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PERSPECTIVE

Circularity Engineering: A Scientific White Paper

Hannes Geist[1*], Oliver Ambacher[1], Katja Brundiers[2], Oana Cojocaru-Mirédin[1], Christoph Eberl[3,4], Peter Gumbsch[4,5], Erik G. Hansen[6,7,8], Holger Neuhaus[1,9], Rüdiger Quay[1,10], Alex Ramey[11], Alexander Reiterer[1,12], Alexander Stolz[1,13], Anke Weidlich[1], Arnim Wiek[11], Frank Balle[1,13,14]

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Abstract

Conventional modern economies are dominated by a linear resource usage model, where raw materials are extracted, transformed into products, used, and then discarded as waste. Conventional engineering practices reinforce this model. To prevent and mitigate the resulting increasingly negative and systemic impacts, particularly on the environment, concepts of circularity have been developed over the past decades. The circular model aims at designing flows of products, components, and (engineering) materials, in ways that retain, regain, and add to their value for as long as possible while minimizing adverse effects. To date, the adoption and scaling of circularity in engineering remains insufficient. Circularity engineering is proposed as the engineering of matter and its interplay with information and energy towards a circular economy. As such, it is optimized for and one of several required contributions to sustainability. It is a new modus operandi across all conventional engineering disciplines. Building on previous work, this scientific white paper introduces a framework for circularity engineering that includes six interconnected building blocks to enable circular engineered systems. The article highlights the added value of circularity engineering, i.e., higher product quality and profitability; discusses conceptual limitations; and proposes future research questions. Finally, we outline the contribution of circularity engineering to sustainability.

Keywords Circularity Engineering · Circular Economy · Design for Circularity · Sustainability Engineering · Resilience · Quality

[*] Corresponding author: efm@inatech.uni-freiburg.de
[1] Department of Sustainable Systems Engineering (INATECH), Faculty of Engineering, University of Freiburg, Emmy-Noether-Str. 2, 79110 Freiburg, Germany
[2] Transformational Sustainability Science Group, Rectorate, University of Freiburg, Engesserstr. 4, 79108 Freiburg, Germany
[3] Department of Microsystems Engineering (IMTEK), Faculty of Engineering, University of Freiburg, Georges-Köhler-Allee 078, 79110 Freiburg, Germany
[4] Fraunhofer Institute for Mechanics of Materials IWM, Wöhlerstr. 11, 79108 Freiburg, Germany
[5] Institute for Advanced Materials IAM-ZM, Karlsruhe Institute of Technology (KIT), PO Box 6980, 76049 Karlsruhe, Germany
[6] Institute for Integrated Quality Design (IQD), Johannes Kepler University Linz (JKU), Altenberger Straße 69, Linz, 4040, Austria
[7] Centre for Sustainability Management, Leuphana University Lüneburg, Universitätsallee 1, 21335 Lüneburg, Germany
[8] Business School, University of Eastern Finland (UEF), Yliopistonranta 1, 70210 Kuopio
[9] Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, 79110 Freiburg, Germany
[10] Fraunhofer Institute for Applied Solid-State Physics IAF, Tullastr. 72, 79108 Freiburg, Germany
[11] Institute for Economics, University of Freiburg, Engesserstr. 4, 79108 Freiburg, Germany
[12] Fraunhofer Institute for Physical Measurement Techniques IPM, Georges-Köhler-Allee 301, 79110 Freiburg, Germany
[13] Fraunhofer Institute for High-Speed Dynamics, Ernst Mach Institute EMI, Ernst-Zermelo Str. 4, 79104 Freiburg, Germany
[14] Freiburg Materials Research Center (FMF), Stefan-Meier-Str. 21, 79104 Freiburg, Germany

1. Introduction

In the conventional, linear economic model, raw materials are extracted, transformed into products, used, then discarded as waste and partly recovered as energy. While instrumental in creating short-term wealth for some, over the course of centuries, this model has led to significant negative consequences, particularly for the environment. This development demands a new modus operandi for engineering research, practice, and education across all engineering disciplines: circularity engineering.

1.1. Engineering and the need for change

The Cambridge Dictionary defines engineering as the "study of using scientific principles to *design* and *build* machines, structures, and other things, including bridges, roads, vehicles and buildings" (Cambridge Dictionary, 2025).

UNESCO defines engineering as "the field or discipline, practice, profession and art that relates to the development, acquisition and application of technical, scientific and mathematical knowledge about the *understanding, design, development, invention, innovation* and *use* of materials, machines, structures, systems and processes for specific purposes" (UNESCO, 2010).

Engineering practices have historically adopted and reinforced the linear economy in key ways (*see also section 4, Table 10, column 2*). The definitions stated above, show that engineering is traditionally defined by developing, innovating, and building the inputs into a linear economic system without considering what happens to these developments after usage. Based on the economic objectives of a linear economy *(section 2.1*), conventional engineering focuses on designing products optimized for the point of sale. This means maximizing functionality and minimizing manufacturing costs for the mass market. Niche strategies of course differ. Economically-driven and legally-constraint, conventional engineering aims to design engineered systems only as safe and long-term qualitative as necessary. Exceeding these minimum requirements is called overengineering (Achtelik, 2025). This focus on manufacturing costs (cradle-to-gate; point of sale) and sales volume unveils an inherent conflict between profitability and quality in conventional engineering. Additionally, the ecological and social impacts along all lifecycle stages are considered as externalities, getting overall little attention. Therefore, conventional engineering is pivotal to the linear economy and a co-driver of its related sustainability problems.

Covering circularity remains a rare exception in engineering education and predominantly a European phenomenon (Mesa & Esparragoza, 2021). This demands a new circular modus operandi for engineering which contributes to a circular economy (section 2.2) as a leverage for sustainability (section 2.3). This work aims to support future engineering scholars and practitioners by conceptualizing and summarizing this necessary future modus operandi of engineering with a deductive and vision-oriented approach, resulting in the proposal of circularity engineering.

That way, it significantly expands on existing review papers which summarize the status quo of circularity in specific facets of engineering in an inductive way (Liu & Kringos, 2024; Mesa & Esparragoza, 2021; Nikolaou & Stefanakis, 2022), and on perspective papers which are more vision-oriented, but don't provide comprehensive actionable overviews about the theory engineers should know as a foundation for engineering effective circular economy solutions (David et al., 2024; Londoño & Cabezas, 2021).

Circularity engineering (introduced in detail in *section 4*) is distinct from existing sustainability- and circularity-focused engineering concepts. Contrary to *environmental engineering*, which mostly takes an end-of-pipe approach and focuses on process engineering, circularity engineering takes an ab initio approach and is discipline-unspecific (Vesilind & Peirce, 2013; Weiner & Matthews, 2003). *Life cycle engineering* (LCE), as a distinct discipline and field (Peças et al., 2016), aims to minimize negative sustainability impacts of the life cycle of a product, taking an ab initio approach, guided by life cycle assessment (Alting & Jøgensen, 1993; Hauschild et al., 2017; Herrmann et al., 2014). In recent years, it has expanded to cover topics of absolute sustainability (Hauschild et al., 2020; Herrmann et al., 2025; Kara et al., 2023) and circularity (Hauschild et al., 2020; Reslan et al., 2022) by complementing bottom-up with top-down approaches (Hauschild et al., 2017). Current mentions of circularity in LCE remain limited to theoretical high-level frameworks (Hauschild et al., 2017; Hauschild et al., 2020; Reslan et al., 2022). In contrast, circularity engineering is not an own discipline or field but a necessary future modus operandi across disciplines and its scope is more comprehensive, covering every engineering activity. Based on their close relationship, the LCE-discipline with its focus on developing

frameworks, methods, and tools, can be a key enabler towards the new cross-disciplinary modus operandi of circularity engineering. *Green engineering* and circularity engineering are closely aligned in their ab initio approach, goals, and prioritized strategies towards these goals (Anastas & Zimmerman, 2003). While green engineering focuses on how to realize the vision of sustainability through circularity with better product and process design primarily (McDonough et al., 2003), the scope of circularity engineering is more systemic, also for example considering the influence of information flows, system dynamics, logistics, and business models.

1.2. Methodology

This work follows the scientific white paper approach successfully pioneered by Allwood and colleagues on material efficiency (Allwood et al., 2011). The goal of a scientific white paper is to stimulate interest in and provide easy access to a topic for readers who just enter a field as currently the case for many engineering researchers starting to engage with circularity. It does so by providing a comprehensive and consistent conceptual overview. Methodologically, a scientific white paper combines the normative nature, wide scope, and openness in structure of a perspective with the comprehensive literature summaries and different forms of synthesis of integrative literature reviews. Original contributions mostly result from different forms of integrative literature synthesis including conceptual frameworks (e.g., *Figures 2 and 5*), novel taxonomies (e.g., *Table 11*), reconceptualization (e.g., *section 3*), and research agendas (e.g., *Tables 3-9*) (Torraco, 2016). Yet, they can also include new data collection and analysis to provide a consistent bigger picture (e.g., Figures 1 & 6).

Advancements towards circularity and sustainability across engineering and related disciplines build upon and strive towards the same fundamental concepts. This circular economy and sustainability theory is normative, diverse, generic, and heterogeneous. The scientific white paper summarizes this complex theory consistently and tailored for engineering. It delivers the first comprehensive overview about the role, tasks, responsibilities and key challenges of engineering across disciplines implementing the circular paradigm to contribute to sustainability. It provides readers with common conceptual ground, quick access to the field, and enables them to build upon without needing to spend time on their own engineering-specific conceptualizations of fundamental concepts again and again.

Rooted in a summary of the fundamental concepts of the linear economy, circular economy, and sustainability (*section 2*), circularity engineering is proposed as a new modus operandi in engineering (*section 3*). The paper translates the conceptually given diametral conceptualization of "linear economy vs. circular economy" to engineering to be consistent with dominant theory and sketch a vision for engineering, while acknowledging that neither the economy nor engineering typically ever fully match these absolute states. The proposed circularity engineering definition (section 3.1), building blocks (section 3.2), and framework (section 3.3) is connected to research practice by outlining exemplary practical research questions for the traditional engineering disciplines at the end of each section. Opportunities for profitability and quality allow for transitioning the status quo towards circularity engineering, even under current economic and legal boundary conditions (section 3.4). Conceptual limitations are discussed to enable effective implementation of the concept (*section 4.1*). Finally, contributions of circularity engineering to sustainability and its limitations are discussed (*section 4.2*).

2. Fundamental concepts for circularity engineering

This section summarizes key concepts that the conceptualization of circularity engineering in *section 3* builds upon and introduces the readers who are new to the circular economy discourse to its conceptual basics.

2.1. The linear economy

The *biosphere* is based on complex global elemental cycles in dynamic equilibria powered by the sun, the gravity of the moon, and the energy stored under the earth's crust. A great acceleration of socio-economic trends caused tremendous destabilizing tendencies of the biosphere since the 1950s (Steffen, Broadgate, et al., 2015). This is reflected in the significant change in Earth systems within the last century (Crutzen, 2002; Crutzen & Stoermer, 2000; Lewis & Maslin, 2015) and humanity leaving its 'safe operating space' (Richardson

et al., 2023; Steffen, Richardson, et al., 2015). The ongoing intervention in natural cycles of the biosphere and creation of new anthropogenic flows led to the emergence of a new sphere following its distinct set of rules and concepts (Redman & Miller, 2015). This *technosphere*, dominated by a linear economic model, is mainly based on linear elemental flows instead of nature's cyclic metabolisms (Chen & Graedel, 2012). The biosphere creates the high structural diversity of life based on only a few elements. Chemodiversity of the technosphere doubled within 11 years to exceed 100 million substances in 2015 (Chemical Abstracts Service [CAS], 2023). Material demand for the technosphere has doubled every 20 years since 1900 (Elhacham et al., 2020) and is expected to almost double again by 2060 (OECD, 2019). The technosphere's mass exceeded the dry weight of the biosphere in 2013 (Elhacham et al., 2020). Unlike the biosphere, the technosphere is sun-powered to less than 15% (IEA, 2023c).

