GRAZIELLA BERNARDO
ARIANNA MAZZA

Designing with invisible hands

Digital product passports and AI in the new Made in Italy

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Tre concetti chiave, quali margini per un vasto panorama tematico, definiscono la "linea rossa" intorno alla quale si sviluppa la collana: estetica, risorse e riuso. L'ampio apparato di questioni e argomentazioni trattate viene qui osservato attraverso valori che sottendono una sostenibilità dell'architettura non esclusivamente legata agli aspetti tecnici e tecnologici, che esplora l'estetica degli edifici sostenibili, il loro rapporto con l'uso delle risorse e con il riuso del costruito esistente.

In questa chiave l'architettura accoglie le impellenti questioni ambientali come un'opportunità per sperimentare nuove configurazioni materiche, fondando il progetto sulle possibilità percettive del fruitore e proiettandosi oltre la definizione disciplinare, considerando le innumerevoli implicazioni con l'ambito della sociologia, psicologia e delle neuroscienze.

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Digital product passports and AI in the new Made in Italy

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The images in this book were created with the assistance of artificial intelligence tools.

Traces for the future

first part

Chapter 1

Weaves of innovation

A blueprint for the future

This volume explores the transformative power of the Digital Product Passport (DPP) within the strategic framework of the European Union's Green Deal, highlighting its central role in catalyzing the ecological transition toward circular economy models. As a cornerstone of the new Regulation (EU) 2024/1781 on eco-design for sustainable products (ESPR), the DPP introduces a paradigm shift: sustainability is no longer confined to energy performance but expands to encompass durability, reparability, material efficiency, and end-of-life management across entire value chains.

At the heart of this transformation lies the convergence between digital infrastructure and artificial intelligence. While the DPP provides the structured architecture for transparency and traceability, AI acts as an active intelligence—a generative force that enables the interpretation, enrichment, and predictive use of product data across its lifecycle.

Unlike the earlier Directive 2009/125/EC, which had a narrower focus on energy-related aspects, the ESPR integrates systemic design thinking. This new approach requires an adaptive, data-rich environment in which AI becomes essential: processing complex datasets, identifying material flows, optimizing life cycle strategies, and enabling real-time decision-making to support reuse, remanufacturing, refurbishment, and industrial symbiosis.

AI's role in ecodesign is not merely supportive—it is strategic and creative. Through machine learning, causal reasoning, and generative algorithms, AI can assist designers in modeling product scenarios that balance performance, sustainability, and aesthetics. In the context of Made in Italy, this represents a powerful opportunity: to fuse technological intelligence with cultural intelligence, preserving the unique character of Italian design while aligning it with global climate goals.

As a result, the DPP is not just a compliance instrument—it becomes a dynamic interface for innovation. AI-enhanced DPPs can translate static information into living knowledge systems: suggesting optimal materials, assessing circularity metrics, simulating environmental impact, and anticipating regulatory requirements. This intelligent infrastructure not only supports regulatory alignment with the EU's Circular Economy Action Plan (CEAP) and Sustainable Development Goals (SDGs), but also fosters strategic foresight and resilience in complex markets.

However, the ESPR brings with it a dense and evolving regulatory lexicon. Especially for Italian SMEs, known for excellence in fashion, design, furniture, and agri-food, navigating this complexity while maintaining identity and competitiveness is a delicate balancing act. To bridge this gap, this volume introduces a glossary of sustainability, conceived not only as a terminological tool, but as a design companion—a resource enhanced by AI-generated insights and visualizations that decode and reimagine key concepts.

These AI-assisted illustrations, created through platforms like Adobe Firefly, offer more than aesthetic value: they represent a new frontier in visual knowledge translation, enabling abstract regulatory language to be experienced through algorithmically synthesized imagery. This fusion of semantic clarity and visual storytelling reflects the dual nature of AI as both analytical and expressive, practical and poetic.

This publication is addressed to a wide audience: from scholars and researchers exploring the theoretical foundations of ecodesign, to enterprises seeking innovation tools, to policymakers shaping new regulatory landscapes. It also speaks to consumers who care about traceability, transparency, and ethical production.

Ultimately, this work proposes a redefinition of Made in Italy—

not only as a hallmark of origin and quality, but as a visionary platform for sustainability and digital transformation. In this vision, AI and DPPs are not peripheral technologies, but central agents of cultural and ecological regeneration, empowering design to become the connective tissue between tradition and transition, between material intelligence and planetary responsibility.

1.1. Made in Italy: living archives of sustainable productive cultures

The Made in Italy label represents far more than a geographical origin—it is a living model of cultural identity, artisanal mastery, and territorial resilience. It embodies a philosophy of production where tradition meets innovation, aesthetics meets functionality, and economic value is harmonized with social and environmental responsibility. At its core, Made in Italy expresses a unique vision of how to produce, rooted in deep technical knowledge, human-scale relationships, place-based creativity, and a profound respect for materials, people, and time. This vision is particularly relevant for sustainable architectural design, where the integration of material intelligence, local resources, and low-impact construction techniques defines both performance and cultural continuity.

The Italian production system is largely composed of small and medium-sized enterprises (SMEs), often family-owned and deeply embedded in local ecosystems. These companies do not simply manufacture products; they cultivate relationships—with their territories, their workers, their raw materials. This territorial embeddedness fosters the use of local resources, both tangible and intangible, such as traditional know-how, climate-adapted techniques, and regionally sourced materials like Carrara marble, Lecce stone, Napolitan tuff, Tuscan terracotta, Venetian cocciopesto, and volcanic basalt from Etna. These materials are not selected solely for aesthetic or historical reasons, but for their intrinsic properties: high thermal mass, moisture regulation, low embodied energy, and adaptability to local climate dynamics—fundamental parameters in the life-cycle assessment (LCA) of buildings.

Traditional Italian construction methods often employed passive design strategies well before modern sustainability standards emerged. Thick masonry walls, lime-based mortars, inner courtyards, ventilated roofs, and stone-paved streets are examples of bioclimatic intelligence embedded in the built environment. These vernacular solutions are being reinterpreted today through modern engineering tools—such as dynamic thermal simulations, material performance testing, and environmental impact modeling—to create architecture that is at once rooted and high-performing. In this sense, the Made in Italy approach aligns with advanced sustainable design paradigms, including nearly Zero Energy Building (nZEB) targets, circular economy principles, and adaptive reuse frameworks.

For example, the glassmakers of Murano continue to leverage centuries-old techniques while integrating electric fusion systems powered by renewables, reducing carbon emissions without compromising on artisanal uniqueness. Similarly, the use of wood from sustainably managed Alpine forests in prefabricated timber buildings has redefined seismic safety, construction speed, and thermal performance in contemporary Italian architecture. Local stone, when properly dimensioned and dry-assembled, offers a highly durable, low-maintenance structural solution compatible with current seismic and energy regulations.

In many regions, SMEs cluster into dense industrial districts, where inter-firm collaboration, informal knowledge exchange, and shared environmental values enhance competitiveness. These districts—such as the goldsmith network in Arezzo, the eyewear cluster in Belluno, or the furniture hub in Livenza—function as open innovation systems, capable of rapid adaptation to changing regulations and market conditions. The 2024 EU Regulation 2024/1781, focusing on eco-design, product durability, reparability, and digital product passports, resonates strongly with the logic already embedded in the Italian system. It provides a normative framework that validates long-standing practices such as modular design, component standardization, and traceable supply chains.

A distinctive feature of the Made in Italy model is its deep-rooted culture of craftsmanship—not only as a manual skill, but as an integrated way of thinking and producing. Italian artisans operate at the intersection of tradition and precision engineering. Their work involves a meticulous selection of materials based on properties like porosity, density, aging behavior, and environmental compatibility. Whether in the stitching of a leather product, the inlaying of wood in bespoke interiors, or the milling of marble elements for façades, the process is guided by a philosophy of longevity, repairability, and minimal waste. In this sense, quality becomes a technical metric of sustainability: a long-lasting, well-constructed object or building component requires fewer resources over its life cycle, reducing environmental impact and improving user well-being.

This philosophy is increasingly reflected in innovative material applications. In fashion, companies like Brunello Cucinelli combine ethically sourced textiles with renewable energy-powered production facilities and socially responsible governance. In architecture and industrial design, firms such as Alessi or Kartell experiment with recycled polymers, biodegradable composites, and mono-material design strategies, facilitating disassembly and post-use recovery. In the agri-food sector, biodynamic farming and short supply chains not only reduce emissions but regenerate soil health and rural economies—demonstrating that material sustainability can extend beyond buildings to landscapes and territories.

Moreover, Made in Italy has a social and territorial dimension. Many manufacturing firms serve as anchors of local regeneration, especially in rural and inner areas. By preserving historical trades—like wool dyeing in Prato, hand-weaving in Sardinia, or stone carving in Puglia—they also preserve construction knowledge that is both low-tech and high-impact. These techniques are being rediscovered in low-carbon retrofitting, restoration of historic buildings, and in the development of educational hubs focused on green construction skills. Projects that integrate craftsmanship, local materials, and participatory design represent a scalable model of inclusive, low-impact architecture.

What makes Made in Italy particularly relevant in the context of the ecological and digital transitions is its intrinsic compatibility with core principles of sustainable design: longevity, traceability, material circularity, and energy efficiency. Italian SMEs, while operating at artisanal scales, often adopt advanced production technologies—from CNC milling and BIM-enabled workflows to blockchain-based supply tracking. This synergy between scale, identity, and innovation makes them ideal actors in the transformation of European manufacturing toward a regenerative, low-carbon paradigm.

In conclusion, Made in Italy is a systemic design culture that bridges material ethics, environmental performance, and social responsibility. It offers a grounded, resilient, and scalable framework for sustainable architecture, demonstrating that it is possible to build in a way that is at once technologically advanced, environmentally sound, and culturally meaningful. For engineers, architects, and designers alike, it represents a living archive of strategies and solutions capable of informing the next generation of ecological construction.

1.2. The new paradigms of circular design

The circular economy (CE) is emerging as an innovative and systemic model that fundamentally redefines the principles of design and production. Far from being a mere strategy for waste reduction, it constitutes a paradigm shift toward sustainability, responsibility, and regeneration. As conceptualized in the literature, the circular economy functions as an "umbrella concept"[1,2], integrating

1. Blomsma F., Brennan G. (2017), *The emergence of circular economy: A new framing around prolonging resource productivity*, in «Journal of Industrial Ecology», 21(3), pp. 603-614, https://doi.org/10.1111/jiec.12603.

2. Homrich A.S., Galvão G., Abadia L.G., Carvalho M.M. (2018), *The circular economy*

diverse disciplinary perspectives—from economics and systems engineering to environmental sciences and design theory—into a unified framework aimed at preserving the value of resources throughout their lifecycle.

Circular design, as one of the key operational domains of this model, reconfigures the role of products within society. Products are no longer perceived as disposable commodities destined for obsolescence, but rather as durable assets that continuously generate value through reuse, repair, remanufacturing, and regeneration. This shift promotes a transition from the "take-make-waste" logic of linear production toward a regenerative circularity, where waste is designed out of the system from the outset.

At the core of this transformation lies a systemic and interdisciplinary approach, deeply rooted in theoretical contributions such as closed-loop systems, cradle-to-cradle design, and regenerative economics[3]. This approach emphasizes the need to design for longevity, adaptability, and disassembly—thereby enabling product life cycles that are extended, transparent, and resource-efficient[4,5]. Within this context, sustainability becomes an embedded quality rather than an afterthought, affecting the entire design logic and material composition of products.

One of the central frameworks guiding circular strategies is the 3R hierarchy—reduce, reuse, recycle—which prioritizes the retention of material and functional value at the highest possible level[6]. This model does not only seek to minimize environmental impact but also unlocks new economic opportunities, enabling

umbrella: Trends and gaps on integrating pathways, in «Journal of Cleaner Production», 175, pp. 525-543, https://doi.org/10.1016/j.jclepro.2017.11.064.

3. Murray A., Skene K., Haynes K. (2017), *The circular economy: An interdisciplinary exploration of the concept and application in a global context*, in «Journal of Business Ethics», 140(3), pp. 369-380, https://doi.org/10.1007/s10551-015-2693-2.

4. Geissdoerfer M., Savaget P., Bocken N.M.P., Hultink E.J. (2017), *The circular economy – A new sustainability paradigm?*, in «Journal of Cleaner Production», 143, pp. 757-768, https://doi.org/10.1016/j.jclepro.2016.12.048.

5. Webster K. (2017), *The Circular Economy: A Wealth of Flows*, Ellen MacArthur Foundation Publishing.

6. Reike D., Vermeulen W.J.V., Witjes S. (2018), *The circular economy: New or*

firms to develop innovative business models oriented around services rather than ownership. The concept of servitization, for example, transforms products into platforms for value delivery over time, encouraging durability and accountability while decoupling growth from resource extraction.

A pivotal role in promoting the circular economy has been played by the Ellen MacArthur Foundation, which has helped define and disseminate the vision of a regenerative business model. Its initiatives highlight how circularity can serve as a pathway for innovation and resilience, contributing to the emergence of new standards and practices across global value chains[7].

Among the thought leaders in this space is Thomas Rau, author of Material Matters, who argues that the true challenge of circularity lies in the extension of producer responsibility. In his vision, manufacturers should be accountable not only for the production phase but also for the entire lifecycle of their products, including post-use recovery. This perspective reframes products as temporary repositories of raw materials, rather than fixed objects to be discarded. Rau's philosophy underpins business models based on product-as-a-service, leasing, and reverse logistics, all aimed at maximizing material utility and minimizing environmental impact[8].

In the circular design landscape, however, the increasing complexity of products presents a formidable challenge. Items such as smartphones, household appliances, and lighting systems are difficult to repair, disassemble, or recycle, due to material heterogeneity and design opacity. In response, the emergence of digital identities for products—such as the Digital Product Passport (DPP)—offers a promising strategy. By enabling traceability and

refurbished as CE 3.0?, in «Resources, Conservation and Recycling», 135, pp. 246-264, https://doi.org/10.1016/j.resconrec.2017.08.027.

7. Ellen MacArthur Foundation (s.d.), *The circular economy in detail*, https://www.ellenmacarthurfoundation.org/the-circular-economy-in-detail-deep-dive.

8. Rau T., Oberhuber S. (2019), *Material matters. L'importanza della materia: Un'alternativa al sovrasfruttamento*, Edizioni Ambiente.

data-sharing across the value chain, the DPP supports more efficient maintenance, reuse, and end-of-life management, while empowering consumers through access to lifecycle information.

