local environment concerning water resources. KTTM has already built a pond on the plant premises to lower its dependence on local water resources and has used rainwater stored in the pond in production processes. However, since rainwater alone was not sufficient to satisfy the demand from these processes, KTTM purchased groundwater from a local water supplier. KTTM was concerned that the continued use of groundwater may cause lower groundwater levels and that the installation of wells may also impact the natural environment. In response, the company more than doubled the capacity of the pond from 600 kl to 1,250 kl. This has allowed KTTM to secure a sufficient amount of rainwater needed for production and reduce its dependence on local water resources (Toyota Industries Report, 2024).

Before expansion After expansion

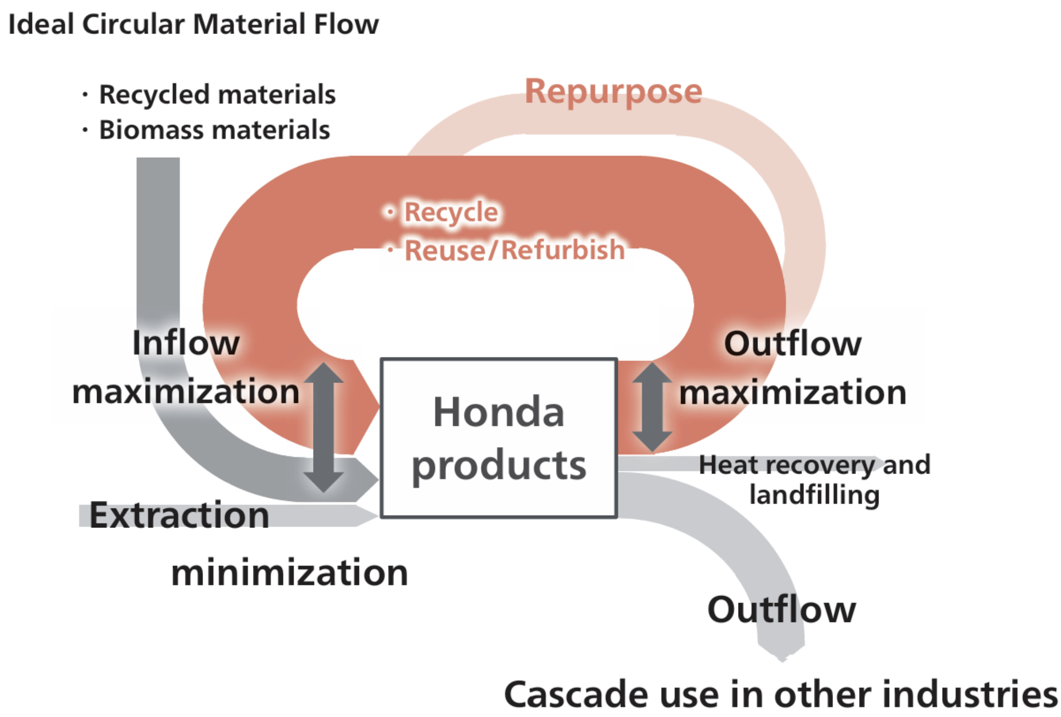
Picture 9. Reducing the Dependence on Local Water Resources

Company 2: Honda Motor Corporation

Recovery and Recycling

Achieving Horizontal Recycling by Maximizing the Use of End-of-Life Products

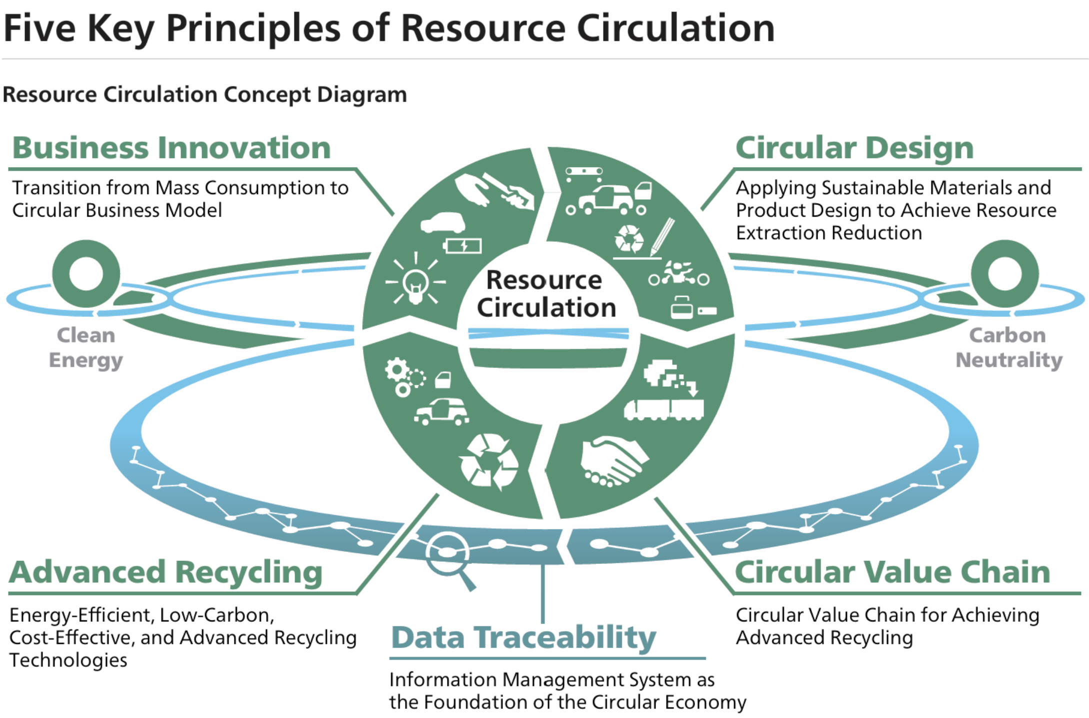
Honda aims to achieve resource circulation through horizontal recycling, which maximizes the use of end-of-life vehicles (ELVs). This approach requires the development of a new “circular value chain.” To build this value chain, Honda is working to acquire capabilities beyond its current corporate activities. The insights and technologies gained from this effort are expected to support new businesses and products designed with a circular economy in mind, as well as the innovative technologies to achieve them. Consequently, they focus on transforming their business from a mass consumption model to a circular one (https://csr.honda.com/longform-content/**;** https://csr.honda.com/).



Picture 10. Horizontal Recycling by Maximizing the Use of End-of-Life Products

Fully utilizing the value of products and parts during their lifecycle and highly efficient recycling of used products while ensuring economic viability throughout a product are both vitally important for resource circulation. To fully utilize the value of products and components, they focus on reusing and repurposing them. They also utilize data to "visualize value" throughout the product lifecycle, facilitating regulatory compliance, proper transactions of products and components, and promoting their effective use. To efficiently recycle used products, it is crucial to incorporate "circular-oriented materials and design" into the products. For the products currently under development, they are advancing the replacement of materials with those designed for circularity, integrating material types, and adapting material specifications and manufacturing methods to accommodate the use of recycled materials. Additionally, they are working on designs that facilitate easy disassembly of end-of-life vehicles (ELVs) and transforming components made of multiple materials into structures that allow for easy separation into single materials, avoiding the inclusion of contaminants during the recycling process. In addition to incorporating these strategies into product design, they also focus on expanding future horizontal recycling efforts. To achieve both environmental sustainability and economic viability, they are working with their partners to develop advanced recycling technologies, including those for dismantling, shredding, sorting, and reprocessing materials (Honda ESG Data Book, 2023).

Honda has established the five essentials of resource circulation and works together with internal and external stakeholders in conjunction with conventional 3R (reduce/reuse/recycle) activities.



Picture 11. 5 Key principles of resource circulation

Business Innovation Honda is committed to shifting to a recycling-oriented business that uses up products and parts throughout their entire life cycle and recycles them with high efficiency.

Advanced Recycling Honda is committed to the research and development of advanced technologies that enable energy-saving, low-carbon, and low-cost recycling.

Data Traceability Honda will work on visualization of social values such as lifecycle CO2 emissions and recycling rate to prove compliance with laws and regulations and to promote appropriate trade and use of recycled materials. The Company is committed to proving maintenance history and improving resource recovery rates through the extensive use of digital technologies.

Circular Design Honda is committed to creating a system premised on recycling, which includes the selection of materials suitable for recycling, easy disassembly and separation design that enables the removal of high-quality scrap, and stable procurement of recycled materials.

Circular Value Chain Honda will work on optimizing specifications across the entire supply chain involved in resource circulation, including material manufacturers and dismantling and shredding industries, to build a circular value chain that maximizes economic efficiency (Honda Sustainability Report 2024).

Below there are some examples of cases regarding the Resource Circulation Concept.

Case 1. Expanded Use of Recycled Materials from Automobile Bumpers for Parts of New Vehicles (Circular Design)

For the “N-VAN e:” light EV scheduled for release in 2024, Honda collected and crushed discarded bumpers from Honda vehicles, revitalized them as sustainable materials, and reused them as accessories for vehicle exteriors and other parts. For the front grille parts, a technology was applied to randomly mix the bumper paint of past Honda models, leaving a rough finish, so that the pattern is unique and attractive.

Picture 12. The sign of product recyclability

Case 2. Use of Sustainable Materials for Floor Carpet Mats (Circular Design, Circular Value Chain)

Starting in April 2024, Honda has adopted a sustainable material, recycled PET material, for the floor carpet mats, a Honda genuine accessory for the N-VAN light vehicle. It is significantly lighter than conventional mats. The use of sustainable materials is an effort to consider recyclability after use and to contribute to a recycling-oriented society in the future. Going forward, the Company will gradually expand the number of vehicle models to which sustainable materials can be applied.

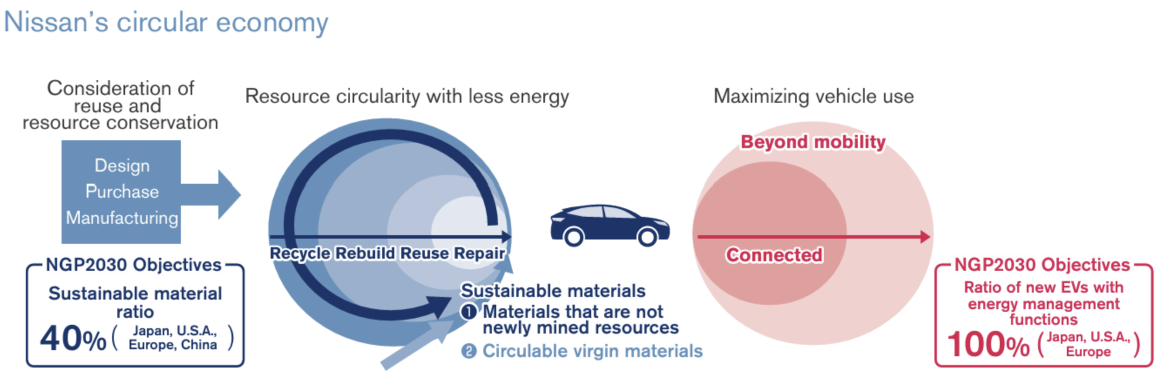
Case 3. Launch of Services Related to Refurbishing Used Cars (Business Innovation)

In September 2023, Honda’s Japanese used car business launched “Imakore+ (Plus),” a program to install new Honda genuine accessories to used cars. In January 2024, Honda launched a new upgrade service for the ACCORD model in its North American used car business, a dealer-installed service that enables the wireless functionality of Apple CarPlay and Android Auto. Such refurbishing programs for recovering and improving product value, adding new product value, and providing utilization services will lead customers to use up the products to the end, and increase opportunities to collect end-of-life vehicle products, thereby making more efficient use of resources (Honda ESG Data Book, 2024)

Company 3: Nissan Motor Corporation

Product life extension/Recovery and Recycling

Nissan aims to incorporate the circular economy, efficiently and sustainably utilizing resources throughout a vehicle's entire lifecycle, while maximizing the value provided to customers and society (Nissan Sustainability Report 2023).



Picture 13. Nissan's circular economy

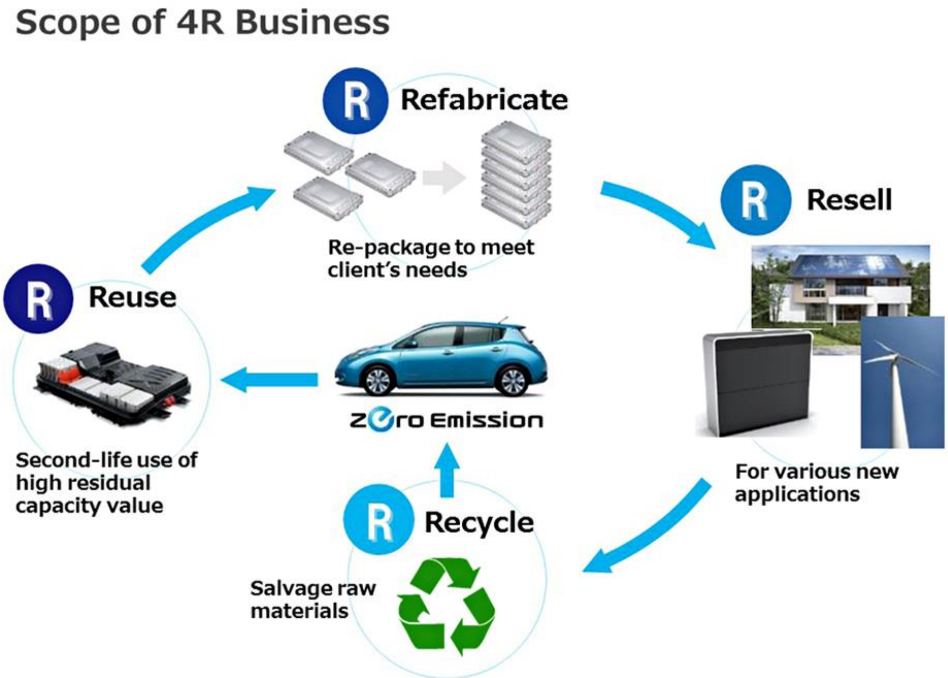
Resource circularity with less energy

Nissan promotes reuse and the saving of resources from the design, purchase, and manufacturing phases. They continuously work on using recycled materials, the proper management of chemical substances, and the reductions of vehicle weight. To use resources effectively with less energy, they continue to expand the application of recycled materials to new vehicles, the use of recycled parts for customer repairs and replacements, and EV batteries in secondary applications. Furthermore, they promote the adoption of circulable materials for cases using new materials as well, toward future sustainable resource circularity (Nissan Sustainability Report 2024).

Case: Nissan gives EV batteries a second life

Promotion of 4R for second-life use for lithium batteries

Nissan EV batteries offer high performance even after being used in cars. As more and more customers switch to EVs, the supply of batteries capable of secondary use is expected to increase significantly. In 2010, Nissan, as an EV pioneer, joined forces with Sumitomo Corporation and established 4R Energy Corporation, which specializes in secondary use of lithium-ion batteries. The intention is to promote the four Rs of lithium-ion batteries— reuse, resell, refabricate, and recycle— and establish a battery circular system which will enable the efficient use of resources



Picture 14. Promotion of 4R for second-life use for lithium batteries

Designing, developing and engineering an electric vehicle is all about sustainability. After all, over their lifetime, EVs are much more environmentally friendly than traditional vehicles. However, when Nissan engineers were drafting the plans for the first-generation all-electric LEAF, they had a key insight: Developing electric cars had to be about more than vehicle performance.

The very first LEAF came to market in December 2010 – Nissan partnered with Sumitomo Corp. to set up 4R Energy Corp. Its purpose: develop the technology and infrastructure to refabricate, recycle, resell and reuse the batteries in Nissan EVs – not for their scrap value, but to power other things.

Picture 15. The 4R plant in Namie, Japan, specializes in the reuse and recycling of batteries from electric vehicles.

When an old EV battery reaches the 4R factory, it is first graded. Sometimes, the battery components are as good as new; they get an "A" grade and can be reused in new high-performance battery units for a new EV. With a "B" grade, the batteries are powerful enough for industrial machinery like forklifts and large stationary energy storage. Deployed in a home or commercial facility, for example, they can capture surplus electricity generated during the daytime by solar panels and then power the building during the night. Even the components of a battery that gets a "C" grade can still be put to use – for example in units that supply backup power when the electric grid fails, say at grocery stores that must have their refrigerators and lights running even during a power outage. The engineers at 4R Energy estimate the recovered batteries have a life span of about 10 to 15 years, dramatically extending the usefulness of EV batteries and reducing their overall carbon footprint.

Energy keeps finding new ways to refabricate, recycle, resell and reuse EV batteries. On Yumeshima, a manmade island in western Japan's Osaka, a solar farm is using 16 lithium-ion EV batteries to cope with energy fluctuations and store its energy output.

Picture 16. The man-made island of Yumeshima in western Japan's Osaka is now home to the world's first large-scale energy storage system, a project that also highlights the potential to reuse electric vehicle batteries.

On Koshikishima, an island off the coast of southwestern Japan, 4R Energy has created an innovative battery management system that makes it possible for wind and solar energy to power the charging network that supports a fleet of all-electric vehicles. It’s the first of its kind and makes an important contribution to the goal of the 5,000 residents to make Koshikishima an "eco island" with zero CO2 emissions.

The company is also developing battery systems that help integrate solar power, local battery storage and the electricity in EVs – and can be used as a home’s emergency power supply. Another use case are the batteries for the automated guided vehicles that are becoming ever more important in modern factories and warehouses (https://www.nissan-global.com/)

5. Discussion.

Japanese automobile companies are increasingly implementing circular business models to align with global sustainability trends, reduce environmental impact, and create long-term value through the efficient use of resources. In this study we analysed how leading Japanese car manufacturers are integrating circular business models into their business strategies:

1. Toyota: Establishing a Recycling-based Society Initiatives.

Business models: Circular Supply Chain, Recovery and Recycling, Product Life-Extension. Toyota is a leader in incorporating circular strategies in its operations, particularly with the development of a circular supply chain for materials and components, **battery and other parts recycling** and recovering, and **remanufacturing** parts to reduce waste and reuse valuable materials extending products life.

Circular Value Creation key elements:

- Battery 3R Initiative;
- Reducing and Recycling waste initiatives: Examples, Reducing waste by reusing coolant, Reducing use of resources by unifying skids, Achieving zero wastewater from production processes by recycling wastewater, Reducing the dependence on local water resources by increasing the use of rainwater.

2.Honda: Resource Circulation Initiatives.

Business models: Recovery and Recycling, Product Life-Extension. Honda has integrated circular economy principles into its **design for recycling** approach, emphasizing the reuse and recycling of materials and parts throughout the lifecycle of its vehicles. Honda also focuses on End-of-Life Vehicle Recycling through horizontal recycling. Mostly, company makes an effort on recycling of fluorocarbons, airbags, ASR. Moreover, Honda is striving to achieve high results in carbon neutrality through mobility solutions, such as resource utilization.

Circular Value Creation key elements:

- End-of-Life Vehicle Recycling;
- Resource circulation with five key principles: Business Innovation, Circular Design, Advanced Recycling, Data Traceability, Circular Value Chain.

3.Nissan: EV batteries second life initiatives.

Business models: Recovery and Recycling, Product Life-Extension. Nissan develops circular business models primarily in **battery reuse** and **remanufacturing** programs. With the rapid growth of electric vehicles, Nissan is focusing on the reuse of EV batteries, which can have a second life in energy storage systems, helping to create a circular loop for the batteries.

Circular Value Creation key elements:

- **4R business model of EV batteries through CE strategies, such as Reuse, Refabricate, Resell, Recycle.**

From our findings, we can see that Japanese car manufacturers particularly are focusing on more ELV recycling by applying business models **Circular Supply Chain, Recovery and Recycling, Product Life-Extension.** From **battery recycling** and **remanufacturing** parts to **vehicle take-back programs (3R, 4R models)** and **sustainable manufacturing**, these companies are paving the way for a more sustainable automotive industry.

6. Implications.

The transition to circular economy business models in the automotive industry has profound implications for both theory and practice.

From a **theoretical standpoint**, it challenges in redefining models of value creation. Theories around value chain optimization, sustainable production, and product lifecycle management need to incorporate circularity principles, such as Recycling, Recovering, Reusing, Remanufacturing and others. Moreover, this study shows necessities for new frameworks for thinking about the closing the material loops by designing of products that can be easily reused or remanufactured at the end of their life.

Practically, it calls automotive companies for necessity to adopt circularity practices, reducing waste and improving resource efficiency by making deep changes in product design, supply chain management, and ELV management. Besides, this study also presents for practitioners existing number of rooms and new opportunities for innovation and value creation keeping a competitive advantage in a global market.

7. Conclusion.

Circular value creation through Circular Economy principles focuses on designing systems that promote reuse, refurbishment, remanufacturing, and recycling, as well as reducing waste and the consumption of raw materials. The study provides some advanced case studies within the automotive industry that illustrate how circular business models are being implemented.

Findings of the study show that Japanese car manufacturers, Toyota, Honda and Nissan, are actively incorporating circular economy principles into their business models to address environmental challenges, reduce waste, and create new value streams. Circular business models not only help reduce the environmental footprint of the automotive industry but also offer long-term economic benefits by circular value creation and opening new revenue opportunities.

From battery recycling to the remanufacturing of used parts, analysed case studies in this work reveal how automakers are rethinking traditional linear business models and moving towards more circular, value-generating systems.

Acknowledgments

This research was conducted as parts of the Grant-in-Aid for Scientific Research Activity in Japan (2022-2025): “Development, empirical research, dissemination of new theories and system techniques for the circular economy to meet the responsibility for production and consumption of SDGs.”

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Construction Sector

Case Studies of Advanced Circular Economy Companies in Japan's Construction Sector

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1. Introduction

In order to present case studies of advanced Circular Economy (CE) companies in Japan's construction sector, preliminary research was conducted on their CE initiatives. The research period spanned from July 1st to November 25th, 2024, focusing on materials and reports from government agencies and industry associations, as well as corporate CSR and sustainability reports. After extracting relevant case examples, detailed information was verified through company and organization websites. This study focused on initiatives implemented after 2015, when the EU introduced its Circular Economy Package, to align with the primary objective of showcasing advanced CE companies.

The preliminary research observed 70 cases of intentionally implemented CE initiatives in the form of buildings, products, and services. Examining the cases by project implementing entities showed that major construction companies, developers, and large architectural firms (including collaborations with manufacturers and other industries) accounted for 55 cases; construction companies and architectural firms for 9 cases; public institutions (municipalities, government agencies, and public foundations) for 4 cases; and waste management and information technology sectors for 1 case each.

In categorizing these cases, business models were classified based on the technical cycle of the Ellen MacArthur Foundation's Butterfly Diagram[1)] (Figure 1). The classification was determined by examining the primary initiatives described in the research materials for each project and identifying which technical cycle they corresponded to. At this stage, as many cases were found to combine multiple technical cycles, the decision was made to apply multiple business models to a single case.

Ranking the results in descending order, the distribution was as follows: 22 projects corresponded to recycle; 20 to maintain/prolong; 8 to both recycle and maintain/prolong; 7 to reuse/redistribute; 7 to refurbish/remanufacture and maintain/prolong; 3 to both recycle and reuse/redistribute; 2 to both reuse/redistribute and maintain/prolong; and 1 to reuse/redistribute and share.

The largest category was recycle with 22 cases. These recycling initiatives included the recycling of construction materials, waste from construction sites, and construction waste, as well as the provision of traceability systems for these construction by-products and waste. The second largest category was maintain/prolong with 20 cases, which included the development, use, and design of long-life building materials, as well as local production for local consumption and forest conservation initiatives. Additionally, 8 cases corresponded to both recycle and maintain/prolong categories. In total, cases that fell into either or both of these categories (recycle and maintain/prolong) amounted to 50 cases, representing approximately 71% of all cases in this study. Furthermore, there were 7 cases corresponding to reuse/redistribute, which included the reuse of building materials or development and design with future reuse in mind. When combined with cases that also incorporated recycle, maintain/prolong, or share, this business model totaled 13 cases, accounting for 19% of all cases. Cases corresponding to refurbish/remanufacture in combination with maintain/prolong amounted to 7 cases, representing only 10% of the total. These included building refurbishment projects designed with CE principles in mind.

From these results, it became clear that cases of Circular Economy implementation in the construction sector are predominantly comprised of recycle and maintain/prolong initiatives, followed by reuse/redistribute cases. This appears to be the result of various legislative measures, such as the Basic Act for Establishing a Sound Material-Cycle Society[2)] promulgated in 2000, the Act on Promotion of Effective Utilization of Resources[3)] enacted in 2001, and the Construction Material Recycling Act[4)] enacted in 2002.

However, it should be noted that this research focused on materials and reports from government agencies and industry associations, as well as corporate CSR and sustainability reports, consequently including many cases led by general contractors and developers. If the research scope were expanded to include small-scale initiatives by private companies and projects reflecting regional characteristics, different results might be obtained.

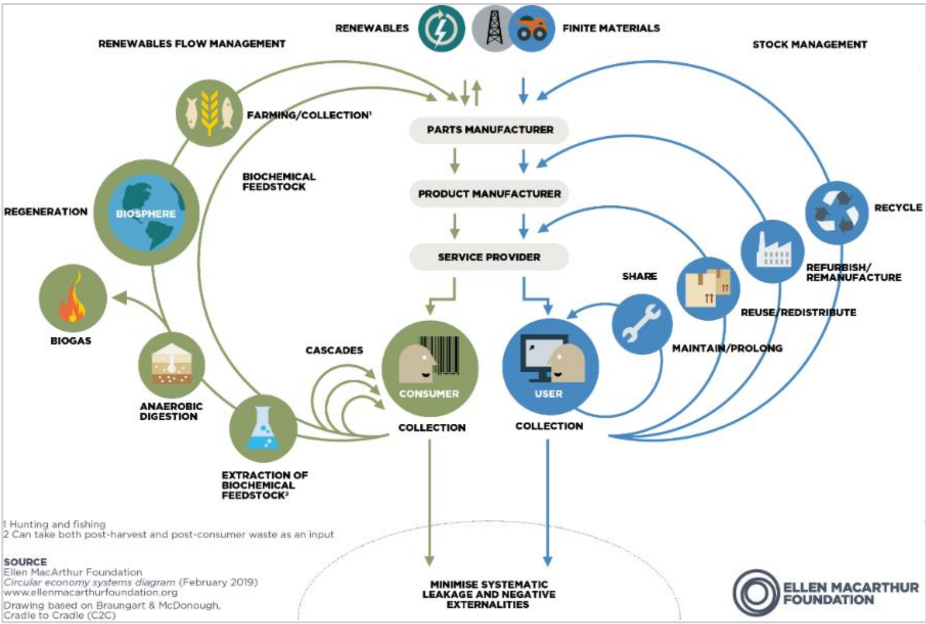

Figure 1 Butterfly Diagram

2. Case Studies of Advanced CE Companies

This section presents three examples of initiatives by advanced CE companies in Japan's construction sector, which correspond to "maintain/prolong," "recycle and maintain/prolong," and "refurbish/remanufacture and maintain/prolong."

Case 1: Example of Maintain/prolong Initiatives

'Port Plus', Completed in March 2022, Obayashi Corporation[5)]

This is an 11-story pure timber fireproof building constructed as the company's next-generation training facility, with all above-ground structural components made of wood. Standing at 44 meters, it was the tallest pure timber fireproof building in Japan as of 2022. To address the challenges of fire resistance in wooden materials and seismic resistance in tall buildings, the project incorporated proprietary technologies, including structural materials achieving three-hour fire resistance (Figures 2, 3, and 4).

The building uses 1,990m^3 of wood, which provides long-term and stable carbon storage of approximately 1,652t of CO_2. Furthermore, throughout its lifecycle - from material production through construction to demolition and disposal - it is estimated to reduce CO_2 emissions by approximately 1,700t (about 40%) compared to steel construction (Figure 5).

Port Plus features the company's proprietary smart building platform WELCS place[6)]. This platform not only incorporates robot utilization, meeting room and seat reservations, and energy visualization, but also continuously adds new functionalities such as monitoring building congestion levels, tracking meeting space usage, facial recognition, temperature screening, and unmanned reception services. Additionally, the number of occupants is determined through image analysis, enabling automatic climate control that balances energy conservation. In the accommodation facilities, optimal control of air conditioning, lighting, and blinds is implemented, along with sleep state visualization using sleep sensors and the introduction of circadian rhythm lighting. In 2023, the building achieved WELL Certification Platinum rank and LEED Certification Gold rank.