In capitalism, the predominant economic objectives in the linear economy are maximizing sales and minimizing production costs to maximize profits. Thus, from the initial design phase, many products are designed for short term and single use. This cradle-to-grave paradigm is yet not fully linear, reflected in a global secondary material use rate of 7.2% in 2023 (Circle Economy Foundation, 2024). The responsible processes are summarized as "downcycling economy" or "recycling economy". They are a feature of the linear economy since they are part of the end-of-pipe waste management of products that have never been designed for recycling and do not allow for continuous usage of materials due to degrading material quality over time (Ellen MacArthur Foundation, 2021; Webster, 2021; World Economic Forum, 2019). In the long term, this model has been linked to a variety of sustainability challenges.

For the purpose of assessing the sustainability impacts of the linear economy, we adopt Gibson's (2006) concept, which is tailored for sustainability assessment and expands on the principles of intra- and intergenerational justice from the Brundtland report (WCED, 1987). According to Gibson, sustainability ensures a sufficient and equitable level of social and economic welfare within and across societies, without compromising the long-term viability and integrity of the supporting environmental, social, and economic systems. Exemplary sustainability problems of the linear economic model are summarized in *Table 1*.

Table 1. Examples for sustainability problems of the linear economy.

Environmental impacts	Social impacts	Economic impacts
• Targets for limiting climate change and biodiversity loss are significantly exceeded (UNEP, 2024a) • Material production accounts for 15-20% of global energy demand and ~18% of all greenhouse gas emissions (IEA, 2023a, 2023b) • Necessary resources for emission reduction in a linear system like green hydrogen or carbon capture and storage will remain very limited (Allwood, 2026; Odenweller et al., 2022) • Mining activities damage ecosystems, impairing their ability to contribute to human wellbeing (Boldy et al., 2021) • Most materials, sooner or later, become waste • Mining and production waste can exceed end-of-life-waste, for electronics by a factor of up to 500 (ivl Svenska Miljöinstitutet, 2015) • Metal cycles are out of homeostasis, resulting in toxic effects on humans and the environment (IRP, 2013) • Plastics, when degrading, release microplastics which are highly mobile, bioaccumulative, and enter the food chain (Thompson et al., 2024; UNEP, 2021) • With more than 13,000 associated chemicals (UNEP, 2023), and a quarter being chemicals of concern (UNEP, 2023; Wiesinger et al., 2021), some off-gassing during usage and recycling prolonging their legacy (Wiesinger et al., 2024), significant risks for humans and the environment exist	• Health risks related to materials and waste vary significantly by income, age, sex, and gender (UNEP, 2023; Wang et al., 2024; World Health Organization, 2021) • Working conditions and wages in artisanal and small-scale mining are often unjust, e.g., cobalt mining in the Democratic Republic of Congo is associated with severe health risks and human rights violations (Schwartz et al., 2021; Sovacool, 2021) • Material usage is six times higher, and climate impact is ten times higher per capita in high-income countries compared to low-income countries (UNEP, 2024a). • Most raw material extraction and refining occur in low-income countries, unevenly distributing the burdens of extraction and the benefits of consumption.	• In Europe, ~95% of a product's economic value is lost after a single use phase (SYSTEMIQ & Ellen MacArthur Foundation, 2017) • Annual material value losses of steel, plastics, and aluminum are in the range of €78 billion in the EU (Material Economics, 2020) • Waste management costs amounted to USD 361 billion in 2020 globally, expected to rise to USD 640.3 billion by 2050 (UNEP, 2024b)

The urgency of addressing these shortcomings of the linear economic model is heightened by the increasing complexity and interconnectedness of global systems. Many materials are now considered critical due to their supply risks and high economic and strategic importance (European Commission, 2020a; U.S. Geological Survey, 2022). Key risk factors include resource scarcity, price volatility, geopolitical and regulatory risks, and market concentrations, as expressed by the Herfindahl-Hirschman Index (Hirschman, 1945) in *Figure 1*. Simultaneously, legislative and consumer pressures for supply chain transparency, ecodesign, and extended producer responsibility are increasing (ESPR, 2024; Maitre-Ekern, 2021), highlighting the need for a systemic shift away from the linear economy.

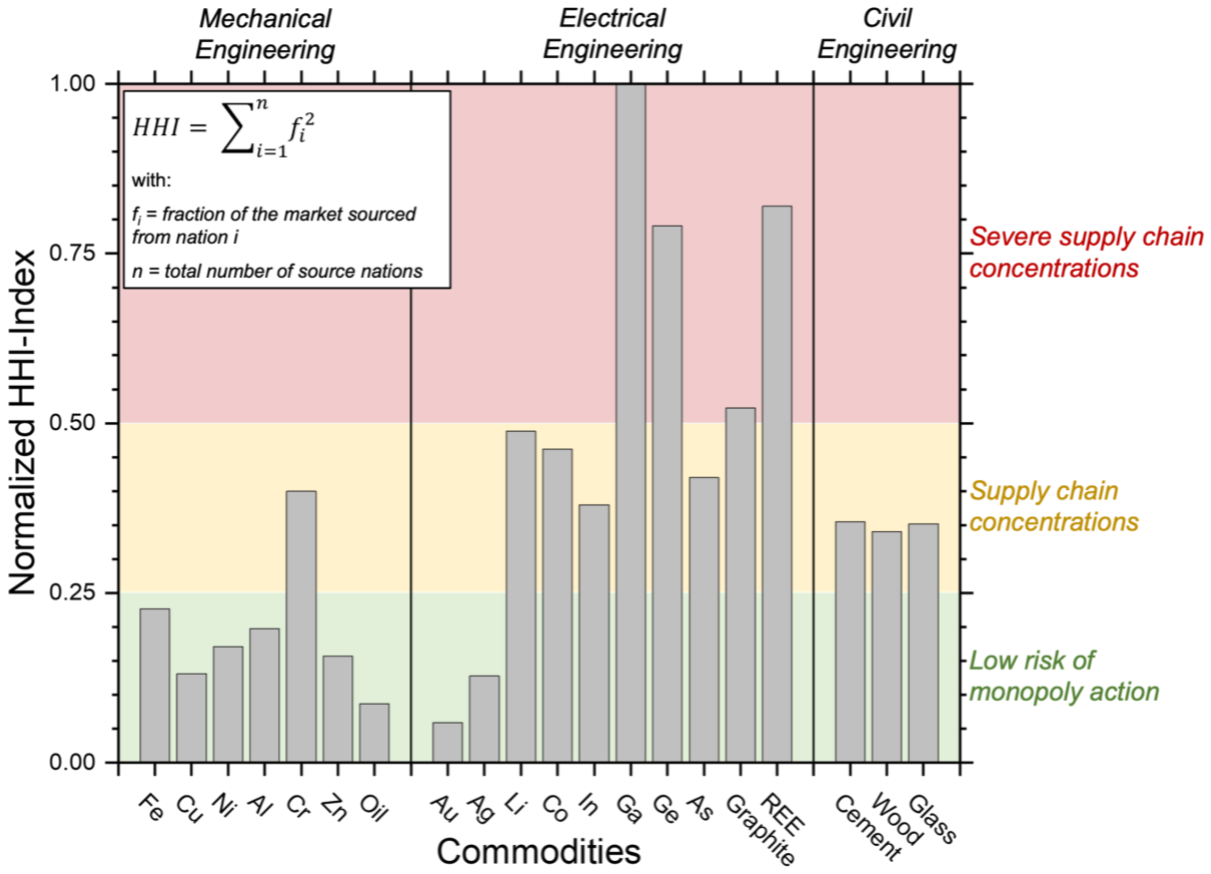


Figure 1. Normalized Herfindahl-Hirschman Index (HHI) as a metric for geopolitical supply risks caused by market concentrations for essential exemplary commodities of mechanical, electrical, and civil engineering applications (own analysis based on data from Mróz, 2022; U.S. Geological Survey, 2023). An HHI of 1 represents a monopoly; a value below 0.25 indicates a market without supply chain concentrations. Supply chain concentrations, as measured by the HHI, correlate with risks of volatile pricing, supply shortages, and complete disruptions.

2.2. The circular economy

The circular economy is an umbrella concept of heterogeneous origins (Blomsma & Brennan, 2017; British Standards Institution, 2017). It blends aspects of multiple schools of thought, most prominently the spaceship economy from the 1960s (Boulding, 1966), industrial ecology from the 1970s (Kampur & Graedel, 2004), performance economy from the 1980s (Stahel, 2006; Stahel & Reday-Mulvey, 1981), biomimicry from the 1990s (Benyus, 1997), and cradle to cradle from the 2000s (McDonough & Braungart, 2002). Diverse concepts from various stakeholders emerged in recent years (Blomsma & Brennan, 2017). A review identified 221 different definitions of circular economy (Kirchherr et al., 2023). Conceptual harmonization is going on scientifically (IRP, 2018; Leipold et al., 2023), legally, e.g., European ecodesign for sustainable products directive (ESPR, 2024), and in standardization, e.g., ISO 59XXX series, EN 4555X series.

While the most generic circular economy definition is from ISO 59004 (ISO, 2024a), an adapted version from EN 45560 (CEN/CENELEC, 2024) is most suitable for engineering:

The circular economy is an economic system that contributes to a sustainable development whereby the value of products, components, materials, and other resources is retained, recovered, or added to the highest level possible for as long as possible, keeping the resources in a circular flow and minimizing losses, waste, harmful emissions, negative externalities, pollution, and the inflow of primary resources, by design.

The circular economy concept mimics nature's sun-powered metabolism of matter in anthropogenic systems. Circular economy is characterized by the following features: Products and systems are designed for circularity from the beginning, so ab initio (Braungart et al., 2007; European Commission, 2020b; Hansen & Schmitt, 2021; Webster, 2021). Products of service (i.e., everything that is used and not consumed; most engineered products) are designed for the technosphere. Materials intended for continuously circulating in the technosphere, so-called technical nutrients, must persist and show excellent recyclability (Geist & Balle, 2025). Products of consumption (i.e., everything that emits matter to the environment by usage or cannot be continuously retained for the technosphere) are designed for the biosphere (Braungart et al., 2007). Materials intended for circulating through the biosphere, so-called biological nutrients, must (bio)degrade. Since existence creates emissions, these emissions must be environmentally benign, ideally not just non-toxic for humans and the environment, but healthy instead for safe continuous circulation (Anastas & Zimmerman, 2003; Braungart et al., 2007; Chen et al., 2014; Krebs & McKeague, 2020; Kümmerer, 2016). Otherwise, and due to upcoming restrictive legislation, full quality and value loss will be risked. Green toxicology is a related discipline (Crawford et al., 2017), safe-and-sustainable-by-design the related strategy providing a detailed framework and proven guidance (Apel et al., 2024; European Commission - Joint Research Centre, 2025). Irreversible mixing of materials must be prevented, and their identity must always be known to keep biosphere and technosphere separate and enable circulation without quality losses. The complexity and diversity of today's products and their constituents increase the dilution and dissipation of materials, pollutants, and energy (Kümmerer et al., 2020). This reduceable, but not fully preventable complexity implies a hierarchy of value-retention in different resource states for circularity engineering, known as inertia principle or material value hierarchy (Blomsma & Tennant, 2020; CEN/CENELEC, 2024; den Hollander et al., 2017; Stahel, 2006):

system > product > assemblies > sub-assemblies > components > engineering materials > substances > elements

There are corresponding generic processing options summarized in *Table 2*. In contrast to many non-engineered systems, most engineered systems qualify for economically and environmentally beneficial value-retention processes (VRPs) on a product or component level before recycling them if designed for that purpose.