Another defining principle of circularity is the shift from ownership to access, as proposed by Rau and Oberhuberet in 2019. This model encourages the distribution of responsibility between producers and users, promoting use-optimization over material possession. New business paradigms such as rental systems, subscription services, and long-term leasing contracts are gaining traction—even in traditionally ownership-centered sectors such as electronics and automotive—facilitating resource conservation and systemic efficiency.

Ultimately, in the circular economy, products cease to be mere goods and become strategic assets, capable of generating value throughout their lifecycle. The MacArthur Foundation emphasizes this vision, advocating for an economic valuation of products that considers not only their market price but also their ecological footprint, cultural significance, and social utility. In this sense, sustainability becomes a driver of innovation, economic competitiveness, and future-ready growth.

1.3. Ecodesign – a tool for political, social and environmental transformation

Design has long catalysed environmental, social, and political transformation. While the term "design" is widely used in both colloquial and technical contexts, employing it in a generalised manner can lead to divergent methodological approaches. Therefore, it is pertinent to commence with industrial design, which originated in the industrial sector as an activity aimed at harmonising aesthetics and functionality in mass production. Today, it is recognised as a strategic process addressing global challenges through innovative and sustainable solutions. According to the World Design Organisation, industrial design bridges the gap between what exists and what is possible. It is a transdisciplinary profession that harnesses creativity to resolve problems and co-create solutions to enhance products, systems, services, experiences, or businesses. At its core, industrial design offers an optimistic vision for the future. It views problems as opportunities for growth and innovation, thereby creating competitive advantages for businesses.

Building upon these considerations, the evolution and definition of ecodesign become evident. Ecodesign is defined as "the integration of environmental sustainability considerations into the characteristics of a product and the processes taking place throughout the product's value chain"[9]. This approach responds to the unsustainable linear economic model-based on take, make, consume, and dispose by promoting a circular economy, regeneration, and waste minimisation.

Since the late 1960s, the concept of ecodesign has evolved to encompass various approaches such as green design, circular design, design for social innovation, and cradle-to-cradle. These methodologies aim to reduce environmental impact and create shared value among the environment, society, and economy. Product innovation has expanded into product-service system innovation and further into social contexts. Historical analysis reveals that periods of environmental crisis have often spurred technological and innovative breakthroughs. The focus on sustainability has deep roots, evident in examples ranging from Michael Thone's bentwood chair—designed in the 19th century for efficient transport and assembly—to Enzo Mari's cultural provocations on self-design; from the poetic and natural designs of William Morris and Alvar Aalto to contemporary projects like Issey Miyake's recycled PET lamps and Freitag's creative reuse of truck tarpaulins. These instances demonstrate that design serves both technical and commercial purposes as well as ethical and social functions.

9. European Union (2024), *Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for products*, L 178/1, Publications Office of the European Union, L 178, 1-62, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32024R1781.

Given that design has always aimed to find solutions where problems exist, the responsibility and potential of ecodesign in this critical historical moment are clear. On one hand, design decisions made during the planning phase significantly impact the environment; on the other, applying fundamental eco-design principles throughout the value chain—such as reduction, reuse, recycling, modularity, use of low-impact materials, and tools like Life Cycle Assessment (LCA) – allows for a holistic analysis of a product's or process's environmental impact. In this context, John Maeda's reflections in his 2006 essay, The Laws of Simplicity, are particularly significant. Maeda posits that simplification is a design strategy to make complex systems more accessible, understandable, and sustainable, encapsulated in the principles of "shrink, hide, embody". Perhaps, because our region predominantly comprises small and medium-sized enterprises (SMEs), we should return to simplicity and clear design principles, avoiding being overwhelmed by the complexity of our current technological era.

Therefore, discussing ecodesign is crucial in creating products and analysing the entire production system. The supply chain—from design to distribution—must be reimagined to ensure greater durability, reparability, and recyclability[10].

Within the context of Made in Italy, adopting ecodesign practices responds to global sustainability challenges and offers an opportunity to strengthen the connection between culture, design, craftsmanship, and innovation. Italy's tangible and intangible cultural heritage is an inexhaustible resource that should be valued through conscious and guided ecodesign practices—not only for conservation but also as an innovative lever for co-creation projects and living labs. Managing and conserving cultural heritage must integrate sustainable practices, focusing on innovative recovery of artisanal traditions and local production to preserve and

10. Bocken N.M.P., de Pauw I., Bakker C., van der Grinten B. (2016), *Product design and business model strategies for a circular economy*, in «Journal of Industrial and Production Engineering», 33(5), pp. 308-320, http://dx.doi.org/10.1080/21681015.2016.1172124.

adapt them to present challenges and needs. Simultaneously, the challenge involves seeking efficient production or conservation processes. Made in Italy should thus be considered a concept that transcends mere production, embodying values ranging from quality to innovation, art to culture, sustainability to social responsibility. It represents a strong identity linked to a centuries-old historical and cultural heritage, blending artisanal tradition with technological innovation, becoming a global symbol of excellence. In this context, ecodesign must play a fundamental role, acting as a mediator and sometimes as a narrator or director of the processes guiding Made in Italy—not only to reduce environmental impact but also as a strategy to enhance the deep-rooted know-how that has always analanalysed developed within its territory, building its excellence.

In summary, ecodesign is a design methodology and a cultural and political vision capable of steering innovation towards a more responsible and resilient future. It invites us to rethink our relationship with objects, production, and the environment, restoring design's original function: to improve people's lives in harmony with the world around them.

Chapter 2

Sustainability roadmap

Digital tools for sustainable Made in Italy

The Digital Product Passport (DPP) is emerging as a key tool in supporting the ecological transition of production systems, particularly those aligned with Italian artisanal and design-driven manufacturing values. By ensuring greater transparency and traceability across the entire value chain, the DPP enables companies to document their products' environmental, technical, and social attributes in a verifiable and standardized format. This facilitates compliance with international sustainability regulations while strengthening consumer trust and market positioning.

One of the most relevant features of the DPP is its ability to map the full product lifecycle—from design and production to use, maintenance, and end-of-life scenarios—creating a digital archive shared and verifiable by all parties involved[1]. This functionality suits the circular economy models increasingly adopted by Italian producers in the fashion, furniture, and design sectors. By digitally recording each component's origin and performance attributes, the DPP supports strategies focused on durability, reuse, and recyclability—turning sustainability from a guiding principle into a measurable, operational practice. Consequently, DPP facilitates the creation of sustainable products with a low environmental impact and can be reused, processed or recycled without compro-

1. Jensen S.F., Kristensen J.H., Christensen A., Waehrens B.V. (2024), *An ecosystem orchestration framework for the design of digital product passports in a circular economy*, in «Business Strategy and the Environment», 33(7), pp. 7100-7117, https://doi.org/10.1002/bse.3868.

mising their value[2]. Another key advantage lies in the DPP's potential to enable interoperability among the diverse information systems used throughout the supply chain. In a production landscape characterized by distributed, multi-actor networks, sharing certified data in a standardized digital format enhances efficiency and reduces uncertainty. For Italian SMEs, this means improved visibility, streamlined compliance, and access to shared knowledge that was previously fragmented or inaccessible. The possibility of sharing information on the technical, environmental and social characteristics of products allows SMEs to reduce the risks and uncertainties arising from a lack of visibility in their supply chain, improving competitiveness and consumer confidence[3].

Nonetheless, implementing DPP in Italian production ecosystems presents several challenges. One of the most critical is data asymmetry. While larger firms often possess detailed information on materials and processes, smaller enterprises may struggle with fragmented or low-quality data. This gap risks slowing down widespread adoption and limiting the benefits of digital traceability. In addition, concerns around data protection and cybersecurity are amplified in cross-border contexts, where regulatory landscapes vary. To address these barriers, the new European Eco-design for Sustainable Products Regulation (ESPR) provides a structured framework for standardization and digital transparency. With the introduction of mandatory DPPs for selected product categories by 2026, the regulation offers both a challenge and an opportunity. Italian firms—especially those that combine traditional craftsmanship with high-quality design—are well-positioned to lead in this transition, provided they receive adequate support in terms of infrastructure, training, and digital integration. In this context,

2. King M.R., Timms P.D., Mountney S. (2023), *A proposed universal definition of a Digital Product Passport Ecosystem (DPPE)*, in «Journal of Cleaner Production», 384, 135538, https://doi.org/10.1016/j.jclepro.2022.135538.

3. Berger K., Scöggl J.-P., Baumgartner R.J. (2022), *Digital battery passports to enable circular and sustainable value chains: Conceptualization and use cases*, in «Journal of Cleaner Production», 353, 131492, https://doi.org/10.101/10.1016/j.jclepro.2022.131492.

the DPP is not just a compliance tool but a strategic asset. It allows Made in Italy to evolve without losing its identity—merging the values of material excellence and cultural continuity with the demands of a digital and sustainable economy.

2.1. Traceability and sustainability: the role of the digital product passport in the circular economy

The Digital Product Passport (DPP) is an advanced digital technology gaining a central role in supporting circular economy (CE) processes. It takes the form of an inter-organisational digital repository designed to collect and manage all information related to a product's life cycle in an integrated and systematic way. This information tracking system will play a crucial role in overcoming the information gaps that currently characterise product lifecycle management, especially concerning data traceability and sharing between the various actors in the value chain.

The DPP is a mandatory tool for organisations wishing to place products on the market, requiring them to collect, store, maintain and share detailed product data. This data covers various aspects of the product, such as its material composition, environmental impact, usage patterns, and regulatory compliance. These obligations derive from increasing regulatory efforts, as evidenced by regulations such as the European Eco-design for Sustainable Products Regulation (ESPR), which stipulates the obligation to implement DPP in many sectors by 2026[4,5]. The DPP comprises an ecosystem of actors and technologies that must collaborate in managing and sharing data. This network includes manufacturers,

4. King M.R., Timms P.D., Mountney S. (2023), *A proposed universal definition of a Digital Product Passport Ecosystem (DPPE)*, in «Journal of Cleaner Production», 384, 135538, https://doi.org/10.1016/j.jclepro.2022.135538.

5. Langley D.J., Rosca E., Angelopoulos M., Kamminga O., Hooijer C. (2023), *Orchestrating a smart circular economy: Guiding principles for digital product passports*, in «Journal of Business Research», 169, 114259, https://doi.org/10.1016/j.jbusres.2023.114259.

suppliers, distributors, end-users and other entities involved in the product life cycle. The effectiveness of DPP depends on inter-organisational cooperation and the ability of these actors to standardise data formats and communication protocols. The variety of actors involved and the complexity of value chains means that DPPs may vary considerably from sector to sector. For instance, in the battery sector, DPPs include information on service life, environmental impact and recyclability, whereas, in the textile sector, the passport may contain details on fibre origin, dyeing processes and sustainability of the materials used[6,7]. In general, the data contained in a DPP includes key information such as product identification (codes and classifications), material composition, environmental impact during the life cycle, conditions of use, and conformity certifications. The main objective of the DPP is to ensure total visibility of the product life cycle, promote transparency and corporate social responsibility, and ensure compliance with environmental regulations.

Despite the revolutionary potential of DPP, its large-scale adoption faces numerous difficulties. The main technological barriers include the lack of interoperability between systems and difficulty managing data centrally. In addition, cultural resistance persists on the part of organisations, which are often unwilling to share sensitive information or change their internal processes to comply with DPP obligations. Challenges related to the lack of clear legal standards and regulatory variations further complicate this cultural resistance, making the uniform adoption of the technology globally difficult[8]. However, despite these obstacles, adopting

6. Berger K., Scöggl J.-P., Baumgartner R.J. (2022), *Digital battery passports to enable circular and sustainable value chains: Conceptualization and use cases*, in «Journal of Cleaner Production», 353, 131492, https://doi.org/10.101/10.1016/j.jclepro.2022.131492.

7. Jæger B., Myrold S. (2023), *Textile Industry circular supply chains and digital product passports. Two case studies*, in Alfnes E. *et al.* (eds), *Advances in Production Management Systems. Production Management Systems for Responsible Manufacturing, Service, and Logistics Futures*, vol. 692, Springer, pp. 350-363, https://doi.org/10.1007/978-3-031-43688-8_25.

8. Berger K., Baumgartner R.J., Weinzerl M., Bachler J., Schöggl J.-P. (2023), *Factors of digital product passport adoption to enable circular information flows along the battery value chain*, in «Procedia CIRP», 116, pp. 528-533, https://doi.org/10.1016/j.procir.2023.02.089.

DPP is a key step for organisations wishing to remain competitive and responsible in sustainability and ecological transition.

One of the key objectives of DPP is to promote a shared language among all stakeholders involved in the value chain. This common language is essential to ensure that all stakeholders have a homogeneous understanding of the information shared. The standardisation of data formats and protocols is essential to enable the proper exchange of information between heterogeneous actors. To this end, DPP uses advanced technologies that enable data storage, retrieval and analysis, significantly improving organisational knowledge management[9]. Furthermore, the European Commission have delineated the DPP as a dynamic instrument accompanying the product through all stages of its life cycle, from design to production, recycling, and disposal. This dynamic aspect is crucial in promoting product circularity, enabling organisations to continuously monitor and optimise resource use. The ability to track the product at every stage allows for the development of reuse, upcycling and responsible disposal models, significantly reducing environmental impact and strengthening circular economy principles[10].

Finally, DPP is fully aligned with the principles of sustainability, in particular the industrial ecology approach, which promotes resource optimisation and waste minimisation. Through its ability to monitor and optimize material and energy flows, DPP is a powerful tool to facilitate the transition to a more sustainable and responsible production model, helping to reduce products' overall ecological footprint and support a more resilient and innovative industry.

9. Wenning R., Papadakos P., Bernier C. (2024), *DPP system architecture*, https://cirpassproject.eu/wp-content/uploads/2024/04/D3.2-DPP-System-Architecture.pdf.

10. Plociennik C. *et al.* (2022), *Requirements for a digital product passport to boost the circular economy*, Gesellschaft für Informatik, https://doi.org/10.18420/inf2022_127.

2.2. Regulatory evolution and international standards

The regulatory framework governing the digital identity of products, materials and resources is evolving rapidly, reflecting the growing focus on sustainability, transparency and traceability throughout the life cycle of goods. In this context, European and international regulations are moving towards a systemic approach capable of enabling the transition from linear to circular models of production and consumption based on extended producer responsibility, smart resource management and digital innovation. A pillar of this transformation is the European Green Deal, launched by the European Commission in December 2019, which sets climate neutrality by 2050 as a strategic goal. The Green Deal is accompanied by a comprehensive legislative package, including the Circular Economy Action Plan (2020), containing more than 35 legislative initiatives to foster sustainable design, material reuse, waste reduction and consumer empowerment. These initiatives aim to ensure that products placed on the European market are more durable, repairable, recyclable and resource-efficient.