Figure 2 Building exterior

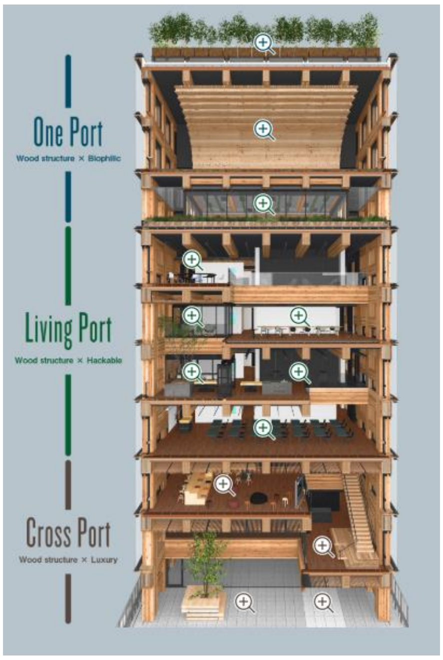

Figure 3 Cross-sectional image

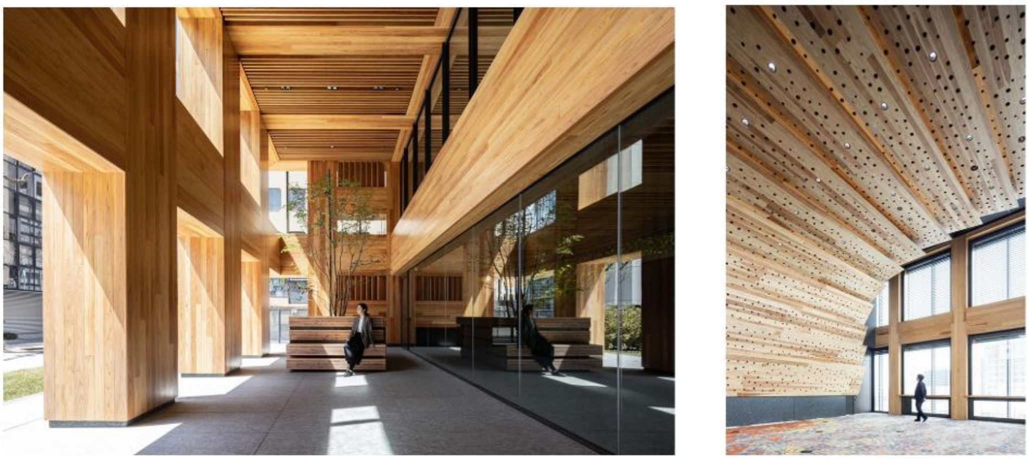

Figure 4 Interior views (Left: Ground floor piloti, Right: 9th floor seminar room)

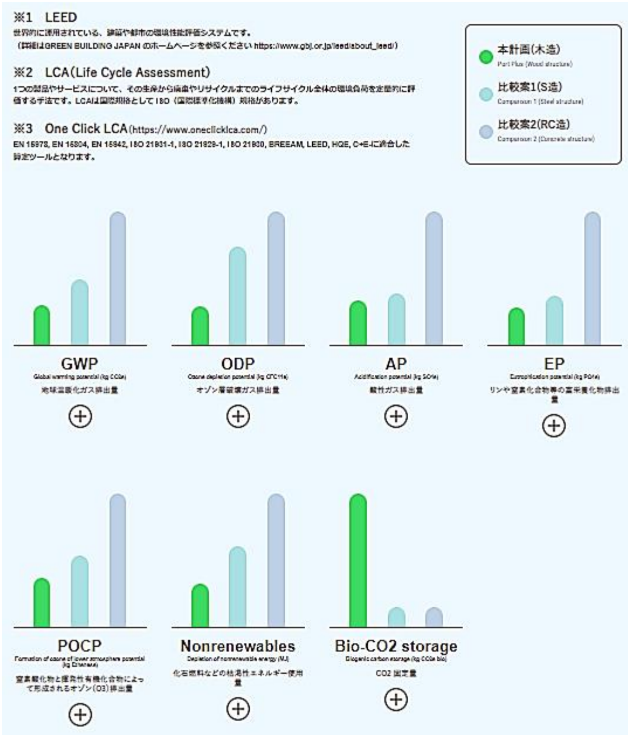

Figure 5 LCA data

Case 2: Example of Recycle and Maintain/prolong Initiatives

Zero Waste Design', Ishizaka Sangyo Co., Ltd.[7)]

Ishizaka Sangyo Co., Ltd.[7)] is a comprehensive plant company that processes construction waste generated from house demolition, renovation, building reconstruction, and road construction (Figure 6). They accept waste materials and process wooden materials into chips for shipment as feedstock for cardboard and particle board. Additionally, their product made from waste plastics mixed into solid fuel is used in paper mill boilers and cement plant kilns.

The company separates individual metals - iron, brass, copper, and aluminum - from composite construction materials and processes them into recyclable forms. Concrete from housing foundations is crushed and utilized as recycled gravel. Through these efforts, they have achieved an industry-defined waste reduction and recycling rate of up to 98%, with an ultimate goal of reaching 100%.

The company also manages neighboring forests and has obtained AAA rank in JHEP certification[8)]. This certification evaluates environments conducive to wildlife habitation, and achieving its highest rank demonstrates the company's highly regarded commitment to forest environmental conservation. Based on this certification, the company has shown its dedication to advancing ecological forest management with a 30- to 50-year perspective.

Drawing on these insights, the company also provides Circular Economy consulting services, offering planning and development of strategies for achieving a circular economy and society, including product recycling strategies, SDGs marketing, eco-friendly housing, green infrastructure, and employee education.

Furthermore, in 2022, the company conducted demonstration experiments[9)] aimed at realizing a smart plant utilizing local 5G and AI at their resource recycling facility. These experiments included visualizing pit conditions (Figure 7), visualizing the work progress from waste unloading to resource recycling and the time required for primary waste processing (Figure 8), monitoring personnel approaching hazardous areas through AI video analysis, and establishing remote operation environments for heavy machinery (Figures 9, 10).

Figure 6 Aerial view of the plant

Figure 7 Visualization of pit conditions　Figure 8 Visualization of work progress and processing time

Figure 9 AI video analysis for hazard zone monitoring Figure 10 Remote operation setup for heavy machinery

Case 3: Example of Refurbish/remanufacture and Maintain/prolong Initiatives

'BRILLIA TOWER Nishijin/PRALIVA', Completed in April 2021, Takenaka Corporation[10)]

This is a case study of Circular Design-Build[11)], a concept promoted by Takenaka Corporation, where high-rise residential housing was constructed while preserving the existing commercial facility (Figure 11). Circular Design-Build is an approach and practical initiative aimed at realizing a Circular Economy by incorporating the selection of reused and recycled building materials and considering disassembly in the design methodology during the design and construction phases. It serves as an alternative to conventional scrap and build approaches, with core concepts of "creating without generating waste," "continuing to use buildings and materials," and "circulating local and forest resources for future generations" (Figure 12).

This redevelopment project combines the reduction and renovation of a 40-year-old commercial facility from an 8-story to a 4-story building while reusing the existing foundation, along with the addition of a 40-story high-rise residential complex. By reusing the existing building frame, the project achieved approximately 25% reduction in required structural components and shortened the construction period by about 20 months. The commercial facility section has been reconstructed to create synergies with the local shopping district, featuring direct access to the rooftop garden from the subway station and revitalizing pathways that connect with the shopping street. The high-rise residential section aims to realize a sustainable and evolving circular society while ensuring high convenience and livability as its core values.

Figure 11 BRILLIA TOWER Nishijin/PRALIVA
(Renovation with downsizing of commercial facility and addition of high-rise residential complex)

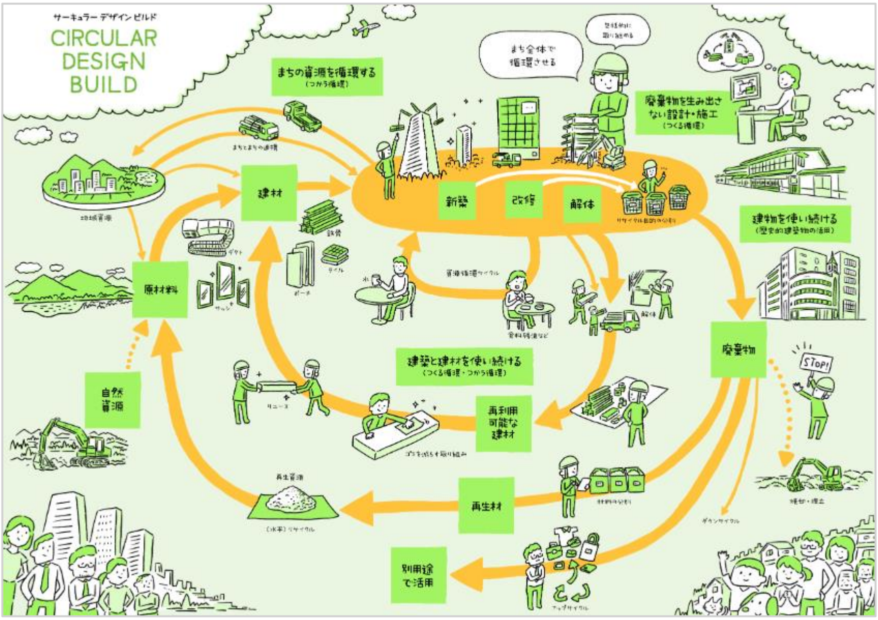

Figure 12 Circular Design-Build

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AI-Powered Smart Green Building: A Focus for Circular Economy

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Abstract

Circular economy emerged in the 1970s with the idea centering around managing the system design and operation to achieve the goals through efficient acquisition and utilization of resources. The fundamental concept of circular economy is based on the product's whole life cycle, from the design of products with an expected longer life cycle; to the creation of products with different uses at different periods of their life cycle; to recycling and reusing components to minimize waste; to the overall systematic approach to supply chain to assess the interconnections between materials, energy, and natural environments. Considering the building as a product, the circular economy and green building are closely related concepts aiming to reduce waste, increase sustainability, and improve resource efficiency. Buildings are complex and integrated systems consisting of multiple sensors, subsystems, and automatically controlled components. According to the United Nations Environment Programme, 36% of global energy use and 39% of energy-related carbon dioxide emission is attributed to building systems. And 30% of building energy usage is wasted due to malfunctioning control, operation, and building equipment. It is estimated additional energy consumption caused by some key building faults is anywhere between 0.37 to 17.96 EJ each year in the U.S. There is a pressing need to design, renovate and operate the built environment for energy efficiency. This requires a multidisciplinary approach, and, in recent years, due to the advances in devices, computational speed achievable on small surface chips, IoT platforms, Artificial Intelligence (AI) has come to play a crucial role in making effective use of these technologies by improving modeling and control of buildings to be energy efficient. In this report, we present state-of-the-art AI research in the domain of smart buildings to support global circular economy initiatives.

Keywords: Circular Economy; Smart Building; Artificial Intelligence.

1. Introduction:

Central to the smart cities' smart economy, and smart environment visions is the circular economy (CE), which aims to optimize resource usage, minimize waste, and extend product life cycles, thereby supporting sustainable development and enhancing the economic, social, and environmental value [1, 2]. A notable sector of the CE initiative is energy system and building/built environment is one of the focus domains. A building consists of multiple sensors, subsystems, and automatically controlled components. According to the United Nations Environment Programee, 36% of global energy use and 39% of energy-related carbon dioxide emission is attributed to building system [3], 30% of building energy usage is wasted [4] due to malfunctioning control and building equipment [5, 6]. It is estimated that additional energy consumption caused by key building faults is 0.4 EJ to 18 EJ each year in the U.S. [7]. Figure 1 illustrates the global energy consumption profile.

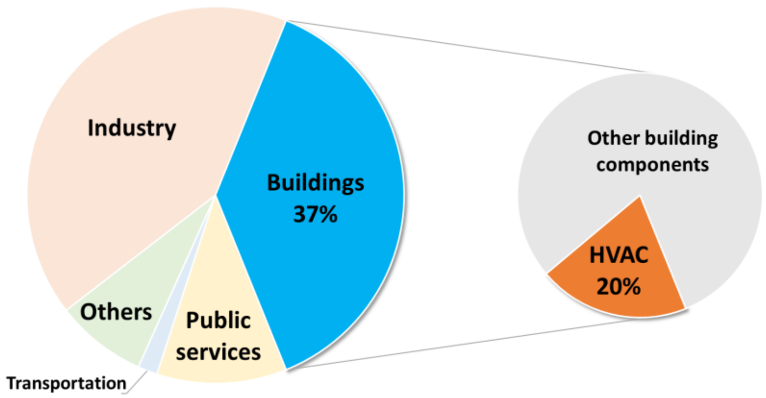

Figure 1. 2018 Global Final Electricity Consumption: 1919 Mtoe (source: International Energy Agency, Key World Energy Statistics 2020.

As the field of Artificial Intelligence (AI) continues to develop, it is intersecting with building science to create sustainable structures. AI technology is becoming a cornerstone for innovation, driving advancements that are reshaping how we approach various domains with increased efficiency. There are applications of AI in people lifestyle which are widespread, for instance AI applications in education including chatbots, expert systems, intelligent tutors, machine learning, personalized learning environments, and virtual learning environments, each offering unique benefits for enhancing teaching and learning experiences. In e-commerce, AI applications include chatbots and virtual assistants for customer support, intelligent product recommendations based on consumer behavior, AI-driven personalization for customized user experiences, and AI-enabled inventory management for optimizing stock levels based on sales trends and demand forecasts. These technologies enhance customer engagement, improve sales, and streamline operations [8]. Also, AI's influence in engineering and manufacturing is significant, where it aids in quality control, fault diagnosis, and the meticulous monitoring of manufacturing operations, thus ensuring precision and reducing waste [9]. In the sphere of navigation, AI enhances our mobility with sophisticated positioning and localization, intelligent route planning and guidance, advanced vehicle control, and voice/speech recognition, alongside managing vast information systems including maps, databases, and leveraging open data sources for robotic systems and autonomous vehicles. In the healthcare field, AI is instrumental in pioneering new drug discoveries, streamlining clinical trials, developing healthcare robotics, enhancing patient care, and leveraging genetics for AI-driven data medicine [10]. As AI evolves, its seamless fusion with these industries is not merely reflective of its adaptability but is indicative of its potential to profoundly alter the professional and personal spheres of our lives. The built environment profoundly affects human wellbeing and energy efficiency. Recognizing this, it's crucial to explore innovative smart building solutions which encompasses a range of environmental factors, including airflow, air chemistry, temperature, and humidity, along with architectural elements like noise, lighting, and green spaces.

In this report, we will first review the state-of-the-art AI technologies in Section 2 followed by its application to smart building domain with use cases in Section 3. We conclude the report with recommended policies in Section 4.

2. Literature Review of AI Technologies, Tools and Applications

AI has significantly impacted engineering through various methods, enhancing productivity precision and accelerating innovation. In the following, we reviewed some essential AI methods that have had a significant influence, particularly on engineering applications in general. While the following is not meant to be a comprehensive review, we provide critical references for Machine Learning (ML) (supervised learning, unsupervised learning, and Reinforcement Learning (RL)) and Deep Learning (DL) (Convolutional Neural Networks (CNN), Recurrent Neural Networks (RNN), Generative Adversarial Networks (GANs), and Transformers).

2.1 Statistical Machine Learning

Among the methods used to extract patterns and insight from data, supervised learning is a fundamental technique in ML. It uses labeled data to predict outcomes based on historical input-output pairs. [11] describes it as a method where a machine is provided with desired outputs, such as class labels or real numbers, to learn the correct output for new inputs. This method employs a variety of algorithms, including Linear Regression, Logistic Regression, Naïve Bayes (NB), Support Vector Machines (SVMs), Decision Trees (DTs), Neural Networks (NNs), and Bayesian Networks

(BNs) [12, 13]. Advanced supervised learning methods like Artificial Neural Networks (ANNs) and ensemble modeling further enhance predictive accuracy by combining multiple models.

In contrast, unsupervised learning works with unlabeled data to infer underlying structures. Techniques such as association rules, K-means clustering, Principal Component Analysis (PCA), latent variable methods, and mixture modeling are commonly used. [13] Highlights the importance of unsupervised learning in discovering hidden patterns without predefined labels, especially when the correct outputs are unknown. Some models, like SVMs and NNs, can operate in supervised and unsupervised settings, showcasing their flexibility. Supervised learning generally excels in offline analysis for classification and regression, producing highly accurate results. In contrast, unsupervised learning is used for real-time data analysis, particularly in clustering and association rule mining, yielding moderately reliable outcomes.

Reinforcement Learning (RL) focuses on modeling the decision-making process (e.g., training the agent to make decisions with good quality) to control dynamic systems such as autonomous driving, robotics, and gaming. RL operates within the Markov Decision Processes (MDPs) framework, where the controller works in discrete time, receiving state signals as feedback and taking actions that alter the system state. These actions are assessed based on a reward function, to maximize long-term cumulative rewards [14, 15]. This approach is highly effective in adaptive and sequential decision-making scenarios, as it optimizes performance without requiring precise system dynamics models.

2.2 End-to-End Deep Learning

ML methods may require significant domain expertise to transform raw data, a.k.a. feature engineering, often resulting in inefficiency and limited ability to handle raw data. In contrast, DL is an end-to-end approach integrating feature engineering and performing tasks (e.g., classification) for automatic execution. This shift towards DL enhances adaptability and precision in managing complex datasets. DL is particularly adept at handling large datasets and learning complex features automatically.

Deep Learning (DL) has significantly advanced with specialized Neural Network (NNs) such as Convolutional NN (CNN), Recurrent NN (RNN), and Transformers. CNNs are particularly effective in image recognition, as they learn spatial hierarchies, making them well-suited for tasks like medical image analysis. RNNs are essential for language modeling and translation tasks, with architectures like Long Short-Term Memory (LSTM) networks addressing the "vanishing gradient" problem through memory cells and gates [16]. Transformers utilize a self-attention mechanism to manage long dependencies in sequential data, allowing for efficient parallel processing. Over time, advancements in DL techniques, computational power, and the availability of large datasets have led to the rise of Large Language Models (LLMs) [17]. Based on transformer architectures, LLMs predict the next token in a sequence and have achieved state-of-the-art performance in language-related tasks such as AI assistants [18]. These models generate coherent text and can be fine-tuned for specific applications such as coding and AI assistants [16].

DL is known to be data hungry. As a result, generative models that simulate realistic scenarios and generate data using techniques like Markov chains or iterative generative processes have garnered significant attention across various applications. Advanced generative models, such as Variational Autoencoders (VAE) and Generative Adversarial Network (GAN), leverage sophisticated techniques to generate complex data-like images by approximating the underlying data distribution [21]. VAE is a generative model that uses Variational Bayes Inference to describe data generation through a probabilistic distribution [19], effectively learning latent representations and generating intricate data, like images, by approximating the underlying data distribution. On the other hand, GAN is an unsupervised generative model consisting of two neural networks: a generator and a discriminator. In this framework, the generator generates data that closely resembles real data, while the discriminator aims to distinguish between real and fake data [20]. This dynamic allows GANs to produce highly realistic images and videos, showcasing their innovative potential in creating synthetic data.

Incorporating DL methods into control and planning processes has significantly improved decision-making and strategic planning. For instance, the development of Decision Transformers involves integrating transformer models with RL, framing RL as a target-return-conditioned sequence modeling problem. Decision Transformers effectively handle long dependencies and support parallel processing, making them highly suitable for planning in complex environments. By treating returns-to-go as the reward metric, Decision Transformers simplify the learning process and address stability issues commonly associated with traditional RL [22]. Furthermore, optimization techniques play a critical role in controlling systems by fine-tuning parameters for stability and performance, as well as in planning tasks such as route planning, resource management, and process optimization. The combination of RL, Decision Transformers, and optimization leads to developing resilient control and planning systems. RL offers a framework for learning policies through interaction, while Decision Transformers provide advanced sequential modeling and optimization to ensure the efficiency and effectiveness of learned policies in achieving broader system objectives.

2.3 AI systems for engineering applications

Building on our review of AI techniques in engineering applications, we will now investigate the systems and tools that support AI technologies. We will explore the architecture and platforms that facilitate the implementation of ML and DL, emphasizing how these tools drive AI-driven innovation in engineering applications. As we delve into the capabilities of these systems, it's essential to consider the spectrum of intelligent behaviors that AI aims to replicate or improve. These behaviors encompass tasks like perception, reasoning, learning, and language understanding, categorized into Computer Vision (CV), Expert Systems, Natural Language Processing (NLP), and Robotics. These tasks enable AI systems to interpret and interact with their environment effectively, highlighting the crucial role of underlying AI systems in their development and deployment. The following discussion will explore these advanced technologies, examining their impact on industry transformation, operational efficiency, and innovation, ultimately shaping the future of technology and business.

2.3.1 Computer Vision

Computer Vision (CV) utilizes ML and NN to extract valuable information from visual inputs, facilitating various tasks such as image classification, object detection, object tracking, and content-based image retrieval [23]. It has significantly contributed to healthcare, agriculture, retail, and automotive industries [24]. Central to these advancements are CNNs, which have driven much of the progress in these areas. The evolution of CNN architectures has been remarkable since the introduction of LeNet-5 in 1998 [25]. Pivotal advancements include AlexNet in 2012 [26], which revolutionized image classification on large datasets, followed by models such as VGGNet [27] and GoogleNet [28] that emphasized network depth and efficiency. ResNet [29] further propelled the field with ultra-deep networks and residual connections, achieving human-level accuracy. These advancements have significantly improved image classification accuracy and efficiency, culminating in the resolution of the ImageNet classification challenge [30]. Several libraries and platforms are available to support CNNs. For instance, Caffe is specially designed for rapid and comprehensive computation of CNNs and includes various tools for visualization, model evaluation, model deployment, and pre-trained models such as AlexNet, GoogleNet, and YOLO [31]. OpenCV [32] is widely used for image processing, while TensorFlow and Keras are well-known for training DL models [33]. Additionally, PyTorch [34] offers flexible capabilities for DL, and Detectron2 is particularly proficient in object detection and segmentation [35].

2.3.2 Expert Systems

Expert systems are designed to replicate the cognitive decision-making capabilities of human experts by utilizing knowledge and advanced reasoning techniques to provide decision support that typically demands domain expertise [36]. Several tools are available to assist in developing expert systems. For instance, CLIPS offers a versatile platform for rule-based, object-oriented, and procedural programming [37]. Jess, a Java-based tool, leverages the Rete algorithm to efficiently process data for creating expert systems [38]. EXSYS provides a dynamic problem-solving environment with its rule-based shell supporting both forward and backward chaining methods [39]. Additionally, Vidwan, a web-based expert system shell developed in Mumbai, facilitates rule-based knowledge encoding and backward-chaining inference, offering a flexible and adaptable platform for expert systems [40]. R1/XCON exemplifies the utilization of expert systems in customizing computer configurations through the selection of software components based on user preferences [41]. Collectively, these systems and tools significantly enhance the functionality of expert systems across various domains, paving the way for pivotal advancements in automated decision-making.

2.3.3 Natural Language Processing

Natural Language Processing (NLP) is an interdisciplinary field dealing with computer and human language interaction. It encompasses computer science, AI, and computational linguistics [16]. NLP enables computers to comprehend and generate human language, serving as the foundation for various technologies such as chatbots, language translation, sentiment analysis, and more. For instance, NLP powers machine translation systems like Google Translate, facilitating multilingual communication and content localization. Additionally, it improves search engine capabilities by extracting vital information from texts, enhancing search results' accuracy and relevance. Virtual assistants like Siri and Alexa utilize NLP for precise user query responses, while chatbots leverage it to enhance customer support services. Furthermore, NLP is crucial for text summarization, creating concise summaries for news aggregation and content curation, as well as for speech recognition, converting spoken language into text for voice-controlled interfaces and dictation software. NLP-based tools (pre-trained language models (PLMs)), including ChatGPT [42], AlphaCode [43], BERT [44], spaCy [45], NLTK [46], AllenNLP [47], and T5 (Text-To-Text Transfer Transformer), are revolutionizing content creation. These tools generate realistic product prototypes, personalized content, and marketing materials, optimizing business operations and enhancing creativity, significantly impacting industries such as advertising, entertainment, design, manufacturing, healthcare, and finance [24].

2.3.4 Robotics Systems

Robotics involves the convergence of engineering, computer science, and AI to design and manage advanced machines capable of independently or semi-independently performing tasks. First-generation robots follow pre-programmed instructions provided by their designers, while second-generation adaptive robots use sensors such as vision and tactile sensors to gather information about their surroundings. Third-generation intelligent robots possess human-like intelligence and high-sensitivity sensors, enabling them to analyze sensory data, adapt to changes in their environment, and execute complex tasks autonomously [36]. These robots are often designed to operate in hazardous or challenging environments. As AI technology progresses, robots continuously improve their capabilities, enabling them to perform increasingly intricate operations and improve their interactions with human operators, thus contributing to ongoing innovation in robotics. In robotics, several powerful tools and frameworks are extensively utilized for the development, simulation, and implementation of robotic systems. These tools encompass ROS, OpenCV, MoveIt, CoppeliaSim, PCL, MATLAB/Simulink, RoboDK, PyRobot, and Webots.

3. AI solutions for Smart Buildings

According to the U.S. Energy Information Administration (EIA), buildings consume nearly half (48%) of the total energy and produce almost 45% of CO_2 emissions in the United States [48]. This drives the need to develop high-fidelity AI models for building systems to improve energy efficiency, minimize waste, improve comfort and safety for occupants, optimize water consumption, and proactively identify potential building issues to streamline maintenance and overall building performance.

3.1 Building Design

The field of building design and construction has undergone significant advancements over the past three decades, largely due to the emergence of Building Information Management (BIM) methods and tools. These advancements have supported various functions such as simulation, analysis, management, coordination, and construction. In the past decade, these systems have been augmented with AI algorithms to generate, predict, and automate the process for ease of design and delivery. The BIM design and delivery processes are now evolving to incorporate simulations and graphical analysis to enhance building design and performance. Generative algorithms are being harnessed to identify patterns and forecast innovative design solutions, improving upon previous iterations. Furthermore, CV is utilized to develop intricate 3D models that building designers can virtually experience. Techniques such as image classification and object detection, powered by CNNs, accurately identify structural elements. These methods facilitate the overlay of real-world images onto planned models, ensuring greater accuracy and realism in the design process [49].

ANNs streamline the development of high-performance structures by utilizing data from simulations to forecast new designs' performance quickly. This approach facilitates the efficient exploration and optimization of design parameters, identifying optimal configurations that improve energy efficiency, structural integrity, and overall performance [50]. Building on this capability, hybrid Deep Neural Networks (DNNs) blend functionality and aesthetics in architectural design, resulting in efficient and visually stunning buildings. GANs have greatly impacted the field of building design and architecture. GANs generate realistic data, simulate intricate scenarios, and contribute to design optimization. In architectural automation, GANs hold significant potential for automating tasks and improving processes in building design, planning, and construction. Notable applications include creating building designs with ArchiGAN [51] and generating house layouts using House-GAN [52]. Furthermore, in conjunction with CNNs, GANs play a crucial role in evaluating daylight performance, thereby enriching building design and optimization in the early stages [52].

3.2 Building Control

Various AI methods have been studied and implemented for building load forecasting including statistical methods such as autoregressive, moving average, exponential smoothing [53], state space [54], polynomial regression [55], and ML methods such as neural network [56] and support vector regression [57]. The application of the ML for energy forecasting is meant to support energy conscious control. Reinforcement Learning (RL) is a promising approach for optimizing building control, which offers a framework for improving system performance, reducing energy consumption, and enhancing cost efficiency. Unlike traditional control, RL-based approaches continuously learn from the environment and occupant feedback to improve energy efficiency considering occupant’s comfort. Therefore, RL can deal with constantly changing simulator inputs such as power demand, the condition of power systems, and outdoor temperature. RL can help maintain optimal Indoor Air Quality (IAQ) by controlling ventilation systems and reducing the risk of health issues related to poor air quality. Optimizing energy consumption and building operations through RL can lead to significant cost savings for building owners and occupants [58].

Notably, integrating NLP into building applications has shown significant promise and potential to gain valuable insights from occupants’ feedback, enabling the detection of comfort-related patterns within building environments. NLP techniques bridge real-world facilities with their BIM representations, supporting buildings by accurately modeling and responding to occupant needs (e.g., energy expenditure) and behaviors [59].

3.3 Use cases

As part of the effort supported by US National Science Foundation, a team of US researchers including Wu (senior author of this report) collected several use cases of new-generation buildings that have been developed, taking advantage of AI/ML methods with the purpose of improving sustainability, occupant comfort, and well-being. We have the use cases summarized as follows.

The Edge, Amsterdam (Figure 2). This building, developed in Amsterdam and often referred to as the "smartest and greenest building in the world," uses AI and IoT to optimize environmental conditions, energy usage, and occupant comfort. AI algorithms process data from numerous sensors to adjust lighting, heating, and cooling in real-time, resulting in substantial energy savings and improved IAQ. Notably, EDGE buildings have achieved milestones such as a 70% reduction in operational carbon emissions at EDGE Stadium Amsterdam, an Energy Label A, and BREEAM-NL score of 79.11% at EDGE Olympic, and WELL Core Gold and Platinum certifications for health and wellness.

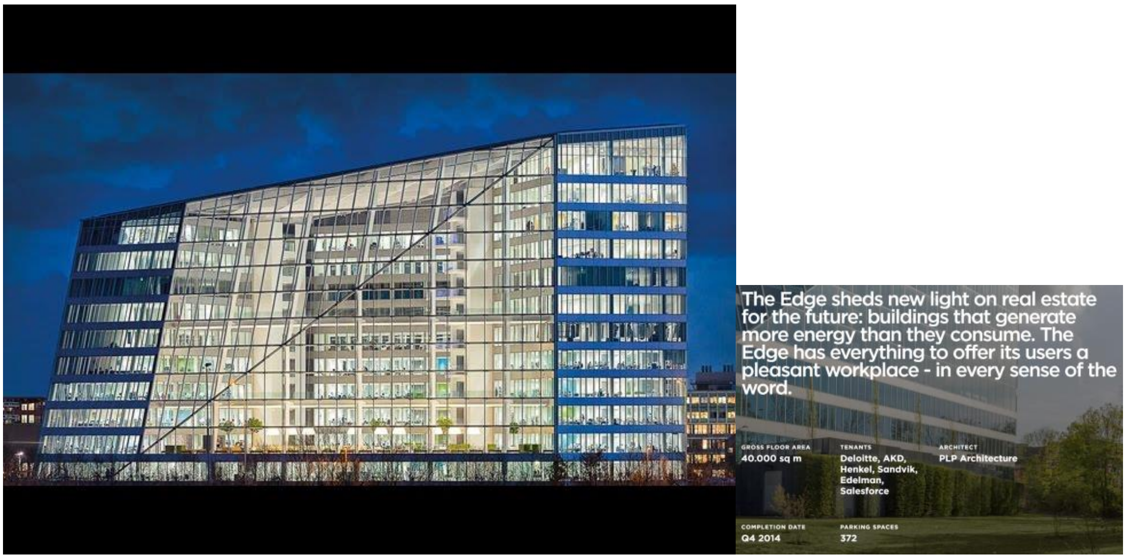

Figure 2. The Edge Amsterdam

Phipps Conservatory and Botanical Gardens, Pittsburgh (Figure 3). The Phipps Conservatory's Center for Sustainable Landscapes uses AI to manage its HVAC systems and environmental controls, ensuring optimal air quality, temperature, and humidity. This contributes to a healthier indoor environment, supported by its LEED Platinum and WELL Platinum certifications. The building cuts annual energy use by up to 80% through geothermal, solar, and wind power and conserves water via rainwater harvesting and ultra-low-flow fixtures. These measures reduce potable water use and manage stormwater effectively. Additionally, the facility's carbon footprint is minimized with significant CO2 reductions and efficient carbon cycling in its water treatment systems.