Table 2. Defining features of the generic processing options in the technosphere of an ab initio circular economy, namely recycling and value-retention processes (VRPs), based on (DIN SPEC 91472:2023-06, 2023; ESPR, 2024; IRP, 2018; ISO, 2024a), listed following the inertia principle.

Process		Level of value retention	Process outcome	Service life perspective	Defining characteristics
VRPs	Maintenance	Product	Used product	Enabling the expected service life	Action to keep a product in a condition where it is able to function as required
	Reuse	Product	Used product	Enabling the expected service life	Using again of a product that is not waste for its initial purpose without the necessity of repair or refurbishment Might include inspection, testing, and cleaning Two generic options: 1. Service life extension: *e.g., redistribute, resell* 2. Service life intensification, *e.g., sharing*
	Repair	Product	Used product	Enabling the expected service life	Fixing specified faults, defects or replacing broken parts Produces fully functional products to be used for their originally intended purpose

Table 2 (cont.). Defining features of the generic processing options in the technosphere of an ab initio circular economy, namely recycling and value-retention processes (VRPs), based on (DIN SPEC 91472:2023-06, 2023; ESPR, 2024; IRP, 2018; ISO, 2024a), listed following the inertia principle.

Process		Level of value retention	Process outcome	Service life perspective	Defining characteristics
VRPs	Refurbishment	Component	(High quality) used product	Enabling almost full additional service life(s)	Increasing or restoring the functionality and/or performance or meeting technical or legal requirements Products for at least the initially intended purpose
	Remanufacturing	Component	New product	Enabling additional full-service life(s)	Standardized industrial processes New products are produced from parts of several used products (~cores), and few new parts Upgrading and updating to the latest technology possible Upgrading means enhancing the functionality, performance, capacity or aesthetics of products Upgrading can in some cases also be performed by customers in the field and categorized as an additional VRP
Recycling		Engineering material, molecule, atom	Recycled material	Ending	Geometrical integrity is entirely lost

Circular economy *(Figure 2)* is characterized by minimizing leakage and negative externalities, designing them benign, and maximizing positive externalities. The variables of system redesign are matter, (renewable) energy, and information. Circulation strategies for matter have existed since humanity began using materials for tools. Renewable energy has become widely available in the last decades. The necessary digital information management for a circular economy has just recently become technologically feasible. Now, the shift towards a circular economy can accelerate.

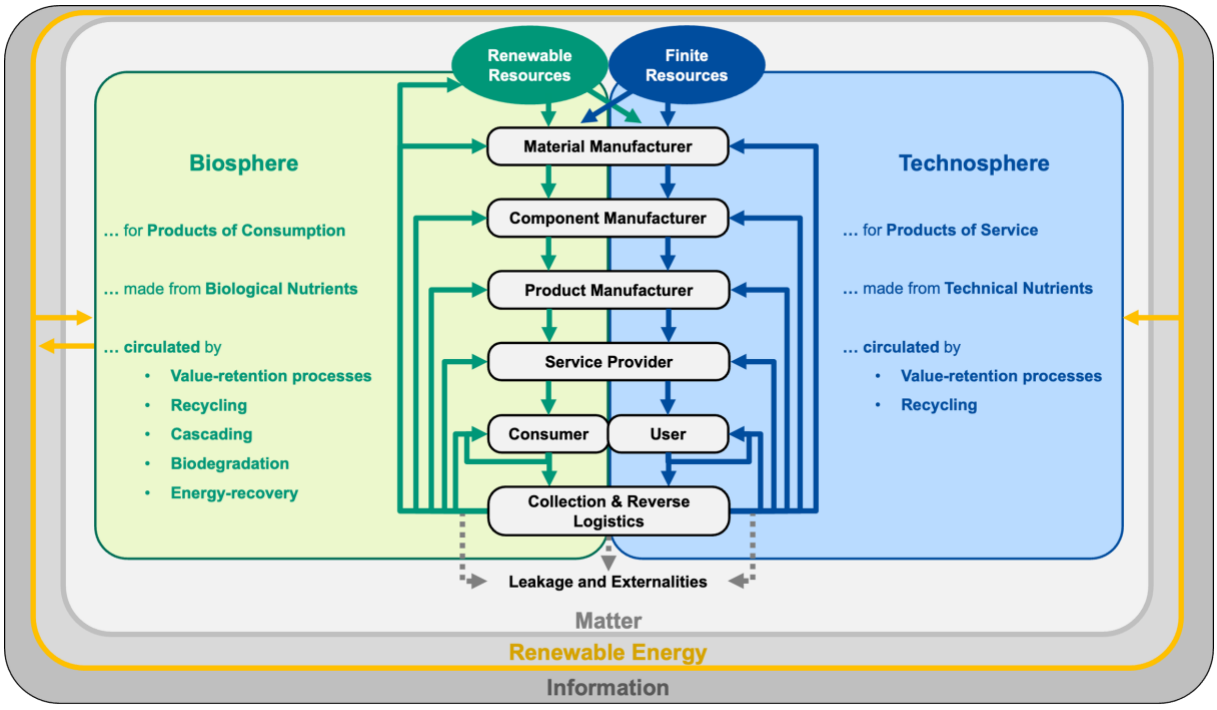


Figure 2. Generic diagram of a circular economy, highlighting the interdependency of the system layers matter, (renewable) energy, and information, as well as the differentiation of two fundamental product types for two separate spheres.

2.3. Contributions of the circular economy to sustainability

In a technology-centric way, there are generic strategies (Huber, 2000; Rudolf & Schmidt, 2025; Schmidt, 2008) to work towards resource sustainability as illustrated in *Figure 3*.

- *Increasing efficiency* is a relational strategy that aims at reducing inputs (e.g., material, energy) while maintaining at least the same outputs (e.g., products). It is the dominant strategy of conventional engineering.
- *Increasing sufficiency* is a relational strategy that aims at reducing consumption (e.g., products, energy) by behavioral change while maintaining at least the same utility (e.g., well-being).
- *Increasing consistency* is a strategy that aims at reducing adverse impacts through new working principles more in harmony with the natural energy flows and material cycles (Huber, 1995).

Research on passing major planetary boundaries for climate change (IPCC, 2023; Rockström et al., 2017) and biodiversity loss (Secretariat of the Convention on Biological Diversity, 2020) shows that strategies reducing negative impacts through increasing efficiency, sufficiency, and consistency are not sufficient for stopping degenerative system dynamics. These strategies often provide smaller benefits than expected or even net-negative impacts due to unintended *rebound* effects (Andrew & Pigosso, 2024), mainly resulting from the partially unpredictable complexity of socio-technical systems (Freeman, 2018; Geels, 2011). Circular economy rebounds include diverse socio-economic mechanisms resulting in increasing overall production or consumption (Castro et al., 2022; Zink & Geyer, 2017). Thus, regenerative dynamics are necessary for circularity (Hauschild, 2015), although difficult to achieve, not always possible, and facing high risks of misunderstanding and greenwashing (Konietzko et al., 2023), captured in the following strategy:

- *Increasing effectiveness* aims to enable, initiate, sustain, or strengthen regenerative dynamics (Fischer et al., 2024), thus doing good rather than less bad (Braungart et al., 2007). While such regenerative practices typically focus on one desired outcome variable, potential trade-offs promoting degeneration of other system variables must be prevented (Fischer et al., 2024; Gibson, 2006). For example, using timber for long-term applications like buildings shows potential for creating significant carbon sinks (Churkina et al., 2020), but only if strong governance and careful planning prevent degenerative trade-offs (Mishra et al., 2022).

Maximizing circularity can even conflict with sustainability (Bartie et al., 2023; Schäfer & Schmidt, 2020). Circularity, in its etymological sense, focusing on closing and slowing loops only, is considered a consistency strategy (Rudolf & Schmidt, 2025) and does not address sustainability holistically:

- maximizing *circularity* can drastically increase environmental burden,
- *material and energy efficiency* improvements can be in conflict,
- *sufficiency* and the growth debate are not always addressed,
- *effectiveness* is not always addressed,
- *resilience* can be undermined by shifting criticality from materials to processes.

Modern circular economy concepts address many of these shortcomings. Examples are the notions of enhancing process efficiency in the twelve principles of circular chemistry (Keijer et al., 2019), of the importance of sufficiency in the circular economy context (Bocken et al., 2022; Mederake, 2022) or the eco-effective circular economy principle “regenerate nature” (Ellen MacArthur Foundation, 2023). The generic circular economy strategies of narrowing, slowing, and closing loops (Bocken et al., 2016), extended by regenerating and informing loops (Konietzko et al., 2020) include:

- efficiency: lightweight design, function integration, material efficient processing, maximizing capacity use of products;
- consistency: low-impact inputs, design with recycled inputs, circular design;
- sufficiency: enabling and incentivizing users to consume as much as needed, product-as-a-service;
- effectiveness: regenerate polluted ecosystems.

The circular economy, conceptually combining several sustainability strategies, can contribute to resource sustainability, but only reliably if optimized towards that end.

Another feature of circularity is *resilience*, which means ensuring desired system states and dynamics, also during periods of continuous pressure, disturbance, and crisis (Marchese et al., 2018). It includes all actions and skills necessary to prepare for, prevent, protect from, respond to, and recover from threats to a sustainable development (Häring et al., 2016). This requires continuous active adaption to changing environments (Anderies et al., 2013). Transformative resilience thinking, dealing with the interplay of system persistence, change, adaption, and transformation (Anderies et al., 2013; Folke et al., 2010), adds insights to circularity transformations regarding ease, reversibility, and hysteresis of change (Perrings, 2006).

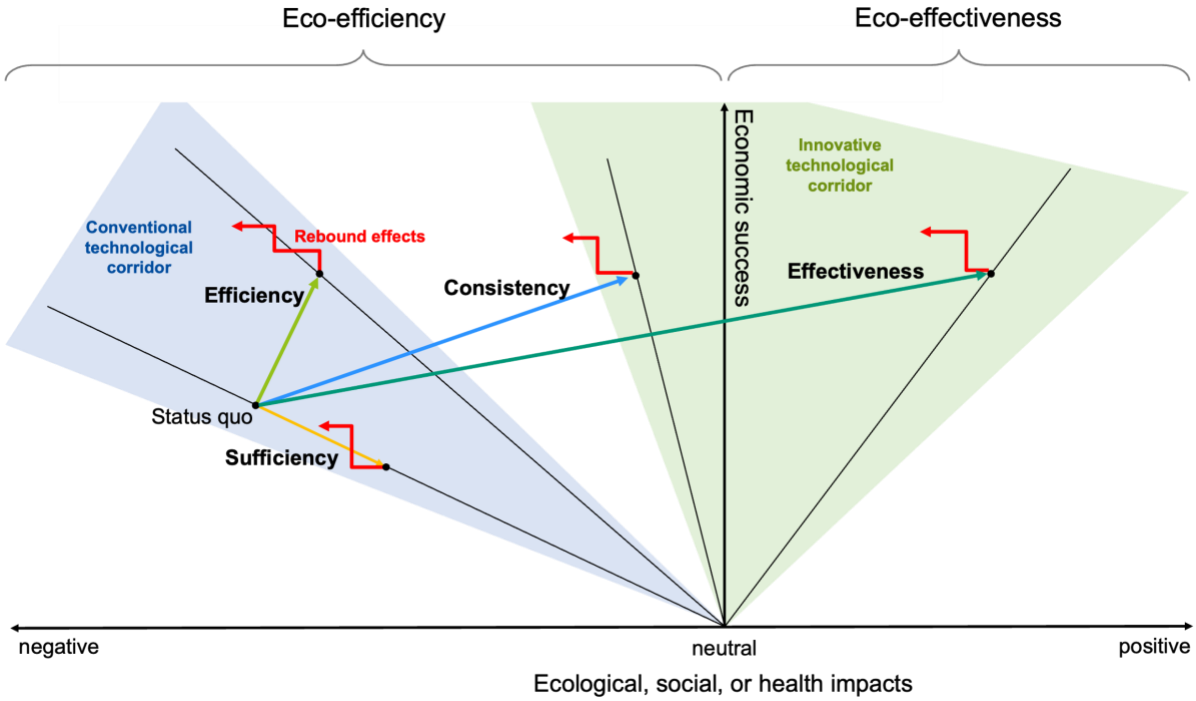


Figure 3. Technology-centric schematic visualization of the economic benefits against the ecological, social, and health efforts of products in light of the generic sustainability strategies (further development of Rudolf & Schmidt, 2025).