One of the most innovative regulatory instruments introduced in this context is the Ecodesign for Sustainable Products Regulation (ESPR), which entered into force in 2024. The ESPR[11] has brought about significant innovations: in addition to replacing the previous Directive 2009/125/EC, it has amended both Directive (EU) 2020/1828 and Regulation (EU) 2023/1542 on batteries, marking a regulatory shift towards a systemic and digital design of products. One of the key elements of the new regulation is the mandatory Digital Product Passport, conceived as a dynamic and interoperable electronic tool capable of collecting and updating relevant data on product composition, origin, repairability, envi-

11. European Union (2024), *Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for products*, L 178/1, Publications Office of the European Union, L 178, 1-62, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32024R1781.

ronmental impact, and disposal methods. The passport thus represents a keystone in the concrete implementation of circular economy principles, serving as a multi-level traceability tool.

This should be no surprise when considering that the digital dimension is central to supporting the so-called "twin transition" — the integration of ecological transition and digital transformation. This approach is also fully endorsed by the National Recovery and Resilience Plans, which recognize digitalization as a key tool for overcoming transparency and data availability barriers across the entire supply chain while fostering the development of advanced material traceability systems, offering new competitive advantages to businesses. The use of technologies such as blockchain, the Internet of Things, and interoperable databases now enables more effective management of material flows, optimization of waste management, and improvement of energy efficiency.

Within the ESPR, the role of the Ecodesign Forum is particularly significant. Established in 2023, it is a permanent platform for dialogue between institutions, industries, and civil society. It is now tasked with proposing updated design standards at the European level for different product categories. The regulation has also introduced restrictions on destroying unsold goods, particularly in the textile sector. It has promoted integrating environmental, social, and governance (ESG) principles into European industrial strategies. At the same time, international organizations such as ISO (International Organization for Standardization) and UNECE (United Nations Economic Commission for Europe) are developing standards and guidelines to support digital traceability through technologies like blockchain, promoting interoperability among global actors.

Another fundamental piece of this regulatory ecosystem is the REACH Regulation (Registration, Evaluation, Authorisation and Restriction of Chemicals), one of the EU's main legal instruments for managing chemicals. It sets criteria for transparency, risk assessment, and shared responsibility across value chains. Integrating REACH requirements into the Digital Product Passport further strengthens the responsible and transparent mapping of materials used, helping to reduce health and environmental risks — particularly for substances identified as "substance of concern".

The construction sector plays a strategic role in the implementation of the European Green Deal, accounting for approximately 40% of the European Union's final energy consumption and 36% of CO_2 emissions, while also being one of the largest consumers of raw materials and producers of waste[12]. Consequently, the transformation of the built environment has become a regulatory priority, driving a shift toward decarbonisation, digitalisation, and circular economy principles. In response, Regulation (EU) 2024/3110, adopted on 27 November 2024, introduces a new legal framework for the marketing of construction products, repealing Regulation (EU) No 305/2011. This revised Construction Products Regulation (CPR) establishes harmonised rules that integrate environmental sustainability, product performance, and digital traceability into a coherent system applicable to the entire value chain of construction products[13]. A central innovation of the CPR is the mandatory implementation of the Digital Product Passport (DPP), which serves as a structured and interoperable data framework containing essential information over the product's lifecycle—such as performance declarations, conformity data, classification, nominal dimensions, environmental performance based on Life Cycle Assessment (LCA), disassembly data, and end-of-life reuse potential[14]. These data modules must align with existing international standards such

12. European Commission (2020), *A Renovation Wave for Europe – Greening our buildings, creating jobs, improving lives* (COM/2020/662 final), Bruxelles, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52020DC0662.

13. European Union (2024), *Regulation (EU) 2024/3110 of the European Parliament and of the Council of 27 November 2024 laying down harmonised rules for the marketing of construction products and repealing Regulation (EU) No 305/2011*, Publications Office of the European Union, L 310, 1-62, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202403110.

14. *Ibidem*, artt. 8-15.

as EN 15804 and ISO 14040/44[15,16,17] and ensure full interoperability with Building Information Modelling (BIM) platforms[18]. The CPR emphasises the necessity for digital integration in construction processes, enabling effective management of data through all phases—from design and construction to maintenance, reuse, and deconstruction. Moreover, the DPP must include documentation related to safety, maintenance, foreseeable misuse, and detailed instructions for installation, operation, and disassembly, ensuring integration with other construction kits and systems[19]. The regulation classifies construction products into "families" and assigns essential characteristics that must be expressed through harmonised methods—either in terms of values, levels, or classes—and verified through European Technical Assessment Bodies (ETABs)[20]. Economic operators, including manufacturers, importers, and distributors, are obligated to ensure the accuracy and availability of DPP data via accessible digital platforms[21]. The CPR outlines essential requirements that products must meet at the building level, including mechanical strength, fire safety, hygiene and health protection, acoustic performance, energy efficiency, and sustainable use of natural resources, as listed in Annex I of the Regulation[22]. Compared to the general framework of the Ecodesign for Sustainable Products

15. CEN (2019), *EN 15804:2019 – Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products*, European Committee for Standardization, Bruxelles.

16. ISO (2006a), *ISO 14040:2006 – Environmental management – Life cycle assessment – Principles and framework*, International Organization for Standardization, Ginevra.

17. ISO (2006b), *ISO 14044:2006 – Environmental management – Life cycle assessment – Requirements and guidelines*, International Organization for Standardization, Ginevra.

18. European Commission (2023), *Digital Product Passport: The gateway to circular value chains*, Directorate-General for Environment, Bruxelles.

19. European Union (2024), *Regulation (EU) 2024/3110 of the European Parliament and of the Council of 27 November 2024 laying down harmonised rules for the marketing of construction products and repealing Regulation (EU) No 305/2011*, Publications Office of the European Union, Annex II and Annex III, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202403110.

20. *Ibidem*, artt. 20-25.

21. *Ibidem*, artt. 26-30.

22. *Ibidem*, Annex I.

Regulation (Regulation (EU) 2024/1781), the CPR addresses the specific needs of the construction sector by linking environmental performance directly to product functionality and regulatory compliance[23]. The integration of sustainability and digital governance in construction regulation facilitates circular economy models and enables traceable, data-driven product stewardship. A growing body of research confirms that the deployment of digital tools such as the DPP is crucial for enabling transparency across value chains and supporting sustainable innovation in the built environment[24,25,26]. Through the CPR, the EU has taken a significant step toward aligning construction regulation with long-term environmental and digital policy objectives, anchoring the transition to a climate-neutral and resource-efficient construction ecosystem.

Another regulation of particular relevance for Italy is Regulation (EU) 2023/2411, which extended the protection of geographical indications to craft and industrial products. For the first time, these products — representing a unique cultural and productive heritage — can benefit from EU-level protection similar to that provided for other products. This regulation is vital for enhancing local supply chains, especially in preserving traditional manufacturing practices that are especially significant in Italy.

However, intensifying data collection and sharing across value chains raises security and data protection concerns. In this regard, regulations such as the General Data Protection Regulation (GDPR) and new cybersecurity directives lay the foundation for

23. European Union (2024), *Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for products*, L 178/1, Publications Office of the European Union, L 178, 1-62, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32024R1781.

24. Joint Research Centre (JRC) (2022), *Preliminary study for the Ecodesign for Sustainable Products Regulation working plan*, Publications Office of the European Union, Luxembourg.

25. Technopolis Group (2024), *Digital Product Passport: State of play and future design recommendations*, DG GROW, Bruxelles.

26. Bauwens T., Heyen D.A., Strupeit L. (2021), *Digitalization and the circular economy: Bridging the knowledge gap*, in «Journal of Industrial Ecology», 25(6), pp. 1436-1449.

responsible digital governance, protecting user rights and industrial data confidentiality while ensuring accessibility to authorized operators. This issue remains open and is still under discussion.

In summary, the convergence of European policies, international standards, and digital innovations is shaping a new regulatory ecosystem focused on sustainability, interoperability, and shared responsibility.

2.3. Early cases of digital product passports, material passports and supporting platforms

The widespread adoption of the Digital Product Passport (DPP) emerges as a strategic measure to promote circular production and consumption models, enabling a more efficient and transparent management of material resources. Recent studies have compared current initiatives around the world, defining criteria to describe, evaluate, and compare them and stimulating debate around the topic[27].

In this context, the construction sector is particularly significant in the experimentation and development of platforms for data collection, the creation of DPP or the integration of Material Passports (MP), understood as digital documents or databases, capable of collecting detailed information on the materials used in a building or construction project, to facilitate reuse, recycling and management throughout the building's life cycle. There are two main reasons for us to consider this sector: on the one hand, the high environmental impact for which the industry is responsible, concerning not only the use of raw materials but also the production of construction waste for disposal, and on the other hand, the innovation potential it offers. We are called upon not only to

27. Jansen M., Gerstenberger B., Bitter-Krahe J., Berg H., Sebestyén J., Schneider J. (2022), *Current approaches to the Digital Product Passport for a Circular Economy: An overview of projects and initiatives*, in «Wuppertal Paper» No. 198, https://epub.wupperinst.org/frontdoor/deliver/index/docId/8042/file/WP198.pdf.

rethink the efficiency of buildings' lives but also to look carefully at the materials used, reuse, and digitisation of information right from the early design stages.

The construction sector has offered the first concrete examples of applying the material passport concept, thanks to projects such as Buildings as Material Banks (BAMB), funded by the European Commission under the Horizon 2020 programme. BAMB has developed digital tools to document the properties of building materials, facilitating their reuse, selective deconstruction and economic valorisation in the next life cycle[28]. According to the framework developed by BAMB, a MP is a set of digital data describing the specific characteristics of materials and components within a product or building. These passports provide detailed information on composition, origin, reuse potential, environmental impact and other relevant properties, facilitating the sustainable management of materials throughout the building's life cycle. The project was tested in six real-life pilot projects to realise the framework. The pilot cases investigated new design, production, construction and maintenance approaches for dynamic, circular buildings. At the end of the initiative, more than 300 material, component and product passports were produced, together with a software prototype for their generation and consultation, supplemented with tools for assessing the potential for reuse. These tools, refined through hands-on testing and stakeholder feedback, helped define standards and methodologies now considered benchmarks for initiatives such as Madaster and Cirpass—this latest initiative, funded by the European Commission through the Digital Europe programme, ended in March 2024. Its main objective was to prepare the ground for the gradual implementation of DPPs in three value chains: electronics, batteries and textiles[29].

28. Durmisevic E. (2016), *Reversible Building Design Guideline*, BAMB document, University of Twente.

29. Cirpass (n.d.), *About CIRPASS*, https://cirpassproject.eu/about-cirpass/.

In parallel, the Madaster platform, launched in the Netherlands in 2017, introduced a digital registration system for building materials based on a unique digital identifier for each component and evaluative models of materials "residual value"[30]. Madaster Foundation, the project leader, is a non-profit organisation that operates globally by collaborating with local partners, without overlapping with existing research organisations, and by stimulating the development of knowledge, methodologies, and concepts through dialogue and public discussion. Madaster won the Digital Top 50 Award for Social Impact which Google, McKinsey and Rocket Internet awards. At the technical level, the platform uses a BIM environment as a data source for MP generation, next to the Madaster Circularity Index and embodied carbon and cost assessments[31]. A material passports pilot project with Madaster in 2019 was conducted in collaboration with the Amsterdam Metropolitan Area (AMA) to stimulate the regional circular economy. Madaster functions as an online public library that records and documents buildings and the products and materials applied within them, similar to how parcel and land ownership is recorded in a land register. Madaster can generate a secure, web-based material passport for all building objects. A material passport contains information on the quality and origin of materials, various items' disassembly possibilities, and their current location. This makes it easier to recover and reuse them in case of renovation and restoration. Buildings, therefore, become documented "storage units" for materials. In addition, circular and financial information flows are linked, thus revealing the historical, current and future value of materials, products, elements, the building itself and all these elements combined.

30. Honic M., Kovacic I., Aschenbrenner P., Ragossnig A. (2021), *Material passports for the end-of-life stage of buildings: challenges and potentials*, in «Journal of Cleaner Production», 319, https://doi.org/10.1016/j.jclepro.2021.128702.

31. Honic M., Fink D., Passer A. (2023), *Circular construction and material passports: Digital tools for the transition to a circular built environment*, in «Circular Economy and Sustainability», pp. 95-111. Springer, https://doi.org/10.1007/978-3-031-39675-5.

Another significant project in the European panorama is Platform CB'23, an initiative from the Netherlands, running from 2018 to 2023, aimed at developing shared guidelines and practical tools for integrating circular economy principles into the construction sector. The initiative involved many stakeholders, including public bodies, private companies, industry organisations and academic institutions. One of the most significant outcomes of the project was the publication of the "Passports for the Construction Sector" guide, which provides a detailed framework for creating and implementing MPs. The guide has two parts: the first part illustrates the step-by-step construction of a passport, while the second part provides insights into the necessary conditions for successfully implementing passports, such as data standardisation, digitisation, information governance and integration with existing regulations[32]. Although the project ended in 2023, the guidelines and tools developed continue to be accessible and used as a reference to promote more sustainable and circular construction practices both in the Netherlands and the rest of Europe.

Alongside these experiences is the development of the Building Heritage Materials Passport (BHMP) concept, which proposes a traceability system specifically designed for historic architectural materials to promote their conservation, conscious reuse and valorisation circularly[33]. The BHMP represents a critical extension of the DPP, capable of integrating cultural, technical and environmental values within an accessible and interoperable digital framework, supporting the regeneration of the built heritage in line with the principles of the circular economy.

Case studies from the construction sector also highlight the importance of multi-stakeholder involvement, including architects, designers, material manufacturers, demolition companies and lo-

32. Platform CB'23 (2020), *Guide-Passports for the Construction Sector-Working agreements for circular construction*, https://platformcb23.nl/.

33. Bernardo G., Guida A. (2024), *Building Heritage Materials Passports (BHMPs) for resilient communities*, in «Colloqui.AT.e», 3, pp. 115-127, https://link.springer.com/chapter/10.1007/978-3-031-71867-0_9.

cal authorities. For example, the Orms project in the UK showed how adopting advanced digital documentation can support selective deconstruction practices, significantly reducing waste and maximising the recoverable value of components[34].

In order for DPP to establish itself as the standard infrastructure for sustainable Made in Italy, multi-level governance is needed to promote it:

- fair access to data for SMEs;
- digital skills training for platform adoption;
- integration into public procurement systems and environmental assessment tools;
- alignment between technology, standardisation and industry policy.

As demonstrated from the various initiatives described, digitalisation can act as a catalyst for systemic innovation. It can transform materials into regenerative assets and transparently reveal the material and information flows that define products' life cycles.