Figure 3. Phipps Conservatory and Botanical Garden

Microsoft's Smart Campus, Redmond (Figure 4). Microsoft’s campus in Redmond utilizes AI and digital twin technology to create a dynamic model of the buildings, enabling real-time monitoring and optimizing the building’s operations, including air quality, lighting, and temperature. The Thermal Energy Center's 875 geothermal wells reduce energy use by 50%. The campus features 2.5 miles of trails, green spaces, and nearly 3,000 preserved and replanted trees to enhance air quality. All-electric kitchens cut energy consumption, supporting Microsoft's carbon-negative goal by 2030.

Figure 4. Microsoft's Smart Campus, Redmond.

4 World Trade Center, New York. At 4 World Trade Center, AI systems manage the building's environmental controls, including HVAC, lighting, and air quality systems. By learning the patterns of occupancy and usage, the AI optimizes these systems to create a healthier indoor environment while also reducing energy consumption. Energy consumption has been reduced by up to 52%, translating to annual savings of around $15.6 million and a reduction of approximately 46,800 metric tons of CO_2 emissions.

4. Discussion and Conclusion

The circular economy (CE) is an economic model aimed at eliminating waste and promoting the continual use of resources. From this aspect, smart green buildings align with the mission of CE. In this report, we focus on building systems and specifically, the innovation of AI to support smart building for energy efficiency. The findings contribute to the growing discourse on how AI can revolutionize building design, operation, and management to address global challenges in climate change and sustainability. We conclude

- Advancements in AI Models for the Built Environment. The study reveals significant advancements in AI methodologies tailored to the unique demands of the built environment. These methodologies enable the creation of dynamic, adaptive systems that respond in real time to environmental conditions. A key breakthrough lies in the integration of AI with IoT and BMS, which enables AI systems to process vast amounts of heterogeneous data, ranging from thermal comfort and air quality to behavioral patterns, ensuring seamless interoperability and real-time optimization. However, challenges remain in scaling these solutions for diverse building types and climates, addressing data biases, and ensuring equitable access. Future research should focus on developing adaptive AI frameworks capable of generalizing across building types, occupant profiles, and climatic conditions to foster inclusivity and resilience in the built environment.
- Ethical and Privacy Considerations. AI-driven systems in buildings raise critical ethical concerns, particularly regarding data privacy and security. While methods like Federated Learning and blockchain offer promising solutions, their integration into standard building operations remains limited. Academic research must advance these technologies and explore their scalability and cost-effectiveness for real-world applications. Additionally, developing transparent AI models with explainable decision-making processes is crucial for gaining occupant trust and ensuring compliance with global data protection regulations.
- AI-Driven Sustainability. AI-driven energy optimization techniques, such as predictive maintenance and dynamic HVAC control advance sustainability goals. Case studies like The Edge in Amsterdam and Microsoft's Smart Campus demonstrate how AI reduces energy use. Adopting

AI-enhanced BIM and digital twin technologies enables predictive analyses and adaptive responses, optimizing resources. These innovations support both operational sustainability and holistic well-being in the built environment.

- Challenges in Certification and Standards. The readiness of certification systems like WELL, LEED, and Fitwel to accommodate AI technologies present critical challenges. While these certifications recognize the importance of smart technologies, their frameworks must evolve to evaluate the ethical use of AI, data privacy, and system transparency. Blockchain and advanced encryption methods offer potential solutions to address these challenges, ensuring trustworthiness in AI-enabled buildings. Industry professionals should advocate for new certification standards that incorporate AI-driven performance benchmarks and prioritize occupant well-being.

Future AI and future smart buildings will have a symbiotic relationship, shaping and defining each other in several aspects of sustainability, efficiency, and occupant well-being.

- *Enhanced and Personalized Health and Comfort.* AI will be pivotal in creating healthier and more comfortable building environments. AI-powered smart systems will monitor air quality, temperature, humidity, and occupancy in real time, adjusting conditions to optimize health and comfort for occupants. Smart buildings will depend on smart AI-powered systems to continuously adapt to occupant needs and environmental conditions. Moreover, AI-powered technologies, such as wearable devices and health monitoring systems, will integrate with building systems, adapting the environment to individual health needs, such as adjusting lighting for circadian rhythms or creating acoustics conducive to particular activities. However, one significant challenge for AI-powered smart systems will be the ability to efficiently model and control buildings using data and models at various levels of fidelity. This entails developing AI systems that can adapt to various operating conditions, whether analyzing historical data in an offline mode to optimize building performance or making real-time adjustments in an online mode based on live data feeds. Achieving this adaptability while maintaining accuracy and efficiency is a complex challenge.
- *Energy Efficiency and Data-Driven Optimization.* AI-based models will be incorporated in all buildings to intelligently manage energy consumption by optimizing heating, cooling, and lighting systems based on occupancy and usage patterns. At the same time, energy-efficient buildings will leverage AI to achieve sustainability goals, reducing their carbon footprint and environmental impact. In this context, AI and smart buildings will generate vast amounts of data. AI will be instrumental in processing and analyzing this data to derive actionable insights. These insights will help building operators make informed decisions to improve health and sustainability further. In return, AI systems will require data from smart buildings to refine their algorithms and provide

more accurate predictions and recommendations. AI challenges will center around data readiness, which involves ensuring that the necessary data sources, sensors, and infrastructure are in place to support AI-driven applications within buildings. This includes collecting and processing data related to environmental conditions, occupancy patterns, energy consumption, and more.

- *Predictive Maintenance.* AI-driven predictive maintenance systems will analyze data from sensors and equipment to detect potential issues before they become major problems, ensuring that building systems operate efficiently and reliably, which is the key feature of LEED-certified buildings. Smart buildings will rely on AI for proactive maintenance to maintain high standards of safety and well-being. As AI systems become more integral to building operations, ensuring that these systems can scale effectively to manage large and diverse buildings is a pressing concern. This involves considerations like accommodating different building types, sizes, and usage patterns while maintaining optimal performance.

Acknowledgements

This research was conducted as part of the Grant-in-Aid for Scientific Research Activity in Japan (2022-2025): "Development, empirical research, dissemination of new theories and system techniques for the circular economy to meet the responsibility for production and consumption of SDGs."

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Towards Circular Construction: Novel Approaches in the German Construction Industry

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Abstract

The construction industry, supported by the materials industry, is a major consumer of natural resources. It is highly important to adopt the philosophy of circular economy into the construction sector. Apart from several existing regulations, guidelines, standards, certification frameworks, and subsidies on the EU and national levels, further innovative solutions are needed to further support circular construction in Germany. Construction engineering companies like Ed. Züblin AG has already started its endeavors in circular construction to promote a circular economy in Germany. Furthermore, automation and robotics have the potential to play a key role in the development of circular construction by increasing productivity, reducing waste, increasing safety, and mitigating labor shortages. Starting with a brief synopsis of the history of construction robotics and the concept of robot-oriented design, this article presents exemplary case studies of research projects and entrepreneurial activities in which the authors have participated that have contributed to the advancement of circular construction. The activities of the authors have systematically led to spin-offs and start-ups, especially in recent years (e.g., CREDO Robotics GmbH, ARE23 GmbH, KEWAZO GmbH, ExlenTec Robotics GmbH, etc.), which shows that the use of construction robots is becoming an important part of the construction industry. With the use of automation and robotics in the built environment, current challenges such as the housing shortage can be addressed using the leading machinery and robot technology in Germany. In connection with new approaches from the field of human-centric use of robots, human labor can be perfectly supplemented in order to compensate for the shortage of skilled workers. Automated construction machinery for infrastructure construction offers highly efficient solutions for the expansion and renovation of roads, railroads, bridges, and tunnels. The knowledge and know-hows gained in these endeavors will lay the groundwork for the next frontier of construction robotics beyond the construction sites.

Keywords: Automated construction machinery, circular construction, circular economy, construction robots, Cradle to Cradle, Germany, Robot-Oriented Design.

1. Background

Circular economy is an economic model that aims to minimize waste and pollution by designing products and processes in a way that resources are kept in use for as long as possible. It focuses on reusing, repairing, refurbishing, and recycling materials and resources, instead of using them only once and disposing them. The concept can date back to the modern environmental movement of the 1960s and

1970s (Ekins et al., 2019). It took another few decades before the idea became the main topic of the emerging research field of industrial ecology. Milestone literature includes Biomimicry (Benyus, 1997), Cradle to Cradle (Mcdonough and Braungart, 2002), and Towards the Circular Economy (Ellen MacArthur Foundation, 2013), which first illustrated the renowned "butterfly diagram" (see Figure 1). To date, the concept has become a mainstream topic with the academia still trying to catch up.

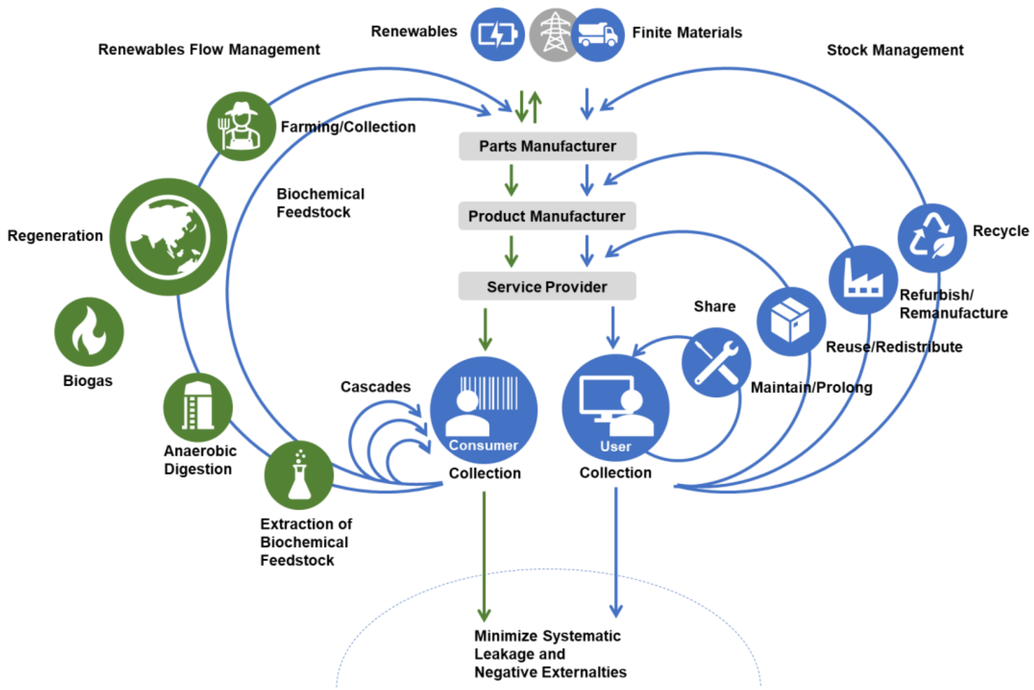

Figure 1 Circular economy systems diagram (adapted from Ellen MacArthur Foundation, 2013)

It is widely known that the construction industry, along with the materials production sectors supporting it, is one of the largest exploiters of natural resources on the global stage, both in physical and biological manners (Spence and Mulligan, 1995). Therefore, it is highly important to adopt the philosophy of circular economy into the construction industry. Derived from the concept of circular economy, circular construction refers to the design and construction approach of buildings and infrastructure that prioritizes the use of sustainable and renewable resources, and waste reduction. It aims to create buildings that can be disassembled, and their components reused or recycled at the end of their life cycle, instead of being discarded as waste. This approach aims to close the loop on material use and promote a more sustainable built environment (Rahla et al., 2021; Çimen, 2023).

The following sections will present a brief introduction of the current situation of circular construction in the EU and Germany respectively.

1.1 Circular construction policies in the EU

According to the European Union, the construction sector in the EU accounts for: 40% of gross final energy consumption; 35% of greenhouse gas emissions; 50% of extracted material resources; 30% of water consumption; and 35% of waste production (European Circular Economy Stakeholder

Platform, 2022). Circular economy is a new economic model pushed by the EU as a strategic objective (see EU policy document Closing the loop - An EU action plan for the Circular Economy; Eco-design Work Programme 2016-2019) (European Commission, 2015; European Economic and Social Committee, 2017). In regard to EU's construction sector, the following circular construction policies and regulatory frameworks for building sustainability assessment are worth noting (González, 2021):

- Transversal regulations on Building Sustainability Assessment by CEN TC 350
- European Framework for Building Sustainability Assessment Level
- Cradle-to-Cradle certification scheme
- Environmental Assessment Methodology (BREEAM) circular framework; Leadership in Energy and Environmental Design (LEED) certification

1.2 Circular construction policies in Germany

The building sector plays an important role in Germany's energy transition. It accounts for 30% of Germany's greenhouse gas emissions. Specifically, residential buildings alone are responsible for 26% of Germany's final energy consumption due to electricity usage and heating. Meanwhile, non-residential buildings are responsible for 47% of Germany's greenhouse gas emissions, despite comprising only 13% of the building volume (Novikova et al., 2018). Therefore, it is required by Germany's Energy Concept to reduce 80% of primary energy demand by 2050 compared to 2008 (BMWK, 2011), as well as by Germany's Climate Action Plan 2050 to cut up to 67% emissions by 2030 compared to 1990 (BMUB, 2016).

The waste management aspect based on closed-loop concept and disposal responsibilities is not new in Germany. The relevant policy has been adopted for more than 20 years. In 2013, there were 339.1 million tons of waste produced in Germany with a total recycling rate of 79%, of which 202.7 million tons are construction and demolition waste. The new German Closed Cycle Management Act (Kreislaufwirtschaftsgesetz, KrWG) aiming at transforming waste management in Germany into resource management came into force on 1 June 2012, which has raised public awareness of closed-cycle waste management even more. (Nelles et al., 2016).

The New Buildings Energy Act (Gebäudeenergiegesetz, GEG) came into force on 1 November 2020, which replaces and unifies the German Energy Saving Act (Energieeinsparungsgesetz, EnEG), the German Energy Saving Ordinance (Energieeinsparverordnung, EnEV) and the German Renewable Energies Heat Act (Erneuerbare-Energien-Wärmegesetz, EEWärmeG). The new law will also be supported by other existing laws and standards (German Energy Agency, 2020).

Furthermore, several voluntary certification frameworks have already been established globally to quantify the environmental impact of specific buildings and reduce it over time. These frameworks include world-renowned LEED and BREEAM certification frameworks, and the system particularly made for the German market, the DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen) certification system.

Other incentives in Germany that are worth mentioning include but are not limited to subsidies provided at the federal and state level, such as (Rheude and Röder, 2022):

- Subsidies provided by the German Credit Institute for Reconstruction with the KfW 55 loan for passive houses;
- Several states have set up/planned a subsidy per ton of biogenic carbon used (e.g., North Rhine-Westphalia, Berlin, Bavaria, Baden-Württemberg).

2. Overview of circular construction landscape

Compared to many other countries, Germany tends to have medium to small sized, highly specialized, locally oriented companies ("hidden champions") in terms of design, construction, and manufacturing in the construction sector with a few exceptions. Like in many other countries, companies in the construction industry of Germany can be generally categorized into several types including design and planning firms (e.g., GMP Architekten, HENN, HPP Architekten, Auer Weber, etc.), construction contractors (e.g., Ed. Züblin AG, Max Bögl Group, Goldbeck GmbH, Hochtief AG, etc.), and construction equipment providers (e.g., Liebherr Group, Putzmeister, PERI Group, Bauer AG, etc.), see Figure 2. In recent years, many of these companies have focused their efforts on sustainable development, although not necessarily on circular construction due to its novelty.

Figure 2 Major companies in the German construction industry

One of these companies that really stands out in circular construction is Ed. Züblin AG. Ed. Züblin AG (parent: STRABAG SE) headquartered in Stuttgart, Germany. Since its founding by Swiss engineer Eduard Züblin in 1898, Ed. Züblin AG is now one of the largest building construction and civil engineering companies in Germany. Züblin has 14,000 active employees, and its annual revenue reached 4.2 billion euro, as of 2021. Sustainability is one of the guiding principles of Züblin. In recent years, Züblin started its endeavors in circular construction to promote a circular economy in Germany. In particular, the company employs a cradle-to-cradle approach, where construction products are designed to be reused or recycled at the end of their lifecycle. Its practice of circular construction is mainly reflected in the following aspects:

1) DGNB Sustainable Construction Sites (first DGNB certified company in Germany):

- Adopting green electricity: All Züblin’s construction sites in Germany are supplied exclusively with green electricity from hydropower.
- Applying 5S method: The 5S method (sort, systematize, shine, standardize, self-discipline) sets clearly defined standards for order and cleanliness on all Züblin construction sites.
- Advanced energy management: The systematic and continuous application of energy management (ISO 50001:2018) creates transparency with regard to energy consumption and supports the construction site teams in reducing their CO2 emissions.
- Implementing lean Construction: With lean management methods, the construction process is precisely timed within the team, avoiding waiting time or interface problems.
- Digitalization of processes: Mobile applications facilitate documentation and verification during project management. For example, app-based digital checklists make it possible to review and document the high standards for health, safety and environmental protection during construction site inspections.

2) The company adheres to the following standards and certifications:

- Quality management DIN EN ISO 9001: 2015
- Work safety SCCP: 2011, DIN ISO 45001:2018
- Environmental protection DIN EN ISO 14001: 2015, EMAS
- Waste disposal company (EfB)
- Energy management DIN EN ISO 50001: 2018
- Value management EMB
- Level-3 carbon-conscious company by independent auditor DNV (Det Norske Veritas)

3) Alliance between Züblin and Magotteaux (parent: Sigdo Koppers):

- Züblin has entered an alliance with the Sigdo Koppers company Magotteaux.
- Since October 2022, these two companies have been working together on the recovery of scrap, recovering around 5,040 tons of steel and avoiding the emission of more than nine thousand tons of CO2 into the environment.
- With the sustainability group strategy adopted in 2021, Züblin together with its parent company Strabag will become climate neutral along the entire value chain by 2040.

4) R-concrete: Züblin’s key to circular design and construction (see Figure 3)

- Recycled concrete (R-concrete, also known as resource-saving concrete) is produced with a significant proportion of recycled concrete aggregate. The production of recycled, resource-saving concrete involves the use of recycled construction aggregates, for example from concrete waste and building rubble, instead of standard raw materials such as gravel, sand and crushed rock.
- It has key features such as short transport distances for increased environmental quality, usage not only in building enclosures but also possible in load-bearing structures, and reduced

construction waste thanks to recycling (instead of downcycling which is already common in the German construction sector).

- R-concrete already has been applied in several projects conducted by Züblin. For example, Factory 56, the carbon-neutral Mercedes-Benz production facility in Sindelfingen, was built by Züblin on a turnkey basis. The façade of the building was made using R-concrete. Another example is the sustainable and resource-saving realization of the New Esslingen District Office following a customized concept for circular construction. First, Züblin systematically demolished the old building. Second, the company used the recycled building materials during the turnkey construction of the new building. The structural framework, for example, was cast to a large extent from the resource-saving R-concrete.

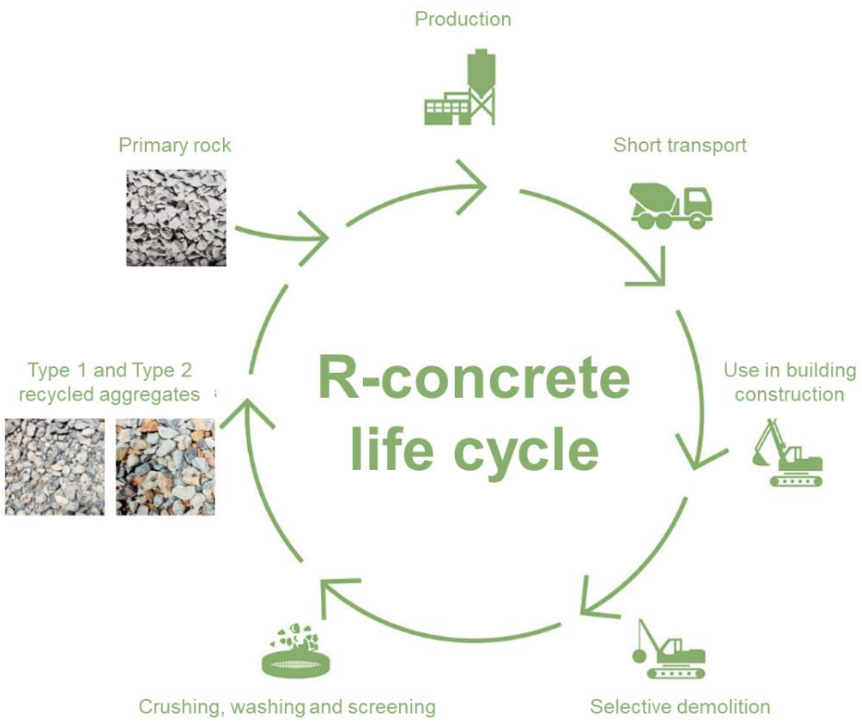

Figure 3 The life cycle of R-concrete (adapted from https://work-on-progress.strabag.com/en/materials-circularity/recycling-beton-overview)

3. Comparative analysis of two German construction companies

To further analyze the characteristics and activities of German companies in terms of construction, two exemplary German construction companies, Züblin (www.zueblin.de) and Goldbeck (www.goldbeck.de), are included as case studies. Specifically, the following five research aspects in circular economy are analyzed and compared between the two companies:

- Circular value chain management (VCM): SCM and Cooperation with various stakeholders
- Recycling resource supply and resource recovery
- CE product service planning, digital marketing, and customer engagement

- CE product architecture design and Life cycle product design
- Sharing platform service and Application software

3.1 Circular value chain management (VCM): SCM and Cooperation with various stakeholders

Züblin:

Züblin has demonstrated significant success in collaborating with a wide range of stakeholders across its projects. This extensive cooperation includes partnerships with suppliers, raw material providers, and specialized sector partners. That's include:

Partnerships in steel construction: In 1992, Ed. Züblin AG took over Stahl- und Komplettbau GmbH (today: Züblin Stahlbau GmbH). This acquisition enabled Züblin to strengthen its expertise in steel construction. The acquisition of NE Sander Eisenbau GmbH in 2011, which specializes in the processing, assembly and distribution of steel, further strengthened Züblin 's steel construction division.

Refractory and Maintenance Services: Züblin 's strategic acquisition of BFB Behmann Feuer-festbau GmbH in Bremen, strengthened its capabilities in refractory construction, chimney construction, maintenance, and environmental protection.

Timber Construction Engineering: Züblin's acquisition of Stephan Holzbau GmbH and Merk-Timber GmbH marked the beginning of its activities in timber construction engineering (Züblin Timber).

Subsidiary Mergers for Structural Reinforcement: In 2017, several subsidiaries, including Josef Riepl Unternehmen für Ingenieur- und Hochbau GmbH, Xaver Bachner Bauunternehmung GmbH, Eberhard Pöhner Unternehmen für Hoch- und Tiefbau GmbH, and Dywidag Bau GmbH, merged under the Züblin Bau brand.

Expansion into Electrical Engineering and Energy Systems: Züblin's acquisition of Hummel Systemhaus GmbH & Co. KG in 2019 extended its capabilities into electrical engineering and energy systems. In the same year, ZÜBLIN also acquired part of Weimer GmbH.

Goldbeck:

Joint Venture with Goldbeck Rhomberg: in 2001, Goldbeck partnered with an Austrian company to create the Rhomberg joint venture, facilitating its entry into the Austrian and Swiss markets.

Precast Concrete Plant in Hamm: In 2009, Goldbeck constructed its own precast concrete manufacturing plant in Hamm, enhancing its production capabilities.

Acquisition of GSE-Group: In 2019, Goldbeck expanded its European presence by acquiring the French industrial and logistics general contractor GSE-Group.

Acquisition of DS-Group: In 2022, Goldbeck acquired all shares of the Danish family-owned DS-Group, further strengthening its market position and capabilities.

3.2 Recycling resource supply and resource recovery

Züblin:

With the planned STRABAG Circular Construction & Technology Center (C3) in Bremen, STRABAG wants to drive forward the development of a sustainable and resource-saving circular economy in the construction sector. Only a fraction of the approximately 229 million tons of construction and demolition waste in Germany is currently processed into high-quality secondary raw materials and used accordingly. Common practice, on the other hand, is the downcycling of construction waste (e.g. as fill material in road construction) or its disposal in landfills. Only 13% of the building materials used nationwide currently consist of recycled materials. The result: resources are becoming increasingly scarce, and pressure on the ecosystem is growing. Although the know-how for efficient and ecological material flow management has been available for a long time, there is still a lack of both demand and supply of recycled construction materials.

The C3 in Bremen is a milestone on the path to achieving a closed building material cycle in the region and to creating a sustainable and circular construction industry. remediation and construction, debris materials will be delivered to the new circular technology center to be separated and recycled as secondary raw mate-rials down to the finest, high-quality particle sizes for use as equivalent substitutes for primary raw materials, e.g. in asphalt and concrete production. For the continuous optimization and further development of the technical processes, STRABAG will expand the center into a technology and research facility with a start-up campus for construction waste recycling and other environmental technology business fields. Collaborating with universities, testing laboratories and specialist institutes, C3 will research and develop new recycling options for the circular economy of tomorrow.

The C3 is being built using sustainable methods of construction and with primarily climate-friendly building materials such as wood and recycled concrete. Following completion, the facility will be operated in an energy self-sufficient and climate neutral capacity. Power is to be generated by photovoltaics and a wind turbine, with electricity storage units to absorb any peak loads. The STRABAG Circular Construction & Technology Center in Bremen has won the German Award for Sustainability Projects in the category of Raw Materials and Procurement.

The C3 project in Bremen is the STRABAG Group's first competence center for sustainable circular economy - further Circular Construction Centers of STRABAG Umwelttechnik are to be built and operated at other locations in Europe in the future.

STRABAG “Work in Progress” with a focus on sustainability: Currently, intensive work is being done on the future of construction through over 400 sustainability and 250 innovation projects. For example, the company uses CO2-reduced concrete in its construction projects, which can lower emissions in the structural phase by up to 50%.

Goldbeck:

Sustainability in construction relies on a circular approach to materials, emphasizing waste separation to enable reuse. In 2023/24, Goldbeck standardized waste management across its German sites to meet EU taxonomy standards and optimize waste ratios. While implementation is generally voluntary, it is mandatory for taxonomy-compliant projects or upon client request. With predesigned recycling centers, Goldbeck achieved a 76% recycling rate at 12 monitored sites, with one project exceeding 70% under EU taxonomy requirements.

Blue Concrete : The new Blue Concrete now proves that this does not have to be at the expense of environmental sustainability. CO_2 savings of more than 35 percent compared to the industry average reported by the Concrete Sustainability Council – all without compromising on quality and at no extra cost. This new Blue Concrete was piloted at the Goldbeck plant in Hamm, where it is now used to produce all precast concrete elements. Step by step, the new formulations and technologies will also be implemented at the other Goldbeck plants.

Reused materials are being used to fit out the office wing, including for the doors, some of the sanitary facilities and the bicycle racks. To this end, GSE is working with a service provider that specializes in the dismantling, processing and sale of fit-out materials. The conservation of resources will also play an important role in future operations: For example, treated service water will be used to supply the sanitary facilities and to irrigate the green areas.

3.3 CE product service planning, digital marketing, and customer engagement

Züblin:

Innovating Building Energy Efficiency with IoT and BIM: Züblin and its partners are pioneering a new approach to energy-efficient buildings by combining IoT-based automation with Building Information Modelling (BIM). This integrated system merges cloud-based building automation with BIM to optimize energy performance across the building's entire lifecycle. Key to this approach is the seamless integration of building services engineering—such as heating, cooling, ventilation, and shading—into the BIM model from the earliest stages. This ensures that all building functions and their critical operational data are available and adjustable within the digital model during both the design and construction phases.

Driving Sustainability Through Data and AI: Operational data collected through these systems will be processed in a cloud-based control platform. Using artificial intelligence (AI), this platform will analyze the data to enhance building management and performance. This innovative integration of technologies is expected to transform resource sustainability. The BIMpact initiative aims to significantly reduce energy consumption, time, and material use, delivering tangible bene-fits in efficiency and sustainability throughout the building's lifecycle.