The circular economy vision addresses social and economic aspects of sustainability only to a limited extend. Economically, the circular economy is still compliant with certain aspects of the status quo, which prioritize economic growth and profit over, for example, political voice and interspecies justice (Ashton et al., 2022; Leipold et al., 2023). Contributions to social sustainability are limited (Garcia-Saravia Ortiz-de-Montellano et al., 2023; Schroeder et al., 2019), but yet existent. As an example, reduced exposure of workers and communities to toxic substances, reduction of harmful waste in the biosphere, etc. are positive effects of safer design as an inherent feature of a circular economy (Braungart et al., 2007; European Commission, 2020b). Additionally, significant (local) employment opportunity is attributed to VRPs (IRP, 2018; Stahel & Reday-Mulvey, 1981), also for people with disabilities (Zufall et al., 2020). Lower prices of reused goods are also known to improve the accessibility to goods, supporting the fulfillment of basic human needs of low-income communities (Hague et al., 2026). But, some evidence suggests that transitioning to a circular economy, without appropriate mitigation techniques, could even harm human wellbeing (Castro et al., 2022), calling for a vision of just circularity (Caredda et al., 2025).

Overall, we emphasize that achieving a circular economy, supported by engineering, is necessary, but in isolation not sufficient in the pursuit of sustainability (Geissdoerfer et al., 2017).

3. Circularity Engineering

Engineering has the potential to enable a transition to a circular economy. However, because engineering is part of the current socio-technical regime that must be transformed (Geels, 2011), it itself must be transformed, enabling it to support systemic change instead of stabilizing the linear economy. This requires intervening at

the deep leverage points of engineering: its paradigms, mindsets, and goals (Abson et al., 2017; Meadows, 1999). Based on the fundamental concepts introduced in *section 2*, this section proposes a definitions of circularity engineering (*section 3.1*), summarizes tasks of circularity engineers (*section 3.2*), synthesizes a summarizing framework (*section 3.3*) and presents a rationale why transformation towards circularity engineering is not just desirable and necessary, but also likely under current boundary conditions (section 3.4). Exemplary open research questions result from the literature summaries in all sub-sections and are summarized in *Tables 3-9*.

3.1. Definition of circularity engineering

Circularity engineering is the engineering of matter and its interplay with information and energy, towards a circular economy; as such, circularity engineering is one of several required contributions to sustainability.

Since the circular economy concept is normative and heterogeneous, the definition of circularity engineering is explicitly based on the conceptual understanding of the circular economy introduced in section 2. Expanding on the aforementioned engineering definition by UNESCO (UNESCO, 2010), engineering is no longer just about understanding, designing, developing, innovating, and using, but also about maintaining and circulating, and all of this with a circularity mindset. The focus of the rest of this work is on the engineering of matter. This includes stocks and flows of solids (systems, products, components, engineering materials, materials), but also liquids and gases (operating and auxiliary materials). The intended interrelation with information and energy is discussed in section 3.2.2. while trade-offs are discussed in section 4.1.3. Based on the definition of circularity engineering, circular developments must always be assessed against principles of sustainability (Blum et al., 2020). Circularity is not maximized but optimized for sustainability instead, striving for a circular economy within planetary boundaries (Desing et al., 2020; Schlesier et al., 2024). Circularity engineering is not a new engineering discipline. It is a new modus operandi across all conventional engineering disciplines, addressing their deep leverage points and aiming at becoming the “new normal”.

3.2. Building blocks of circularity engineering

Engineering minimal viable circular systems requires the symbiotic combination of several logically interdependent aspects. The necessary aspects beyond core tasks of engineering are structured based on ISO circular economy standards. The building blocks are not a direct mapping of these standards, but rather an interpretation and extension of the ISO framework adapted to the context of engineering practice. The necessity and data demand for information management are derived from ISO 59040 (ISO, 2025). The standard introduces the Product Circularity Data Sheet (PCDS) as a platform for consistent data sharing across value networks to provide the necessary information for high-quality and safe circulation to each of its actors. ISO 59010 provides guidance on the transformation towards value networks and circular business models, highlighting their fundamental necessity for circular industrial systems (ISO, 2024b). The following subsections summarize these building blocks to provide a simple taxonomy for the tasks of circularity engineering.

3.2.1. Design for Circularity: Engineering’s core tasks Design for Circularity is a connecting element between the three key challenges of circularity engineering: product design, material selection, and process integration. Engineering design poses a key leverage point for reducing negative impacts, since ~80% of most product’s environmental impact is determined during the design phase (European Commission, 2012). Design for Circularity enables circularity on a (engineering) material, component, and product level by designing products, their functions, performance, materials, geometry, and manufacturing processes for multiple use cycles, VRPs, and finally, recycling (*Figure 4*).

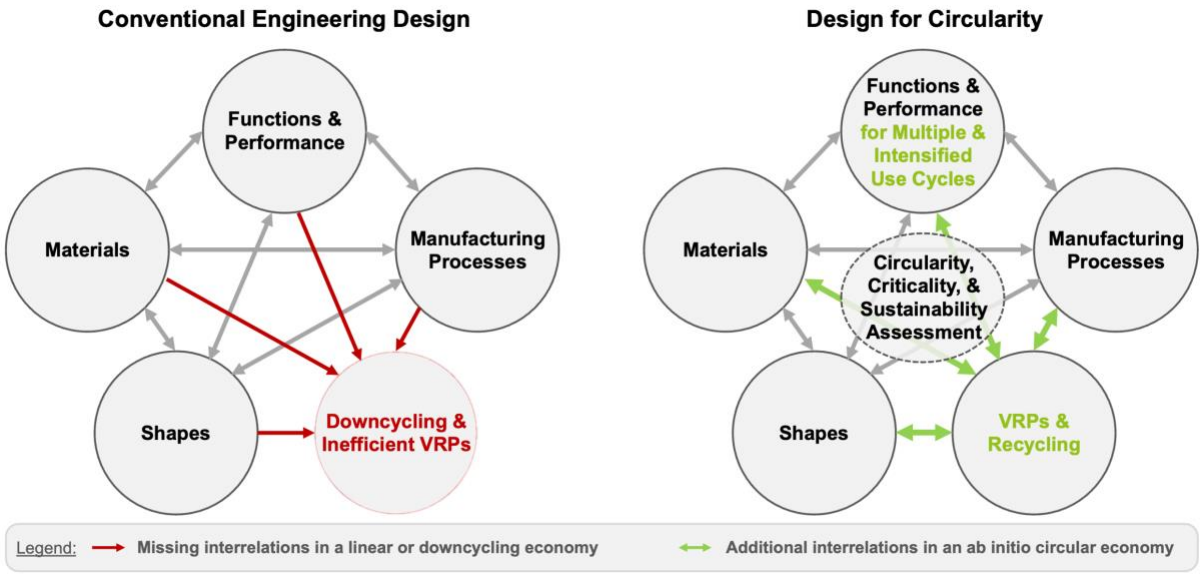


Figure 4. Key dimensions of engineering design and their interrelation in a linear economy (left), based on Michael F. Ashby (2017), and a circular economy (right), a further development of Ashby's work. Circularity performance (circularity) and circularity impact (criticality and sustainability) assessments enable optimizing product system circularity performance, to maximize the contribution of circularity engineering solutions to sustainability.

Building block 1: Product design

Product design is the process of defining the functions, function structure, and working principles of a product's hardware and software, its sub-assemblies, and components, as well as the shape and requirements of all components. Integrating product design with the product life cycle concept to contribute to sustainability has a long history in Europe (Brezet & van Hemel, 1997; UNEP & TU Delft, 2006, 2009). Following the inertia principle, product design starts with design for multiple-use cycles by analyzing, designing out, resisting, postponing, reversing, and managing different types of obsolescence (Asif et al., 2021; den Hollander, 2018; den Hollander et al., 2017; Premanand et al., 2026). This can be summarized as design to create, preserve, and recover value (IRP, 2018).

Design for intensified usage by enabling product sharing can create additional value. Designing to preserve value includes designing for durability, viability, and serviceability, including multiple-use-cycle spare part planning. This can be potentially simplified by identifying priority parts for VRPs or defining carry-over-parts in a modular product design (CEN/CENELEC, 2020). Further designing for longevity and extended use as part of a design for product integrity (den Hollander et al., 2017), design for an ideal use time (Bakker et al., 2014), or design that users keep care of products (Ackermann et al., 2021) can preserve value. Design to recover value includes supporting and withstanding VRPs, their specific process steps, and recycling.

Often ignored is to optimize the multiple-use-cycle compatibility of software and hardware. Their compatibility and adaptability can extend or limit the service life of hardware and promote, hinder, or prevent VRPs (Kutscher et al., 2020; Suppipat & Hu, 2022). Smart products can further drive smart circular strategies (Alcayaga & Hansen, 2025).

Although a first standard on circular design is available (CEN/CENELEC, 2024), the field is methodologically and tool-wise not sufficiently developed yet (Aguiar et al., 2022).

Table 3. Questions on product design as a key challenge of circularity engineering.

Mechanical Engineering	
OQ1	How can Design for Circularity be integrated methodologically into all phases of the product development process?
OQ2	How can material bonds be debonded on demand beyond reversible adhesives so that the joining partners remain undamaged as components and uncontaminated as material systems?
OQ3	How can testing methods, procedures, and infrastructure be modified to enable cheap and reliable multiple-use-cycle testing of products and components?

Table 3 (cont.). Questions on product design as a key challenge of circularity engineering.

Electrical Engineering	
OQ4	How can electronic products and components be designed for non-damaging, energy, and cost-efficient disassembly to be fed into VRPs or recycling?
OQ5	How can highly pure, often rare, and cost-intensive semiconductors be recovered from electronic and solar systems in an environmentally friendly way, without downcycling?
OQ6	How can electronic devices and components with a long service life (e.g., LEDs, electronic filters, ICs based on silicon carbide in AC-DC inverters) be separated and tested to enable reuse, as well as being trusted by producers and customers?
OQ7	How can strong and significant technological advancements, such as CMOS scaling, rendering components obsolete, be anticipated by design for later phases of reuse?
OQ8	How can energy efficiency, safety, and performance be increased while reducing costs and shifting to circularity engineering as necessary for rapidly developing technologies (e.g., batteries, solar modules, or power electronics)?
Civil Engineering	
OQ9	How to design infrastructure to achieve predictable conditions after its long-intended use time (50-100 years), and how to address the accumulation of uncertainties in such long periods?
OQ10	How to plan and design affordable structural health monitoring and how to deal with the large amount of available building stock being in unknown condition for urban mining?
OQ11	How can the circularity engineering concept be transferred to large or wide-spreading buildings and infrastructure networks like bridges, streets, and dams?

Building block 2: Material selection

Engineering materials are selected by match-making between design requirements and the property profiles of available engineering materials (Ashby, 2017). Materials selection starts with identifying whether the fundamental requirements for technical or biological nutrients apply as introduced in *section 2.2*. Engineering materials should further support VRPs (e.g., cleanability), usage extension (e.g., longevity), or usage-intensifying options (e.g., robustness for sharing). Supporting recycling in the technosphere relies on reducing a product's material and chemical diversity (Kümmerer et al., 2020) due to its concentration-dependency (Schäfer & Schmidt, 2020). The ability to engineer or 'program' materials to different properties to give desired functionality, even with the same composition, by tailoring their microstructure can be employed (Eberl, 2023). Materials properties, way beyond the properties of the known bulk materials, can be achieved with metamaterials or architectured materials (Estrin et al., 2021; Fang et al., 2022), reinforced by processing options like 3D printing (Kulagin et al., 2020; Ziemke et al., 2019). Other key objectives are reducing the criticality risks of materials (Peck et al., 2015) and supporting the overall product eco-effectiveness. Sourcing materials from circular origin typically leads to and should promote a regionalization and diversification of supply (Stahel & Clift, 2016). There are strong interdependencies with business models, process integration, and value networks that determine economic decision-making in material choice.