2.4. Artificial Intelligence and Causal reasoning in digital product passports for circular manufacturing

Artificial Intelligence is playing an increasingly central role in the evolution of sustainable design and manufacturing practices, particularly in the development of Digital Product Passports (DPPs), which are being promoted by the European Commission as essential tools for enabling transparency, traceability, and circularity across product value chains. While traditional AI techniques have already

34. Costa A.R., Hoolahan R. (2024), *Material Passport: Accelerating Material Reuse in Construction*, Lancaster University and Orms Designers & Architects Ltd, London, https://doi.org/10.5281/zenodo.10472214.

proven useful in supporting ecodesign through predictive analytics, pattern recognition, and optimisation—especially in sectors like fashion, furniture, construction, and food where Italy excels—these methods often fail to explain the causal mechanisms that underlie environmental or operational outcomes, limiting their value for long-term sustainability strategies. This is where Causal AI emerges as a critical innovation: a class of machine learning approaches designed to infer and model causal relationships, rather than mere statistical correlations, between variables in complex systems. By using tools such as directed acyclic graphs (DAGs), causal discovery algorithms, and counterfactual reasoning models, Causal AI enables stakeholders to answer not only predictive questions (what will happen?) but also interventional and counterfactual ones (what would happen if we acted differently?)—providing a level of insight, transparency, and accountability that is essential in regulated and sustainability-driven domains[35,36]. In the context of digital product passports, this means that the DPP can evolve from a passive data container into an active, intelligent infrastructure capable of understanding and recommending actions across the product life cycle. According to Ompusunggu *et al.* (2024)[37], a Causal AI-powered DPP integrates semantic knowledge graphs, domain ontologies, and real-time data from sensors and digital twins to dynamically model environmental key performance indicators (KPIs), such as greenhouse gas emissions, energy consumption, and material circularity potential. These models can support circular product design from the earliest development phases by tracing how design decisions, material choices, and process variables causally affect end-of-life

35. Assaad C.K., Devijver E., Gaussier É. (2022), *Survey and evaluation of causal discovery methods for time series*, in «Journal of Artificial Intelligence Research», 73, 767-819, https://doi.org/10.1613/jair.1.13350.

36. Gong C., Yao D., Zhang C., Li W., Bi J. (2023), *Causal Discovery from Temporal Data: An Overview and New Perspectives*, in «arXiv», https://arxiv.org/abs/2303.10112.

37. Ompusunggu A.P., Tjahjowidodo T., Wicaksono H. (2024), *Causal AI-powered Digital Product Passports for enabling a circular and sustainable manufacturing ecosystem*. Proceedings of the 12th International Conference on Through-life Engineering Services (TESConf2024), Cranfield University, UK, https://doi.org/10.57996/cran.ceres-2579.

outcomes and recovery strategies. This approach is particularly valuable in Made in Italy sectors, where heritage, quality, and sustainability intersect: in fashion and textiles, for instance, causal models can quantify the lifecycle impact of fabric blends or finishing processes; in design and furniture, they can link joinery techniques and material selection with recyclability and emissions performance over time; in agro-food, they can connect terroir-based practices and packaging innovations with shelf life and carbon footprint; in artisanal crafts, they can help preserve traditional methods while ensuring environmental compliance; and in the construction and architectural design sectorone of the most resource-intensive domains globally – Causal AI-enhanced DPPs can support material traceability, simulate energy and carbon performance of building components across their lifecycle, and optimise retrofit strategies for heritage buildings. When integrated with Building Information Modeling (BIM) and digital twin frameworks, these tools allow architects and engineers to evaluate, with causal precision, how early design decisions (such as facade geometry, insulation type, or structural system) impact long-term sustainability metrics including embodied carbon, thermal performance, disassemblability, and reuse potential. Moreover, by aligning this causal infrastructure with FAIR data principles (Findable, Accessible, Interoperable, Reusable) and integrating it into system engineering and design tools, the DPP becomes a live, explainable interface between product, process, and policy, improving regulatory compliance, project transparency, and public trust. The benefits are measurable: emissions reductions between 5-25% have been projected when such systems are implemented at scale, alongside enhanced operational efficiency and improved stakeholder coordination[38,39] (Ompusunggu *et al.*,

38. Ompusunggu A.P., Tjahjowidodo T., Wicaksono H. (2024), *Causal AI-powered Digital Product Passports for enabling a circular and sustainable manufacturing ecosystem*. Proceedings of the 12th International Conference on Through-life Engineering Services (TESConf2024), Cranfield University, UK, https://doi.org/10.57996/cran.ceres-2579.

39. Pidikiti V.S., Vijaya A., Valilai O.F., Wicaksono H. (2023), *An Ontology Model to Facilitate the Semantic Interoperability in Assessing the Circular Economy Performance*

2024; Pidikiti *et al.*, 2023). As the European Union advances toward mandatory DPP frameworks for strategic sectors, the adoption of Causal AI represents not only a technological advancement but a strategic imperative for Italy's industrial and architectural excellence. By embedding causal intelligence into the digital identity of materials, products, and systems, companies and professionals can support transparent, data-driven circularity while reinforcing the unique values that define the Made in Italy brand on global markets.

of the Automotive Industry. Procedia CIRP, 120, 1351-1356, https://doi.org/10.1016/j.procir.2023.01.231.

Chapter 3

Grammar of the new present

Glossary of digital product identity for Made in Italy

Adopting the Digital Product Passport represents a strategic step toward a circular and regenerative economy, especially for the Made in Italy production system. The digitalisation of processes makes it possible to trace the entire life cycle of products and enhance traditional materials, processes and skills, supporting practices oriented towards durability, reuse and recycling. In this scenario, the construction of a shared language is not an accessory element but a fundamental prerequisite to guide the cultural, regulatory and design transformations required by this transition. The glossary of digital product identity takes the form of a true tool of meaning: it does not merely define terms but helps to articulate visions and paradigms, offering a conceptual basis useful for dialogue between designers, companies, institutions and local communities. Words are not neutral: using them precisely means outlining the trajectories of sustainable innovation, facilitating the adoption of virtuous practices and constructing an operational lexicon that supports the convergence between tradition and innovation. In this sense, terminological clarity becomes a prerequisite to effective eco-design strategies and ensuring consistency between environmental, economic and cultural objectives. The European Commission, through Regulation (EU) 2024/1781 on eco-design for sustainable products, recognises the importance of defining common and traceable criteria so that sustainability becomes structural in production processes and not just a marketing attribute. However, the full implementation of these tools also requires a change of vision: new interpretative frameworks are needed that are capable of connecting technical knowledge with the cultural values of Made in Italy. In this context, the glossary is a space for negotiation and construction of shared meanings, in which words guide the evolution of practices, make complex concepts comprehensible and promote alignment between all the actors involved. Therefore, integrating a common language in sustainable design means providing a grammar of transformation, making the interdependencies between materials, processes, knowledge and territories visible, and strengthening Made in Italy's cultural identity as a flywheel for fair, ethical and inclusive development.

3.1. Generative Graphics: Digital Passport through Artificial Intelligence

The illustrations presented in this paper were created using generative artificial intelligence, an emerging technology distinguished by its ability to create original content from large datasets. As of November 2022, with the public release of advanced models such as ChatGPT, generative AI has revolutionised the way we conceive creative production, marking an epistemological discontinuity in the processes of design, visual communication and storytelling. In the design and visual sphere, this technology makes it possible to experiment with new modes of representation that go beyond the limits of traditional visualisation.

Generative AI learns by analysing large databases-including images, text, sound, and video-to recognise recurring patterns, formal structures and semantic features. This deep learning process can construct an abstract representation of the data, operating in a multidimensional latent space in which all information is translated into relationships between vectors and parameters. In this computational space, new contents are generated: these are not mere replications or reworkings but novel configurations that synthesise and reinterpret the training data. The originality of the output thus derives from the algorithm's ability to combine learnt elements innovatively, generating statistically plausible images that never existed before.

What makes generative AI particularly significant for the Digital Product Passport context and for the visual communication of sustainability is its ability to translate, abstract, technical or systemic, complex concepts into immediately readable graphical representations. Terms related to the circular economy, such as 'durability', 'traceability' or 'modularity', can be visually interpreted through targeted prompts, which guide the algorithm in constructing images consistent with the semantic and cultural meaning of the term. In this sense, the interaction between the designer and AI is neither neutral nor automatic but takes the form of co-creation. The prompt textual or descriptive command given to the algorithm becomes the point of mediation between design intention and automatic generation, requiring specific linguistic and visual skills.

Artificial intelligence, therefore, is not limited to being a mere operational tool but takes the form of a true "cognitive partner"[1], capable of amplifying the designer's imaginative and speculative capacities, opening up new scenarios for communication of complexity. Learning to dialogue with these systems, refining the use of language and translating technical content into visual input requires a new design literacy in which lexical competence becomes fundamental. Indeed, the lexicon is not only a means of transmitting content but an epistemic device that conditions how we interpret and represent reality.

The objective of this experimentation is twofold: on the one hand, to explore the expressive potential of generative AI in the context of the conceptual visualisation of key terms of the circular

1. Floridi L. (2023), *The Ethics of Artificial Intelligence: Principles, Challenges, and Opportunities*, Oxford University Press.

economy and digital product identity; on the other hand, to verify how the use of generated images can support the understanding and dissemination of a specialised language, helping to bridge the gap between technical skills and visual culture. In a context where sustainability communication requires clarity, accessibility and involvement, artificial intelligence can act as a catalyst to generate new forms of visual narration that combine conceptual rigour and aesthetic impact[2].

The project's initial phase focused on selecting the artificial intelligence tool for image generation. The choice fell on Adobe Firefly (a deep learning-based model hosted in the cloud), not only for its accessibility — the free version also allows for generating a substantial number of images — but for its direct integration with graphic design software. Compared to other AI generators, Adobe Firefly stands out for its seamless connection with the most widely used professional design tools and for supporting a workflow oriented towards design, rather than mere random generation. As we worked with an active Adobe licence, we could fully utilise this resource, generating content directly within platforms like Illustrator and Photoshop. This allowed us to maintain design control over the output while embracing the unpredictability and ambiguity introduced by the AI. During the visual generation process (over a thousand images were generated), the results proved to be surprisingly far from our initial expectations. The AI often produced ambiguous, unexpected, or visually dissonant interpretations of the concepts we aimed to explore. It was precisely this distance that led us to select and include those images we found most surprising — the ones that seemed most capable of evoking new layers of meaning and opening up a more critical reflection on the act of visual representation itself. It is essential to highlight that we did not intentionally influence the style of the images or embed specific iconographic references within the prompts.

2. Giorgi A. (2025), *Generazione AI: Come potenziare creatività e produttività con l'AI generativa*, Hoepli.

The AI operated within an open framework, free from aesthetic constraints or precise content indications. For this very reason, in several instances, the AI appeared almost unable to produce a coherent visual rendering of certain terms, as if those concepts were, even for the machine, too abstract or unstable to be visually translated. Starting from the premise: "what would a machine see today if we asked it to represent words like extended responsibility, digital circularity, or algorithmic transparency?", the technical limitations became an opportunity for critical analysis, where generative graphics acted as a tool for investigating the semantic complexity of emerging languages.

In constructing the prompts — the textual commands submitted to the model — we followed a process developed over successive stages. Initially, each image was generated using a keyword to assess the model's immediate response. Later, we introduced the full definition of the term to observe how the AI dealt with a higher level of conceptual density. We soon realised that, as the model is primarily trained on English-language data, prompts written in English tended to yield more technically consistent and visually coherent results. However, we deliberately chose to work mostly in Italian. While sometimes leading to simplified outputs,Italian-language commands seemed to encourage greater interpretative freedom, fostering a looser, more imaginative engagement with complex concepts. We used English prompts only in selected cases, when the terminology was particularly specialised or required greater clarity.

An interesting insight emerged from analysing the length and structure of the prompts. The most concrete and recognisable visual outputs were often generated from shorter prompts — typically between twenty and forty words —containing only a condensed definition segmented. The longer and more detailed the prompt, the more fragmented or unclear the visual outcome became, as the AI struggled to translate the volume of information into a coherent image. This confirmed that textual precision and intentional brevity remain essential tools for guiding truly effective image generation even when working with AI. Lastly, the decision not to accompany the images with specific textual descriptions deliberately granted the reader complete interpretive freedom.

3.2. From glossary to action: visions for innovation and sustainability

This work offered a technical glossary of the main terms related to adopting and developing the digital product passport, a significant step towards creating a more sustainable and circular production ecosystem. Gathering all the information necessary to create a digital passport takes a long time. Companies already possess much of the data to be entered internally; however, since the entire product lifecycle is involved, it will be necessary to cooperate with all the stakeholders in the supply chain for the DPP to be complete. Therefore, it becomes essential to structure new professional figures and training courses to develop digital skills – especially in SMEs – a crucial element for adopting these tools. It is necessary to implement a concrete training action capable of bridging the existing digital divide between large companies and small businesses and between central and peripheral territories to ensure the quality of the data generated. Only in this way can traceability and sustainability become an integral part of widespread skills.

The glossary's main objective is to stimulate debate and foster constructive discussion among the various stakeholders. The words have been selected to set up participatory tables to promote discussion, knowledge sharing and the adoption of best practices to build a common and coherent language.

One of the key aspects is the glossary's role in facilitating communication between the different actors in the supply chain, improving mutual understanding and encouraging the exchange of data. In a context where a lack of effective communication is often identified as one of the main barriers to adopting digital and sustainable tools, a well-structured glossary becomes essential to break down language barriers and foster fruitful collaboration. The transparency offered by DPP should not be perceived merely as regulatory compliance, but should be used as a strategic lever: on the one hand for companies, on the other hand for the end user. It can promote critical and informed consumption, strengthening the active participation of citizens in sustainable purchasing choices. In this context, the consumer assumes an active and conscious role; therefore, even the end user can find in the glossary a valuable tool to navigate the key concepts of sustainability and digital transformation.

In contemplating the future, artificial intelligence (AI) presents a remarkable opportunity for managing and optimising digital passport data. In particular, the use of AI for the automatic creation of passports and the selection and validation of the necessary data could improve the accessibility and functionality of this tool. The challenge is to make these systems as transparent and efficient as possible, avoiding the risk of burden shifting, i.e. shifting the environmental load from one stage of the product life cycle to another. Integrating AI into an integral and complementary part of the product design process represents a great opportunity for the manufacturing sector.

A further development concerns the application of blockchain to digital passports. Although the high energy consumption of blockchain technologies is a challenge, this tool offers indisputable advantages in terms of traceability and transparency of information. In combination with AI, blockchain could ensure secure and accessible data management, minimising resource use and improving the production process's environmental impact. The continuous refinement of these digital tools will reduce the amount of information processed, focusing only on information essential for the passport, positively affecting the product's overall sustainability.