Highlighting Projects and Experiences: Under the theme Work in Progress, they share real-world examples, experiences, and success stories to il-lustrate the benefits of their buildings. By showcasing their projects through photos, they bring their products to life, demonstrating their impact and quality. To further engage their audience, they leverage social media platforms, such as their newsroom (Züblin Newsroom), and Instagram to present their works and activities. These channels serve as dynamic tools for sharing updates, achievements, and insights into their ongoing projects.

Coordinating excellence and ensuring success in complex construction projects: Züblin brings people, materials, and machines together at the right time and in the right place to ensure the seamless execution of even the most complex construction projects. By delivering on time, maintaining the highest quality standards, and optimizing costs, Züblin takes on some of the project risk, significantly reducing the burden on its customers.

Advanced project support: Applying lean construction principles, Züblin improves project planning and execution through computerized building models. This approach enables thorough planning reviews, process optimization, precise quantity takeoff, dynamic scheduling, and effective cost control, ensuring efficient and successful project outcomes.

Goldbeck:

With Goldbeck Building program, customers are automatically enrolled as Plus5 service members, which provides an array of comprehensive support services:

Commissioning service: Goldbeck ensures a seamless start-up process by adjusting the building's technology and optimizing climate control and energy consumption. Additionally, this service includes familiarizing users with the building's facilities and assisting with the operation of various systems and equipment, ensuring they are correctly configured and functioning as intended.

building system performance and issue management: This service focuses on proactively identifying and resolving potential issues. It includes an annual review consisting of visual inspections and system checks to confirm that everything remains in optimal working condition.

Proactive support: Customers are assigned a dedicated Goldbeck representative who provides proactive, individualized advice and management, helping prevent issues before they arise.

These services are available on-site for five years at no additional cost to the customer, ensuring continuous support and peace of mind.

Effective energy management can lead to substantial reductions in energy and media consumption—potentially up to 30% in non-residential buildings. This success hinges on accurate and reliable consumption data collection, empowering you to take control of your data and strategically leverage it to achieve your energy goals.

Digital parking offers the flexibility to extend parking spaces anytime and operates fully digitally without the need for tickets or cash. It supports e-mobility by providing charging options and can be conveniently controlled through a single remote control.

3.4 CE product architecture design and life cycle product design

Züblin:

This is just one example of Züblin's expertise in complex turnkey construction projects. Züblin's capabilities extend to refurbishment, renovation, energy efficient refurbishment, remodeling and restoration. Züblin is a leader in tunnelling and steel construction and demonstrates on-site efficiency in earthworks and timber construction, which are often seamlessly combined with traditional building methods. In addition, the company has extensive experience in all aspects of underground construction, including tunnelling projects.

Goldbeck:

Goldbeck specializes in constructing turnkey projects using industrially manufactured system components, ensuring speed, cost-efficiency, and quality. Among their key products are car parks and sports halls, showcasing their versatile expertise.

3.5 Sharing platform service and application software

Züblin:

The aim of the software application is to provide both project management and other Project participants with a better overview of the project, improve processes and increase efficiency and avoid any waste in the value creation process by relying on cycle control and continuous optimization in our construction projects.

They apply the mandatory LEAN principles and tools and ensure that the process runs without hesitation or delays. A well-structured process plan is created and monitored on a daily basis. By qualifying construction partners for LEAN Construction at an early stage and pursuing project goals in short cycles, they ensure that projects are completed on time. To avoid delays, they closely coordinate the flow of resources, materials and information.

Each step is visualized with the help of cycle control boards that are accessible to all team members. Innovative tools, such as digital component tracking and continuous improvement processes, are integrated throughout the team. The aim is to develop a comprehensive digital solution for the construction site.

Digital protocols: The digital logging apps are used to record and process production parameters. The data is recorded by site personnel using mobile devices.

Web-based tool: for staff and equipment scheduling enables digital resource management and the efficient deployment of staff and equipment.

Tools for analyzing automatically collected drilling data: capture and interpret automatically collected manufacturing data from drilling rigs. The collected data is not only used for documentation purposes, but can also be analyzed and provide information about certain processes (e.g. construction phases or obstacles depending on certain types of equipment or specific subsoil conditions).

Digital standards for injections, drilling and dewatering: Digital data acquisition is already standard in specialist civil engineering for drilling and grouting work. In addition, complex injection tasks can be carried out fully automatically under computer control. We also implement web-based remote maintenance and monitoring of complex dewatering projects.

They have the digital takt board with the simple traffic light system that can great an overview of the work-flow for every trade involved in the Project. It uses a display screen to show the scheduled deadline of the construction tasks and updated the status from both sides (Management and BIM Model). This application is self-developed and prove its value at the several construction sites.

The implementation of BIM 5D® establishes an extensive, transparent, and dynamic information network for all construction stakeholders, making it an integrated approach for the design, construction, and operation phases of projects. This framework should also incorporate the remodeling of existing projects and statistical elements. By utilizing BIM 5D®, construction processes become significantly more efficient, as it allows for the identification of improvement opportunities and the prevention of costly errors. Additionally, it can accurately estimate project costs, simulate potential changes seamlessly, and facilitate subsequent planning. This leads to enhanced precision on-site for workers and ensures comprehensive documentation and maintenance plans for safe and efficient operations.

Goldbeck:

The lean principle is applied in indoor spaces with a high repetition factor, in an early phase of the project life cycle and in an interactive workshop setting during the planning and preparation phase. This approach helps to define the cycle control system and the cycle plan for projects, as can be seen in the example of Weimarer Strasse in Munich. Communication on the construction site is facilitated using a control panel on the construction site, on which all tasks are written down.

An app was developed that enables site managers to create project-related recommendations for action in the form of a PDF checklist at the start of a project, particularly in the area of construction site logistics.

A new application, the GB TPTC app, was also developed. This is used to obtain 2D plans (in future also 3D) directly from the BIM model and link them to the cycle planning. The app supports the use of standard processes, standardized work packages and content. It also offers practical functions such as widgets and an integrated meeting agenda.

3.6 Summary

In summary, both Züblin and Goldbeck comply with EU standards, including quality management and environmental protection, while integrating LEAN principles and digital tools into their processes. Table 1 shows the comparison between Züblin and Goldbeck.

Table 1 Comparison between Züblin and Goldbeck

Aspect	Züblin	Goldbeck
Lean construction	Fully integrated LEAN Principles, ensuring process run smoothly without delays uses a structured process with delay monitoring to avoid downtime for all those involved in the construction work and minimise all other waste.	Applies LEAN Principles primarily in indoors spaces with a high repetition factor, focusing on early project phases and implementation of integral planning methods, cycle planning/control (TPS) on construction sites, and mobile applications for quality assurance optimizes project efficiency.
Digitalization & BIM Integration	Implements BIM 5D® for comprehensive project integration, cost estimation, and error prevention. Uses digital protocols, tracking tools, and web-based resource management.	Developed an app (GB TPTC) that links 2D/3D BIM models to cycle planning. The app standardizes processes and work packages.
Communication & Collaboration Tools	Provides a digital takt board that updates project status in real-time and integrates BIM models with management input. Uses digital logging apps for real-time documentation.	Uses an app that enables site managers to generate project recommendations in PDF format and supports standardized processes.
Turnkey Construction & Specialized Expertise	Specializes in complex turnkey construction, including refurbishment, renovation, energy-efficient upgrades, and restoration. Expertise extends to tunnelling, steel construction, earthworks, and timber construction.	Specializes in industrially manufactured system components for turnkey projects. Key products include car parks and sports halls, ensuring speed, cost-efficiency, and quality.
Underground & Structural Expertise	Extensive experience in underground construction, particularly in tunnelling and deep foundation projects. Combines traditional and modern construction methods seamlessly.	Focuses on prefabricated, modular construction rather than deep underground works. Known for efficiency in structural system assembly.
	Integrates IoT-based automation	Energy efficiency is optimized

Energy Efficiency Strategy	with BIM to optimize energy performance across a building's lifecycle.	through the installation and removal of ventilation and refrigeration systems, along with the integration of modern heating solutions, while expert guidance on subsidy programs (BAFA, KfW) is provided to maximize savings and ensure effective climate control and energy management.
Data & AI Usage	Collects operational data via IoT sensors and uses AI-driven analysis to enhance building management.	Annual reviews and system checks ensure continued energy efficiency and identify potential improvements.
Project Communication & Engagement	Shares real-world experiences through the Züblin Newsroom, social media, and project showcases.	Throughout their newsroom on the website, they also showcase their projects to others.
Project Planning & Optimization	Uses computerized building models for dynamic scheduling, cost control, and process optimization.	Assigns a dedicated representative for proactive support and issue prevention.
Additional Services	Demonstrates project impact and quality through shared photos and success stories.	Customers automatically become Plus5 service members, granting them continuous support for five years.

Züblin stands out for its advanced automation, real-time data tracking, and BIM 5D® technology, enabling the management of both traditional and high-tech infrastructure projects. It enhances customer experience by offering interactive 3D models before construction, allowing for easy modifications based on client preferences. Additionally, real-time IoT data analysis and AI-driven optimizations improve efficiency and project outcomes.

Goldbeck focuses on early-stage cycle planning and project standardization, stands out with fast, pre-fabricated construction for cost and time efficiency. The company ensures long-term energy performance through its Plus5 service, which provides proactive issue management for five years.

Both companies maintain newsrooms on their official websites to share updates on their projects and activities. These platforms showcase their progress, innovations, and construction advancements, often accompanied by images of their work.

By leveraging sensor technology, both firms enhance project quality and safety, providing real-time in-sights into building performance. This transparency allows customers to access critical project data, ensuring high standards of construction.

In terms of project focus, Goldbeck specializes in sports halls, warehouses, and car parks, while Züblin is more suited for complex underground projects, turnkey solutions, timber construction, and tunneling.

Both companies are committed to sustainability, actively working to reduce CO_2 emissions in concrete production and incorporating prefabricated materials into their projects.

Ultimately, Züblin and Goldbeck share the same goal—operating within a circular economy to create sustainable, recyclable, and energy-efficient buildings.

Züblin and Goldbeck, with their expertise in design, construction and modular building solutions, have the opportunity to lead by example and develop whole-building, truly sustainable approaches rather than simply complying with regulations. Their success depends on avoiding greenwashing, commercialization and cherry-picking (Diaz Gonçalves & Saporiti Machado, 2023). By showing transparency and commitment to the circular economy, they can set new industry standards and drive significant change in the built environment in Germany.

4. A case for construction automation and robotics for circular construction

Another technology that could play a crucial role in promoting circular construction in Germany and beyond is construction robotics. As discussed above, the construction industry, together with the materials industries which support it, is one of the major global exploiters of natural resources. While the need of public housing due to the population explosion is continuously increasing (United Nations, 2019), the material and labor costs are rising. The increased competition and shrinking profit margins are some further challenges facing the construction industry. According to McKinsey Global Institute, the construction industry has an intractable productivity problem. Furthermore, the report confirms that while sectors such as retail and manufacturing have reinvented themselves, construction seems stuck in a time warp. Global labor-productivity growth in construction has averaged only 1% a year over the past two decades, compared with growth of 2.8% for the total world economy and 3.6% in manufacturing (McKinsey Global Institute, 2017). Therefore, using innovative solutions to increase the productivity of the construction sector becomes critical to the sustainability of the construction industry.

Furthermore, the construction sector is responsible for 36% of the energy use and for producing 39% of the global carbon dioxide (CO2) emissions including operational energy emissions and embodied emissions that are resulted from materials and construction processes along the whole life cycle (International Energy Agency, 2019). Take concrete as an example: Invented more than 200 years ago, cement concrete continues to be the most frequently used building material. Its usage globally (in tonnage) is twice that of steel, wood, plastics, and aluminum combined (Cockburn, 2021). The ready-mix concrete industry, the largest segment of the concrete market, is projected to surpass $600 billion in revenue by 2025 (Manjunatha et al., 2021). In addition, concrete production uses substantial amount of energy and raw materials, which results in a large amount of total CO2 emissions (around 7.0%) into the environment (Unis Ahmed, 2022).

More importantly, labor safety in the construction sector is a major issue facing the industry today. The reduction in the number of onsite construction workers at height, through applying construction robots, can substantially reduce the chance of fatal accidents and other injuries on the construction sites. According to Eurostat, there were 3355 fatal accidents at work in EU-28 states during 2020, of which 21.5% happened in the construction sector (Eurostat, 2022). In other words, more than 700 accidental deaths took place within the construction industry in EU countries just in 2020. The reduction in the number of onsite construction workers at height, through applying advanced technologies, can substantially reduce the chance of fatal accidents and other injuries on the construction sites.

In addition, as the global population is continuously aging, the construction industry is expected to bear the brunt for the years to come. In fact, many countries and regions have already experienced labor shortages in the construction sector, especially high-skilled ones (Mohd Rahim et al., 2016; Ceric and Ivic, 2020; Ho, 2016). The fact that the construction industry suffers from a bad public image (also known as “3D”: dangerous, dirty, difficult) also aggravates these shortages due to its lack of ability to attract younger workforce. Apparently, novel solutions are needed to mitigate these shortages.

Therefore, improving productivity, reducing waste, enhancing safety, as well as mitigating labor shortages in the construction industry will contribute significantly to the sustainable development of the construction industry. In recent years, several technologies and innovations have already been introduced and implemented in the building sector, including but not limited to new design theories (e.g., passive solar houses, open building), standards (e.g., Cradle to Cradle design, BREEAM, LEED, DGNB), materials (high performance bricks, concrete, glass, insulation), building components (e.g., triple-glazed windows, green facades, greenhouses, sunshades, ventilation), and equipment (e.g., solar panels, heating and cooling systems), to foster the sustainable development of the sector. As a result, construction automation and robotics can also play a significant role in this process, just as it already did in other industries such as manufacturing and agriculture.

4.1 The rise of construction robots

The construction automation and robotics is a new yet flourishing research topic. Ever since the first stationary construction robotics (see Figure 4) debuted in the 1960s in Japanese modular prefabrication of the legendary Sekisui Heim M1 that was designed by Dr. K. Ohno , then from the late 1970s the first on-site construction robots (see Figure 5) were developed by Japanese general contractor Shimizu Corporation due to the lack of skilled labor, low construction quality, and bad public image, about 50 construction robot systems have been developed in the 1980s. Other catalysts also include high land prices, high interest rates, and high living cost which required rapid, on-time, high quality construction project delivery on site as planned as well as immediate return on investment. As a result, from the 1990s, on automated construction sites (e.g., the pioneering Shimizu Manufacturing System by Advanced Robotics Technology, also known as SMART System, developed by Shimizu Corporation in 1992, see Figure 6) have also become a worldwide research and development topic (Bock and Linner, 2016a).

Figure 4 Stationary use of construction robots in the factory at Sekisui Heim and its legendary M1 model (photo: T. Bock)

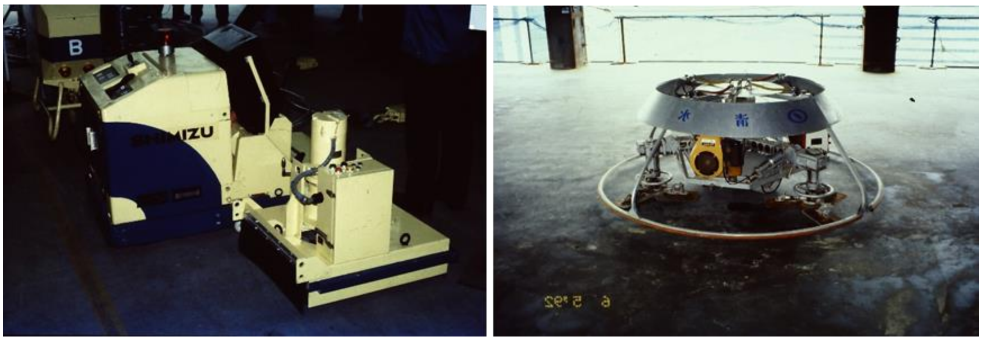

Figure 5 First on-site construction robots developed by Shimizu Corporation (photo: T. Bock)

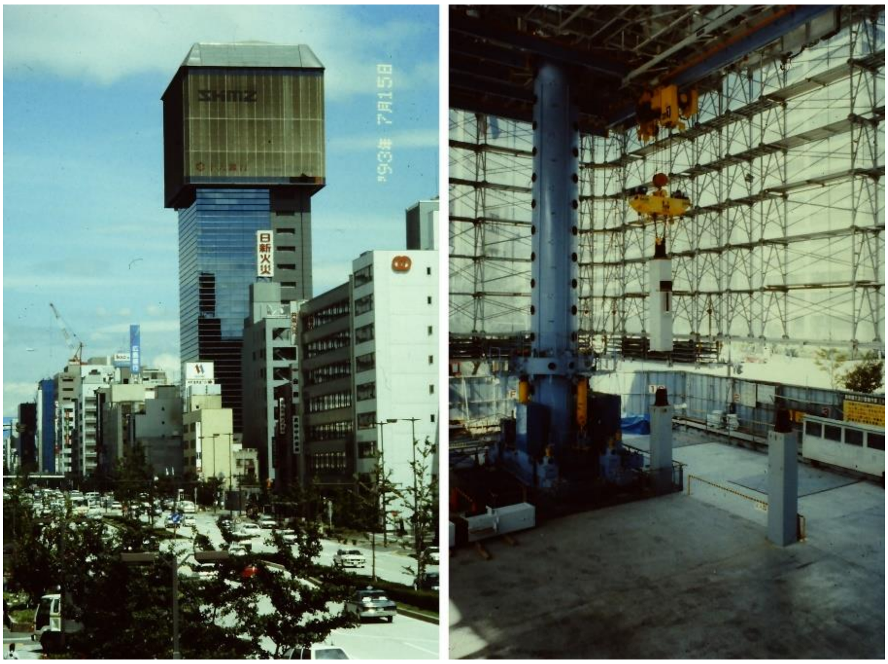

Figure 6 The pioneering automated construction site “SMART” developed by Shimizu Corporation (photo: T. Bock)

Further innovation push was triggered by earthquakes, landslides, volcano eruptions, and tsunamis where initially since 2000s, teleoperated construction robots (see Figure 7) and since 2010s, autonomous scrapers, graders, rollers, compactors, trucks, and excavator fleets for large engineering projects such as dams, roads, bridges and tunnels have been developed and applied (see Figure 8). For maintenance, inspection, and repair of buildings and infrastructure such as tunnels, roads, dams, and power plants, various maintenance robots were developed (see Figure 9).

Figure 7 Teleoperated construction robot for tunnel construction (photo: T. Bock)

Figure 8 Autonomous heavy machinery fleet for infrastructure projects (Photo: T. Bock)

Figure 9 Maintenance robot Enryu T-53 developed by TMSUK Co. Ltd. (photo: T. Bock)

As a national project on circular construction, the Solid Material Assembly System (SMAS, see Figure 10) based on an earthquake-proof reinforced concrete block assembly and disassembly robot was successfully developed and tested at the Building Research Establishment (BRE) of Japan's Ministry of Construction between 1984 and 1988. The robot utilized a FANUC robotic arm with a specially designed end-effector with gripping and bolting functions to better coordinate the vertical reinforcement bolting connections of the customized "Lego-like" concrete blocks (i.e., passive compliance, see Figure 10 right), meanwhile integrating a glass fiber sensor to check the proper position of these connections (i.e., active compliance). A supply pallet system for 8 concrete blocks was also designed to coordinate with the operation of the robot. During this project the co-author T. Bock developed the notion of Robot-Oriented Design, which suggested that architects and engineers should already consider the application of robotic technology on the construction sites when designing the compliant buildings and their elements, eventually achieving shorter on-site assembly time and higher profitability (Bock, 1988). The Robot-Oriented Design concept was applied to the first automated construction site SMART (see Figure 6) and to Obayashi's Automated Building Construction System (ABCS) from 1992 onwards, and also laid the foundation for the development of many construction robot systems. Furthermore, the Robot-Oriented Design concept has also catalyzed many closed loop deconstruction systems such as Hat Down Method by Takenaka Corporation and Taisei's Ecological Reproduction System (TECOREP) (Bock and Linner, 2016a).

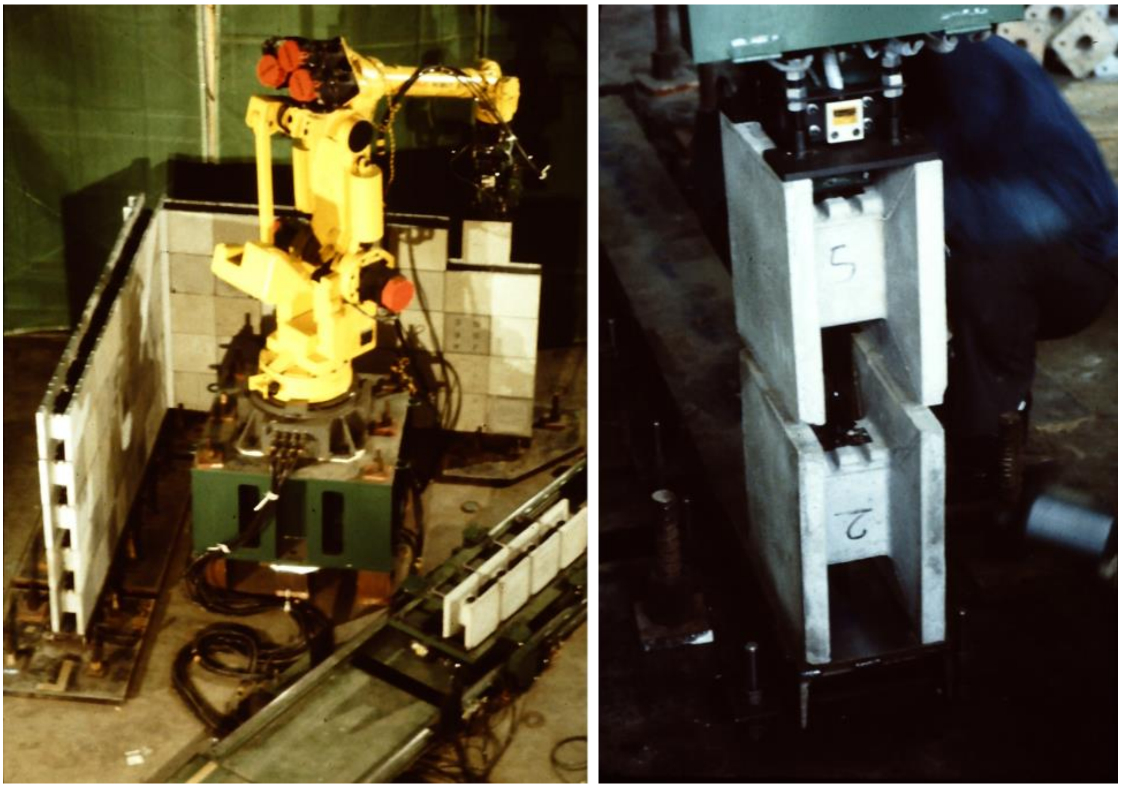

Figure 10 The SMAS robot developed for the assembly and disassembly of reinforced concrete blocks using Robot-Oriented Design concept (photo: T. Bock)

4.2 Case studies on the construction robots developed by University of Karlsruhe and Technical University of Munich

Today, the application areas of construction robots continue to expand. Recently, researchers have summarized some 200 existing construction robot systems into 24 categories based on their functions and features (Bock and Linner, 2016b). The following sections demonstrate the research endeavors led by the co-author T. Bock and his team to develop construction robots to promote circular construction at two German universities throughout the past few decades.

After the German reunification, there was an increased need for construction, especially for affordable housing - as is the case today. Together with SÜBA Bau AG, T. Bock developed the production system for the "x8 Haus" (see Figure 11) as part of his professorship for automation in construction operations at the civil engineering faculty of University of Karlsruhe (now Karlsruhe Institute of Technology) in 1990. It offered 100 m^2 of living space on two stories with a bathroom-toilet building service module, without a basement and can be prefabricated in 8 days by a specially developed multifunctional system with portal robots, assembled on site in 8 hours and sold for 80,000 German Marks (see Figure 12).

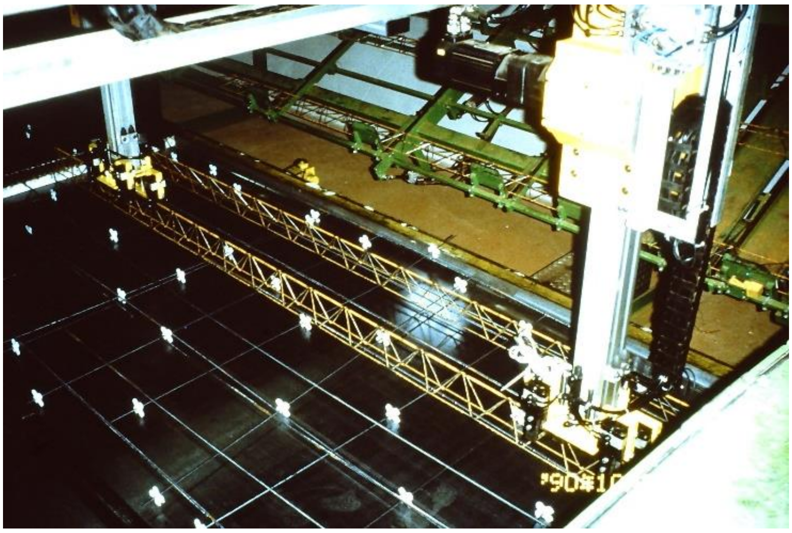

Figure 11 Robotic reinforced concrete parts production system for the “x8 Haus” (Photo: T. Bock)

Figure 12 The built “x8 Haus” applying the Robot-Oriented Design concept (Photo: T. Bock)

As mentioned above, construction robots are robots or automated devices that are developed primarily for tasks on the construction sites. It is a highly cross-disciplinary field which requires an integration of a variety of knowledge and expertise such as civil engineering, architecture, industrial design, construction management, robotics, mechanical engineering, electrical engineering, and informatics (Bock and Linner, 2016b). Over the years, the Chair of Building Realization and Robotics at Technical University of Munich together with its start-ups and spin-offs such as such as CREDO Robotics GmbH (https://credorobotics.com/), ARE23 GmbH (https://www.are23.com/), KEWAZO GmbH (https://www.kewazo.com/), ExlenTec Robotics GmbH (https://robotics.exlentec.com/) have vigorously contributed to the automation and robotization of construction especially regarding circular construction with several research and innovation projects. The following section will introduce three exemplary case studies on how Prof. Thomas Bock and his team contributed to the field of circular construction with construction robotics in recent years.

4.2.1 Consultancy on Investigating the Potential of Implementing Robotics and Automation in the Context of Large-scale Housing Development for Hong Kong

The public housing construction industry in Hong Kong, predominantly using prefabricated concrete as the construction material, faces conspicuous challenges of high demands, safety, an ageing workforce, inconsistent quality and stagnant productivity.

The consultancy project commissioned by the Construction Industry Council (CIC) of Hong Kong SAR evaluates the current on-site construction operation and identifies the existing bottlenecks that can be enhanced by implementing robotics and automation. In the current housing construction field, the systematic and scientific method to approach this type of undertaking, especially when closely associated with the industry and authorities, has not been comprehensively discussed.

Therefore, this project highlights the activities that signify these objectives, which include five key activities: literature review, industry survey, on-site case study, co-creation workshops and potential pilot project. As a result, a range of robotic applications that are tailor-made for Hong Kong's prefabricated public housing industry are recommended and hierarchically categorized. In addition, a semi-functional prototype of multifunctional façade-processing robot (e.g., painting, cleaning, grinding, inspection, marking, etc.) was designed, built and tested in laboratory as a proof of concept (see Figure 13 and Figure 14). The robot can work on the façade of high-rise public housing buildings in Hong Kong and beyond in collaboration with workers. In conclusion, the findings will inspire the construction industry to initiate and explore innovative, compatible as well as feasible solutions to the implementation of the robotic application in the future (Pan et al., 2018).