Table 4. Open questions on material selection as a key challenge of circularity engineering.

Mechanical Engineering	
OQ12	What determines the VRP-compatibility of materials, e.g., their remanufacturability?
OQ13	How to deal with trade-offs between sustainability aspects, criticality, and circularity in material selection processes?
OQ14	How to operationalize the recyclability of materials over multiple recycling cycles beyond oversimplified Boolean or mass-based approaches?
OQ15	How to bridge the knowledge gap between the known toxicological and criticality properties of substances and the engineering materials with only partially known compositions selected by engineers?

Table 4 (cont.). Open questions on material selection as a key challenge of circularity engineering.

Electrical Engineering	
OQ16	Which elements and materials in electronics must be substituted to promote environmentally friendly recycling?
OQ17	Which technologies are missing or currently economically unattractive for recycling essential elements and materials from electronics, and how can circularity engineering overcome existing limitations and problems?
OQ18	Which elements and materials in electronics show the highest economic and criticality relevance to trigger industries' shift to circularity?
OQ19	Is achieving earth-abundant, non-critical electronics, solar modules, and batteries possible?
Civil Engineering	
OQ20	Which construction material substitutions will work on a global and not just regional scale?
OQ21	Which construction materials can prospectively become critical?
OQ22	Which measuring systems can detect structural changes, and how can their feasibility be considered during material selection?

Building block 3: Process integration

Implementing the circular economy into all intra-organizational processes, including production, administrative, supportive, and management, is summarized as process integration. This includes engineered processes like manufacturing, VRPs, recycling, and all non-engineering processes (like administration, marketing, etc.) in organizations.

Process integration must overcome several barriers (structural, operational, financial, technological, and attitudinal) (Ritzén & Sandström, 2017), by:

- defining clear responsibilities and information flows,
- providing sufficient infrastructure,
- establishing circular production, VRPs, and recycling,
- and overcoming risk aversion and non-progressive perceptions of the circular economy.

Intra-organizational learning is essential for a successful circular transformation of organizations (Agyabeng-Mensah et al., 2021; Hansen & Schmitt, 2021).

Table 5. Questions on intra-organizational process integration as a key challenge of circularity engineering.

Mechanical Engineering	
OQ23	How can the remaining lifetime of components and products be determined and measured cheaply and with high certainty during and after usage?
OQ24	How can the obsolescence of products, components, and materials be prevented, postponed and reversed?
OQ25	How can VRPs be highly automated in a cost-efficient way?
Electrical Engineering	
OQ26	How can recycling, VRPs and the market adoption of their products be motivated across the electronics and solar industry and their supply networks?
OQ27	Which options exist or must be created to develop and demonstrate pilot lines for the production, disassembly, VRPs, and recycling of circular electronics and photovoltaics?
Civil Engineering	
OQ28	How to enable affordable structural health monitoring?
OQ29	How to enable proof of circular concepts and the verification of assumptions in the context of timespans of up to 100 years?
OQ30	How can measurement data be used profitably to monitor and manage the entire circular process and its safety?

3.2.2. Engineers partnering interdisciplinarily The following three building blocks recognize the partnerships and related collaboration required outside of engineering for enabling circularity. Their realization is partially determined and can be constrained by the specific regional economic, regulatory and cultural

context (e.g., material tradability and feasible loop scale, extended producer responsibility stringency, consumer acceptance, and available reverse-logistics infrastructure). There is, for example, strong strategic pull with clear targets for the topic in China (Chinese National Development and Reform Commission, 2026) and the EU (European Commission, 2020b) which is lacking in other regions.

Building block 4: Information management

Information management provides the required information to relevant stakeholders at the right time to enable circular systems and make them manageable and predictable while enabling learning. Today's downcycling and, for some materials, high recycling costs, result largely from losing material, component, and product identities during usage (Berg et al., 2022). By marrying the Internet of Things with circular products, new flows of information across value networks can be achieved to enable downstream smart VRPs and recycling and upstream feedback to (circular) product redesign (Alcayaga & Hansen, 2025; Alcayaga et al., 2019; CEID, 2020). For example, digital product passports are necessary to support overcoming information asymmetries and facilitate automated identification, sorting, inspection, and disassembly. Transparency and long-term compliance of circular material systems can be achieved by in-depth composition knowledge, authenticity guarantees, documented chains of custody, standard compliance, and prevention of restricted substances accumulating in circular material systems. While information management is in rapid heterogeneous development with digitization, it is non-mature, and the discourse about conceptual requirements is ongoing (Jansen et al., 2023; Jensen et al., 2023; Plociennik et al., 2022). First typologies (Araujo et al., 2025), requirement standards (ISO, 2025), and assessment standards (ISO, 2024c) for circularity data pave the way.

Predictability includes multiple-use-and-lifecycle modeling and predictions of engineering, circularity, and sustainability performance (Asif et al., 2016; Saidani et al., 2017; Suhariyanto et al., 2017). In operation, predictions about the remaining service life and the structural health of engineered systems become necessary (Coulon et al., 2019; Merkle et al., 2023).

New system configurations are usually less efficient than optimized mature systems. For successful system transformations, rapid organizational learning within value networks is required (Vermeulen, 2015). New design concepts, materials, and processes risk lower efficiency and infant quality problems due to lower reliability and accuracy of related models and predictions. Installing learning loops can mitigate and even reverse those risks.

Building block 5: Value networks

Value networks are what would be called "supply chains" in a linear system, but go far beyond them. In a circular economy, a network of multiple actors collectively operates a system aiming at producing value that barely degrades, that is used as intensely as possible, in which value is restored to the highest level possible for as long as possible, and is recovered after usage. Therefore, "value" is in the center and no longer supply. The central coordinator is of high importance for systems' configuration, effectiveness, and value distribution (Hansen & Revellio, 2020).

New actors should be considered as parts of value networks (Urbinati et al., 2017). New and existing upstream actors, like suppliers, cooperate for value creation, management, and retention, bound by shared information management. Downstream, customers become partners for the continuous improvement of circular business models, the mitigation of circularity barriers, and as major suppliers (Zhu et al., 2011). Important for all actors of value networks is to build a joint circular behavioral regime that drives their everyday practices (Nkiko, 2026). New and existing actors cooperating in increasingly interlinked networks replace linear supply chains (Haase et al., 2024; Urbinati et al., 2017). The resulting diversification can increase system's resilience.

Together with process integration and information management, value networks ensure that the information of materials, components, and products is not lost and technical contamination, systemic contamination, and contaminated interaction are prevented (Baxter et al., 2017).

Building block 6: Circular business models

The way engineered systems can be commercialized and managed in the circular economy is defined by circular business models. Business models cover elements of value creation, proposition, delivery, and capture; as well as how value is maintained, unlocked, and shared (Lüdeke-Freund et al., 2024; Lüdeke-Freund et al., 2019; Schaltegger et al., 2012). Circular business models act as enablers for circularity engineering, for example by:

1. Maximizing backflows of products after usage (take-back or collection rates)
2. Making returns plannable in quantity, quality, time, and location
3. Taking back with ideal timing for value retention and replacement
4. Shift optimization logic from point-of-sale to use value, lifetime extension, longevity, and increased utilization (incentive alignment for building blocks 1-3).

Different types of circular business models (Hansen et al., 2020; Lüdeke-Freund et al., 2019; Tukker, 2004) are:

- *Product-oriented*: selling products with deposits, or rebuy guarantees, *e.g., bottle deposit*
- *Use-oriented*: Product leasing, or product sharing, *e.g., bike sharing*
- *Result-oriented*: Pay-per-Service, *e.g., Pay-per-Lux for lighting.*

Circular business models can facilitate product piracy protection, improve customer experiences, and improve brand loyalty. Business models adopting a stronger service-orientation, have a higher potential for circularity and sustainability (CEID, 2020). Careful design of product-service-systems can reduce climate impacts by up to 80% in case studies; unconscious design can even increase them (Sarasini et al., 2024). Circular business models set the boundary conditions and determine the free variables for all other building blocks (Bocken et al., 2016). Value creation, for example, as specified by the circular business model, specifies the applicable circular processing options (*Table 2*), the phases of the multiple use or life cycle system that engineering should design for, and the applicable circular design strategies in building blocks 1-3. Value capture in terms of the take-back system and the type of circular business model sketched above, determines the economic optimization logic for engineering and especially engineering design (Centobelli et al., 2020).

Table 6. Questions on business models, value networks, and information management in the context of circularity engineering.

OQ31	How do different business models influence the key building blocks of circularity engineering?
OQ32	How can the formation of interdisciplinary consortia from industry, research, politics, and society be motivated to develop circular industrial systems (e.g., training, funding policy, legislation)?
OQ33	How can digital product passports (material passports) be made market-available as quickly as possible, and what are their data requirements to enable economic, safe, resilient, and plannable circularity?

3.3. Framework of circularity engineering

The proposed circularity engineering framework (*Figure 5*) further expands on the six building blocks to provide a comprehensive theory of change. For the first time, this framework summarizes the role, tasks, and responsibility of engineering across disciplines in advancing circularity for sustainability, as introduced in the previous subsections. Informed by a circularity mindset, key changes to engineering processes (building blocks) influence the system variables of matter, energy, and information in a way that results in circularity for technosphere and biosphere, following the inertia principle, optimized for contributing to sustainability.

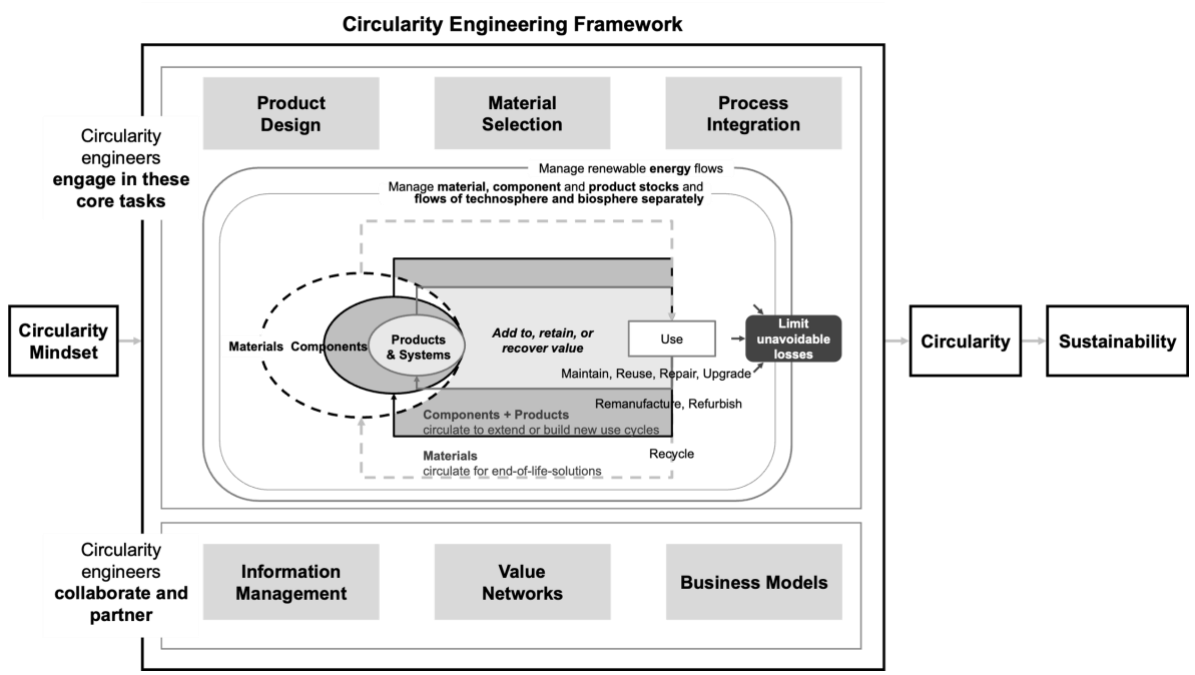


Figure 5. Framework for circularity engineering. In this comprehensive framework, circularity engineering, focusing on 6 building blocks, is driven by a circularity mindset, and results in circularity, optimized for contributing to sustainability.