Another key aspect is the democratisation of information: adopting the digital product passport cannot be limited to making data available. It must ensure that this information is accessible to all stakeholders in the supply chain. This process is about making data available and creating a fair and inclusive ecosystem in which producers, consumers, and institutions can interact transparently and informally.

The application of these tools and technologies will also positively impact Made in Italy, which is traditionally a symbol of quality, innovation, and sustainability. Integrating the digital passport with eco-design and the circular economy strengthens the sector's competitiveness, opening up new scenarios and opportunities. Responsible and circular design practices and enhancing craft traditions and techniques can ensure environmental sustainability and strengthen Made in Italy's cultural heritage and global competitiveness.

Storytelling and narration are other crucial tools that can facilitate the adoption of these technologies. Effectively communicating the importance and benefits of the digital passport, not only through data and technicalities but also with stories that speak of tradition, sustainability, and innovation, is essential to engaging all actors and facilitating a transition to a more sustainable and resilient production model.

In conclusion, the adoption of the digital product passport and its evolution through advanced technologies such as artificial intelligence and blockchain, in combination with an eco-design approach, represent a promising way forward for the future of Made in Italy. These tools will not only contribute to making the production chain more transparent and efficient. They will also foster the creation of an inclusive and sustainable economic model capable of tackling the global challenges of climate change and promoting fair and inclusive economic growth.

Living words

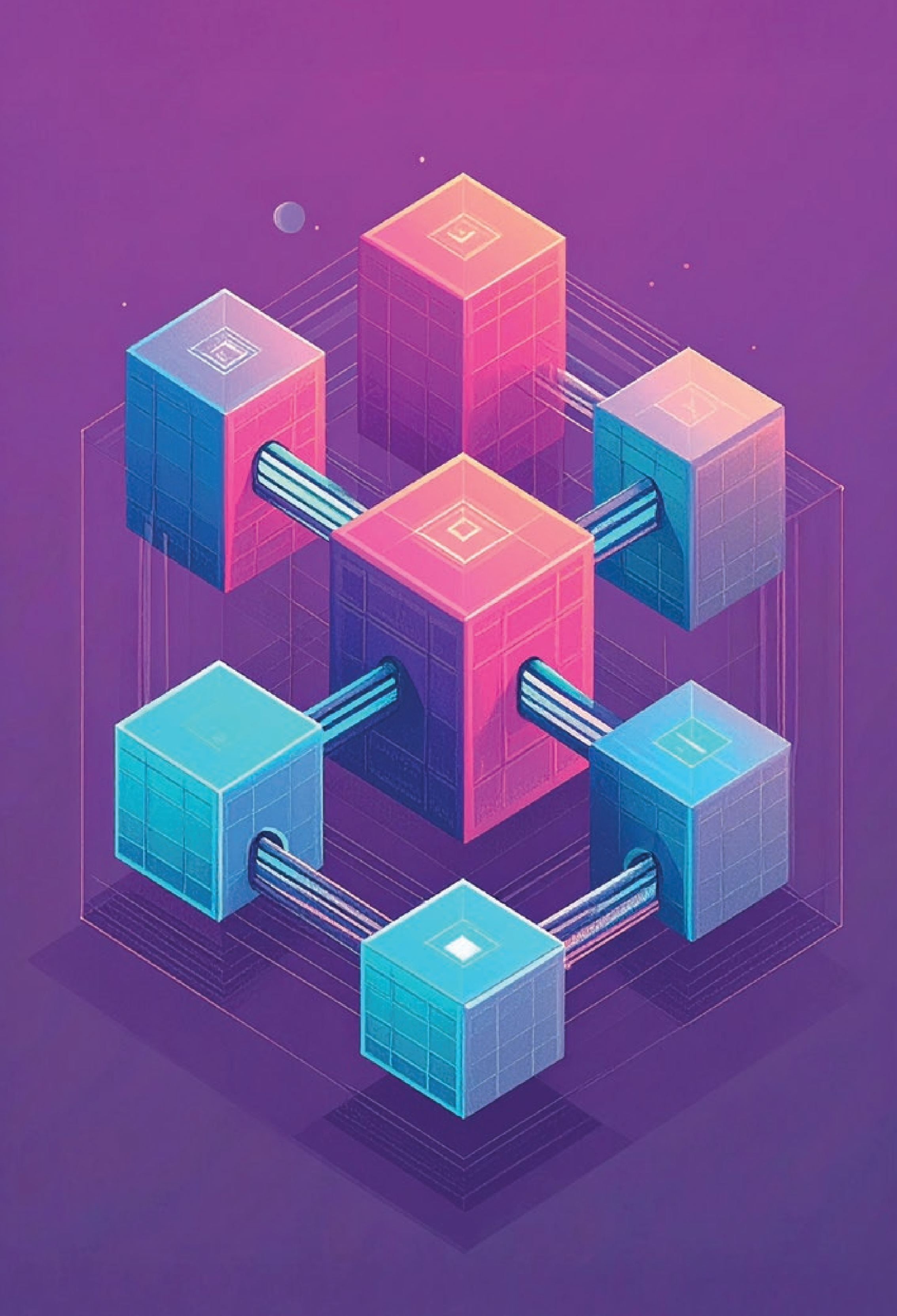
second part

Blockchain

Blockchain is a model for managing information in a distributed system, i.e., a network of interconnected nodes (computers) that collaborate without a central controlling entity. In this system, data is not stored in a single server but replicated and shared among all participants, providing greater security, transparency, and resistance to failure or manipulation. Since 2023, there have been no officially recognised standards, and the scientific literature and popular implementations adopt different interpretations and variants of this general concept[1].

Blockchain represents an innovative method because it allows everyone participating in the network to see the same information, who is changing it and how. The term distributed ledgers is fundamental: data is not stored in one central location but distributed across multiple computers. The system collects information in blocks and links them together to form a chain. This way, it is always possible to see who recorded the information first and in what order.

1. Tabatabaei M.H., Vitenberg R., Veeraragavan N.R. (2023), *Understanding blockchain: Definitions, architecture, design, and system comparison*, in «Computer Science Review», vol. 50.



Building Heritage Material Passport

A Building Heritage Material Passport refers to a Material Passport applied to local building techniques to enhance local resources, identify traditional building-related skills and trades, preserve historical memory, and improve materials' traceability[1]

The use of digital passports applied to heritage would make it possible to have available the complete DNA of the life cycle of existing buildings, not only to pursue the principles of circular economy, as demonstrated by several initiatives developed in Europe, but in particular to enhance the potential, identification, and preservation of an area's historical memory.

1. Bernardo G., Guida A. (2024), *Building Heritage Materials Passports (BHMPs) for resilient communities*, Colloqui.AT.e, Convegno Artec.

Building Information Modeling (BIM*)*

BIM (Building Information Modeling) is a method that uses a shared three-dimensional digital model of a built asset, such as a building or infrastructure, to optimise design, construction and management processes, providing a reliable basis for decision-making[1]. Beyond being a simple digital representation, BIM constitutes a true information system that integrates essential building data, including details on materials, installations, energy performance and maintenance, supporting the entire life cycle of the building. The sharing feature means that the model is accessible to all those involved in the process (architects, engineers, builders, managers, etc.), facilitating collaboration and optimised information management to reduce errors and inefficiencies.

1. ISO (s.d.), *ISO 19650-1 – Building Information Modelling – BIM – Part 1: Concepts and terminology*, British Standards Institution, s.l.

Burden shifting

Burden shifting is a concept used mainly in the context of life cycle assessment (LCA) and the circular economy, which describes the transfer of negative environmental impacts from one stage of the life cycle of a product or service to another without actually reducing the overall impact[1]. For example, companies may reduce pollution at one stage of the production process but cause it to increase at another, such as during transport or disposal. To prevent burden shifting, organisations should adopt a Life Cycle Thinking (LCT) approach, which considers the entire life cycle of a product, addressing environmental impacts at all stages and avoiding shifting problems without solving them.

1. ISO (2006b), *ISO 14044:2006 – Environmental management – Life cycle assessment – Requirements and guidelines*, International Organization for Standardization, Ginevra.

Carbon footprint

The Carbon Footprint represents the total sum of greenhouse gas emissions and removals, expressed in CO_2 equivalent (greenhouse gas emissions are converted into an equivalent amount of carbon dioxide using a parameter called Global Warming Potential – GWP). Based on a life cycle assessment, this measure only considers the impacts of climate change[1]. Devised to quantify the impact of human activities on the environment, the Carbon Footprint allows us to assess both direct emissions, generated, for example, by the combustion of fossil fuels for energy production, heating and transport, and indirect emissions, linked to the production and disposal of consumed goods, food and services. Reducing the carbon footprint is possible through various strategies, such as adopting renewable energy (solar and wind) and changing consumption and travel habits[2].

1. European Union (2024), *Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for products (L 178/1)*, Publications Office of the European Union, Luxembourg.
2. United Nations Development Programme (2023), *The Climate Dictionary. Speak climate fluently*, https://www.undp.org/publications/climate-dictionary.

Carbon neutrality

Carbon neutrality, or net zero, means minimising emissions of carbon dioxide – the most widespread greenhouse gas – and offsetting the remaining emissions by removing them from the atmosphere or balancing them with equivalent actions. In line with the Green Deal, the European Union has committed itself to achieving this balance by 2050. For every tonne of climate-changing gases emitted, another tonne must be captured, e.g. through plant photosynthesis or other natural solutions. In this context, ecodesign and biogenic materials – derived from renewable resources and capable of storing carbon – become key tools for designing more sustainable products and environments.

Causal Artificial Intelligence

A class of artificial intelligence systems designed to identify, model, and reason about cause-and-effect relationships within data, rather than relying solely on statistical correlations. Causal AI enables interventional and counterfactual reasoning, allowing systems to answer questions such as What will happen if we do X? or What would have happened if Y had not occurred? Grounded in the theory of causal inference, Causal AI leverages tools such as structural causal models (SCMs), causal graphs (e.g., Directed Acyclic Graphs – DAGs), and do-calculus to simulate outcomes, guide decision-making, and enhance generalization across contexts. These foundations are extensively developed in the work of Judea Pearl[1] and expanded in recent research on causal representation learning[2].

This approach supports transparency, robustness, and explainability in AI systems—critical features in applications where actionability and impact evaluation are central. Major research labs and technology providers, such as IBM Research and Microsoft Research, identify Causal AI as a key frontier for reliable, human-aligned, and ethically grounded artificial intelligence[3,4]. In the field of Digital Product Passports (DPPs) and ecodesign, Causal AI provides strategic value by modeling the downstream effects of design choices, materials, and production processes. It enables

1. Pearl J. (2009), *Causality: Models, Reasoning, and Inference* (2nd ed.), Cambridge University Press.

2. Schölkopf B. (2021), *Causal Representation Learning: A Review*, https://arxiv.org/abs/2102.11107.

3. IBM Research (2022), *Causal AI: The Next Frontier in Artificial Intelligence*, https://research.ibm.com/blog/causal-ai.

4. Microsoft Research (2023), *Causal AI: Learning and Reasoning About Interventions and Counterfactuals*, https://www.microsoft.com/en-us/research/project/causal-inference.

predictive insights that support circularity, traceability, and sustainable innovation in alignment with climate goals and emerging regulatory frameworks.

Causal Artificial Intelligence

Circular design

The circular design is a regenerative economic model that aims to decouple economic growth from the consumption of finite resources, as opposed to the traditional linear take-make-dispose approach[1]. This paradigm promotes the reduction of waste and the valorisation of resources through strategies that favour reuse or recycling (e.g. lengthening the value of materials as much as possible), sustainable design (evaluations at the design stage), encouraging production systems with a reduced environmental impact, favouring innovation if it is low impact or improved, and promoting collaboration between realities to create ecosystems of value. Borrello and Pascucci highlight how the circular economy integrates principles from different schools of thought, offering a new perspective for the transition to innovative industrial systems capable of improving environmental and economic sustainability through greater efficiency in the use of resources[2]. In this vision, as described by Milstein, materials and goods are not destined to become waste but are continuously recovered, regenerated or reintroduced into the production cycle, thus minimising environmental impact[3].

Regarding products, the circular economy considers their entire life cycle, which consists of several stages. The production phase encompasses all processes that lead to the creation of a good, from the extraction of the raw material to its distribution. After production, the operational phase begins: the product serves

1. Ellen MacArthur Foundation. (n.d.), *The circular economy in detail*, cit.

2. Borrello M., Pascucci S., Cembalo L. (2020), *Three propositions to unify circular economy*, in «Sustainability», 12(10), 4069.

3. Heisel F., Hebel D.E., Webster K. (2022), *Building better – less – different: Circular construction and circular economy fundamentals, case studies, strategies*, Birkhäuser.

its function and remains in use until it becomes unusable. Finally, the circular phase starts, during which actors recover the product, break it down into its constituent materials, and send them to recycling centres instead of disposing of them as waste. This process allows these materials to be reintroduced into the production cycle, reducing the need for new resources and limiting environmental impact. Integrating these steps into a circular system is essential for a more sustainable and resilient economy, strengthening the link between innovation, efficient resource management and waste reduction[4].

4. Salgado M.S., Ferrari A.M., Settembre-Blundo D., Cucchi M., García-Muiña F.E. (2022), *Life cycle costing as a way to include economic sustainability in the circular economy: New perspectives from resource-intensive industries*, in «Circular economy and sustainability», pp. 161-176.

Class of performance

The performance class indicates a scale of levels that measures a product's performance according to criteria defined in Annex I of ESPR 2024/1781[1]. These criteria include parameters such as energy efficiency, durability, reparability, reusability, recyclability, and environmental impact throughout the product's life cycle. The classification follows a standardised methodology for products of the same type, allowing them to be compared in a structured way and facilitating more informed choices with a view to sustainability and the circular economy.

1. European Union (2024), *Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for products (L 178/1)*, Publications Office of the European Union, Luxembourg.

Component

A component is a product manufactured as a distinct unit, i.e., an autonomous and identifiable element within a larger system designed to perform one or more specific functions[1]. For example, a processor in a computer, a hinge in a piece of furniture, or a battery in an electric car are all essential components that contribute to the functioning of the final product.

In design, conceiving a component sustainably means integrating environmental considerations from the earliest stages of development, avoiding the mistake of limiting sustainable choices only to production or disposal. The design phase is crucial to reducing the overall environmental impact by carefully selecting materials, predicting energy consumption during production, and evaluating use and end-of-life patterns. Shape and size influence sustainability, as does reparability-oriented design to extend product life and reduce waste.