Figure 13 The multifunctional façade-processing robot showcasing the painting function on the façade of public housing buildings in Hong Kong (image: R. Hu)

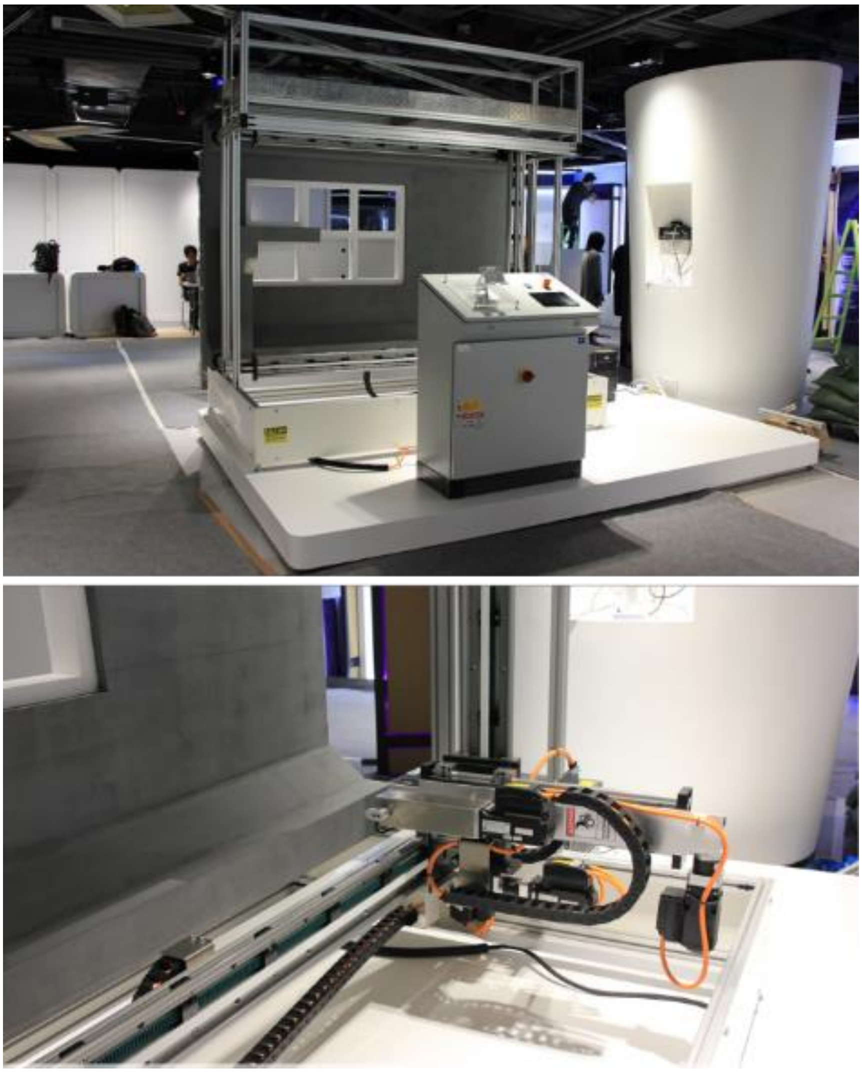

Figure 14 The semi-functional prototype of the multifunctional façade-processing robot displayed in the Construction Innovation and Technology Application Centre in Hong Kong (photo: R. Hu)

4.2.2 HEPHAESTUS cable-driven façade installation robot

HEPHAESTUS is short for Highly Automated Physical Achievements and Performances Using Cable Robots Unique Systems. The HEPHAESTUS project explores the innovative use of robots and autonomous systems in construction, a field where the incidence of such technologies is minor to non-existent. The project aims to increase market readiness and acceptance of key developments in cable robots and curtain walls. The installation of curtain wall modules (CWMs) is a risky activity carried out in the heights and often under unfavorable weather conditions. CWMs are heavy prefabricated walls that are lifted normally with bindings and cranes. High stability is needed while positioning in order not to damage the fragile CWMs. Moreover, this activity requires high precision while positioning brackets, the modules, and for that reason, intensive survey and marking are necessary. In order to avoid such inconveniences, there were experiences to install façade modules in automatic mode using robotic devices.

In HEPHAESTUS, a novel system has been developed in order to install CWMs automatically. The system consists of two sub-systems: a cable driven parallel robot (CDPR, see Figure 15) and a set of robotic tools named as Modular End Effector (MEE, see Figure 16). The platform of the CDPR hosts the MEE. This MEE performs the necessary tasks of installing the curtain wall modules. There are two main tasks that the CDPR and MEE need to achieve: first is the fixation of the brackets onto the concrete slab, and second is the picking and placing of the CWMs onto the brackets. The first integration of the aforementioned system was carried out in a controlled environment that resembled a building structure. The results of this first test show that there are minor deviations when positioning the CDPR platform (Iturralde et al., 2022). In future steps, the deviations will be compensated by the tools of the MEE and the installation of the CWM will be carried out with the required accuracy automatically.

Nevertheless, the initial on-site test results suggest that the robot can potentially boost productivity by 220% for an average construction job, compared to the conventional façade installation method. Furthermore, a study on the cost-benefit analysis of construction robots estimates that the HEPHAESTUS cable-driven robot for facade installation is theoretically worth investing in in the UK, as well as in the majority of G20 countries (Hu et al., 2021).

Figure 15 HEPHAESTUS cable-driven façade installation robot on a testing site (photo: T. Bock)

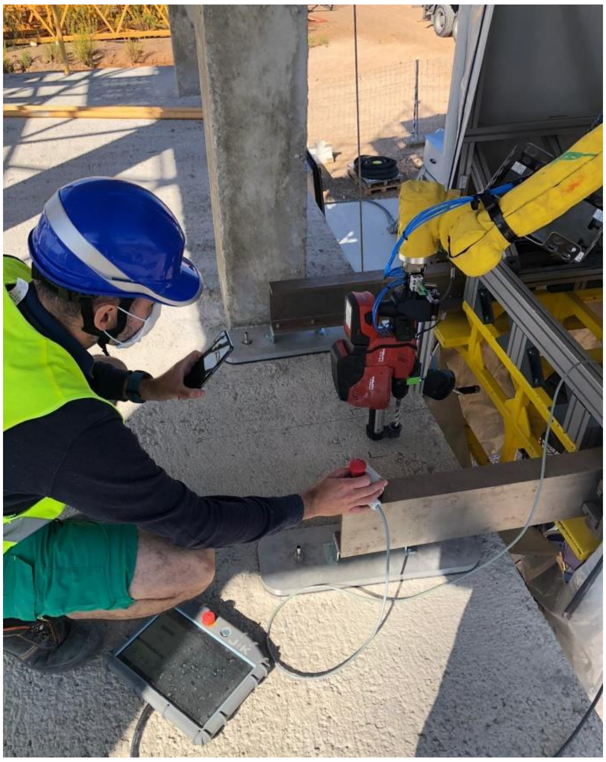

Figure 16 Checking the performance of the modular end-effector of the HEPHAESTUS robot (photo: S. Palencia Ludeña)

4.2.3 ARE23 wall painting robot

ARE23 GmbH was co-founded in 2020, and the CEO, Dr.-Ing. Wen Pan is a researcher at the Chair of Building Realization and Robotics. It is an augmented robotics engineering company whose mission is to support laborers in the construction space with artificial intelligence (AI) and robotics-driven technology. It automates the wall coating industry and digitalizes the entire operational process with affordable solutions. Its product range of small and large-scale spray coating robots used for residential and commercial-sized projects complements human skills, improves productivity and cuts costs.

Providing the workforce with a catalogue of robotic spraying solutions will allow the industry to satisfy the increasingly growing labor demand while guaranteeing premium paint application quality. A 3-axis machine for an interior surface coating robot that can autonomously scan a surface, determine its optimal path, and spray hard to reach surfaces. Leveraging Vention's cloud-9 programming environment, they were able to write their own code and quickly merge it with their existing operating system (ARE-OS). ARE23's specific combination of automation technology enabled by its advanced software platform will drive the digital transition in the construction coating industry. The start-up aims at developing a range of robotic solutions for the painting, plastering and coating of industrial spaces.

For example, the "TITAN" range (see Figure 17) is developed for larger commercial, and industrial applications, while the "COMPACT" range (see Figure 18) is suitable for residential, hotels, and offices. The initial test results suggest that both variants of the robot can potentially boost productivity by 250% compared to the conventional manual wall spraying method, with the same number of operators involved in both methods. The fully functional “COMPACT” product will be ready for the commercial pilot in early 2023.

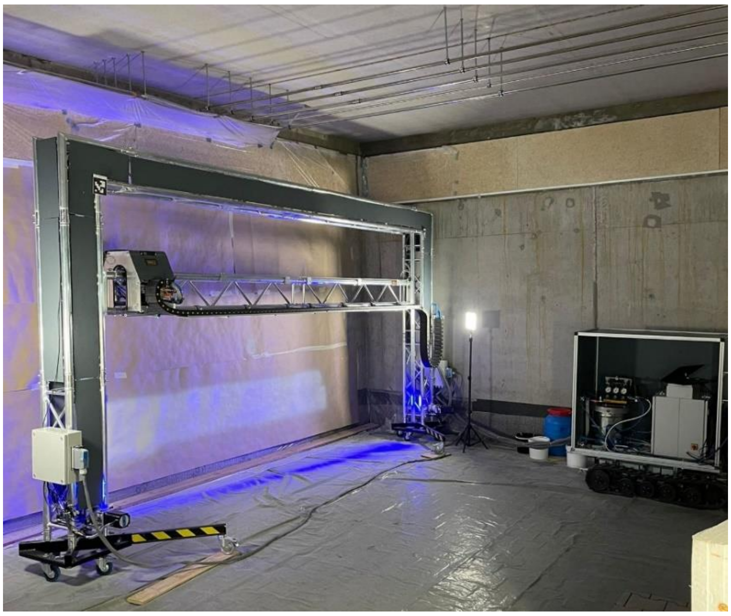

Figure 17 Prototype of the “TITAN” range on a pilot project site (photo: ARE23 GmbH)

Figure 18 Proof-of-concept prototype of the “COMPACT” range (photo: ARE23 GmbH)

4.2.4 KEWAZO hoisting robot for vertical material transport

Scaffolding assembly, a potentially hazardous and time-consuming task in construction, is responsible for the majority of casualties within the construction industry in most industrialized nations (Follini et al., 2018). Therefore, it is highly urgent to improve the safety and efficiency of the scaffolding assembly process.

Co-founded by several TUM graduates including former members of the Chair of Building Realization and Robotics in 2018, KEWAZO GmbH emerged with a clear mission to transform on-site construction operations through the implementation of robotics and data analytics. The founding team brought together diverse expertise in construction robotics, civil engineering, computer science, and business. The company revolutionizes the challenging realm of scaffolding, a profession known for its extreme complexity, laboriousness, and danger. By harnessing the power of automation and intelligence, KEWAZO's innovative approach supersedes hazardous logistical procedures, offering unparalleled efficiency to the construction industry. KEWAZO offers LIFTBOT, an intelligent robotic hoisting system for the construction and industrial sectors. One of its first application cases of the technology is scaffolding. LIFTBOT involves a state-of-the-art robotic hoist system integrated with a data analytics platform. Addressing the critical issue of labor shortages and safety in the construction especially for scaffolding, KEWAZO's innovative approach saves up to 70% of labor costs while simultaneously enhancing the working conditions and safety for the aging construction workforce. Furthermore, the robotic system boasts effortless installation, requiring under 20 minutes and minimal space. It operates wirelessly and with great degree of autonomy, granting the customers seamless control and ease of operation (see Figure 19) (KEWAZO GmbH, 2023).

Figure 19 KEWAZO's LIFTBOT in operation on a construction site (photo: KEWAZO GmbH)

Currently, the company has already more than 20 robots on-site all over the EU, UK, and US. Soon the solution will be used to transport all kind of construction materials on construction and industrial sites. It has become a global leader among construction robotics start-ups, with a dedicated team of over 40 employees and two locations in Germany and the US. In 2023, the start-up announced the closing of its $10 million Series A funding round, bringing the total funds raised to date to approximately $20 million. Through close collaboration with its customers, manufacturing partners, and industry experts, KEWAZO is marching ahead to digitalize construction sites and elevate the working conditions for millions of construction workers worldwide (KEWAZO GmbH, 2023).

5. Key learnings and potential risks of Germany's circular construction

Compared to other countries, Germany usually has small to medium sized, highly specialized, locally oriented companies ("hidden champions") in terms of design, construction, and manufacturing in the construction sector with a few exceptions.

Circular construction is a very new concept for the construction industry in Germany, but it has huge potential in addressing the critical social, environmental, and economic issues of our time. Therefore, innovative approaches need to be adopted in parallel to achieve the goal of circular construction.

As more and more construction companies begin to set foot in circular construction, however, the implementation process of circular construction should avoid the following main dysfunctions (Diaz Gonçalves & Saporiti Machado, 2023):

- Greenwashing which means that employing persuasive marketing and public relations language to deceive customers into believing that their products, services, or procedures have a significant positive impact on the environment, when it is not entirely accurate or not true at all.
- Commodification which indicates that environmental and social considerations will be esteemed and safeguarded only if they provide profits.
- "Cherry Picking" which suggests that only put emphasize on selected aspects in sustainability that are easy to achieve or profitable while ignoring other relevant but important environmental or social aspects.

6. Conclusion

In summary, the construction industry is a major consumer of natural resources. It is crucial to adopt the philosophy of circular economy into the construction sector. There are several existing regulations, guidelines, standards, certification frameworks, and subsidies on the EU and national levels to support circular construction in Germany. Construction engineering companies like Ed. Züblin AG and Goldbeck GmbH has already started its endeavors in circular construction to promote a circular economy in Germany.

Furthermore, innovative solutions such as construction robot and Robot-Oriented Design can potentially play a significant role in the sustainable development of the construction industry by improving productivity, reducing waste, enhancing safety, as well as mitigating labor shortages. The research and innovation endeavors represented by several research projects and entrepreneur activities conducted by the Chair of Building Realization and Robotics at Technical University of Munich along with its in-house spin-offs and start-ups such as CREDO Robotics GmbH, ARE23 GmbH, KEWAZO GmbH, ExlenTec Robotics GmbH over the years contributed significantly to the knowledge and know-hows in the construction industry, especially for circular construction.

In connection with new approaches from the field of human-centric use of robots, human labor can be perfectly supplemented in order to compensate for the shortage of skilled workers. Automated construction machinery for infrastructure construction offers highly efficient solutions for the expansion and renovation of roads, railroads, bridges, and tunnels. Advances in the field of digital connection and programming of robots increasingly facilitate the use of these solutions. Future research will be conducted on the universal simulation environment for customized robotic applications for a resource-efficient and human-centric construction industry. Furthermore, the knowledge and know-hows gained in these endeavors will lay the groundwork for the next frontier of construction robotics beyond the construction sites, such as dismantling modular buildings and infrastructure (Figure 20) and constructing space architecture (Figure 21).

Figure 20 Concrete dismantling and recycling robot Garapagos (Photo: T. Bock)

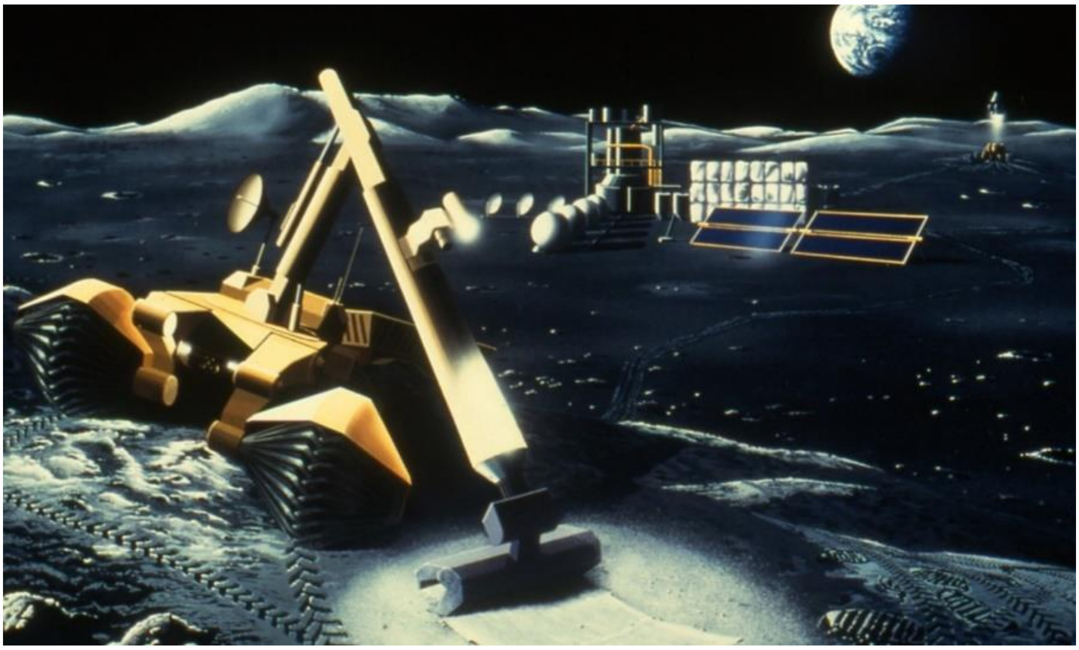

Figure 21 Next frontier for construction robotics: space stations and colonies (Photo: T. Bock)

Acknowledgments

This research was conducted as parts of the Grant-in-Aid for Scientific Research Activity in Japan (2022-2025): "Development, empirical research, dissemination of new theories and system techniques for the circular economy to meet the responsibility for production and consumption of SDGs."

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Applying Circular Economy in the Construction Sector: Comparative Case-studies Analysis from Italy

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Abstract

Resource scarcity and climate change are two of the biggest challenges of our times. The concentration of greenhouse gas is rising steadily since the Industrial Revolution, leading to an average global temperature that is higher and higher and we are consuming resources for 1.75 planet. The construction sector is one of the main responsible of the emissions and therefore is object of great attention from policy makers and academia aiming at finding innovative solutions to cut emission of this sector that, alone, is responsible of the 40% of greenhouse gas emissions. In addition, the construction and demolition waste accounts for the 35.9% of the total waste, representing the largest category. Circular economy is seen as an opportunity to thrive and tackle climate change, fostering a new model of economy that overcomes the linear process of "take-make-dispose", which is the basis of the current economic system. Indeed, circular economy aims at implementing thriving systems without continuing with the consumption of the finite resources, but eliminating the concept of waste and pollution, maintaining products and materials in loop at their highest value and regenerating nature. Circular economy principles have been applied to the construction sector, trying to overcome the focus on energy efficiency of building and widening the perspective to embrace the whole life cycle in the discourse. However, an holistic vision is still missing.

The purpose of this contribution is to explore and present the policies related to the circular economy at International, European and Italian level, starting from ISO standards which are currently under development, the first circular economy action plan enacted in 2015, the current European Green Deal and the new circular economy action plan. Moving from a strategic to a regulative framework, a European directive does not exists targeting the construction sector since the building stock and the climate conditions vary significantly across EU. However, the Level(s) framework has been developed and tested, representing a common EU framework of core sustainability indicators for office and residential buildings. Level(s) framework inspired already many regulations that are in force in some Member States, and the Italian case of the minimum environmental criteria is presented. Lastly, the manuscript presents an overview of the circular economy application in the Italian construction sector, and the Webuild company case study is presented together with the Manni Group one.

Keywords: Circular economy, Construction sector, Italy.

1. Introduction

Resource scarcity and climate change are two of the biggest challenges of our times. At present, we need 1.75 planets (https://data.footprintnetwork.org) to provide the necessary resources and capacity to absorb our waste, with the consequence that the overshoot day is being anticipating every year: in about 7 months all the resources that the planet is able to regenerate for the entire year have already been consumed by the humankind. Projecting this trend in 2030, we will need more than two planets (Global Footprint Network, 2023). In addition, industrialization, deforestation and large-scale agriculture has been growing exponentially in the last one century and a half; as a consequence, never seen quantities of greenhouse gases (GHGs) have been released in the atmosphere (United Nations website). Scientifically, it has been established that the concentration of GHGs in the earth's atmosphere is directly linked to the average global temperature on Earth. This concentration has been rising steadily, leading to a higher and higher mean global temperature, since the time of the Industrial Revolution. The most abundant GHG is the carbon dioxide (CO_2) that accounts for about two-thirds of GHGs. It is largely the product of burning fossil fuels.

The construction sector is one of the main responsible of the emissions and consequently it is object of great interest from researchers and policy-makers aiming at finding new innovative solutions to cut emissions, specifically when it comes to building conservation and renovation (Sáez-de-Guinoa et al., 2022). In fact, constructions are impacting on both the sides of resource consumption and waste production: it is estimated that construction materials like cement and iron, together with industrial process for the construction industry, are responsible for the 40% of GHGs emissions (European Construction Sector Observatory, 2019), while the construction and demolition waste (CDW) represents the largest category produced in Europe in 2018 accounting for 35.9% of the total waste produced (Eurostat, 2021).

Circular Economy is an opportunity to face resource scarcity, offering an alternative to the linear model of consumption and production based on the "take-make-dispose" process, towards a circular model in which resources are looped and kept in the system as long as possible and at their highest value. In addition, in April 2022 it has been mentioned for the first time that Circular Economy is a solution to tackle climate change, due to its application to many sectors of economy (IPCC, 2022). As a consequence of this extreme flexibility of the concept, a clear and unique definition does not exist (Kirchherr et al., 2017, 2023) The Ellen Mac Arthur Foundation (EMF) is a pioneer in the field. Founded in 2010 by Ellen Mac Arthur, today the association is one of the biggest entity recognized at international level promoting the concepts of the circular economy and the sustainable transitions[1]. The first report drafted titled "Towards the circular economy" was disrupting since for the first time it has been demonstrated the validity of the concept, both in terms of strategic opportunities that will raise and in terms of economic benefits. The report asserts that the transition towards the circular economy is economically viable and scalable for different products and it demonstrates the advantages for both companies and consumers (Ellen Mac Arthur Foundation, 2013).

1 https://ellenmacarthurfoundation.org/network/overview

2. Circular economy policies at international and European level

2.1 The international level

The technical Secretariat ISO/TC 323 has been established in 2018 made up of experts from over 65 different countries and growing, with the aim to develop International standards related to CE to establish a common reference and standardize the implementation of CE principles in organizations and business models. The ISO 59000 series of documents that are still under development, even though four out of six are in a more advanced status, being the final text received or registered for formal approval (DIS or FDIS). The other two are still in their infancy, being or with a committed draft received (CD) or with proof sent to secretariat or ballot initiated (DTR). More details are provided below.

1) ISO/FDIS 59004 - Circular Economy – Terminology, Principles and Guidance for Implementation https://www.iso.org/standard/80648.html?browse=tc

This document defines key terminology, establishes circular economy principles, and provides guidance for its implementation by using a framework and areas of action. It is intended for private or public organizations, acting individually or collectively, regardless of their type or size, and located in any jurisdiction or position within a specific value chain or value network.

2) ISO/FDIS 59010 - Circular Economy — Guidance on the transition of business models and value networks https://www.iso.org/standard/80649.html

This document provides guidance for an organization seeking to transition its business models and value networks from linear to circular. This document applies to any organization dealing with products or services regardless of its size, sector or region.

3) ISO/FDIS 59020 - Circular Economy — Circular Economy — Measuring and assessing circularity https://www.iso.org/standard/80650.html?browse=tc

This document specifies a framework for organizations to measure and assess circularity, enabling those organizations to contribute to sustainable development. It is applicable to multiple levels of an economic system, ranging from regional, inter-organizational, organizational to the product level. The framework aims at providing guidance on how the circularity performance of an economic system can be measured and assessed using circularity indicators and complementary methods. The framework can be used to determine the effectiveness of circular actions executed by public and private organizations. The framework can include consideration of social, environmental and economic impacts when assessing circularity performance by allowing input from a variety of complementary methods.

4) ISO/DIS 59040 - Circular economy – Product Circularity Data Sheet https://www.iso.org/standard/82339.html?browse=tc

The document provides a general methodology for improving the accuracy and completeness of circular economy related information based on the usage of a Product Circularity Data Sheet when acquiring or supplying products. This general methodology contains then a set of requirements that need to be established by an organization aiming to use the concerned data sheet when acquiring or supplying products, which also includes the trusted reporting and exchanging of circular economy related information. The document also provides guidance for the definition and sharing of a Product

Circularity Data Sheet, considering the type, content and format of information to be provided. This guidance and these requirements are intended to be applicable to all organizations, regardless of type, size and nature. These requirements implement a qualitative approach for business-to-business data exchange to be inclusive with small and medium businesses/enterprises and to protect confidential information.

5) ISO/CD TR 59031 - Circular economy – Performance-based approach – Analysis of cases studies https://www.iso.org/standard/81183.html?browse=tc

Not updated information are available since it is still at the beginning of the process.

6) ISO/DTR 59032- Circular economy – Review of business model implementation https://www.iso.org/standard/83044.html?browse=tc

Not updated information are available since it is still at the beginning of the process.

The relation between the standards can be exemplified as follows:

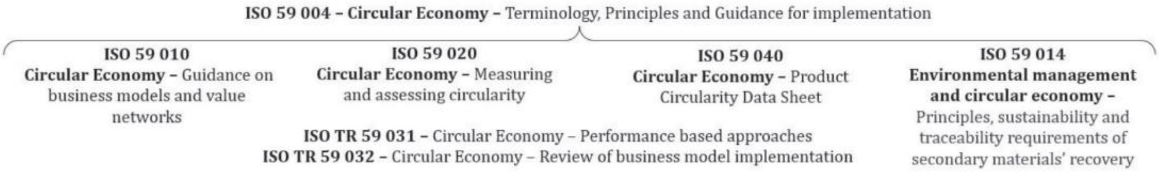

Figure 1: relation between the CE ISO standards. Source: draft of ISO standards available at https://www.iso.org/obp/ui/en/#iso:std:iso:59020:dis:ed-1:v1:en

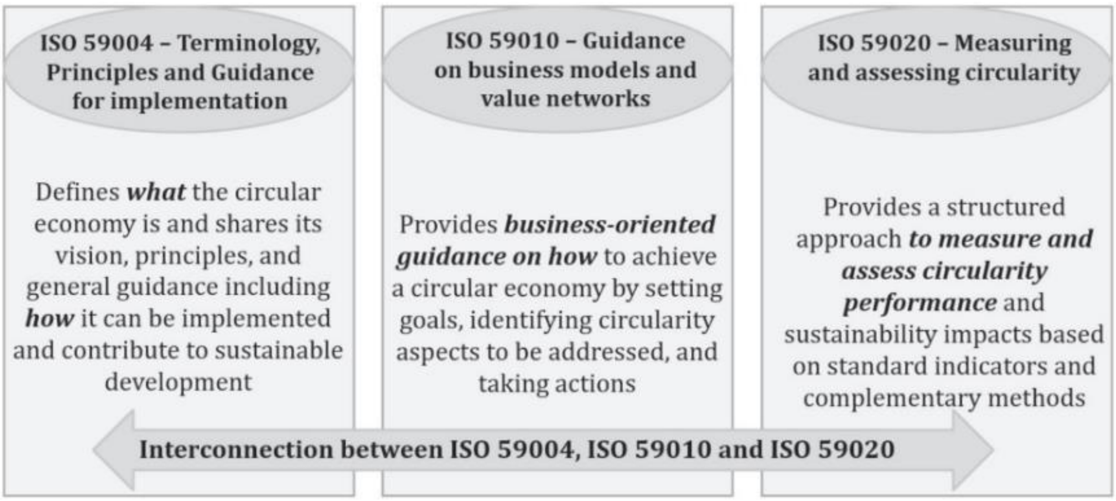

Figure 2: relation between the CE ISO standards. Source: draft of ISO standards available at https://www.iso.org/obp/ui/en/#iso:std:iso:59020:dis:ed-1:v1:en

In particular, for the ISO 59004 standard a preview of the contents is available. The document is about CE principles and guidance for implementation, proposing a sequence of steps for CE implementation in organizations, summarized below.

- **Analysis of the context and reference situation when it comes to the CE**, through the analysis of current resource management, the flow of resources, sectors with relevant opportunities in terms of circularity transitions, the analysis of the current environmental impact as well as social implications, exploration of options to use energy and sustainable resources, assessment of legal and regulatory requirements that could influence the action plan. In addition, the organization should understand how much CE will be relevant for the organization and the stakeholders;
- **CE purpose, mission, vision and goals definition**. The organization is called to develop a mission in alignment with CE principles, a vision that includes a commitment and inspires actions for the transition, to be shared with local stakeholders;
- **CE strategic priorities and action plan development:** the organization should develop ideas and a list of actions, starting from those having the biggest potential that have to be prioritized. The phase is also dealing with the establishment of a monitoring strategy and the creation of value. In this case, some elements to be considered are suggested: technically and economically feasibility of CE practices that add value to the organization, a clear definition of a comprehensive CE value creation model that includes and is supported by transition pathways and, lastly, a comprehensive CE value creation model that can be achieves through implementation of relevant CE practices.
- **CE implementation.** In this phase strategic priorities of the action plan are put in place, and it is important to integrate those practices into organizational culture, through raising awareness initiatives and by building capacity.

2.2 The European level

As far as CE in Europe is concerned, the reference policy document is the New CE Action Plan. It has been adopted by the commission in March 2020, as one of the main pillar of the European Green Deal which is considered the EU agenda for sustainable growth. However, as its name predicts, it is rooted in previous initiatives promoted by the European Commission, starting from 2015 when the first CE action plan was adopted. This initial plan included measures stimulating the Europe's transition towards a CE while fostering sustainable economic growth and the generation of new jobs. 54 actions were included in the plan, and after three years of implementation, all of them have been achieved even if for some actions the work continues also beyond 2019. Actions were related to the whole life cycle going in detail of different phases of the production and consumption process. The actions are divided according to the topic they mainly refer to: production, consumption, waste management, market for secondary raw materials and sectorial actions concerning some on strategic sectors (e.g. plastic, food waste, critical raw materials, construction and demolition, biomass and bio-based materials, innovation and investments, monitoring). A comprehensive report has been drafted by the European Commission and released on 4th March 2019 with the aim to present the main achievements and the open challenges of the transition towards a CE and climate neutrality. In this report it is stated that in 2016 the employment rate in circular jobs increased of 6% compared to 2012 and circular activities such as repair, reuse or recycling generated almost €147 billion in added value requiring around €17.5 billion of investments.

The most important results coming from the implementation of these actions constituted the milestones towards the adoption of the European Green Deal and the New CE Action plan. In this respect, when it comes to the production processes and the circular design, in November 2016 the Eco-design working plan 2016-2019 has been issued, with the purpose of identifying Commissions' priorities under eco-design and energy labelling. In Europe, both Eco-design and Energy labelling Directive are framework directives and therefore they should be transposed by Member States which set out binding requirement specific for each product group. Working plans have the purpose of identifying categories of products to be investigated in the next three coming years to be analysed in depth and for which new measures can be prepared. Eco-design directive and Energy Labelling measures have been then modified including new material efficiency requirements such as ease of repair and the facilitation of the end-of-life treatment. Beyond these mandatory aspects, voluntary tools have been developed such as the EU Ecolabel and the Green Public Procurement criteria. In October 2019, 10 Eco-design implementing regulations have been adopted especially concerning household appliances like refrigerators, washing machines, dishwashers and televisions.