The *circularity mindset*, though yet to be fully defined, requires shifting from a cradle-to-grave to a cradle-to-cradle mindset. Turning circularity engineering into action requires new *competencies* by engineers. Research on circular design competencies (Sumter et al., 2020, 2021) perfectly relates to the building blocks of circularity engineering:

- Product design, material selection, and process integration depend on the competencies of "design for multiple use cycles", "design for recovery", "circular impact assessment", and "circular materials and manufacturing".
- Information management depends on the competency of "circular economy communication".
- Value networks depend on the competencies of "circular economy collaboration" and "circular user engagement".
- Business models depend on the competencies of "circular business models" and "user engagement".

Systems thinking is both a circular design competency (Sumter et al., 2021) and a key sustainability competency (Redman & Wiek, 2021), considering the interplay of the engineered system variables of matter, energy, and information across scales and time with the resulting performance in different dimensions.

Mindset and competencies must be flanked by new engineering processes, methods, and tools, supported by meaningful terminology (*see Appendix A*), to enable circularity engineering to become the "new normal". Creating purpose for engineers and providing significant opportunities for sustainability, resilience, profitability, and quality, drives engineers to embrace the added complexity (Hansen & Große-Dunker, 2013; Hansen & Schmitt, 2021).

Table 7. Open questions on the novelty for engineering.

OQ34	How can the requirements for engineered systems be formulated to include circularity for sustainability in addition to technical feasibility, performance, and economic viability?
OQ35	How to model and assess product systems circularity performance (~circularity) and their circularity impacts (ecological, economic, social, criticality) over multiple use cycles?
OQ36	How to effectively and efficiently teach the novel required competencies to engineers in practice and education?
OQ37	How to adapt research methods to the requirements of circularity engineering research and its transformative aspiration?
OQ38	How to deal with unpredictable shifting normative objectives in the future in terms of the long-term resilience of circular industrial systems?

3.4. Quality and profitability through circularity engineering

Visionaries claimed, that higher quality and safety can be achieved at lower costs with circularity engineering (Braungart et al., 2007). Overcoming this fundamental trade-off of conventional engineering, explained in *section 1.1.*, is part of the transformational quality of circularity engineering. The following subsections summarize determinants of this theoretical potential and how it might be realized.

3.4.1. Engineering for higher quality Quality in the linear economy mainly focuses on the point of sale and is inherently compromised by cost pressure *(*cf. *section 1.1)*. In contrast, circularity engineering enables reaching new levels of engineering quality over time (Alcayaga et al., 2020).

In a circular economy, service or performance is sold instead of products. Providing this service or performance as cheaply as possible is the typical economic objective of a company. The resulting objective of circularity engineering is to design products as well as possible: i.e., safe, reliable, qualitative, up-to-date, and desirable for as long as possible at the highest value level possible, increasing the quality of engineered systems. For energy-related-products, this implicates the system engineering challenge to provide services with as few devices as possible that are as energy efficient as possible. Shifting to product-as-a-service for lighting can for example reduce the energy consumption per area by 44% (Oberhuber & Rau, 2021). Considering material safety by design, or achieving better-than-new-quality by remanufacturing (e.g., pre-used mechanically loaded parts show increased reliability) can additionally improve product quality. New feedback loops in engineering design based on analyzing backflows of used products and their processability enable continuous quality improvements (Alcayaga & Hansen, 2025; Lindkvist Haziri & Sundin, 2020). On a material level, upcycling leading to increasing material quality and value (Jehanno et al., 2022), or to accumulating material-related know-how (Braungart et al., 2007), can improve the quality of engineered systems over time. Modern quality includes aspects like eco-friendliness that go far beyond functionality and reliability (Kianpour et al., 2014). Therefore, sustainability performance, transparency, and eco-effectiveness are additional quality dimensions. Finally, higher value network resilience can provide more reliable service provision.

Table 8. Open questions about quality in circularity engineering.

OQ39	How can engineers deal with unforeseen loads that can challenge circularity and the remaining quality of engineered systems, especially posing significant risks over multiple use cycles and long lifecycles?
OQ40	How to design products, and the services they provide, to be inclusive for all?
OQ41	How to promote circularity engineering quality of products (e.g., stating the product is now non-toxic) without damaging the brand value (e.g., by triggering customers' surprise that it was toxic before)?
OQ42	How to promote circularity engineering quality if it partially conflicts with a brand's core value (e.g., fast fashion or longevity)?

3.4.2. Engineering for higher profitability Statistical material costs (incl. costs for semi-finished products and purchased parts) accounted for 54.7% of the overall expenses of German manufacturing enterprises in 2020, while labor costs accounted for only 20.8% (Federal Statistical Office of Germany, 2022). Major industrial trends like outsourcing and automation reduce labor costs exclusively. “Statistical material costs” must be differentiated into material, component, and product costs for circularity engineering (*Figure 6*). Their absolute values and relative differences along with engineering aspects determine the economic feasibility of circular processing options.

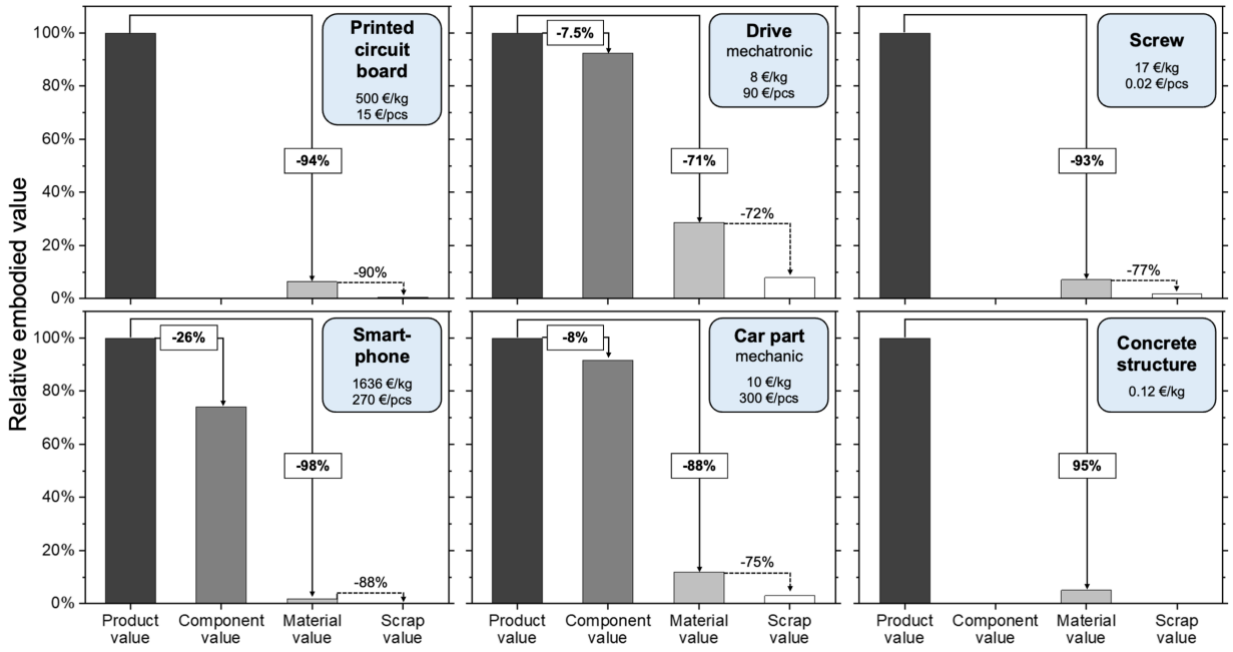


Figure 6. Analysis of the relative embodied value of six different engineering products, exemplary for electrical, mechatronic, mechanical, and civil engineering (from top left to bottom right). The typically significant relative differences (arrows) between the product, component, and material value of products cause the hierarchy of value-retention options, the inertia principle.

A sufficient absolute product value and a large difference between product and component value, like for smartphones, support VRPs on a product level. VRPs on a product or component level are typically feasible with a sufficient absolute product value and a small difference between product and component value, like for the drive and car part. An insufficient absolute product value, like for the screw, or a small difference between product and material value usually make recycling the most-feasible option. If the material value is low, like for reinforced concrete structures, easily available volumes must be high and collection distances short to make recycling economically feasible. Today's scrap value is typically 70-90% below the material value, which is not representative of the circular economy. Refunds in take-back systems to VRPs are typically higher than the scrap and material value; e.g., smartphone take-back for refurbishment brings 150€, while its material value is 5€, and its scrap value 60 cents.

Systemic profits of a value network can increase significantly in a circular economy of engineered systems, but not necessarily by increasing sales volumes. Here, “systemic profitability” refers to the aggregate net surplus across the entire value network (e.g., suppliers, OEMs, service providers, reverse logistics, remanufacturers/recyclers, and users), rather than the margin of a single actor. Circular strategies can shift value capture between actors; therefore, governance and benefit-sharing mechanisms (contracts, deposits, service pricing, etc.) become a design-relevant boundary condition. The service price can be held “as new” since the quality of the product increases. This is expected to increase user satisfaction. Costs can strongly decrease with circularity engineering, for example by:

- Applying VRPs: e.g., remanufacturing automotive products decreases statistical material costs by ~95% and increases labor costs by ~220% (IRP, 2018), yielding new products for ~33% lower costs (Federal Statistical Office of Germany, 2022).
- Optimizing VRPs: e.g., higher automation can half the labor costs of remanufacturing (Geist & Balle, 2024a). This can qualify additional products for remanufacturing;
- Scaling VRPs: e.g., most components in automotive products can be remanufactured several times (Geist & Balle, 2024b). Circular business models can achieve take-back rates >95% (DIN SPEC 91472:2023-06, 2023);

- Design for Circularity: By designing products for VRPs, these can be optimized through decreased manual labor efforts, lower material demand, scaled through qualifying further products for VRPs and designing products for more VRP-cycles.

The examples and *Figure 6* show that the opportunities for value network profitability also follow the inertia principle. Increased profits can be reinvested into accelerating their transformation toward sustainability and regeneration.

Table 9. Open questions about the economics of circularity engineering.

OQ43	How can traditional sectors be convinced to innovate their business models fundamentally?
OQ44	How can circular systems transformation be motivated if the stakeholders who profit from circularity and the key enablers who make the highest effort for it are different ones?
OQ45	How can circular systems transformation be motivated if the expected significant economic benefits are only receivable mid- or long-term?
OQ46	How can circular material economics be assessed and predicted systematically already during the development process of product-service systems?

4. Discussion

Based on the features of conventional vs. circularity engineering (*Table 10*), we first discuss current limitations of circularity engineering and how to minimize them. Second, we discuss the contributions of circularity engineering to sustainability.

Table 10. Conventional engineering and circularity engineering – comparable overview of selected aspects. The concepts are discussed in their generic forms. Real-world conventional engineering practice does typically not fully align with this extreme conceptualization, since the linear economy is typically never fully linear (cf. section 2.1.).