1. ISO (2020b), *ISO 6707-1:2020 – Buildings and civil engineering works – Vocabulary – Part 1: General terms, International Organization for Standardization*, Ginevra, https://www.iso.org/obp/ui/en/#iso:std:iso:6707:-1:ed-6:v1:en.

Construction Product Regulation (CPR)

The Construction Product Regulation (CPR) sets the essential requirements for construction products in the European Union, ensuring that they meet specific safety and performance standards[1].

These requirements cover several key aspects, including structural integrity, fire safety, health protection and prevention of physical injury, acoustic properties, energy efficiency and thermal performance, control of harmful emissions and sustainable use of natural resources. The aim is to ensure that buildings and infrastructure are safe, sustainable and energy efficient, contributing to higher quality and reliability in the construction sector.

1. European Commission (2022), *Annexes to the proposal for a regulation of the European Parliament and of the Council laying down harmonised conditions for the marketing of construction products, amending Regulation (EU) 2019/1020 and repealing Regulation (EU) 305/2011*, COM(2022) 144 final. Brussels, 30 March 2022.

Construction and demolition waste (CDW)

Construction and demolition waste (CDW) comprises waste materials generated during the construction, renovation and demolition of buildings and infrastructure. Construction waste results from constructing structures such as houses, commercial buildings, industrial plants, schools and dams. Demolition waste, on the other hand, comes from the destruction of buildings, roads, pavements and other structures.

According to Directive 2008/98/EC on waste[1], CDW represents more than one-third of all waste generated in the European Union. These materials include concrete, wood, metals, glass and plastics. Despite available recycling technologies, recovery rates vary widely between member states, ranging from less than 10% to over 90%. The EU aims to increase reuse and recycling of CDW to at least 70 per cent, promoting practices such as selective dismantling to improve material separation and recovery. In addition, careful management of hazardous waste in CDW, such as asbestos, is essential to reduce environmental and health risks. These actions are part of the European strategies for a circular economy, aimed at minimising waste generation and maximising the valorisation of resources.

1. European Commission (2008), *Waste Framework Directive*.

Cradle to Cradle (C2C)

The Cradle to Cradle (C2C) concept, also known as regenerative design, promotes a system in which designers create materials to be continuously reused, without generating waste. This approach relies on four fundamental principles: 1) analysing the biological and technical cycles of materials, 2) designing products that allow easy reinsertion into their natural or industrial cycles, 3) considering the entire life cycle of materials to ensure their long-term circulation, compatible with the environment and human life, and 4) developing business models that incentivise the return of materials, maximising their reuse. The main objective of C2C is eco-efficiency, i.e. the idea that human activities can benefit the ecosystem, as opposed to eco-efficiency, which focuses on reducing negative environmental impacts[1].

1. Braungart M., McDonough W. (2003), *Dalla culla alla culla. Come conciliare tutela dell'ambiente, equità sociale e sviluppo*, Blu edizioni.

Design for Deconstruction, Disassembly and Adaptability

Design for Deconstruction (DfD) and Design for Disassembly and Adaptability (DfD/A) are similar concepts but with some differences. Both represent important approaches within the circular economy.

DfD originated in the construction industry in the 1990s[1] and focuses on designing buildings to be easily dismantled at the end of their life cycle. This approach's main objectives are to reduce waste production, maximise the recovery of valuable materials and components, and encourage their reuse and recycling. In practice, DfD plans selective dismantling from the outset, turning it into an efficient and sustainable process that contributes to the circularity of materials[2].

Design for Disassembly (DfD) has a similar focus but tends to be applied in more general contexts, not just limited to construction. This approach focuses on designing products and structures for easy disassembly, allowing the separation and recovery of individual components, reducing waste and promoting reuse. DfD is, therefore, a principle that can be applied to a wide range of sectors, from manufacturing to electronics, to improve resource efficiency and reduce environmental impact[3].

Finally, Design for Disassembly and Adaptability (DfD/A) is a broader concept that extends to DfD. Although it includes the

1. Kibert C.J. (2003), *Deconstruction: The start of a sustainable materials strategy for the built environment*, in «Industry and Environment», pp. 84-88.

2. Macozoma D. (2002), *Understanding the concept of flexibility in design for deconstruction*, in *Design for Deconstruction and Materials Reuse*, pp. 118-127.

3. Ostapska K., Rüther P., Loli A., Gradeci K. (2024), *Design for Disassembly: A systematic scoping review and analysis of built structures Designed for Disassembly*, in «Sustainable Production and Consumption», 48, pp. 377-395.

possibility to easily disassemble products at the end of their life, DfD/A also strongly emphasises adaptability over time. In other words, it not only facilitates disassembly but also allows for modifications and transformations during the life cycle of the product or building, avoiding waste and improving its longevity. This approach considers flexibility in design, allowing objects or buildings to evolve and adapt to new needs without being disposed of or destroyed[4].

4. ISO (2020a), *ISO 20887:2020 – Sustainability in buildings and civil engineering works – Design for disassembly and adaptability – Principles, requirements and guidance*, International Organization for Standardization, Ginevra, https://www.steelconstruct.com/wp-content/uploads/ISO-20887_2020_01.pdf.

Digital Product Passport (DPP)

The digital product passport is a tool that collects accurate, complete and up-to-date data on a product along the entire value chain, intending to improve its traceability. The information contained in the passport is accessible to all stakeholders involved without compromising the protection of confidential business information. This tool becomes particularly important with the entry into force of the European Directive on the eco-design of sustainable products[1], expected within 18 months, which will help consumers make more informed choices by improving access to relevant information.

The digital product passport will enable a wide range of actors, such as manufacturers, importers, distributors, retailers, customers, repairers, reconditioners, recyclers, market surveillance and customs authorities, and civil society organisations, to access, update, and enter relevant data. This tool aligns with the principles of the circular economy, fostering transparency and collaboration between the various actors in the value chain.

A 2023 study[2] identifies the main actors involved in creating a PLR, which include suppliers, manufacturers, service providers, customers and third-party recycling companies. The approach suggests that these actors have flexible and interchangeable roles, where customers can also be suppliers and client companies, in perfect harmony with circular principles. The central theme of the

1. European Union (2024), *Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for products (L 178/1)*, Publications Office of the European Union, Luxembourg.

2. Jensen S.F., Kristensen J.H., Adamsen S., Christensen A., Waehrens B.V. (2023), *digital product passports for a circular economy: Data needs for product life cycle decision-making*, in «Sustainable Production and Consumption», 37, pp. 242-255.

study concerns the definition of the most relevant data to be collected and shared, and the study identifies seven main categories: use and maintenance, product identification, materials and components, guidelines and manuals, supply chain and reverse logistics, environmental data and compliance.

The European Commission and other studies[3] emphasise that the involvement of numerous actors and the collection of a large data set are necessary prerequisites for the success of DPP. This approach opens the door to new forms of collaboration, where data are exchanged on dynamic platforms, fostering a continuous flow of information that supports the transition to more sustainable business models.

While the DPP collects and centralises all essential information about a product throughout its life cycle, the figure authorised to manage, process and make this data available to all stakeholders is the Digital Product Passport Service Provider (DPP Service Provider). The DPP Service Provider is an independent entity (a person or a company) authorised by the manufacturer or distributor of the product. Its main task is to manage the data contained in the Digital Product Passport and ensure that this data is accessible to anyone who has the right to consult it, such as other companies or actors involved in the product supply chain, in compliance with applicable European laws. Numerous studies have explored crucial issues regarding digital passports, including who are the stakeholders involved in the process, what role do they play, what kind of information require and to what extent, and whether this information should be made public or require higher levels of security and protection.

3. Berger K., Baumgartner R.J., Weinzerl M., Bachler J., Preston K., Schöggl J.-P. (2023), *Data requirements and availabilities for a digital battery passport – A value chain actor perspective*, in «Journal of Cleaner Production», 4, https://doi.org/10.1016/j.clpl.2023.100032.


Digital Product Passport

Digital twin

The digital twin is a virtual and dynamic representation of a physical entity, such as a product, system or process, which is constantly updated to reflect the real state of the latter. This digital model is synchronised in real-time with the physical object or system to which it corresponds, enabling data collection that engineers or system managers can use to optimise management and make informed decisions. In other words, the digital twin acts as a 'knowledge model', providing an accurate representation of operational reality that organisations can use to analyse and predict behaviour and performance[1].

In simplified terms, the digital twin is the digital replica of a physical entity that collects and uses information to improve its management and monitoring.

1. Semeraro C., Lezoche M., Panetto H., Dassisti M. (2021), *Digital twin paradigm: A systematic literature review*, in «Computers in Industry», 130, 103469.

Downcycling

Downcycling refers to the process in which materials are recycled into lower-quality or reduced-value products. Currently, most forms of recycling are downcycling, as technological limitations prevent the complete recovery of materials in their original state. This means that although materials such as paper are recycled, they lose some of their original properties-such as strength or quality, due to the degradation of fibres or the inability to reuse certain components, such as coatings. For example, when paper is recycled, the fibres become shorter; manufacturers must add new fibres to maintain strength, preventing the process from being completely closed.

Although downcycling reduces the need for virgin materials, it should be considered a last resort in the recycling hierarchy. As long as technologies remain limited and products degrade during recycling, downcycling will remain a necessary method to extend the life of materials. However, companies should pursue superior sustainability techniques whenever possible to improve the effectiveness of recycling efforts and reduce their environmental impact[1].

1. Chini A.R. (ed.) (n.d.). *Deconstruction and materials reuse – An international overview* (CIB Publication 300, Final Report of Task Group 39 on Deconstruction), University of Florida.

Ecodesign

Over the years, numerous terms related to sustainability and design have emerged since the 1960s and 1970s, reflecting evolving thinking and approaches to environmental challenges. While sharing the common goal of promoting more sustainable design practices, these concepts have diversified and specialised to meet increasingly complex needs. In this context, approaches such as Ecodesign, Green design and Design for Sustainable have represented specific responses, with distinct but complementary focuses, to reduce environmental impacts and promote more integrated sustainability. While Ecodesign considers the entire product life cycle, Green design focuses on specific aspects. Design for Sustainable embraces a systemic approach that requires a collective effort among all stakeholders, balancing environmental, social and economic needs to ensure global sustainability.

Ecodesign, as defined by the European Commission in 1998, represents the systematic integration of environmental aspects into a product's design, aiming to improve its environmental performance throughout its entire life cycle. This concept, central to environmental and industrial policies in the 1990s[1], focuses on considering the product's environmental impact at an early design stage. The ecodesign principle goes beyond improving product performance in terms of functionality: it aims to reduce the natural resources used, minimise waste and emissions, and optimise material management throughout the entire life cycle, thus significantly contributing to sustainability.

Over time, companies and institutions have adopted Ecodesign as an integrated approach that meets regulatory requirements and

1. Schäfer M., Löwer M. (2021), *Ecodesign—A Review of Reviews*, in «Sustainability», 13, 315.

proposes more efficient and innovative solutions to reduce environmental impact, as highlighted by EU Directive 2024/1781. The latter emphasises the need to include environmental considerations at every stage of a product's life cycle, from design through production to end-of-life, where material management and recycling become key. Ecodesign is not only limited to the design of a product but also considers its ability to be reused, recycled or recovered, thus making the production cycle more circular.

In this context, ecodesign requirements are crucial. They set performance targets that address the efficiency of the product and its sustainability by reducing negative environmental impacts. These requirements translate into specifications the product must meet to be considered eco-friendly, including criteria related to natural resource consumption, greenhouse gas emissions, recycling, and waste management. Among the main eco-design requirements[2], we find adaptability, which refers to the possibility of modifying a product, system or module to suit a particular purpose; assembly, which refers to the integration of interconnected components to ensure the functionality and repairability of the product; and durability, which represents the ability of a product to maintain its function and performance over time under conditions of use, maintenance and repair. Durability is a key aspect of the circular economy as it extends the useful life of products, reducing the need to use new resources and minimising waste generation. Designing focusing on durability implies a significant reduction in the demand for virgin resources, contributing to a more sustainable life cycle management of products[3]. These concepts are essential to ensure that design responds to immediate needs and fits into a circular economy logic, where waste minimisation and resource optimisation are central objectives.

2. ISO (2020b), *ISO 6707-1:2020 – Buildings and civil engineering works – Vocabulary – Part 1: General terms*, International Organization for Standardization, Ginevra, https://www.iso.org/obp/ui/en/#iso:std:iso:6707:-1:ed-6:v1:en.

3. ISO (2017), *ISO 17738-1:2017 – Thermal insulation products – Exterior insulation and finish systems – Part 1: Materials and systems*, International Organization for Standardization, Ginevra, https://www.iso.org/obp/ui/#iso:std:iso:17738:-1:ed-1:v1:en.

Ecodesign

Economic footprint

The economic footprint represents the ability of an organisation—be it a company, an association, or a public body—to maintain a sustainable economic balance over time, ensuring business continuity without compromising future resources. Along with environmental and social sustainability, it is one of the three fundamental dimensions of integrated sustainability.

This footprint includes direct, indirect, and induced economic impacts generated by the entire value chain. The assessment of this footprint uses indicators such as income, employment, labour productivity, research and development activity and intensity indicators[1].

1. WifOR Institute (s.d.), *Case study: The Economic and R&D Footprint of the Graphene Flagship Project*, https://www.wifor.com/en/economic-footprint/.

Economic footprint

Embodied carbon & Operational Carbon

The embodied carbon indicates the total greenhouse gas (GHG) emissions released throughout the upstream stages of a product's life cycle, including raw material extraction, processing, manufacturing, and transportation to the point of use. It accounts for all emissions embedded in the product before it begins its functional life and excludes emissions from the product's use and, in many assessments, its end-of-life stage unless a cradle-to-grave boundary is explicitly applied. Embodied carbon is measured in carbon dioxide equivalents (CO_2e) and plays a critical role in product sustainability, especially for materials, components, and goods with high resource intensity. Strategies to reduce embodied carbon include material substitution, recycling, design optimization, and shorter supply chains.

The Operational Carbon indicates greenhouse gas (GHG) emissions generated during the use phase of a product's life cycle, as it performs its intended function. This includes emissions from energy consumption, fuel use, or other resource inputs required for operation. Operational carbon varies widely by product type—for example, electricity use in electronic devices, fuel consumption in vehicles, or energy demand in household appliances—and is influenced by efficiency, user behavior, and the carbon intensity of energy sources. Reducing operational carbon typically involves improving energy performance, integrating renewable energy, or changing user practices.


Embodied carbon & operational carbon

Embodied energy & Operational energy

In the context of circular economy and energy efficiency, embodied energy and operational energy are key to assessing the overall environmental impact of buildings and products.