Another milestone towards the adoption of the European Green Deal is represented by the adoption of the **CE package in January 2018**. As part of this package, the development of a new monitoring system for the CE is important to highlight. In fact, it responds to the necessity of measuring the transition in a clear and possibly commonly-defined way, being difficult universally to frame the "circularity" phenomenon. Moreover, with a unique score or a single index it is impossible to capture the extreme complexity of the transition towards circularity; the proposed monitoring system includes 10 indicators covering the different phases life cycle of products and competitiveness aspects. The use of these indicators in not mandatory for the Member States, however some of them have developed additional indicators completing the picture depicted by the European Commission. The monitoring framework has been updated by the European Commission in 2023, with the addition of indicators about material footprint and resource productivity in order to monitor material efficiency, and also consumption footprint to monitor if EU consumption fits within planetary boundaries. The new framework supports the EU's CE and climate neutrality ambitions under the European Green Deal.

The complete list is reported in Table 1.

Table 1 Proposed indicators for CE monitoring in EU

Category	Indicators	Notes
Production and consumption	1) Material Consumption	
	2) Green Public Procurement	Financing aspects
	3) Waste generation	Consumption aspects
Waste management	4) Overall recycling rates	Share of recycled waste
	5) Recycling rate for specific waste streams	Packaging, biowaste, etc.
Secondary raw materials	6) Contribution of recycled materials to raw materials demand	
	7) Trade of recyclable raw materials between the EU Member States and with the rest of the world	
Competitiveness and innovation	8) Private investments, jobs and gross value added related to CE sectors	
	9) Innovation	
Global sustainability and resilience	10) Global sustainability	Consumption footprint and GHGs emission from
	11) Resilience	production activities; Material import dependency

The indicator framework is able to capture the changing occurring in the priority areas for the European Commission and it is able to assess whether measures put in place are effective. It is published on a website[2] and some indicators are calculated through a sum of more than one sub-indicator.

As part of the CE package, a Europe-wide strategy for plastics in the CE and a report on critical raw materials and the CE are also mentioned as key fact.

In the same year (July 2018) the revised legislative framework on waste has entered into force and it is mandatory for the Member States to adopt legislations according to the new target and objectives stated by the EU. Among others, new ambitious yet realistic recycling rates are defined requiring that by 2030, 70% of all packaging waste should be recycled as well as the 65% of municipal waste by 2035. In addition, landfilling of municipal waste should be reduced and maintained up to 10% of municipal waste.

As mentioned before, in the CE action plan the consumption practices and the investments in innovation are also present. Concerning the first one, EU states that the transition towards a CE is not

[2] https://ec.europa.eu/eurostat/web/circular-economy/indicators

possible without the active engagement of citizens in changing their consumption patterns. In order to shift purchasing towards more sustainable choices, two methods for the identification of environmental performance of products have been conceived: the Product Environmental Footprint (PEF) and the Organisation Environmental Footprint (OEF). Lastly, it is worth to mention the efforts made by the European Commission in investing in innovation and supporting the adaptation of the industrial sector base, with more than €10 billion in public funding for the transitions. Together with this initiative, the Commission also addressed regulatory obstacles that may hinder circular innovation. Stakeholders engagement is also crucial for the transition to happen and, in this framework, industry engagement has led to the adoption of Construction and Demolition Waste Protocol and Guidelines with the aim to increase confidence in waste management and in the quality of recycled materials in the construction sector.

Thanks to the implementation of the 54 actions, the EU is recognised as a leader in CE policy-making globally, and the action plan encouraged at least 14 Member States, 8 regions and 11 cities to put forward CE strategies. (EMF website https://ellenmacarthurfoundation.org/circular-examples/the-eus-circular-economy-action-plan).

As said before, all the 54 actions included in the first CE action plan has been completed within 2019 and, in December of the same year, the European commission adopted the **European Green Deal**. It consists in a package of policy initiatives set up to paving the road for a green transition, with the ultimate goal of reaching climate neutrality by 2050. The European Green Deal will transform EU into a modern and competitive system, decoupling economic growth from the use of finite resources and ensuring a fair and prosperous society with no person and no place left behind.

The green deal aims to achieve these three main goals. First, it focuses on achieving net-zero emissions by 2050 proposing specific strategies that can help curb emissions across all sectors, with a strong focus on energy. The objective is to increase the share of renewable energy in the EU's energy mix. Second, it plans to decouple growth from resource exploitation: while reductions in emissions have been achieved in the last decade, Europe remains one of the major contributors of resource consumption in the world. Described as a "generation-defining task," achieving this objective will not only require a boost in technological advancements but also rethinking lifestyles, communities, and societies. Third, there is the need to foster an inclusive green transition and to leave none behind, supported through the Just Transition Mechanism, which will provide between 65€ and 75€ billion over the period of 2021-2027 to alleviate the socio-economic impacts of the transition. As intermediate goal, the package of initiatives and the investments are aimed at reducing at least 55% net GHGs emissions by 2030, compared to 1990 levels.

As one of the main pillar of the European Green Deal, in March 2020, the European Commission adopted the **New CE Action Plan**[3]. The Commission announced that the transition to a CE will reduce pressure on natural resources and will create sustainable growth and jobs, but, of utmost importance, it is also considered a prerequisite to achieve the EU's 2050 climate neutrality target and to halt biodiversity loss.

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3 https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

The new action plan is composed of 35 action to be implemented in the timeframe 2020-2023 focusing in different areas in respect to the previous action plan. In fact, the key actions are listed under seven macro-areas that correspond to as many overall goals and targets: a sustainable product policy framework, key product value chains, less waste more value, making the CE works for people, regions and cities, crosscutting actions, leading efforts at global level, monitoring the progress. Within the design of sustainable products, the idea is to broaden the Eco-design directive beyond energy-related products improving product durability, reusability, upgradability and reparability, increasing the recycled content. Priority areas of interventions are electronics, textiles and ICT. Among the key product value chains, it is worth mention for the scope of the present research the construction and building category. In the Action Plan, the Commission proposes to launch a new comprehensive strategy for a Sustainable Built Environment aiming at coordinate and ensure coherence climate goals, energy and resource efficiency, construction and demolition waste, accessibility, digitalization and necessary skills. In detail, the strategy should promote circularity principles through the revision of the construction product regulation, promoting the adaptability of the built environment, using Level(s) tool (see paragraph 3.2 for more details) to integrate life cycle assessment in public procurement, revisioning the legislation for construction and demolition waste and promoting initiatives to reduce soil sealing fostering the reuse of abandoned sites and contaminated brownfields. The strategy for a Sustainable Built Environment is still not published in the EU framework, even though it was expected in 2021. However, some of the actions have been addressed in the "Renovation Wave for Europe"[4] in which particular attention has been paid to greening buildings.

In the three years passed from the adoption of the CE action plan, many results have been achieved. The Commission adopted a proposal for a new regulation on sustainable batteries (2020), a Global Alliance on CE and Resource Efficiency (GACERE) has been launched in 2021 and new proposals about organic pollutants in wase and waste shipments are adopted. In March 2022 the European Commission adopted a package of measures proposed in the CE action plan consisting in sustainable products initiative (including a proposal for Eco-design for sustainable products regulations), the EU strategy for circular textiles, a proposal for a revised construction products regulation and a proposal for empowering consumers in the green transitions. In April 2022 both the Industrial Emissions Directive and the European Pollutant Release and Transfer Register have been revised. As far as the construction products regulation is concerned, some other measures have been adopted in November 2022 with the revision of the EU rules on packaging and packaging waste and a communication on a policy framework for bio-based, biodegradable and compostable plastics. More recently, in 2023 the European Commission proposed a Directive on Green Claims and common rules for promoting the repair of goods and, as mentioned, the revision of the monitoring framework. Lastly, several initiatives have been adopted about microplastics such as the REACH restriction addressing intentionally added microplastics, a proposal for a regulation on preventing pellet losses to reduce microplastics pollution.

[4] https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1603122220757&uri=CELEX:52020DC0662

2.2.1 From policies to regulations in the construction sector

As previously explained, the European framework concerning the CE is of strategic nature and it is mainly represented by the CE Action Plan.

Dealing with the construction sector, the "Level(s)[5] – A common EU framework of core sustainability indicators for office and residential buildings" has been developed and published in 2017. It has been designed by the EU with the purpose of including circularity in the life cycle perspective and create a common language helping professionals to improve building performance and policy makers to align their legislation to the environmental objectives. It works in support of the harmonization of monitoring strategies and indicators across the Member States.

Level(s) differs from the certification schemes like LEED, BREEAM or C2C since it does not set benchmarks (that should be established at national level, due to the not-homogeneity of the building stock and climate condition in the whole EU) but it is considered more like a set of tools to reflect the different aspects of sustainability. In fact, it is released as **user manuals and reporting templates**[6], explaining the sustainability concept, how to implement it and how to measure the results. Level(s) is focusing on **six overarching macro-objectives**; for each of them key indicators are identified as it is show in the table below.

[5] https://environment.ec.europa.eu/topics/circular-economy/levels_en

[6] Free download available https://susproc.jrc.ec.europa.eu/product-bureau/product-groups/412/documents

Table 2 Level(s) macro-objectives and key indicators

Macro-objective	Indicator	How to measure
1. Green house gas emissions along a building's life cycle	1.1 Use stage energy performance	$kWh/m^2/yr$
	1.2 Life cycle Global Warming Potential	$kgCO2equivalents/m^2/yr$
2. Resource efficiency and circular material	2.1 Bill of quantities	Unit quantities, mass and years
	2.2 Construction and demolition waste and materials	Kg of waste and materials per m2
	2.3 Design for adaptability and renovation	Adaptability score
	2.4 Design for deconstruction, reuse, recycling	Deconstruction score
3. Efficient use of water	3.1 Use stage water consumption	m^3/yr of water per occupant
From 1-3 FULL LCA	10 impact categories	
4. Healthy and comfortable spaces	4.1 Indoor air quality	Parameters for ventilation, CO2 and humidity
	4.2 Time outside of thermal comfort range	% time out of range during the heating and cooling seasons
	4.3 Lighting and visual comfort	Level 1 checklist
	4.4 Acoustic and protection against noise	Level 1 checklist
5. Adaptation and resilience to climate change	5.1 Protection of occupier health and thermal comfort	Projected % time out of range in the years 2030 and 2050 (see also indicator 4.2)
	5.2 Increased risk of extreme weather events	Level 1 checklist
	5.3 Increased risk of floods events	Level 1 checklist
6. Optimised life cycle cost and value	6.1 Life cycle costs	€/m2/yr
	6.2 Value creation and risk exposure	Level 1 checklist

Three are the "levels" identified to map the sequences in a building project: Level 1 is qualitative and involve the conceptual design of the building project with the project definition and the concept design. No metrics are foreseen in this stage. Level 2 is related to the detailed design and construction with the outline of the spatial planning, the detailed design and the technical design (construction project). In this stage there are references to the international standards to use and the methodology that can be applied, quantifying the performance of building design. Finally, Level 3 is related to as-built situation and in-use regime and, therefore, to the monitoring and feedback process of the real building. Each macro-objective is explained in the user manuals together with the indicators, identifying all the aspects to be taken into account according to the level of the project and differentiating the contents in the case of new buildings or deep renovation of existing ones.

As mentioned above, the Level(s) framework is paving the direction for the harmonization of the way sustainability is considered and can be assessed at building level but it is not mandatory to be transposed in the Member States' legislation. However, many states have their own regulation when it comes to the minimum building performance to guarantee.

Specifically, potential linkages between other existing policies and regulations have been identified to integrate CE into binding requirements for Member States (European Union, 2021). Four policies are selected as potentially implementing CE principles for building design:

- Potential revision of the **Construction Products Regulation**
- Potential revision of the **Energy Performance of Buildings Directive**
- Potential revision and expansion of **GPP criteria**
- Development of **guidance for local and regional authorities**

In terms of integrating circularity into harmonized technical specifications of the **Construction Product Regulation**s for methods and criteria to assess and declare the performance of construction products, the following actions could be useful: i)Map the various commitments, regulations, actions, initiatives, tools, standards, procurement criteria and voluntary agreements that require product level data linked to circularity to be effectively implemented. Involve the various stakeholders and policy makers in defining 'core/mandatory' and 'additional/aspirational' data fields that should be filled by construction product & material suppliers in a harmonised way; ii)Build consensus on the required data and information: Define the 'core' & 'aspirational' data and information (fields/attributes) that should be available for all construction products and materials to support circular design and implementation. This should build upon and align, where appropriate, with the harmonisation work of CEN/TC 350 –EN15804 in particular to avoid duplication of effort. It should also consider aspects of digitisation and ease of collation and updating throughout the asset/building life cycle. Define implementation mechanisms: Develop further the optimal mechanisms for reporting, transferring and updating such information by suppliers to their customers and tools that support more informed decision making, such as BIM alignment and whole life data access and updating. iii)Define implementation mechanisms for reporting, transferring and updating such information by suppliers to their customers and tools that support more informed decision making, such as BIM uploads to provide instant LCA.

In terms of integrating circularity into the revision of **Energy Performance of Buildings Directive**, specific aspects could embed the whole life-cycle carbon approach and circularity performance requirements for new and existing buildings. In details, EPBD could require the circularity assessment of buildings through the adoption of a general common framework into the calculation of the energy performance, such as the potential for reuse and higher values of recycling and GHGs emissions produced over the whole life-cycle. Also, there might be opportunities to set more ambitious targets for emissions and the use of energy in buildings. Financial measures that are linked to energy efficiency, could also be targeted towards interventions that foster circularity. Lastly, the directive imposes that owners and tenants have to be informed about the purpose, objectives and potential financial instruments available to increase cost-effectiveness, but there might be potential to incorporate guidance on the importance of CE principles for buildings design.

As for the development of revision for **Green Public Procurement**, it is currently a voluntary tool based on the Level(s) framework. Additional GPP requirements could be considered to further support circularity such as the development of criteria for building sectors that have not yet been covered by Level(s). It is particularly interesting the case of the public buildings and Green Public Procurement. As an example, Italy enacted the National Green Public Procurement Action Plan (2018) in which it is stated that all public procurement must comply with minimum environmental criteria (Criteri Ambientali Minimi (CAM) in Italian language). The CAM are requirements defined for the various phase of the purchasing process of the public administrations with the purpose of identifying best design solution, products and services from an environmental point of view. Their systematic and homogeneous application makes it possible to prefer environmentally preferable products and produces a leverage effect on the market, inducing less virtuous economic operators to adapt to the new requests of the public administration. In Italy, the effectiveness of the CAM has been ensured by the transposition of the Action Plan in laws (Law 221/2015 and Legislative Decree 50/2016 and subsequent modifications) which made the CAM application mandatory. The objective is not only to reduce the environmental impacts but to promote a more sustainable and circular production and consumption models. To date, CAM have been adopted in 18 categories of supplies and assignments, among which the construction sector is included.

In the document, the "Level(s)" framework is cited, especially because the recommended use of LCA methodologies and for the consideration of indicators related to the health, comfort and potential risks for the maintenance of adequate levels of performance. The application of the CAM is considering and supports the existing regulations already in place like the directive related to the energy performance of buildings (2010/31/UE), the EU regulation about the construction products (305/2011) and the waste management directive (2008/98/CE). Concerning the integration of CE principles, a paragraph is dedicated to disassembly and end-of-life: it is stated that the project relating to new buildings, including demolition works and building reconstruction or renovation, requires at least 70% in weight of the building components subject to disassembly or deconstruction or other recovery operations. The threshold has to be demonstrated through a disassembly and selective demolition plan drafted by the applicant to the tender. Another requirement is related to the use of construction materials (e.g. iron, bricks, wood, concrete, insulation) produced with at least a pre-defined percentage of recycled materials. In addition to the minimum requirements, in the law there are some additional criteria that, if guaranteed by the applicant to the tender, allow to collect extra scores for the evaluation process. As an example, a premium score is attributed to the economic operator who decides to undertake a LCA and LCC study to assess the environmental and economic sustainability of the project as well as the use of BIM technology for the different phases of the construction.

As for the provisions of guidance on local and regional planning, it has as objective the integration of circularity principles through EU funding policies. In terms of tools, the setting of circularity requirements could be within the new Cohesion funds and the renovation wave fundings. Guidance should be offered to policy makers, and should be process oriented, providing a flexible framework to them tailored to the local contexts. It could also be a guidance on how to implement Level(s).

Recently in July 2024 the **new Ecodesign for Sustainable Products Regulation (ESPR)** entered into force as a cornerstone of the Commission's approach to more environmentally sustainable and circular products. Il replaces the Ecodesign Directive 2009/125/EC which was more related only to energy-realted products. The ESPR extend the scope to cover virtually and physical products, as well as reinforces the range of ecodesign requirements that can be set for products, which can comprise requirements relating to durability, circularity and the overall reduction of the environmental and climate footprint of products, amongst many others. The ESPR includes a set of other measures such as the Digital Product Passport (DPP) which might have an impact on the construction sector. DPP is a digital identity card for products, components, and materials, which will store relevant information to support products' sustainability, promote their circularity and strengthen legal compliance. This information will be accessible electronically, making it easier for consumers, manufacturers, and authorities to make more informed decisions related to sustainability, circularity and regulatory compliance. It will also allow custom authorities to perform automatic checks on the existence and authenticity of the DPPs of imported products. Information to be included in the DPP will be identified by the Commission, in close consultation with all relevant stakeholders, and will depend on the specific product in question. This information can include:

- Product's technical performance
- Materials and their origins
- Repair activities
- Recycling capabilities
- Lifecycle environmental impacts.

The Construction Product Regulation will be rely on DPP.

3. Academic society research trend in the construction sector

When it comes to the CE applied in the construction sector, few definitions have been elaborated by scholars with that specific focus, and one only is considering the life cycle of a building in the definition. A more specific and shared definition of the meaning of CE in the construction sector is therefore needed (Benachio et al., 2020).

As reported by Giorgi & Lavagna (2024) at least five topics promoted by European policies are the most discussed in literature, in respect to circular construction:

- the improvements in circular management of inflow and outflow materials from the building process, improving waste identification and quality processing, flow management and planning during the construction phase and the end of life;
- reuse strategy as the best practice of building materials management;
- quantification and mapping of secondary materials stored in products, buildings and infrastructures, for the geolocation of reusable and recyclable urban material resources;
- the change in design process to circularity thus referring to reversibility, adaptability, flexibility, and design for disassembly are the main strategies to extend products and buildings' useful life;
- Construction technologies, as well as modular elements, dry technologies, mechanical connections, off-site constructions, as relevant enablers to achieve a circular design process;

- The importance of Building Information Modeling (BIM) to monitor the use of resources during the whole life cycle, sharing information between operators and simulating building and components reuse scenarios.

For example, architects and engineers are encouraged to design buildings with the end of their lifecycle in mind, facilitating the disassembly and reuse of materials. This approach not only reduces waste but also conserves resources (Sáez-de-Guinoa et al., 2022). Moreover, incorporating materials such as recycled steel, reclaimed wood, and bio-based composites can significantly reduce the environmental footprint of construction projects. For instance, bio-based building materials derived from agricultural waste have been explored for their potential in sustainable construction (Chen et al., 2024; Röck et al., 2020; Thormark, 2006). Finally, BIM technology facilitates efficient design, construction, and management processes, enabling better resource utilization and waste reduction. A study demonstrated that BIM could lead to substantial greenhouse gas emission savings in pavement management systems, suggesting its broader applicability in construction (de Bortoli et al., 2023).

Despite this flourish research, in practice CE practices are rarely applied in a systemic manner and in a life cycle perspective (Giorgi&Lavagna, 2024). In fact, according to the review carried out in 2020 by Benachio et al., (2020) only one study has examined all life cycle stages, while most have focused on just one, thus indicating that research in this field is still primarily concerned with applying CE concepts to individual life cycle stages of the built environment. This suggests that current research is still exploring how to implement CE practices in specific construction scenarios, rather than adopting a more holistic approach. Two levers could foster this holistic approach. On the one hand the policy and regulatory support and on the other hand the Stakeholders Collaboration and Education. By harmonizing regulations across Europe and providing incentives for sustainable practices can encourage the adoption of CE principles. The European Green Deal and the Circular Economy Action Plan are pivotal in setting ambitious targets and providing frameworks for sustainable construction (Sáez-de-Guinoa et al., 2022). Moreover, fostering collaboration among architects, engineers, contractors, policymakers, and clients is essential. Educational initiatives can raise awareness and build capacity for implementing CE practices within the industry.

Many scholars have also highlighted the lack of known standardized practices to implement CE in the construction industry (e.g. (van Bueren et al., 2019)), however recently a literature review is showing the available practices clustered according to the life cycle stage, as reported in Figure 3.

Life Cycle Stage	Circular Economy Practices	References
Project Design	Design and use of modular buildings	Kyrö et al. (2019)
	Design for adaptability of existing buildings	Mangialardo and Micelli (2018); Maerckx et al. (2019); Geldermans (2016); Sanchez and Haas (2018a,b)
	Design for Disassembly of building structures	Leising et al. (2018); Mangialardo and Micelli (2018); Maerckx et al. (2019); Eberhardt et al. (2019b); Rasmussen et al. (2019); Sanchez and Haas (2018a,b); Manelius et al. (2019); Nijgh and Veljkovic (2019); Eberhardt et al. (2019c)
	Use of a scale to analyze the level of implementation of Circular Economy practices in the company	Nuñez-Cacho et al. (2018)
	Use of a simulation in a BIM model to analyze the reuse potential of the materials of different types of designs early in the project.	Akanbi et al. (2018); Akanbi et al. (2019a,b)
	Use of Life-cycle analysis to find the benefits of reusing different types of materials in the design stage	Eberhardt et al. (2019a); Eberhardt et al. (2019b); Hossain and Ng (2018)
	Use of material stock data to help reuse of materials of a new building	Oezdemir et al. (2017); Heinrich and Lang (2019); Gepts et al. (2019); Ajayabi et al. (2019); Arora et al. (2019); Manelius et al. (2019)
Manufacture	Change of use of materials, by giving it ownership to the manufacturers to reuse the materials after the end of life of the first building	Swift et al. (2017); Leising et al. (2018)
	Development of material passports	Leising et al. (2018); Sauter et al. (2018); Honic et al. (2019); Munaro et al. (2019)
	Reuse of secondary materials in the production of building materials	Nußholz et al. (2019)
Construction	Reuse of building materials in a new construction	Smol et al. (2015); Sanchez and Haas (2018b); Mangialardo and Micelli (2018); Tallini and Cedola (2018); Maerckx et al. (2019); Rasmussen et al. (2019); Ajayabi et al. (2019); Nordby (2019)
	Waste reduction	Esa et al. (2016); Adams et al. (2017)
	Off-site construction	Adams et al. (2017); Minunno et al. (2018); Mangialardo and Micelli (2018)
Operation	Use of a tool to evaluate the state of materials during the lifespan and end of life of a building	Akanbi et al. (2019b)
	Use of water management practices	Pimentel-Rodrigues and Siva-Afonso (2019)
	Minimize recuperative maintenance with preventive maintenance	Adams et al. (2017)
End of Life	Analyze the potential for reuse or recycling of existing materials and if it is feasible comparing to using new materials.	Sanchez and Haas (2018b)
	Management of demolition waste	Ghisellini et al. (2018); Maerckx et al. (2019)
	Use of a circularity tool to evaluate existing buildings and give the best possible solutions to refurbishment	Bertino et al. (2019)
	Deconstruction of building structures and parts	Adams et al. (2017); Hopkinson et al. (2019)

Figure 3: CE practices according to the life cycle stages of building construction. Source: Excerpt from Benachio et al., (2020)

Moreover another complexity that is added and it is particularly valid for the European scenario is the current status of the European building stock, which is heterogeneous but old. Renovation practices are therefore fostered, but the pace is very slow (1% in respect to the 3% requested to meet the energy efficiency target). Based on the renovation strategies pursued in the current market, these can be summarised in the following main types: upgrading/improving energy systems, insulation and windows and installing photovoltaic (PV) products (Sáez-de-Guinoa et al., 2022). Focusing on existing buildings renovation, the application of the different CE strategies would bring great benefits given the reduction of pressure on non-renewable resources and waste generated in the sector. Moreover, it will reduce energy demand and dependence on scarce materials, resulting in greater resilience to environmental and economic crises. However, a standardized procedure for assessing circularity in the building sector has yet to be established. While various initiatives and certifications are emerging, they primarily focus on sustainable construction rather than specifically on circular buildings, even though their indicators should be fully compatible (ibid.).

Despite the clear advantages, the adoption of CE principles in Europe's construction sector remains limited. A systematic review identified several barriers hindering this transition, including:

- **Regulatory Challenges**: Inconsistent policies across EU member states create confusion and impede uniform implementation of CE practices.
- **Economic Factors**: High initial costs associated with sustainable materials and technologies deter stakeholders from embracing CE strategies.

- **Technical Limitations**: A lack of standardized methods for assessing the circularity of building materials and processes hampers progress.
- **Cultural Resistance**: The industry's entrenched preference for traditional construction methods poses a significant obstacle to change.

These challenges highlight the need for comprehensive strategies to facilitate the integration of CE principles into the construction sector (Gasparri et al., 2023a).

4. CE policies in Italy

Italy is one of the EU Country having a national strategy for the CE transition. Being a Member State of the European Union, all the European Directives have been ratified in order to put in place binding targets for specific sectors. As an example, waste and energy management are regulated by specific directives at European level, and therefore targets have been transposed into the Italian legislation. Consequently, in 2002 the law no. 120/2002 put into force the target of 6.5% of reduction of GHGs emissions in the timeframe 2008-2012, as well as its update after the Doha Amendment (Law no. 79/2016) that has been valid for the timeframe 2013-2020. In 1994, Italy also ratified the UN Convention on Climate Change and in 2015 the Law no. 221/2015 has been adopted to foster green economy interventions and contain the over-exploitation of natural resources. Nevertheless, the most important policy document at national level, is the National Strategy for Sustainable Development (SNSvS), adopted in 2017 by the Italian Ministry of Environment (actually named Ministry of Environment and Energy Safety). The purpose of this document is to translate into the Italian context the principles of Agenda 2030 for sustainable development that is the basis for a global development respectful of the planet and the environment. Also in this case, a two-fold analysis is performed: if the document is directly addressing CE, the role of urban areas has been investigated, while if the document is important for sustainable development, it has been explored if the CE role is acknowledged.

4.1 National Italian Strategy for Sustainable Development (SNSvS),

Descending from the UN 17 SDGs, the SNSvS outlines the pathway to achieve the Agenda 2030 goals, tailoring them to the Italian context and targeting a sustainable future in economic, social and environmental terms, as a shared and essential value for facing the global challenges of Italy. The strategy is outlining the Agenda 2030 "5P" framework, namely People, Planet, Prosperity, Peace and Partnership, from which 15 strategies are defined covering different sectors like, among others, the management of natural resources. Additionally, 55 indicators have been identified to monitor the efforts and the efficacy of the strategies. In the preface it is stated that the document summarizes a vision for a new CE model with low CO2 emissions, resilient to climate change and other global challenges like biodiversity loss, the modification of fundamental bio-geo-chemical cycles (carbon, nitrogen, phosphorus) and changes in land use. The Italian Legislative Decree (D.lgs.) 152/2006 foresees that the strategy should be revised every three years, and therefore in 2022 an update of the SNSvS has been released. The process ended with the formulation of the new National Strategy for the Sustainable Development 2022 (SNSvS22). It worth to be mentioned that the cornerstone of the strategy is the achievement of the goals through territorialisation. In fact, within 12 months from the approval of the law, the Italian Regions and Autonomous Provinces must approve their Sustainable Development Strategy, as well as the activation of an integrated monitoring system that shows the contribution to the achievement of sustainability objectives. The Minister has always supported the decisive role that territories might have as places where the effective transition takes place. Therefore, many activities have been put in place to allow local and regional government to adopt their own instruments to both achieve the objectives established at national level and to enhance the efficacy of the monitoring system. The SNSvS22 is articulated into two parts: the first one is dedicated to the presentation of the "Vectors of Sustainability" interpreted as cross-cutting themes that intercept the aspects of interconnection and indivisibility of sustainable development objectives and are configured as enabling factors, essential to activate the transformative paths within administrations, territories and society. The second part is aimed at exploring the "5P" framework and how the SDGs have been tailored into the Italian context together with indicators and their actual values. Three are the vectors of sustainability:

1) Coherence of policies for sustainable development through a multi-governance vision, the sustainability assessment of public policies and the integrated monitoring system of sustainability assessment;
2) The culture for sustainability promoting education and training, as well as information and communication activities;
3) Participation for a sustainable development with the mapping of potential stakeholders and the institution of strategic collaboration and agreements.

When it comes to the monitoring system, the SNSvS22 has identified a core selection of 55 indicators to monitor the Italian context in relation to the SDGs and a second-level set of 190 indicators to monitor the national strategic objectives. The core selection is comprising 33 of the 43 identified indicators in the first version of the strategy, but the remaining 10 have been included into the second-level indicators.

In terms of inclusion of the CE into the strategy, an explicit link is made in the document with the National Strategy for the CE (SNEC – see the paragraph below for more details), and in the section dedicated to "Prosperity" the document is directly mentioning the necessity of creating a new circular economic model aiming at a more sustainable and efficient use of resources, minimizing the negative impacts on the environment, thus fostering the progress of human kind. In this respect, the circular material use is calculated among the core indicators, intended as the percentage of secondary raw material used into production processes as well as the recycle rate. Also, the section related to the "Planet" is proposing strategies and principles coherent with the CE ones, such as the preservation of the biodiversity, of the environment especially integrating the value of the natural capital into policies, planning instruments and monitoring tools. In addition, strategies are put in place to decrease emissions and increase the efficiency of water management systems.