Engineers' Tasks	Features of Conventional Engineering	Features of Circularity Engineering
1. Product Design	• As well and safe as necessary • Design for single & limited use • Design for individual use • Design for specialists to maintain • Maximize efficiency • Design for consumption • Design for manufacturing • Minimize manufacturing costs	• As well and safe as possible • Designs for intensified & multiple uses • Designs for shared use • Designs for users to maintain • Optimizes circularity performance for sustainability (circularity impact) • Designs for service • Design for manufacturing, VRPs, & recycling • Minimize multiple-use-cycle costs
2. Material Selection	• Select materials indiscriminate of social, environmental, & health impact • Select raw / new materials • Select cheap available materials • Accept material complexity • Select the best performant material for the point of sale	• Selects materials to not harm social/environmental systems • Selects durable & recyclable materials (for technosphere) • Selects biodegradable materials (for biosphere) • Selects recycled / reclaimed materials • Selects pure / simple materials; avoid mixing of materials • Select abundant, available, & local materials • Reduces materiality
3. Process Integration	• Engineering focus: manufacturing • Inherently includes downcycling • Partially integrates engineering processes / some segregated engineered processes • Departmentalism	• Engineering focus: manufacturing, VRPs, & recycling • Inherently includes quality preservation, retention & improvement • Comprehensively integrates all engineering & non-engineering processes • Organizations collaborate for process integration

Table 10 (cont.). Conventional engineering and circularity engineering – comparable overview of selected aspects. The concepts are discussed in their generic forms. Real-world conventional engineering practice does typically not fully align with this extreme conceptualization, since the linear economy is typically never fully linear (cf. section 2.1.).

Engineers' Tasks	Features of Conventional Engineering	Features of Circularity Engineering
4. Information Management	• Information asymmetries (competition & lack of information infrastructure) • Material information gets lost with the sale of a product	• Strategic and shared use of information to enable circular business models, efficient reverse logistics & stock management, value networks, VRPs, & recycling • Material information must always be known to keep the biosphere & technosphere separate and enable circulation without quality losses
5. Supply Chains & Value Networks	• Supply chains (linear; include only upstream stakeholders) • Supply is centered • Value degrades rapidly & is entirely lost after one use phase • Roles of supplier, manufacturer, distributor, & user are distinct • High inherent vulnerability	• Integrated value networks (circular; include both upstream and downstream stakeholders, e.g., reverse logistics & users) • Value is centered • Value barely degrades, & is continuously retained or even improved • Roles are mixed and multiple, e.g., a customer can be both a user & a supplier in the value network • High inherent resilience
6. Business Models	• Emphasis on turnover, driving short-term profit • Product orientation (functionality at time of sale) • Emphasis on externalizing burden & responsibility of products after sale • Competitive approaches	• Emphasis on profits • Emphasis on long-term value retention, improvement, & profitability • Service-orientation (performance over time) • Emphasis on efficient & plannable take-back & collection of products after use • Collaborative, synergistic approaches

4.1. Limitations of circularity engineering

This section summarizes limitations of the circular economy that are specific to engineered systems. Respecting the limitations of circularity engineering is necessary for unleashing its full potential by reducing them as far as possible and managing the remaining ones.

4.1.1. Losses, transition time, and rebounds Losses are unavoidable in circular systems (Cullen, 2017) making some use of new resources inevitable in a growing or steady-state economy (Figge et al., 2023). Entropy efficiency can evaluate qualitative and quantitative losses simultaneously (Hornbogen, 2001). Losses occur in all lifecycle stages. Exemplarily, losses can be caused by imperfect take-back rates, or by design, like for electronics where low elemental concentrations prevent economic recovery (Christian et al., 2014). Losses demand new circularity-shifted dynamic equilibria between VRPs, recycling, and new production and disproof the vision of the "perfect circle". Finally, a circular economy is limited by the absolute capacity of biosphere, technosphere, and global elemental cycles. This affects mainly the biosphere and critical raw materials in the technosphere.

Circularity is also limited by the necessary system transition time damped by stock dynamics. Stock shortfalls are a function of demand growth and use time. For example, steel recycling is predicted to surpass new production no earlier than 2050 besides high recycling rates, due to its usage in predominantly long-lasting applications with growing demands (Pauliuk et al., 2013). Benefits of circularity engineering occur primarily delayed in time. Circularity engineering can incorporate feedstock from the existing downcycling economy and waste sinks only if not creating contaminated or toxic material cycles and without stabilizing linear design and downcycling. This requires defining separate material flows of so called "dirty alloys" (Raabe et al., 2022) that must be safe or by purifying material flows during recycling processes, e.g., by dissolution recycling of plastics (Zhao et al., 2018), reintegrative mining of iron from red mud (Jovičević-Klug et al., 2024), or Cu-removal during steel recycling (Souza Filho et al., 2024).

Circularity rebounds like "imperfect substitutability" or "classical economic rebounds" (Castro et al., 2022; Figge & Thorpe, 2019; Zink & Geyer, 2017) must be analyzed and managed, or even avoided by design (Das et al., 2023). Potential trade-offs between circularity aspects like recyclability and durability, repairability and reliability, modularity and durability, or modularity and efficiency should be treated similarly (CEN/CENELEC, 2024; Revellio et al., 2020).

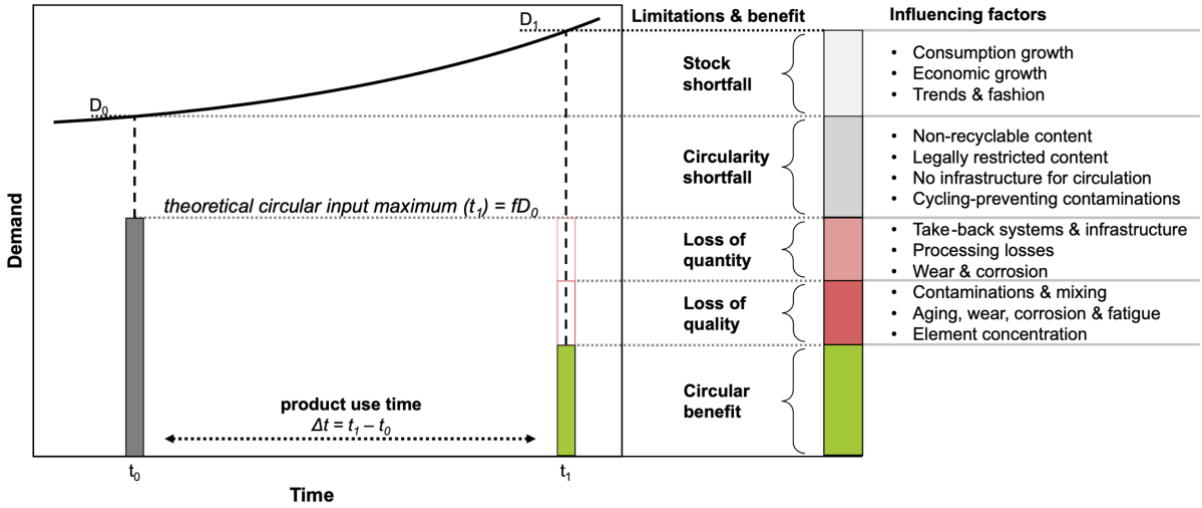


Figure 7. Generic loss mechanisms, stock dynamics, and their influencing factors, limiting the actual share of inputs of circular origin in a system – further development of the work of (Ashby, 2021).

Circularity Engineering must be aware of its limitations (*Figure 7*), operationalize them, and minimize them by applying the building blocks of circularity engineering (*Table 11*).

Table 11. Loss types with exemplary corresponding circular countermeasures including specific recommendations.

Loss type	Circularity countermeasure	How can losses be reduced?
Stock shortfall	Business models	Intensifying use by sharing, product-as-a-service, renting, etc. Promoting sufficiency Combining material-efficient design, production processes, and lightweight design with circularity
	Product design	Timeless design and functionality can prevent obsolescence due to trends and fashion
Circularity shortfall	Business models	Incentivizing circular material selection, product design, circular processing infrastructure, and information management Defining permitted use cases or incentives to avoid circularity-preventing contaminations
	Material selection	Preventing non-recyclable content Preventing content from being legally restricted in the future by selecting healthy materials and using predictive compliance Ensuring the availability of circulation technology and infrastructure for the selected materials Ensuring cleanability from circularity-preventing contaminations
	Product design	Enabling VRPs Enabling separation to enable circulation through appropriate joints and product architecture Ensuring cleanability from circularity-preventing contaminations
	Process design & value networks	Ensuring the availability of circulation technology and infrastructure Preventing the loss or accumulation of certain material constituents by appropriate processing conditions
Loss of quantity	Business models	Optimizing back-flows of products, components, and materials in quantity and timing Reducing quantity losses from over-usage by ensuring defined use periods Reducing quantity losses from misuse through fines

Table 11 (cont.). Loss types with exemplary corresponding circular countermeasures including specific recommendations.

Loss type	Circularity countermeasure	How can losses be reduced?
Loss of quantity	Convenient take-back systems	Reducing efforts for product return
		Reducing other barriers to product return
	Material selection	Preventing materials only cyclable with high losses
		Reducing use-time losses by selecting wear and corrosion-resistant materials
		Reducing losses of recyclable materials that are actually not recycled due to too low concentrations by reducing material and chemical diversity
		Reducing losses by preventing non-separable recycling-preventing mixtures of materials
		Reducing losses of recyclable materials that are not recyclable within the same recycling process
		Choosing materials that are already available in the cycle in a highly-refined state in great quantity for recycling.
	Product design	Enabling circulation first on a product, then on a component, and lastly on a material level (inertia principle)
		Reduce barriers to take-back by design (low weight, low volume, handleable geometry, no sharp edges, etc.)
		Enable non-damaging disassembly for VRPs and easy separation of materials for recycling processes
		Anticipate future advances in the state-of-the-art on a product level (good enough for re-use)
	Process design & value networks	Material-efficient production, VRPs, and recycling
		Process innovations that keep products, components, and materials longer in use, make them recoverable, and recyclable
	Information management	Ensure a material, component, and product identity for high-quality circulation, minimizing quantity losses
		Provide all relevant information for value retention for processes
		Track product, component, and material history for remaining possible use time prediction
		Feedback-loop from use, EoPU, EoCU process & product data to circular design processes to design future quantity losses
		Preventing legal restrictions due to a lack of knowledge about the material composition
		Preventing the wasting of products by wrongfully perceived non-recyclability
Loss of quality	Business models	Optimizing reverse-flows of products, components, and materials regarding quality, e.g., with financial incentives
		Reducing quality losses from over-usage by ensuring defined use periods
		Reducing quality losses from misuse
	Material selection	High elemental concentrations
		Separable, recyclable, recycling-compatible
		Wear-resistant
		No or slow and predictable aging effects
		Corrosion-resistant (e.g., self-passivating)
		Long fatigue life, high fatigue strength
	Product design	Reducing quality losses of components and products by optimum lifetime prediction
		Designing out or minimizing aging, wear, corrosion, and fatigue by design
		Designing out the total quality loss of components and products by fracture
		Designing durable components and products
		Enable non-damaging disassembly to prevent damage by VRPs
		Enable easy separability of materials for recycling processes
	Process design & value networks	Enable separate flows for every material during processing
	Information management	Prevent the mixture of material flows in technosphere and biosphere by providing material identities
		Preventing the mixture of material flows and processing-caused impurities by providing processing instructions

4.1.2. Circularity and material efficiency Material efficiency means providing material services with less material production and processing (Allwood et al., 2011). Some scholars describe circular strategies as a type of material efficiency strategies (Allwood et al., 2011; Brändström & Saidani, 2022). A *complementary relationship* exists regarding production wastes, which should first be avoided before being recycled, also within a circular economy. This includes, for example, the 40% of steel and 60% of aluminum that do not directly reach final products (Allwood & Music, 2024) and can be operationalized by applying Material Flow Cost Accounting (ISO, 2011). *Trade-offs* can exist especially in material-efficient design (designing with less material), as supported by empirical evidence (Geist & Balle, 2024b):

- minimized safety factors might limit durability and fatigue life,
- less material reduces the amount of material that can wear off before limiting a component's functioning,
- less material reduces the possibilities of typically subtractive surface treatments in VRPs like remanufacturing (Geist & Balle, 2024a),
- materials used in small amounts or thin layers might not be economically recyclable (CEN/CENELEC, 2024).