The embodied energy is the total amount of energy consumed throughout the upstream stages of a product's life cycle, including raw material extraction, processing, manufacturing, assembly, and transportation to the point of use[1]. It represents all the energy invested before the product is used, often referred to as cradle-to-gate or cradle-to-site energy. Embodied energy is typically measured in megajoules (MJ) or kilowatt-hours (kWh) per unit of product. It is a key metric in life cycle assessment (LCA) and sustainability analysis, especially for energy-and material-intensive products. Reducing embodied energy can involve the use of recycled materials, efficient manufacturing processes, and local sourcing. It becomes crucial to consider embodied energy from the initial planning stages. In many cases, renovating an existing building, preserving its materials and thus embodied energy, maybe more sustainable than demolition and reconstruction, even if the latter results in a more operationally efficient building.

The operational energy consumed during the use phase of a product's life cycle, as it performs its intended function. This includes all electricity, fuel, or other energy inputs required to operate, maintain, or recharge the product during its service life. In low-efficiency conventional buildings, operational energy can make up to 80-90% of the total energy consumption[2]. However,

1. Guidetti E., Ferrara M. (2023), *Embodied energy in existing buildings as a tool for sustainable intervention on urban heritage*, in «Sustainable Cities and Society», 88, 104284, https://doi.org/10.1016/j.scs.2022.104284.

2. Habash R. (2022), *Building as an energy system*, in *Sustainability and Health in*

with technological improvements and the introduction of more restrictive regulations, the incidence of operational energy is gradually decreasing, bringing the focus towards embodied energy. Operational energy is influenced by product efficiency, usage patterns, and the energy mix (e.g., fossil vs. renewable sources). It is typically measured in kWh per year or over the product's lifetime, and is a major focus of energy performance standards, eco-labeling, and regulatory compliance.

Intelligent Buildings, Woodhead Publishing, pp. 59-94, https://doi.org/10.1016/B978-0-323-98826-1.00003-X.

Energy-related product

An energy-related product is any good that impacts energy consumption during its use: it includes products that consume energy directly (such as household appliances, electronic devices, or heating systems) and those that contribute indirectly to energy consumption, e.g., through thermal insulation or the efficiency of the materials used[1].

1. European Union (2024), *Directive 2024/1781 of the European Parliament and of the Council on Ecodesign for Sustainable Products Regulation (ESPR).*

Environmental footprint

The Environmental Footprint measures the environmental impacts associated with a product, process, or organisation throughout its life cycle, from extraction of raw materials to disposal or recycling[1]. This approach identifies and quantifies the consumption of natural resources (such as energy, water, and soil) and the emissions generated (such as CO_2, air pollutants, or waste) at each stage[2].

The assessment can focus on a single impact category, such as climate change, or a broader set of sixteen environmental categories, following a harmonised methodology based on Life Cycle Analysis (LCA)[3]. The main applications of this methodology are the Product Environmental Footprint (PEF), which measures the environmental impacts of goods and services, and the Organisation Environmental Footprint (OEF), which assesses an organisation's overall environmental performance.

These tools, developed within the framework of European policies, aim to standardise the measurement of environmental impacts and support more sustainable and transparent decisions by companies, consumers and institutions.

1. European Commission (2021), *Raccomandazione (UE) 2021/2279 della Commissione del 15 dicembre 2021 sull'uso della Product Environmental Footprint per misurare le prestazioni ambientali dei prodotti*, in «Gazzetta ufficiale dell'Unione europea», L 471/1.

2. ISO (s.d.), *ISO 14000/44 – Environmental management – Life cycle assessment – Requirements and guidelines*, British Standards Institution, s.l.

3. ISO (2006a), *ISO 14040:2006 – Environmental management – Life cycle assessment – Principles and framework*, International Organization for Standardization, Ginevra, https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en.

Global Warming Potential (GWP)

The Global Warming Potential (GWP) is an indicator used to measure the environmental impact of greenhouse gases[1]. As a reference point, GWP is expressed using carbon dioxide (CO_2), the most common and studied greenhouse gas. Since CO_2 has a GWP of 1, other greenhouse gases, such as methane or nitrous oxide, have a GWP greater than 1, as they have a stronger impact on global warming than CO_2. GWP is, therefore, crucial for assessing the environmental impact of a given product, process or material, as it allows one to compare the impact of different greenhouse gases on climate change, facilitating more informed choices and promoting greater sustainability.

1. Morganti L., Esnarrizaga P.E., Pracucci A., Zaffagnini T., Cortes V.G., Rudenå A., Brunklaus B., Larraz J.A. (2024), *Data-driven and LCA-based Framework for environmental and circular assessment of Modular Curtain Walls*, in «Journal of Facade Design and Engineering», 12(1), pp. 9-42, https://doi.org/10.47982/jfde.2024.305.

Greenwashing

Greenwashing refers to practices in which a company makes misleading claims about its positive environmental impact or the sustainability of its products and services to convince consumers that it is actively contributing to the fight against climate change. In some cases, greenwashing may result from a lack of knowledge about environmental issues, but in others, it may be a deliberate action driven by marketing and public relations strategies that exploit the growing public support for environmental policies with the intention of gaining economic benefits[1].

In June 2024, the Council of the European Union[2] reached a preliminary agreement on the directive on environmental claims, a measure that aims to combat greenwashing in particular. The directive aims to make companies' environmental claims more credible, protect consumers from misleading practices, and promote a more transparent and sustainable market.

1. United Nations Development Programme (2023), *The Climate Dictionary. Speak climate fluently*, cit.

2. Council of the European Union (2024), *Proposal 11312/24 for a Directive of the European Parliament and of the Council on substantiation and communication of explicit environmental claims (Green Claims Directive) – General approach*, https://data.consilium.europa.eu/doc/document/ST-11312-2024-INIT/en/pdf.

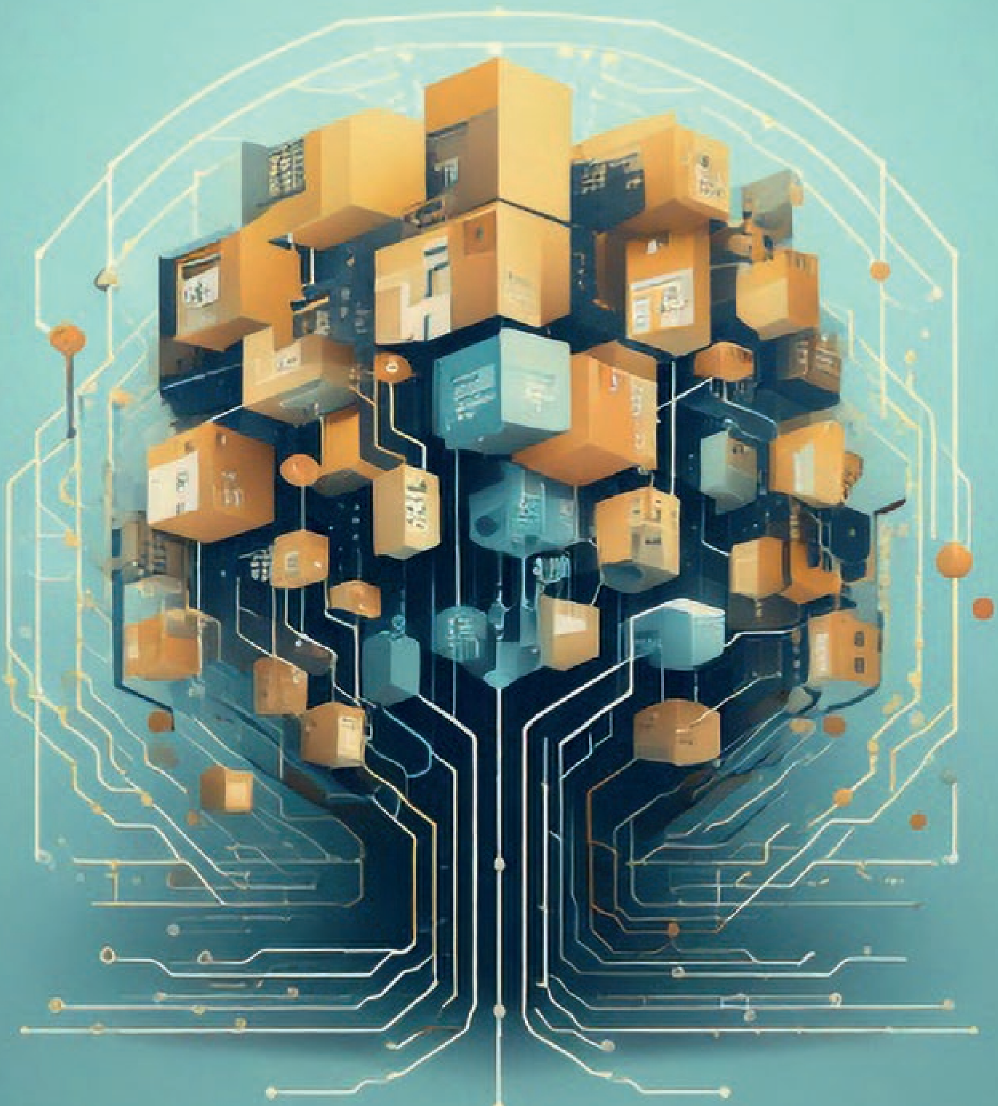
Information accessibility

Accessibility is a key factor that concerns how easily users can access, use, visualise, analyse, and interact with certain information. In particular, digital accessibility focuses on the ability of a wide audience to access data about a product or system. Ensuring that data is easily accessible, understandable and usable is essential to facilitate the flow of information between stakeholders, enabling more transparent communication and effective resource management. Ensuring the accessibility of information is therefore crucial for the involvement of all stakeholders and for improving sustainability, as it allows for deeper analysis and understanding of data, facilitating informed decisions.

Information inheritance

Information inheritance is a function that allows some or all of the data relating to a product at the end of its useful life to be transferred to a new product[1]. This process can include information on the product's life cycle, resources used, environmental impact and performance. The inheritance of information facilitates traceability and resource management throughout the product life cycle, promoting sustainability and reuse of information, improving efficiency and fostering innovation in new product design. The transfer of this information is essential to improve recycling, reuse and upcycling practices.

1. Psarommatis F., May G. (2024), *Digital Product Passport: A Pathway to Circularity and Sustainability in Modern Manufacturing*, in «Sustainability» (Switzerland), 16(1), https://doi.org/10.3390/su16010396.



Life Cycle Thinking (LCT)

Life Cycle Thinking (LCT) is an approach to analysing the environmental, economic and social sustainability of products, services, technologies and systems by considering the entire product life cycle. Life Cycle refers to all consecutive and related phases of a product's life, including raw material acquisition, production, processing, manufacturing, storage, distribution, installation, use, maintenance, repair, improvement, reconditioning, reuse and end-of-life[1]. LCT promotes a holistic and integrated view of sustainability, which helps organisations and decision-makers identify critical areas where they can improve efficiency, reduce negative impacts and optimise resource use.

Among the main tools used to apply the LCT approach is the Life Cycle Assessment (LCA)[2]. This assessment process measures the environmental effects of a product throughout its life cycle. LCA aims to improve resource use efficiency and reduce negative impacts by supporting informed decisions on improving a product's sustainability. LCA, commonly referred to as a 'cradle-to-grave' analysis, comprises three main steps: (1) identifying and quantifying environmental burdens, such as energy and natural resources consumed, emissions and waste produced; (2) assessing the environmental impacts of these burdens; and (3) exploring options to reduce environmental impacts[3].

Although the LCA tool is widely recognised as useful for improv-

1. European Union (2024), *Directive 2024/1781 of the European Parliament and of the Council on Ecodesign for Sustainable Products Regulation (ESPR)*.

2. *ISO 14040:2006, 3.2. Environmental management — Life cycle assessment — Principles and framework*.

3. European Environment Agency (s.d.), *Glossary: Life-cycle assessment (LCA)*, https://www.eea.europa.eu/help/glossary/eea-glossary/life-cycle-assessment.

ing sustainability, it has certain limitations. LCA requires specialised technical skills that can be difficult to integrate into small and medium-sized enterprises and less structured sectors. Furthermore, LCA assessments tend to be expensive, and the quality of available data can vary significantly. To overcome these challenges, stakeholders are developing initiatives such as data standardisation, specialised training, and simplified versions of LCA to make it more accessible and practical for small and medium-sized enterprises and less structured sectors. Another aspect concerns the social impact of LCA. Although this methodology may favour more efficient production processes with less environmental impact, assessing how it affects social dynamics remains important, particularly about the sustainability of supply chains and local suppliers.

Life Cycle Thinking (LCT)

Linear economy

The linear economy, also called “take-make-waste”, is based on a model in which resources are extracted, processed into products, used, and, once consumed, thrown away. As awareness of the finite nature of natural resources and negative environmental impacts, such as climate change and loss of biodiversity, has increased, it has become evident that the linear economy is unsustainable because, in this system, materials and products follow a one-way flow: from raw material to waste. The shift to a circular economy, which promotes reuse, recycling and waste reduction, has become at the heart of contemporary global challenges to reduce environmental impact and preserve resources for future generations.

Linear economy

Material footprint

According to the European Commission, a material footprint is "the total amount of raw materials extracted to meet final consumption demand"[1]. This concept refers to the total amount of natural resources, such as minerals, wood, and fossil fuels, that are extracted from the environment to produce goods and services for final consumption. The material footprint measures the impact of consumption activities on the demand for natural resources, indicating the overall use of raw materials during the production and consumption cycle.

1. European Union (2024), *Directive 2024/1781 of the European Parliament and of the Council on Ecodesign for Sustainable Products Regulation (ESPR)*.

Material footprint

Material passport

Material passport refers to a digital tool used to collect, organise and make accessible, detailed information on the quality and quantity of materials in a product or building throughout its life cycle. It is conceived as an optimisation system to facilitate the traceability of materials over time and facilitate their reuse, disassembly and management in a circular perspective[1].

These passports are essential from the earliest design stages, as they enable informed decisions in material selection, disassembly planning and reducing waste and CO2 emissions. However, they can also be generated at later stages of the life cycle, serving as tools to document and make accessible key material data.

European projects such as BAMB (Buildings As Material Banks) have demonstrated the possibility of creating prototype passports capable of tracking the residual value of materials and products throughout the supply chain[2]. Another significant example is the Dutch Madaster platform, which provides data on CO2 emissions and the value of materials used, facilitating the circular management of buildings and infrastructure[3].

In addition, solutions based on advanced digital technologies have emerged: integrating the passport with tools such as BIM (Building Information Modeling) supports more informed design choices and accurate disassembly planning[4]. Platforms such as

1. Costa A.R., Hoolahan R. (2024), *Material Passport: Accelerating Material Reuse in Construction*, Lancaster University and Orms Designers & Architects Ltd, London, https://doi.org/10.5281/zenodo.10472214.