However, in the Regional strategies of sustainable development annexed to the document, the CE is mentioned only when it comes to the waste management, thus confirming the sectorial (and limited) application currently adopted of the concept. The Emilia-Romagna region has inserted in the regional strategy Agenda 2030 an indicator about resource decoupling, that can be translated into the ratio between the GDP and the raw material consumption. In detail, the proposed indicators is analysing the ratio between the expenditures and incomes of the families and the production of solid waste. The Liguria region is posing the CE as a cornerstone of its strategy, promoting transversal and cross-cutting themes between CE and sectorial analysis of sustainable development. The Veneto region is adopting CE practices into the strategy of regeneration of natural capital, pursuing the circularity into production and consumption processes.

4.2 National Recovery and Resilience Plan (Piano Nazionale di Ripresa e Resilienza - PNRR)

After the Covid-19 pandemic, the EU put in place structural measures to sustain the economy of Member States by adopting the Next Generation EU (NGEU) programme in July 2020. Around €800 billion (in grants and loans) are made available to recover and to increase the resilience from the current crisis. The most relevant part is comprised into the RRF (Resilience and Recovery Facility) that has a validity of 6 years, from 2021 until 2026. To receive funds from RRF, Member States need to submit Recovery and Resilience Plans (PNRR in Italy), outlining how to invest the funds to meet climate and digital goals. Minimum 37% of the expenditures is for climate investments, while a minimum of 20% is to sustain the digital transition. The RRF is performance-based and therefore the Commission is financing each Country only when the agreed milestones and targets have been achieved. 6 policy pillars have been identified within the RRF regulation:

1) Green transition – directly linked with the EU Green Deal and the target of GHGs emissions reduction of 55% by 2030 compared to 1990's level;
2) Digital transition – monitored by the DESI index counting the digitalisation of economy and society;
3) Smart, sustainable and inclusive growth;
4) Social and territorial cohesion;
5) Health, economic, social and institutional resilience;
6) Policies for the next generation.

CE is directly mentioned in the plan, under the Green Transition pillar, even though it is targeting waste management policies such as waste prevention and recycling, prevention of pollution and control (e.g. air, water, noise, pollution) and other climate change mitigation measures such as sustainable industries.

The Italian PNRR is contributing to the six pillars as shown in the following Figure 4.

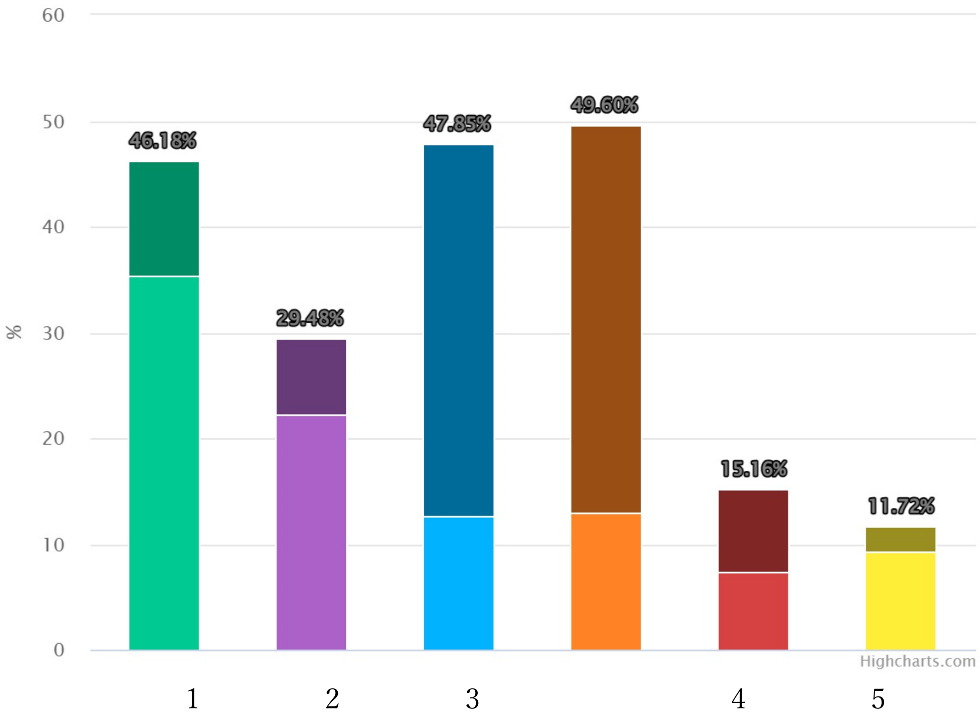


Figure 4: Contribution of the interventions to each policy pillar. Since each measure contributes to two policy areas, the total contribution is the 200% of RRF funds allocated to Italy. (Source: European Commission website)

The plan is composed by three leading strategic axis and six missions. The former are digitalisation and innovation, ecological transition, and social inclusion while the missions identified consist in:

1) Digitalisation, innovation, competitiveness, culture and tourism;
2) Green revolution and ecological transition;
3) Infrastructure for a sustainable mobility;
4) Education and research;
5) Cohesion and inclusion;
6) Health.

Mission 2 is the one more linked with CE, that is directly cited within the PNRR, even though it reflects the nature of the European RRF and mainly targets waste management and resource productivity. However, in the mission 1 component 3 dedicated to tourism and culture, CE is considered as the right perspective to promote a green approach to reduce the ecological footprint for the production and the participation to cultural events, orienting people towards more responsible and environmental-friendly behaviours. Among the mission 2 component 1 collecting measures for sustainable agriculture and CE, the National Strategy for the CE is proposed. More details are provided in the dedicated paragraph. The plan is also sustaining innovative start-ups (mission 2 component 2.5) in the CE discourse as well as the decontamination of sites left vacant by industrial activities in order to reuse them (Mission 2, component 4.3).

4.3 CE national strategy (SNEC)

As already mentioned, within the mission 2 component 1 – Sustainable agriculture and CE - the PNRR is foreseeing the adoption of a National Strategy for the CE (SNEC). Its root can be traced since 2017 when, after public consultation, the document "Towards a CE model in Italy. Document of framework and strategic positioning" has been published. The document was aiming at providing an overview of CE and the Italian positioning on the topic, ensuring coherence with the goals of Paris Agreement, the SDGs and the European Union target. After 2017, many changes in the international context occurred, like the urgency of reducing GHGs emissions, climate change strong effects, the fast technological development, the Covid-19 pandemic and Ukrainian war, to cite some of them. In addition, the new CE action plan has been issued at European level, thus influencing and supporting the transition towards circularity. Consequently, the strategic lines identified in 2017 were not reflecting the current global challenges and needed to be updated. For these reasons, the SNEC is aiming at answering the big challenges of preventing the production of waste, maximizing its recovery, reuse and recycling. Through the eco-design, durable and repairable products should be incentivized, additionally creating a new supply chain of secondary raw materials. In addition, important is the role of the Public Administration supporting the transition with a simplification of the legislation, as well as the role of citizens in terms of increased awareness and participation. A CE strategy should foster the transition towards national supply chains of energy and raw materials. Among the objectives, the strategy is identifying new administrative tools to strengthen the market of secondary raw materials making them competitive if compared to virgin raw materials (e.g. through public procurement and Minimum Environmental Criteria, end of waste, extended producer responsibility, fostering the product ad a service and sharing practices). The strategy is also aiming at identifying tools and measurable targets to achieve climate neutrality objectives.

The National Strategy for the Circular Economy proposes 5 business models capable of leading to a production system consistent with the aims of the circular economy:

1. Circular supply chain "from the beginning" (**eco-design** from the early stages of product design);
2. **Recovery** and **recycling** (manufacturing secondary raw material and other "near zero waste" strategies);
3. Extension of product life (fostering the **durability** of the product).
4. **Sharing platform** (use what you need and when you need it, creating market places in which the owners can make available their goods to whom is interested in using them);
5. **Product as a service** (which is inextricably linked to the durability of the goods above).

In Figure 4 the infographic proposed by MITE regarding the product cycle according to the circular economy is reported. Moreover, in the paragraph 9.2 of the SNEC a set of indicators is proposed to monitor each system according to the pillars for the CE, as considered in this strategy:

- Production and Consumption;
- Waste management;
- Secondary raw materials;
- Competitiveness and innovation;
- Global sustainability and resilience.

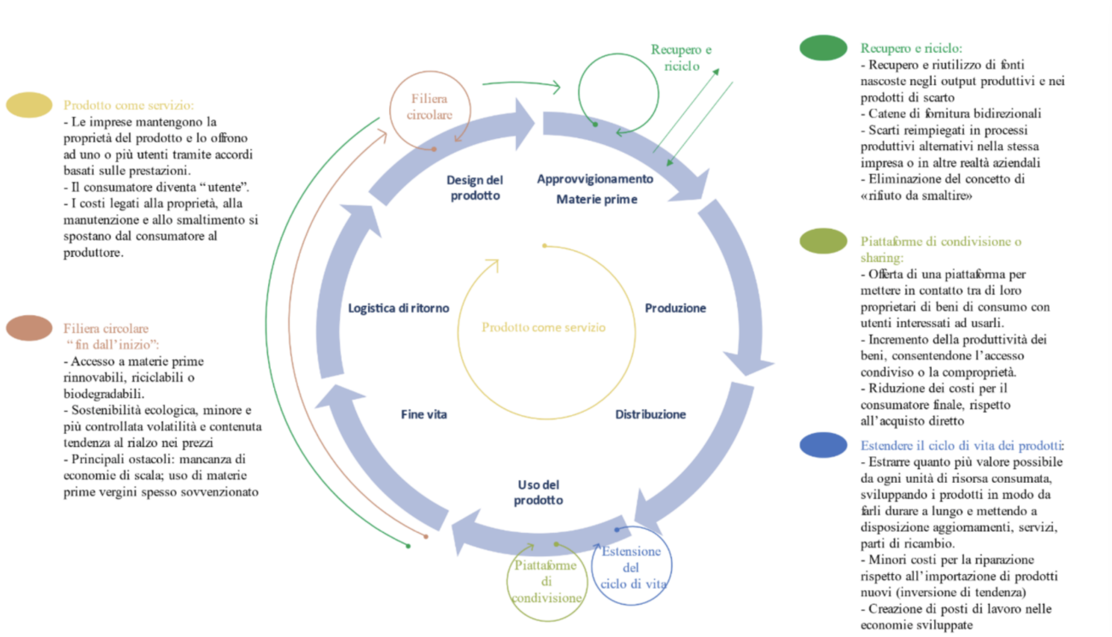


Figure 5: product cycle according to the circular economy Source: (MiTE)

In operational terms, the eco-design has been translated into a useful product development checklist, according to Menapace (Menapace, 2022):

• **Materials**: rationalize the use of material resources (efficiency in the use of materials), seeking to replace non-renewable materials with renewable, recycled, biodegradable and compostable materials. The objective is to "create" new materials that best contemplate sustainability and circularity (e.g.: secondary raw material that replaces, even partially, virgin raw material). Knowledge of the environmental characteristics of materials is essential to avoid pursuing design choices that do not favor the circularity of resources;

• **Production processes**: increasing efficiency in the use of raw materials; improve procurement and distribution logistics; minimize the production of processing waste or ensure that these are managed as by-products. Industrial symbiosis processes (where the waste of one production process becomes a secondary raw material for another) offer an important contribution to enhancing the waste of production processes by reducing process costs and obtaining revenues from sales; in order to facilitate the implementation of these processes, Decision Support Systems will have to be developed, which guarantee up-to-date and reliable data, integrating all information sources into a single access interface;

• **Procurement:** use energy supplies from renewable sources; enhance the use of resources at local level to reduce the environmental impacts of transport and create a local product identity;

• **Disassembly and modularity:** to allow the disassembly of the different components of a product more easily in relation to the types of materials used; encourage the design of products following the principle of modularity to allow the replacement of parts, the recovery and reuse of assemblies and subassemblies;

• **Recyclability:** encourage the recovery and recycling of materials, avoiding having multi-material components with irreversible joints that cannot be sent to the recycling process;

• **Repairability and maintenance:** to allow the replacement of technologically obsolete or damaged parts and to promote maintenance that allows the extension of the life cycle of the product itself;

• **Substitution and management of hazardous substances**: looking for material solutions that do not contain hazardous substances to make products more easily recyclable. However, for many products, the presence of specific hazardous substances in them is dictated by the need to guarantee certain performance and characteristics (including durability) which, on the basis of current knowledge and available technologies, cannot be achieved with alternative substances. It is therefore also necessary to ensure the proper management and recovery of hazardous substances;

• **Reuse**: any operation by which products or components that are not waste are reused for the same purpose for which they were designed;

• **Post-consumer collection:** a fundamental phase to allow a product or part of it to be sent for maintenance or reuse;

• **Regeneration**: allowing working and reusable parts of a used product to be reused in a new product/process;

• **Quality of recycling:** promoting the recycling process, trying to maintain the characteristics of the materials as much as possible. A reduction in the quality of the material inevitably leads to a lower economic value;

• **Eco-design of production processes:** from end of pipe to cleantech. "End of pipe" or end-of-cycle technologies owe their definition to the fact that they intervene on the treatment of pollution after it has been produced, thus acting downstream of the production process: gaseous emission abatement plants and biological or chemical-physical wastewater treatment plants are an example. Cleantech technologies need to intervene upstream to avoid environmental externalities, such as reducing water

4.4 Bellagio Chart (2020) and Italian Report on CE (2022)

The Bellagio declaration is a document elaborated by ISPRA[7] (Istituto Superiore per la Protezione e la Ricerca Ambientale) from Italy, European Environmental Agency (EEA) and an advisory board encompassing Environmental Protection Agency (EPA) representatives from Finland, Ireland, Netherlands, Portugal and Slovakia. Other European Institutions have been consulted to ensure the alignment with the work carried on in the European Green Deal and the CE Action Plan in order to make a step forward the implementation of the measures included therein. The Bellagio Principles is a set of seven principles that underline the essential elements of the transition to a CE:

- *Monitor the CE Transition*

The transition to a CE has to be considered holistically and among all the relevant initiatives coming from both public and private entities. The monitoring framework should assess the big picture

[7] https://www.isprambiente.gov.it/it

of the transition capturing all the changes happening to the material and waste flows, the lifecycle of products, business models and consumer behaviour, including the economic, environmental and social dimension of these changes.

- *Define indicator groups*

In this section has been outlined the topic to be considered in order to build a robust monitoring framework. Indicators should be identified for materials and waste flows, for environmental footprint assessment to respect the planetary boundaries, for economic and social impact to capture positive as well as negative impact of the transition and lastly to identify indicators that are able to reflect policy, process, and behaviour changes.

- *Follow indicator selection criteria (RACER)*

Indicators should be selected to create a transparent monitoring framework for the circular transition and, therefore, following the RACER criteria: Relevant, Accepted, Credible, Easy to monitor, and Robust. However, experimental indicators can be encouraged even if not all the RACER criteria may be initially fulfilled.

- *Exploit a wide range of data and information sources*

In support of the monitoring framework, data sets are essentials and may consist of official statistics available at Europe and National level, other data produced at local level as well as by international sources. Together with statistics, policy information can be inserted in the monitoring to track qualitative changes and express their assessment. New data sources can also be used, such as the ones coming from the private sectors.

- *Ensure multilevel monitoring*

Different levels of governance and consequently different scales are involved in the transition. Stakeholders from global to local can contribute for the development of coherent metrics that capture the multiple dimension of the CE transition.

- *Allow for measuring progress towards targets*

The monitoring framework supports the progress to relevant policy targets and objectives, informing if the right policies are in place and well implemented or helping in identifying corrections or new policies if needed.

- *Ensure visibility and clarity*

A clear and effective monitoring framework will support policy makers and inform citizens and stakeholders. User-friendly communication channels should be identified and used as well as open data made fully and freely available.

The application of Bellagio chart principles brought to the identification of 7 key indicators that are at the basis of a comparative analysis carried on between France, Germany, Spain and Poland, that are the top-five economies in the EU. Italy resulted to be in the first position in Europe considering a combination of the 7 above-mentioned indicators: waste recycling rate; utilization rate of materials from recycling; resource productivity; waste production and material consumption ratio; share of energy from renewable sources in total gross energy consumption; repair of goods; soil consumption. As it is possible to see, the attention to urban areas is here absent, mainly focusing on resource consumption and waste management. Land take is the only indicator that connect this strategy with the local scale of policy-making.

5. The construction sector in Italy

In Italy the construction sector is characterized by a turnover that exceeds 400 billion euros/year, generating work for about 2.6 million people, that corresponds to about 12% of national employment. The construction sector relies almost exclusively into domestic production: 95.8% of the purchases made by construction companies are produced by the national production system, while only 4.2% are made up of imported products (Luiss Business School & MiSE, 2020). After the economic and financial crises of the early 2000's there are positive trends in the investments of the construction sectors and, specifically, in all the activities: redevelopment, new residential construction, new non-residential construction and public works (ibid).

As show in the following image, the construction sector is among the average performers in terms of adoption of CE practices in relation to economic savings, and it has been estimated that the adoption of CE managerial practices could lead to an annual GHGs emissions reduction of almost 1.9 $MtCO_2$ by 2030, with the largest contribution coming from the construction sector that could contribute more than 45% (Energy & Strategy group, 2022). Among the most frequent CE practices adopted in Italy, the recycle and design for disassembly ones are the most addressed, while repurpose of taking back to the system and product-as-a-service are not really diffused. In the case of the construction sector, the recycling, designing out waste and repurposing are the most implemented CE practices (ibid.).

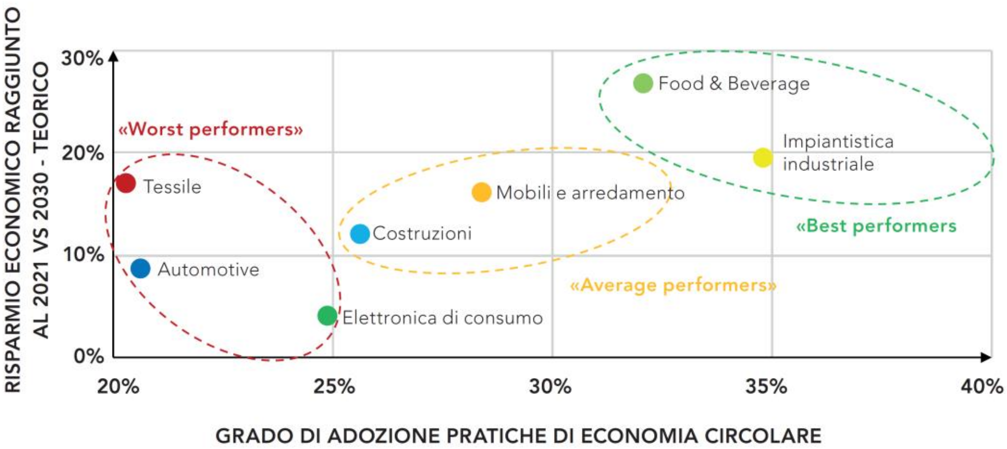


Figure 6: degree of adoption of CE practices in Italian economic sector. Source: Energy & Strategy group, (2022)

In the short period, three are the focus areas with the highest potentialities to embed innovative policies for the development of the sector: construction and demolition waste, materials and construction systems, integrated design (Luiss Business School & MiSE, 2020). In particular, in terms of waste production, in 2020 the construction sector has been responsible for the production of 48%

on the total special non-hazardous wastage (ISPRA, 2022). The design for disassembly approach supported by the transition towards digital technologies like BIM is playing a key role in the transition towards circularity, offering an integrated assessment of buildings throughout the whole life-cycle and not only in the construction phase (Luiss Business School & MiSE, 2020). However, the Italian construction sector is still lagging behind in digital technologies, as well as in the technical and managerial skills of small and micro-enterprises, which are still particularly fragmented and with few multitasking working units (ibid.).

If speaking about construction, three are the domains that can be addressed to achieve the transition and innovation: **circular product, circular process, and circular platform**. This draws on the understanding the product-process construction paradigm does not suffice anymore in capturing the sector complexities and driving change toward concepts of holistic, democratic, and long-term sustainability, balancing between economic, environmental, and social aspects. Sector digitisation and the exploration of new integrated support tools, namely, digital platforms, become strategic in managing product and process complexities toward the transition to more sustainable business operating models (Gasparri et al., 2023b). To enable the circular looping of finite materials and resources, the use of integrated digital platforms is key in managing resources and organisational infrastructures towards circular models of collaboration and value co-creation. The integration of product, process and platform domains is necessary to enable CE strategies implementation across construction scales and dimensions and requires the exploration of multi-disciplinary approaches and new holistic assessment (ibid.). The Green Building Council Italia in 2020 produced guidelines for the circular design of buildings, as a result of the work done by the working group dedicated to the CE. According to the document (Green Building Council Italia, 2020), some **general principles** should be followed:

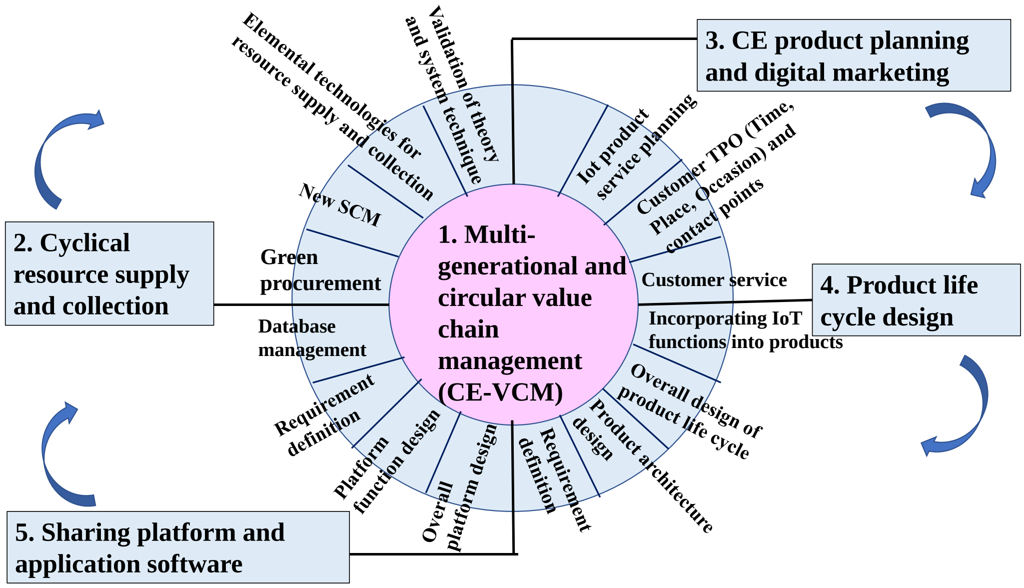
a. Circular economy and sustainable building design principles are applicable to all actors along the value chain;
b. Sustainable choices must take into account the full life cycle costs and the financial and non-financial return on investments;
c. Viable business models must exist or be developed for each economic operator in the supply or value chain;
d. The principles should be applied taking into account proportionality: benefits should outweigh costs.

In terms of **durability**, another principle to be mentioned is that the durability of buildings depends on better design, better performance of building products and information sharing. **Adaptability** is fostered through the prevention of premature demolition of buildings by developing a new design culture. Finally, in terms of **waste management and prevention**, the guiding principle is to design products and systems so that they can be easily reused, repaired, recycled or recovered.

5.1 Case studies analysis for the construction sector in Italy

The case studies analysis will be performed according to the five research topics identified within the project methodology as follows:

- Circular value chain management (VCM): SCM and Cooperation with various stakeholders
- Recycling resource supply and resource recovery
- CE product service planning, digital marketing, and customer engagement
- CE product architecture design and Life cycle product design
- Sharing platform service and Application software



5.2 We build company

Among the biggest construction companies in Italy, the biggest one in terms of turnover is **Webuild**. Webuild SpA (formerly **Salini Impregilo SpA**) is an Italian industrial group specialising in construction and civil engineering. The company was formally founded in 2014 as the result of the merger by incorporation of Salini into Impregilo. Webuild is the largest Italian engineering and general contractor group and a global player in the construction sector.

The company is active in over 50 countries of 5 continents (Africa, America, Asia, Europe, Oceania) with more than 85,000 employees. Its experience ranges from the construction of dams, hydroelectric plants and hydraulic structures, water infrastructures and ports, to roads, motorways, railways, metro systems and underground works, to airports, hospitals and public and industrial buildings, to civil engineering for waste-to-energy plants and environmental protection initiatives. It takes first place in the water sector of the Engineering News-Record rankings, the benchmark for the entire construction industry. The company is listed on the Milan Stock Exchange and it is directed by Pietro Salini.

In terms of CE, there is a part of the company website that is dedicated to the topic and is listed among the company strengths. The complete list of success factors is reported below:

1. Responsible Behaviour: Strong ESG Standards
2. Solid ethical principles: integrity, fairness, transparency, sustainability;
3. Policy frameworks and governance systems that comply with the highest standards;
4. Rules and procedures to protect people, the environment and society in general;
5. Clear and transparent communication with our stakeholders;
6. **Climate protection and circular economy:** a robust framework for reducing greenhouse gas emissions in support of the circular economy;
7. Protection of labour rights and promotion of safe and secure working environments for all workers.

As it is possible to see, CE is listed together with climate protection in the mission and its main aim seems to be the GHGs emissions. The environmental protection has been a priority for the company since 2002, when they have been among the first industries adopting a specific Environmental Policy to monitor the performance. The company is committed to optimize the use of natural resources, promoting production and use methodologies aimed at their reuse and enhancement. In particular, they have a solid environmental track record: projects adopt the principles of the Circular and Green Economy, combining the principles of quality and "state-of-the-art" construction with the principles of environmental efficiency. Also in terms of management systems, the company is aiming at reducing the environmental impacts deriving from construction activities, by guaranteeing maximum transparency towards stakeholders about mitigation activities and performance.

Supply Chain Management and Cooperation with various stakeholders

For the Webuild Group, the development of the CE is mainly linked to SDG 12 and 13 - which are namely responsible consumption and taking actions to combat climate change and its impacts - and is one of the pillars of its sustainability policy. Webuild adopts practices aimed at minimizing the use of natural resources (including by reusing them) and intensifying the recovery of waste materials within the same work or in neighbouring areas. The circularity of the practices adopted by Webuild allowed the company to reduce waste produced by 46% in 2020 compared to 2019, while recovered waste is the 69% of the total waste generated. In addition, the volume of water consumed on construction sites has been reduces of 10% compared to 2019.

Moreover, in 2023, 79% of purchased materials were sourced within a 160 km radius of project sites to minimize transportation emissions and support local economies. The company also prioritizes certified sustainable materials, ensuring suppliers adhere to environmental and ethical standards. Webuild has introduced supplier rating systems that evaluate environmental impact, circular economy compliance, and carbon footprint.

In 2022:

- the 52% of electric energy is generated by renewable resources (compared to the 2021 figure that was 35%);
- the GHGs emission from scope 1-2 has been reduced of 57% compared to 2017 values;

- Webuild reuses the 100% of extraction material.

In terms of collaboration with stakeholders, Webuild works with local governments, universities, and NGOs to enhance sustainable practices in construction projects. The Supplier Development Hub provides training programs and workshops for subcontractors on circular economy principles and sustainable construction techniques. Finally, the company actively engages in partnerships with waste management companies to ensure material recovery and waste minimization.

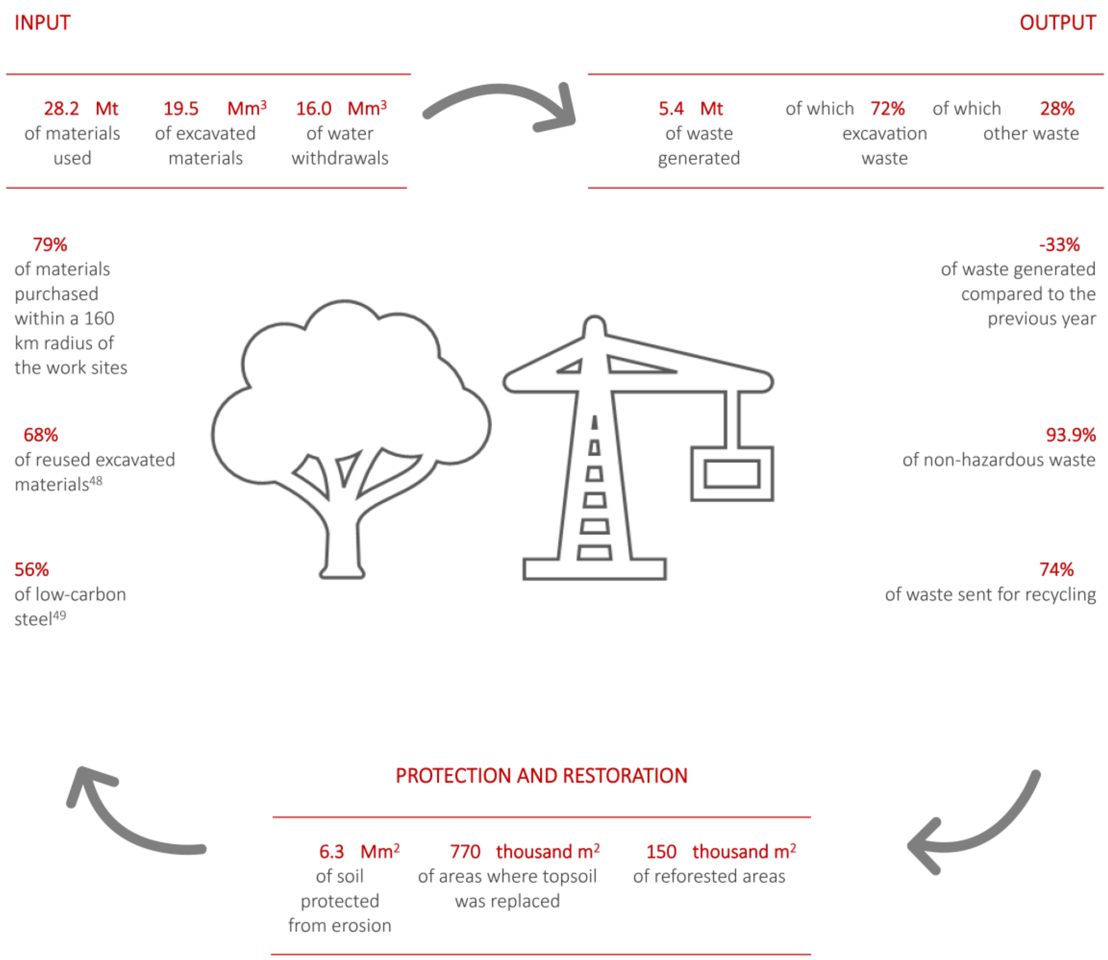


Figure 7: figures of CE process withing Webuild**.** Source: Webuild consolidated non-financial statement, 2023.