Nevertheless, material-efficient design can help to reduce stock shortfalls and reduce initial investment costs in circulatable materials. Circularity engineering combines both concepts to utilize their complementary potential (Bocken et al., 2016). It resolves the trade-offs by defining circularity as the primary strategy: *design first for circularity and then optimize the material efficiency of the design (slowing and closing before narrowing loops)*.

4.1.3. Circularity and energy (efficiency) The material and energy systems are reciprocally interrelated: energy is material-intensive (kg/MJ) and materials are energy-intensive (MJ/kg). While typically being more energy-efficient than linear production, circularity can also consume more energy than linear production, especially on a materials level e.g., for concrete recycling (Cullen, 2017). For (non-mature) energy-related products, VRPs without efficiency-upgrading can be ecologically worse than linear replacement due to the influence of efficiency improvements on the use phase energy consumption (Gutowski et al., 2011). The circular economy concept relies on renewable energy, but today's global demand is covered by only ~5% of non-bioenergy renewables (IEA, 2023c). The necessary clean-energy transition increases the material intensity of the energy system. The total mineral demand for energy technologies quadruples in scenarios in line with global sustainability targets (IEA, 2021). Digitization of the circular economy, as part of its precondition "information management", will increase the energy consumption and the need for electronic devices. Of these, only 22.3% are collected for recycling, and processed with a recycling efficiency of 43% (Baldé et al., 2024). This issue is underrepresented in the scientific and political discourse and ignored in state-of-the-art requirement lists for digital product passports (Jansen et al., 2023).

Besides these conceptual trade-offs, circularity, renewable energy, and energy efficiency must go together. Circularity engineering must predict, monitor, and intentionally design the interplay of energy, information, and material systems. Design for Circularity, especially the reduction of chemical and material diversity, and following the inertia principle, will increase the energy efficiency of circulation. Calculating optimal use periods, designing for upgrading, and upgrading in VRPs keep the technology and efficiency of products up to date (Asif et al., 2021; Bakker et al., 2014; Stahel, 2006), as illustrated in *Figure 8*. Promoting energy transition and digitization while making their hardware part of the circular economy can finally mitigate conceptual trade-offs.

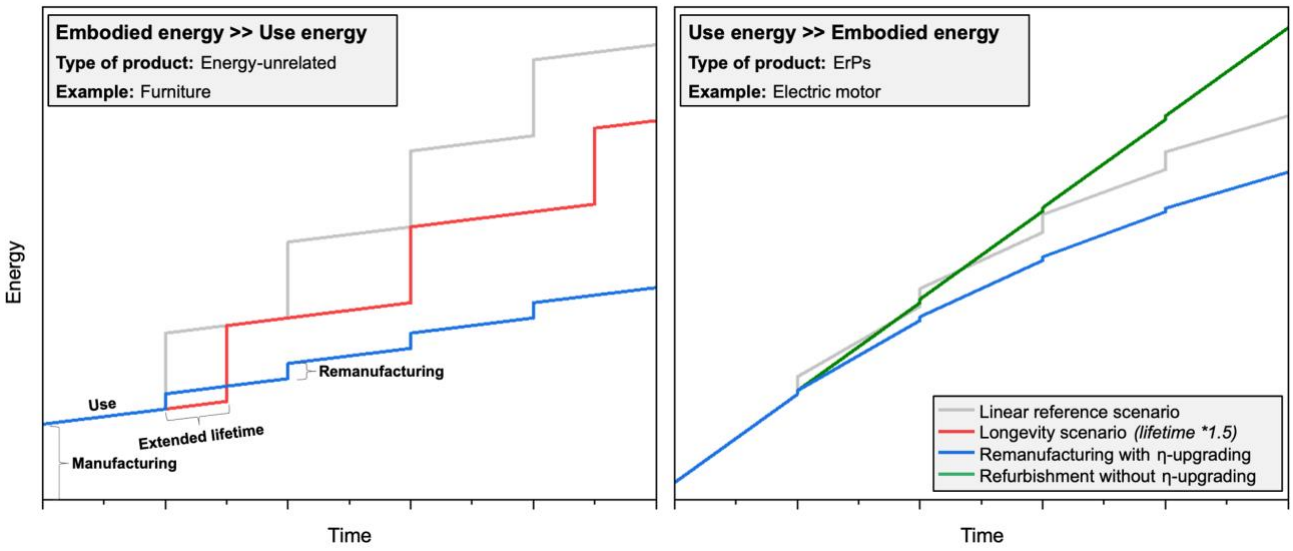


Figure 8. Cumulative multiple use- and lifecycle energy of energy-unrelated (left) and energy-related products (right) from linear and different circular production pathways, including the option of lifetime extension. For energy-related products, the energy consumption of the use phase is typically significantly higher than the embodied production energy. Circular processing options without efficiency (η) upgrading to the latest state of the art can therefore fall behind linear replacement scenarios. Similar analyses for linear product systems were published by Allwood and colleagues (Allwood et al., 2011).

4.2. The contributions of circularity engineering to sustainability

While circularity engineering addresses important environmental sustainability aspects, it only marginally contributes to economic and social dimensions. The contributions of circularity engineering to sustainability and its limitations are discussed by juxtaposing it with the maximally achievable contribution of engineering to sustainability, a concept proposed as "sustainability engineering" (*Table 12*).

Sustainability science, in its transformational mode, generates in collaboration with societal actors evidence for solutions that address root causes of sustainability problems while working towards sustainability goals (Lang et al., 2012). Sustainability science is guided by the normative concept of sustainability, which has been shaped by key international frameworks such as the Brundtland Report (WCED, 1987), the Agenda 21 (UNCED, 1992), the Millennium Development Goals (UN, 2000), and the more recent Sustainable Development Goals established in 2015 (UN, 2015). These frameworks provide both broad and specific targets, emphasizing intra- and intergenerational justice. Combining the need to avoid irreversible environmental degradation (Rockström et al., 2009) with the need for social wellbeing for a dignified life (Fanning & Raworth, 2025; Raworth, 2012, 2017) resulted in the concept of a "safe and just operating space for humanity" and the notion of strong sustainability, where economic aspects are grounded within social wellbeing and healthy ecological life support systems (Rockström et al., 2009). Sustainability engineering aims to achieve these strong sustainability features holistically, by contributing to it in all aspects as much as possible for engineering.

Table 12. Comparing circularity engineering and sustainability engineering.

Attributes	**Circularity Engineering**	**Sustainability Engineering** (Fanning & Raworth, 2025; Lang & Wiek, 2022; Raworth, 2012; Seager et al., 2012; Wiek et al., 2011)
Transformative aspiration	"Safe operating space for humanity"	"Safe and just operating space for humanity"
Normative orientation and goals	Circularity • Resource maintenance • Human health (non-toxicity) • Ecological sustainability • Product quality • Commercialization for profitability and growth	Sustainability (cf. Gibson, 2006) • Resource maintenance and efficiency • Human health and social wellbeing (Quality of product impact) • Equitable economic models • Soc-ecol. civility, democratic governance • Socio-ecological systems integrity • Justice (within and across generations) • Precaution and adaptation • Immediate and long-term integration
Key Drivers	• Demands • Wants	• Urgency of sustainability problems • Need for solutions
Design Approach	• Circular design: transformative from linear to circular • Integrates circularity strategies of narrowing, slowing, closing, informing, and regenerating loops • Interdisciplinary methods • Collaboration with stakeholders or ideally, transdisciplinary research	• Just design: transformative from exploitative to regenerative • Integrates sustainability strategies: effectiveness (sustainability goals w/out trade-offs), sufficiency (demand), efficiency (supply), consistency • Interdisciplinary methodology • Transdisciplinary research
Key tasks	• Product design • Material selection • Process integration • Circularity performance and circularity impact assessment	• Identify sustainability problems • Design sustainable products and services • Integrate processes of production, consumption, and governance of technology in socio-ecological systems
Cooperation with	• Value network actors • Entrepreneurs • Standardization and policymakers	• Governance brokers • Social organizations • Social and sustainability entrepreneurs • Standardization and policymakers
Competencies	• See circular design competencies in *section 4.3*	• Functionally integrated set of key competencies in sustainability

Circularity engineering aspires to transform engineering norms, goals and assumptions, enabling economic transformation and a "safe operating space for humanity." Sustainability engineering aspires to transform not only the engineering norms, goals, and assumptions to ensure a "safe and just operating space for humanity," but also the very social and economic systems underpinning engineering activities. As such, circularity engineering is a *necessary*, yet, *on its own not sufficient* condition for sustainability (Geissdoerfer et al., 2017), whereas sustainability engineering aspires to evolve into a necessary and comprehensive condition for sustainability.

For instance, circularity engineering aims to contribute to resource-focused sustainability transformations. Sustainability engineering, driven by the urgency of sustainability problems (Seager et al., 2012), aspires to produce products and services fostering participation and deliberation, building towards the principles of justice and socio-ecological civility and democratic governance (Fanning & Raworth, 2025; Raworth, 2012, 2017). Creation of products and services goes along with building equitable economic models that prioritize sufficiency of livelihoods and consumption (vs. growth, profitability) as well as wellbeing and regeneration (Leipold et al., 2023; Raworth, 2012; Sarewitz et al., 2012).

The transition to circularity and sustainability engineering requires further research with interventions at the deep leverage points of engineering education, research, and practice, aligned with transformational sustainability science (Lang et al., 2012; Wiek & Lang, 2016). Circularity engineering, as a key approach for resource-focused sustainability, is a necessary field of sustainability engineering.

5. Conclusions

This work provides a launch pad towards the transformation of the status quo of engineering. Circularity engineering generates a great deal of environmental and social benefits while being economically attractive and leveraging engineering quality. This offers the opportunity for alignment around transformation towards sustainability, even within the conventional way of economic thinking. A new modus operandi of engineering relies on careful integration into all engineering disciplines, the related interdisciplinary scientific and practical discourse, and finally, action. With this manuscript, we wish to open the room for this conversation and collaboration towards action to occur, and invite comments and critiques.

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Data Availability Raw data for Figure 1 is available in the cited references. Figure 6 is based on confidential data. Apart from these two cases, no additional data is used in this work.

Declarations

Competing Interests The authors declare no competing interests.

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Appendix

Appendix A. Reflections on typical circular economy terminology in the context of circularity engineering.

Reflections on Terminology:

- Life cycle → better: use cycle
- End of Use (EoU) & End of Life (EoL) → better: End of Product Use (EoPU) & End of Component Use (EoCU)
- Virgin material → better: new material

Reason: *"Life cycle thinking" implies "death", making it an is inherently linear terminology (Geist & Balle, 2025). "Life cycle" would only be fine in Hinduism with a design for reincarnation. "Virgin" in Christianity implies preferability and purity. Scientific terminology should be free of such implications that limit their global applicability and meaning.*

- Secondary material → better: recycled material
- Secondary component/product → better: circulated component/product

Reason: *"Secondary" implies only a second, not continuous usage or being only secondarily preferable after "primary" or better fossil materials.*

- Biological and technical cycle → better: biosphere and technosphere

Reason: *"Spheres" imply open circulation within them and introduce a time axis while cycles imply continuous usage of materials in always the same application.*

- Circular Economy, Circularity and Circularity Engineering

Comment: *These terms imply circles which are an oversimplified (see section 5.1.1) and misleading metaphor (see: biosphere & technosphere). Nevertheless, these terms are already well established and strong efforts are made in recent years to improve their underlying understanding. The authors explicitly recognize this wording as non-ideal and encourage the readers to reflect the different approaches of spheres and circles with their implications. The underlying understanding of the upper mentioned terms in this work is always the one of spheres.*