In terms of products, the Group developed a special optimized concrete mixes, characterized by a reduced cement content or the use of up to 65% recycled materials from other industrial supply chains. Also with regard to metal materials, the use of solutions with steel with a high recycled content is becoming increasingly popular: on the next start-up projects in Italy, Webuild aims to reach shares of over 90% of the recycled content. The 56% of the steel used in 2023 was low-carbon steel with 90%

or more recycled content, and the special cement blends with a high percentage of recycled aggregates reduced carbon emissions by approximately 22,000 tons.

Figure 8: examples of new materials developed by Webuild

Recycling resource supply and resource recovery

Webuild is committed to maximizing waste recovery and recycling while minimizing landfill disposal across its projects. In 2023, 74% of waste was recovered, reused, or recycled, significantly reducing landfill dependency. Over 68% of excavated materials from tunneling and infrastructure projects were reused on-site or repurposed for other construction activities. For example, the Bicocca-Catenanuova railway project in Italy achieved a 99% waste recovery rate, employing mobile crushers and advanced sorting technology to maximize material reuse.

Considering water management, Webuild also developed a Webuild Water Efficiency (WWE) system, a digital monitoring solution to optimize water usage and minimize wastewater in construction sites. The Forch project on the Fortezza-Ponte Gardena railway line implemented an innovative water treatment system that breaks down surfactants, ensuring safe water disposal and reuse. In Australia's Snowy 2.0 hydropower station, Webuild integrated a closed-loop water recycling system to reduce freshwater consumption.

CE product service planning, digital marketing, and customer engagement

Webuild leverages digital technology to enhance the circular economy through data-driven decision-making, digital marketing strategies, and stakeholder engagement. In terms of digitalization for CE, the company uses a traceability system for excavated earth and rocks that enables real-time tracking and optimization of material reuse across multiple projects. Moreover, AI-driven procurement systems ensure that suppliers align with circular economy principles, reducing resource waste and improving supply chain efficiency. Finally, Webuild's "Cantieri Trasparenti" initiative uses digital tools and webcams to provide real-time updates on construction processes, increasing transparency and engagement with local communities.

When it comes to customer and community engagement, many tools are available on the company website:

- Webuild's We Build Value is a digital magazine that disseminates information on sustainable construction and circular economy initiatives to a broad audience;
- The company has launched social media campaigns and virtual site tours to educate stakeholders on the benefits of circular construction;

- In 2023, Webuild organized more than 20 stakeholder meetings to discuss sustainability strategies and implement feedback from local communities.
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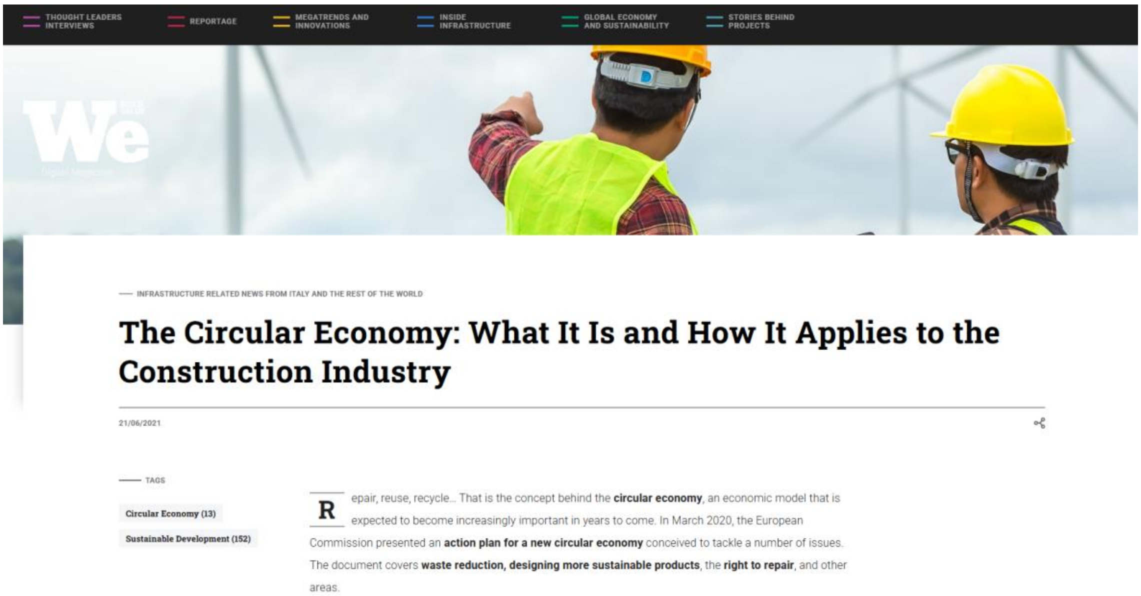

Figure 9: excerpt of Webuild magazine website

CE product architecture design and Life cycle product design

Webuild embraces the eco-responsible design, adopting an approach that considers the whole life cycle of infrastructures and considering the socio-environmental aspects in the diverse phases of projects development. The company has experience in adopting eco-design and eco-construction schemes, with about 50% of projects located in urban areas adopting LEED, GSAS or IS.

Among the examples, an Italian case study is the ENI Headquarters in Italy, which adopts the LEED Leadership in Energy and Environmental Design (Gold). The building auto-produces energy thanks to solar panels and saves the 40% of rainwater which is reused. All iron and concrete come from less than 200 km from the construction site and contain recycled content greater than 90% for iron and more than 5% for concrete. In the construction of the building all the indications of the Level(s) framework has been considered. Webuild also analysed the potential synergies between Level(s) and the LEED certification system, as both can be considered instruments of enhancement real estate in terms of sustainability. A mapping of the potential synergies came out for future optimizations in the case of coexistence of the Level(s) tool with other sustainability certification schemes. In order to achieve the result, a workgroup has been created with multidisciplinary skills to manage different topics like LCA, certificates EPDs, resource saving, etc.). The complex reached the Gold level of the LEED certification.

Webuild also integrates design-for-disassembly principles, allowing infrastructure components to be reused or repurposed at the end of their life cycle. In fact, the company employs prefabricated modular construction techniques, reducing onsite waste and improving resource efficiency (e.g. Figure 10). Moreover, the Green TBM (Tunnel Boring Machine) initiative optimized tunneling efficiency, cutting 20% of energy consumption per cubic meter of tunnel excavated.

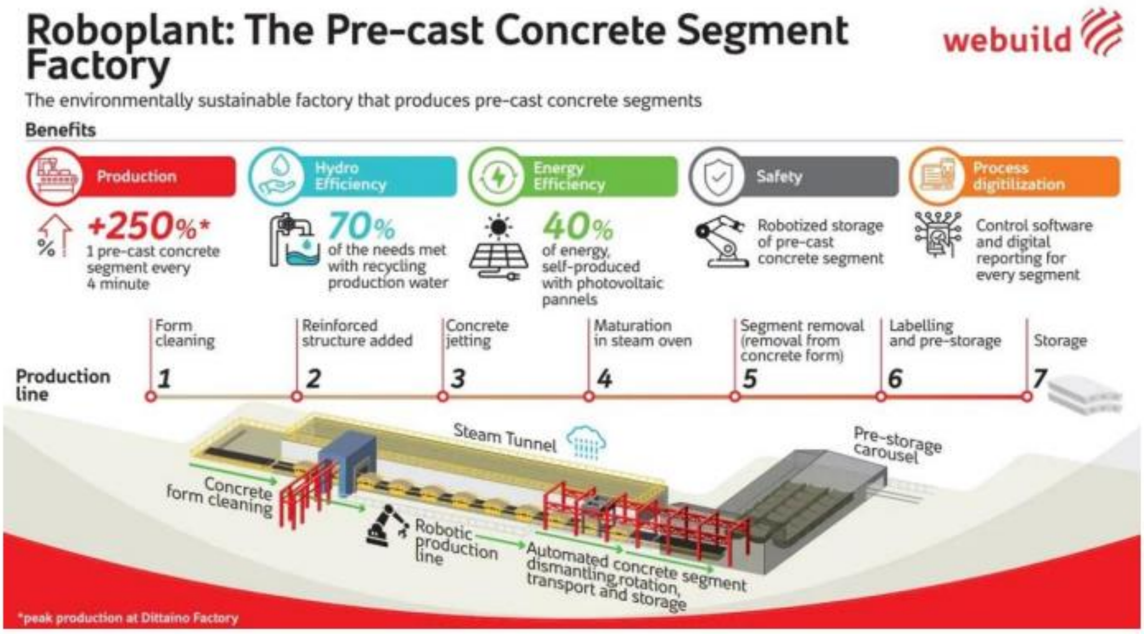

Figure 10: exemplification of the Webuild sustainable factory that produces pre-cast concrete segments

Sharing platform service and Application software

In terms of **software**, the use of digital technologies is fostered, especially through the use of BIM systems for the design and management of the construction phases, as well as as above mentioned, the digital traceability of construction site water resources. Both data-driven applications and innovative construction technologies are acknowledged. To the first category belong the Webuild Circular system that assesses and enhances circularity in infrastructure projects by measuring life cycle impacts and optimizing resource utilization; the SMILE AI-powered maintenance system that reduces downtime for tunnel boring machines and conveyor belts, extending equipment life and minimizing waste; a fleet management platform to optimize the use and location of construction equipment, reducing unnecessary material consumption and energy use. In terms of innovative technologies, some applications can be mentioned such as:

- The automated Roboplant factory in Catania that produces tunnel segments with 100% reusable molds, minimizing material waste and environmental impact;
- Smart tunnel lighting systems that use AI and sensors to optimize energy efficiency and improve worker safety;

- Webuild's AMICO platform to calculate and evaluate the embodied carbon footprint of infrastructure projects, helping to make data-driven decisions for sustainability.

5.3 Manni Group

Manni Group is a leading Italian industrial company founded in 1945 by Luigi Manni – an Italian entrepreneur - specialized in steel processing, energy efficiency solutions, and off-site construction. They offer products, solutions and skills for the world of dry construction, promoting new scenarios to overcome energy waste and pollutant emissions in the existing building stock, through new buildings or retrofit interventions, helping Real Estate and Design Studios to achieve a higher value of the projects thanks to the environmental ethical principles and building know-how. Reporting to the Manni Group Holding are operating companies working in 3 business areas, engaged in the production, processing and marketing of high-tech products and advanced design services. Steel Manni Sipre an Italian leader in pre-processed steel elements, structural components and systems for use in the construction industry. Manni Inox is a benchmark for stainless steel. Insulating panels Isopan is a leader in the production of insulating metal panels for walls and roofs targeting key international markets. Renewable energy and services Manni Energy operates in renewable energy engineering, O&M services and energy efficiency.

The company has long been committed to sustainability and has fully embraced the principles of the CE in its business model. Manni Group's dedication to the CE is linked to the minimization of the consumption of natural resources and reduction of waste production. The company actively promotes the creation of a fully circular steel sector, recognizing the importance of extending the lifecycle of products and materials. To achieve this, Manni Group invests in research and development, employing Life Cycle Assessment (LCA) methodologies to guide its operations. Collaboration with partners and suppliers is also deemed essential to meet the objectives outlined in their Sustainability Policy.

CIRCULAR ECONOMY AND INNOVATION

Manni Group promotes an inclusive form of industrialisation, which increases the efficiency in the use of resources and reduces its environmental impacts and those of the chain, reconfiguring the processes; it therefore invests in scientific research and innovation as a tool by which to make this change. Operating within the construction chain, it contributes towards the development of innovative, low impact and low carbon emission construction, in which healthy, safe materials are used. This is why:

INNOVATION

- It sees Innovation as a strategic driver and to this end invests in Research and Development, using Life Cycle Analysis (LCA) as a tool by which to guide its work, with the aim of providing the client with high value, safe, healthy and efficient products.

RESPONSIBLE PRODUCTION

- It is inspired by the principles of circular economy to minimise the consumption of natural resources and the production of waste and drives for the creation of a fully circular steel industry.
- It shares strategies and goals with its partners and suppliers and considers their collaboration as essential if it is to achieve the Sustainability Policy goals.
- It takes part in entrepreneurial initiatives, projects and companies aiming to promote the development of the green and circular economy and the international launch of initiatives that combine innovation with economic value and the protection of the natural capital.

CONSTRUCTION

- It promotes and develops off-site and dry construction systems in the firm belief that they can constitute tools by which to decarbonise the industry, developing a model of circular construction. It also promotes tools to renew the built environment in order to reduce to zero soil consumption.
- It supports the dissemination of sustainability ratings systems for buildings as a tool by which to assess and minimise their environmental impacts, as well as guarantee healthy environments and the well-being of the end users.

Figure 11: Excerpt from sustainability policy of Manni Group 2024. Available at: https://mannigroup.b-cdn.net/2024/07/Sustainability_Policy_2024_EN.pdf

Supply Change Management and Cooperation with various stakeholders

Manni Group's dedication to the circular economy is evident in its operational strategies, which focus on reducing resource consumption, extending product life cycles, and minimizing waste generation. These efforts align with global sustainability goals, including the United Nations Sustainable Development Goals (SDGs) and the European Green Deal. The company prioritizes sustainable procurement, closed-loop logistics, and collaboration with industry partners to drive circularity . Some key principles are followed to embrace the strategy:

1. **Resource Efficiency** – Manni Group optimizes material use by employing advanced production techniques that reduce waste and maximize the reuse of raw materials, particularly in steel processing.

2. **Sustainable Design** – The company invests in research and development to create innovative construction solutions that prioritize durability, modularity, and recyclability. For example, in Milan, Manni Group collaborated with a real estate developer to transform an abandoned factory into a residential complex, reusing 70% of the original building materials.
3. **Energy Efficiency** – The company integrates energy-efficient solutions into its products and services, contributing to lower carbon emissions in the built environment.
4. **Stakeholder Engagement** – Collaboration with suppliers, customers, and industry partners is central to Manni Group's sustainability vision.

Manni Group has prioritized a sustainable and transparent supply chain, ensuring compliance with environmental, social, and governance (ESG) policies. The company fosters collaboration with suppliers, clients, and institutions to create a more resilient and circular supply chain. The company sources steel with at least 55% recycled content, significantly reducing the demand for virgin materials, it partners with ISO 14001-certified suppliers to ensure environmental responsibility in raw material sourcing. In fact, Manni Group prioritizes suppliers that adhere to environmental, social, and governance (ESG) criteria. All new suppliers are assessed using a list of qualitative and quantitative criteria such as, technical and management skills, quality of performance, economic reliability, compliance with ethical requirements, preservation and protection of the environment and biodiversity, adoption of significant social and environmental practices. It is strategically important for the company to strengthen the ESG reporting of supply, making it a priority to constantly monitor the environmental, social and governance impact of the entire supply chain, supporting the partners in their sustainable development process.

Manni Group also works with universities, research institutions, and government bodies to develop new circular steel processing technologies, and by participating in European research projects focused on recyclable and bio-based construction materials. The company also collaborates with construction firms and clients to implement circular solutions on a project basis.

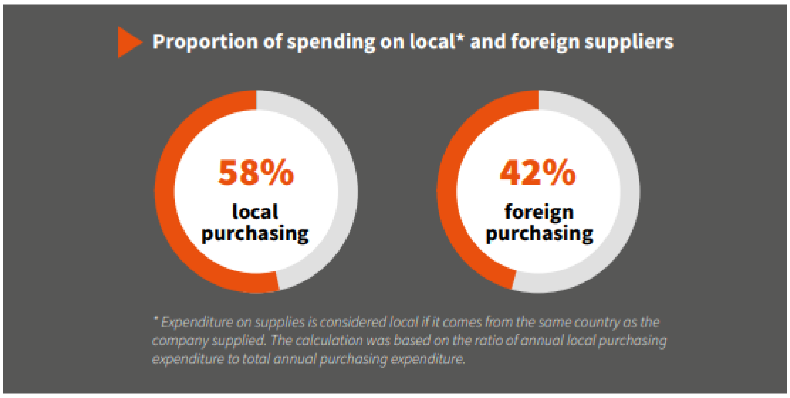

Figure 12: excerpt from the sustainability report of the company showing the composition of suppliers in 2023

Recycling resource supply and resource recovery

Manni Group actively promotes waste recovery and recycling in all stages of its production processes. They are committed to purchase materials which meet precise standards in terms of recycled contents. In 2023 the Group purchased steel with a minimum percentage of recycled steel of 55%. Moreover, Manni Group has been pioneering off-site and dry construction systems, which play a crucial role in advancing circular economy principles in the construction sector. These techniques offer several advantages:

5. **Minimized Waste**: Off-site construction significantly reduces material waste compared to traditional on-site building methods.
6. **Enhanced Material Reusability:** Dry construction allows for the disassembly and reuse of building components, extending their lifecycle.
7. **Improved Energy Efficiency:** Prefabricated elements are designed for optimal energy performance, reducing the overall carbon footprint of buildings.

In terms of innovative materials used by the company, steel is one of the most sustainable materials in construction due to its recyclability. Manni Group prioritizes the use of recycled steel in its manufacturing processes and ensures that its products are designed for reuse and recycling at the end of their lifecycle. Steel is 100% recyclable, and Manni Group ensures that steel scraps and off-cuts are reintegrated into new production cycles, operating according to a zero-waste model. Another example is that in collaboration with partners, Manni Group processes and reintegrates rockwool offcuts into the production of new insulation panels, exemplifying effective resource recovery. The company also collaborates with recycling facilities to refine and process steel waste into reusable raw materials.

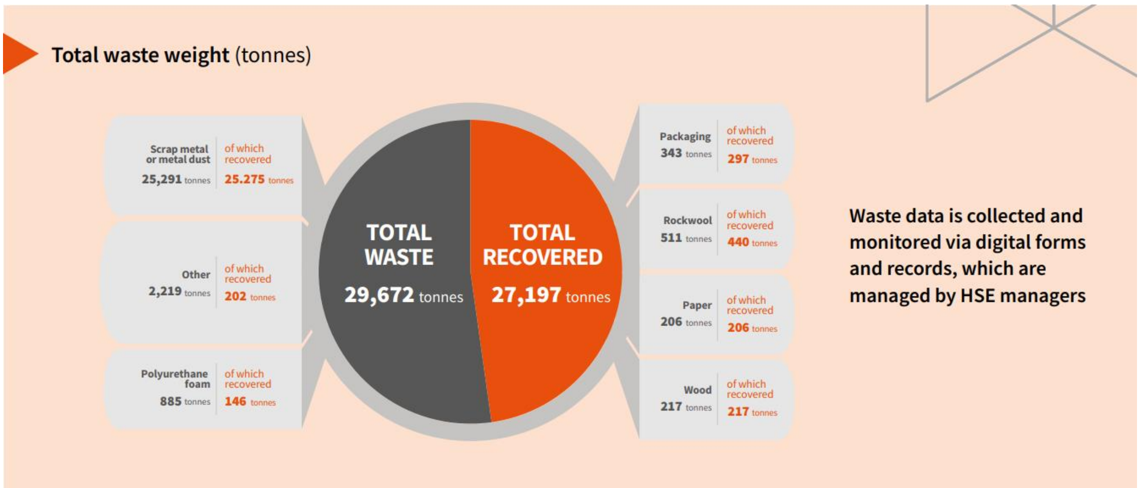

Figure 13: excerpt from the sustainability report of the company showing the waste composition and recovery in 2023

Through Manni Green Tech and Isopan (two of the subsidiary of the Group), the company developed advanced insulation solutions that contribute to energy savings and the reduction of greenhouse gas emissions in buildings. These products enhance indoor comfort while supporting circular economy goals by reducing energy consumption. Manni Group is also exploring bio-based and recycled materials for construction applications. The integration of these materials helps decrease reliance on virgin resources and lowers the environmental impact of building projects.

CE product service planning, digital marketing, and customer engagement

Manni Group integrates digital tools and marketing strategies to enhance customer awareness and participation in circular economy initiatives. In this regards, there is a program oriented to CE which encourages clients to return used building materials for recycling, promoting a circular lifecycle for products and also a modular building leasing models which means that the company offers leasing options for prefabricated buildings, allowing for temporary use and subsequent reuse, reducing material.

In terms of digital marketing, Manni Group conducts webinars to educate industry professionals on best practices in circular construction. The company also provide clients with transparent environmental data by producing Environmental Product Declarations (EPDs), thus facilitating informed decision-making. Manni Group's Building Information Modelling (BIM) platform also offers digital libraries where designers can select sustainable, circular materials for their projects, promoting environmentally conscious design.

In terms of customer engagement, Manni Group launched an online training platform for engineers and architects, offering courses on circular building design and sustainable material selection. Finally, a magazine is also available online (https://blog.mannigroup.com/) which collects insights and information gravitating around the products offered by the Group as well as webinars. The magazine is organized in the form of a blog.

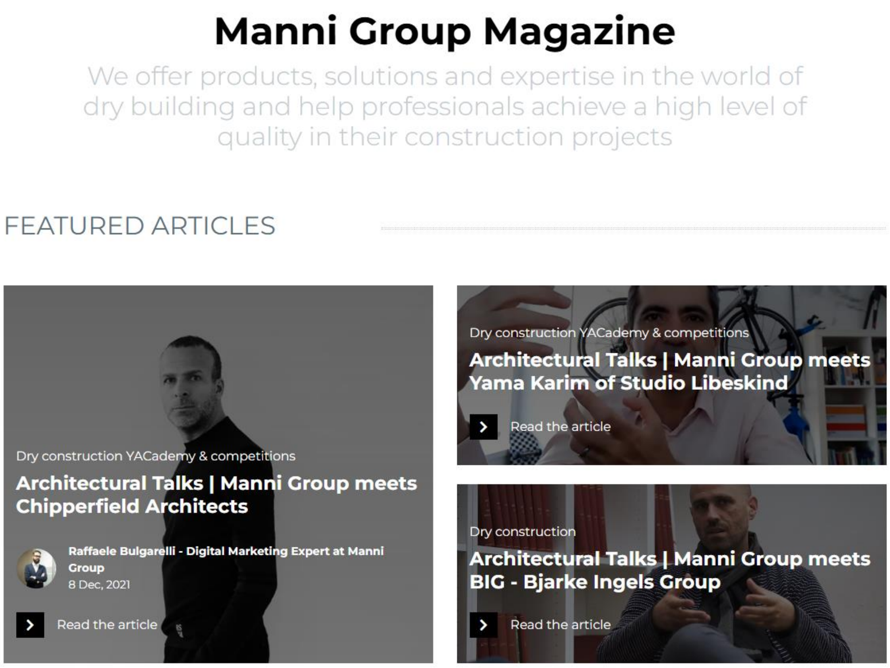

Figure 14: capture of the Manni Group Magazine website

CE product architecture design and Life cycle product design

In pursuit of a circular construction model, Manni Group develops off-site and dry construction systems. These methods serve as practical tools to decarbonize the building sector. The **Light Steel Frame (LSF) Systems** developed by the Group ensure 100% recyclability, providing durability and design flexibility.

Manni Group has successfully applied circular economy principles in various projects, demonstrating the feasibility and benefits of sustainable construction:

1. Green Building Certifications

Manni Group's products and construction systems contribute to obtaining green building certifications such as LEED and BREEAM. These certifications recognize high-performance, environmentally responsible buildings.

2. Sustainable Urban Development Projects

The company has been involved in large-scale urban regeneration initiatives where circular economy principles guide the selection of materials, design strategies, and construction methods.

3. Modular and Prefabricated Buildings

By promoting modular construction, Manni Group enables buildings to be disassembled and repurposed, reducing demolition waste and enhancing resource efficiency.

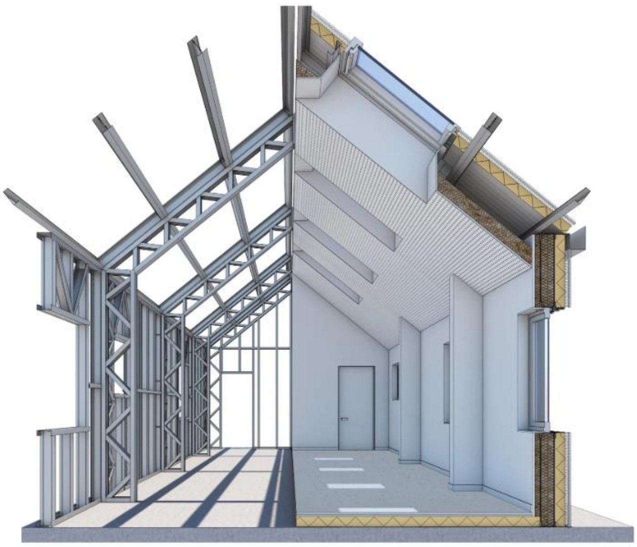

Figure 15: examples of Manni Group's projects and software usage, available on the website

For example, in collaboration with European municipalities, Manni Group has participated in **S**mart City urban regeneration projects, focusing on adaptive reuse of old buildings, energy-efficient renovations, and material recovery for future construction. It is the case of Verona, where a new Platys Center of 50.000-square metre area has been built, devoted to new sports and leisure activities of the city. The redevelopment project by the Magnoli & Partners architecture firm aims to transform the area into a “Bio Campus”, creating a space that enhances both human well-being and the environmental sustainability of the city. This vision for the Platys Center integrates cutting-edge sustainable design and innovative technological solutions. Thanks to this approach, the Platys Center became the first in Europe to achieve SITES® Silver level certification from GBCI® (Green Business Certification Inc.), the most comprehensive framework for planning and certifying sustainable and resilient land development projects. This certification requires adherence to stringent criteria, including the preservation of natural resources and biodiversity, reduction of emissions and energy consumption, and a meticulous selection of building materials, with a strong emphasis on fostering a harmonious relationship between the built environment and the community. As a result, all Platys Center buildings are nZEB (nearly Zero Energy Buildings), meaning they generate more energy than they consume. This is achieved through a combination of advanced design strategies and innovative construction techniques. As reported in Manni Group website, the huge emphasis on environmental sustainability and energy efficiency throughout all stages of the project, from planning the design until its implementation, was also reflected in the solutions provided by Manni Group.The metal structures of the building were manufactured using **pre-fabricated steel** elements supplied by the Manni Sipre service centre, which are **fully recyclable and in line with the modularity concept behind the whole project**. Moreover, Isopan envelope solutions were also used. Thanks to the ADDWind ventilated façade system and the Isodeck PVSteel roofing panel, a high level of performance is ensured, not only when it comes to functionality, resistance and thermal insulation but also when it comes to aesthetics and design.

Figure 16: details from the Manni group website. Available https://mannigroup.com/en/projects/platys-center/

To ensure continuous improvement in sustainability, Manni Group also employs Life Cycle Assessment (LCA) methodologies to evaluate the environmental impact of its products. This approach allows the company to identify areas for improvement in material sourcing, production, and waste management; provide transparent environmental data to customers and stakeholders; optimize processes to enhance resource efficiency and reduce carbon emissions. In 2023, they decided to perform LCA studies on prefabricated Light Steel Frame construction solution and compare them with a construction system based on traditional brickwork. The aims of the study were to identify the main environmental impacts to single out areas for improvement; to determine the environmental benefits of adopting Light Steel Frame technology compared to a traditional construction system; to promote transparent, reliable and truthful communication aimed at helping customers make more informed purchasing choices. The results of the LCA study show that the LSF system has environmental advantages over the traditional system.

Manni Group also built many pavilion for the Milan Expo in 2015, using 8000 tons of structural steel elements. Many of those pavilion should have been designed for disassembly and reuse after the event.

Sharing platform service and Application software

The company leverages digitalization and data-driven platforms to facilitate material reuse and energy efficiency. Among the IoT-Based solutions, the Group developed the **MEvision Platform,** which is a real-time monitoring system for energy optimization in buildings, contributing to reduced energy consumption. Moreover, Manni Group employs blockchain-based tracking technology to ensure full material traceability.

Acknowledgments

This research was conducted as parts of the Grant-in-Aid for Scientific Research Activity in Japan (2022-2025): “Development, empirical research, dissemination of new theories and system techniques for the CE to meet the responsibility for production and consumption of SDGs.”

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地の塩、世の光

The Salt of the Earth,The Light of the World

【青山学院スクール・モットー】

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