2. BAMB (2020), *Materials Passports. Buildings as Material Banks*, https://www.bamb2020.eu/topics/materials-passports/.

3. Madaster (s.d.), *What's in it for me?*, https://madaster.com/madaster-benefits.

4. Honic M., Kovacic I., Aschenbrenner P., Ragossnig A. (2021), *Material passports*

Circularise[5] or Concular employ technologies such as blockchain or RFID to ensure data traceability while protecting information confidentiality.

Depending on the scale of the project, the team can construct the passport using simple tools, such as Excel sheets, or more complex cloud-based software or relational databases. However, creating passports for existing buildings is more complex than for new buildings and requires adopting standardised data collection systems (such as Uniclass) and advanced analysis tools.

Finally, recent studies have highlighted the importance of passports in recovering and valorising historical building heritage. In particular, the 2024 BHMPs (Building Heritage Materials Passports) project seeks to bridge the gap in the documentation and management of traditional building techniques, developing tools suitable for rural contexts and inland areas, such as the Basilicata region[6]. This perspective is essential considering that only 30% and 50% of Italy's building stock have adequate documentation and that more than 74% of Italy's housing stock dates back to before 1975. Documenting and transmitting knowledge of traditional materials and techniques is a functional and cultural act because it helps to strengthen the identity of places and future generations.

for the end-of-life stage of buildings: challenges and potentials, in «Journal of Cleaner Production», 319, https://doi.org/10.1016/j.jclepro.2021.128702.

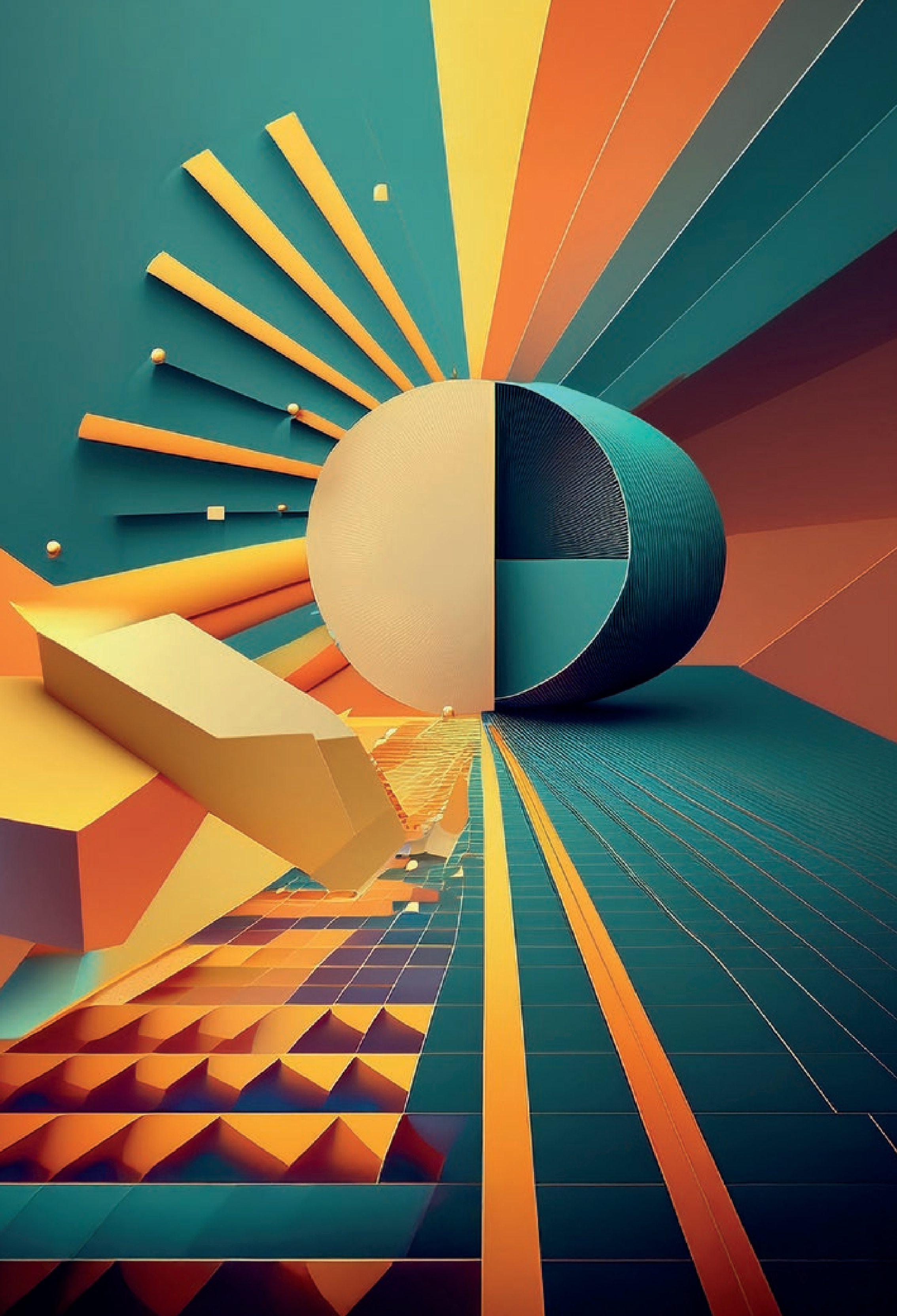
5. Circularise. End-to-end supply chain traceability.

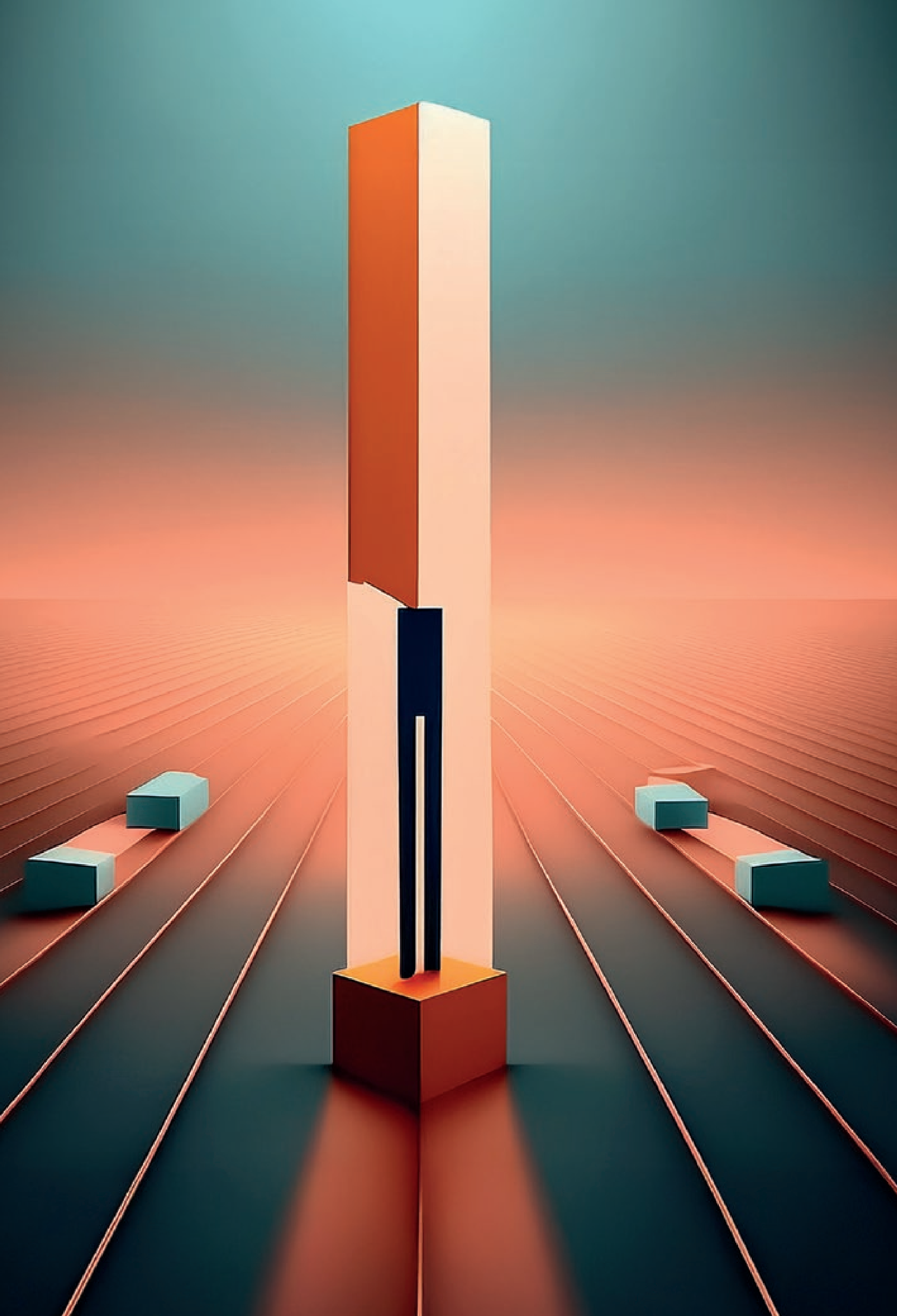
6. Bernardo G., Guida A. (2024), *Building Heritage Materials Passports (BHMPs) for resilient communities*, in «Colloqui.AT.e», 3, pp. 115-127, https://link.springer.com/chapter/10.1007/978-3-031-71867-0_9.

Obsolescence

Related to the term obsolescence[1], which refers to the loss of an item's ability to adequately meet performance requirements due to changes in conditions of use, technological needs or the market environment, are two other concepts: premature obsolescence and planned obsolescence. The former occurs when a product's functions become non-operational, or its performance deteriorates before its expected useful life ends. This deterioration may be caused by inadequate design or by subsequent interventions that impair its functions without such changes being due to normal wear and tear. Planned obsolescence, on the other hand, can occur in many different areas but is most common in electronic products. The paradox of planned obsolescence is that it is deliberately used as a market strategy by manufacturers, who design products with a limited lifespan so that they become obsolete after a certain period, thus prompting consumers to replace them.

1. ISO (2011), *ISO 15686-1:2011 – Buildings and constructed assets – Service life planning – Part 1: General principles*, International Organization for Standardization, Ginevra, https://www.iso.org/obp/ui/#iso:std:iso:15686:-1:ed-2:v1:en.



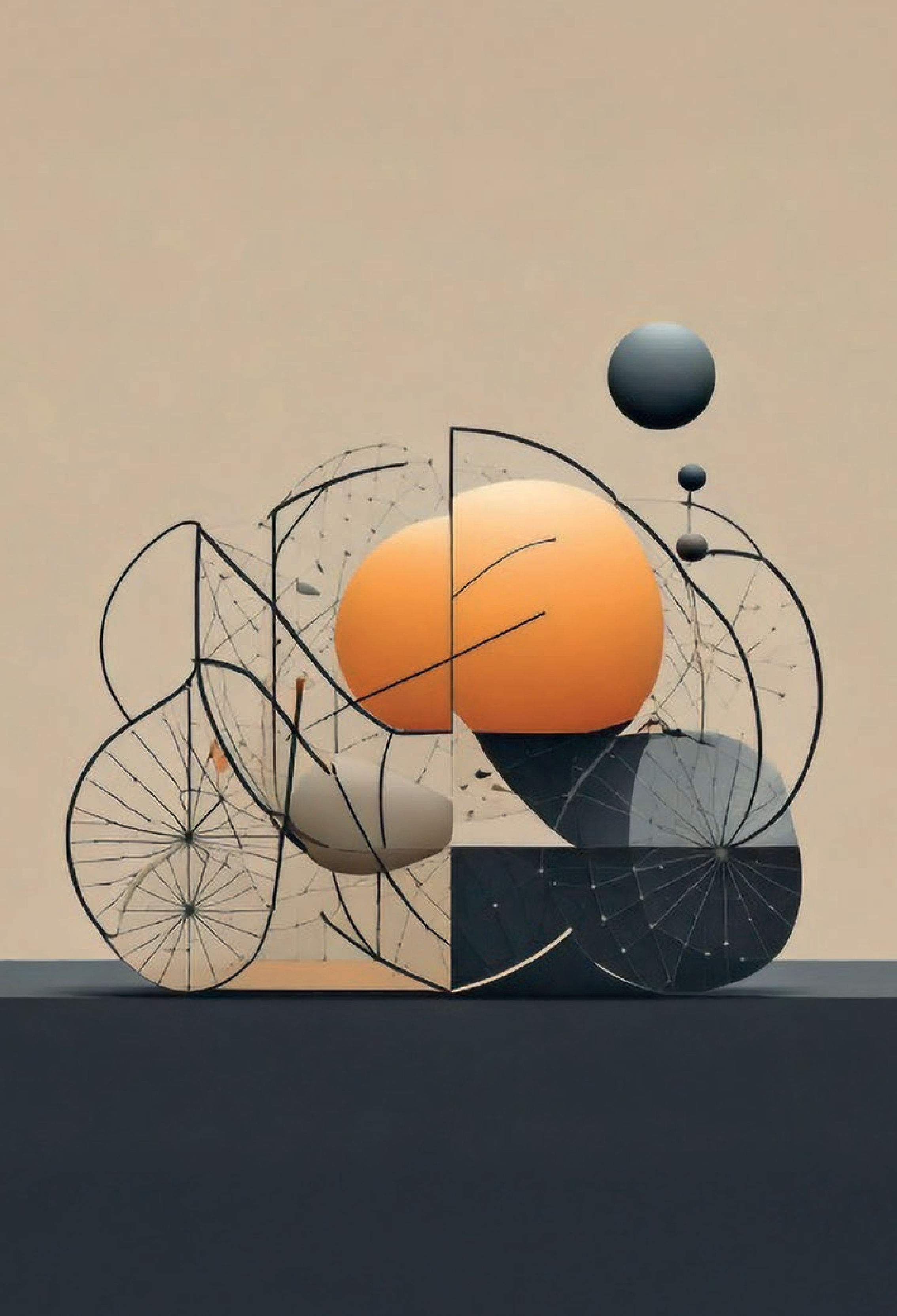


Operative Phase

Production phase: the production phase covers all stages of product creation, from the origin of raw materials to the arrival of the product at the point of sale. This phase addresses crucial aspects such as resource extraction, manufacturing, and distribution of the finished product. The efficiency and environmental impact of production depend on choices such as the use of resources, production technologies, and transport methods.

Operative phase: this phase begins when the product arrives in the hands of prosumers (consumers who can also produce or modify the product) and involves the product's actual use. The product's operability continues until it can no longer be repaired or its components can no longer be replaced, marking the end of its useful life. The duration and intensity of use depend on the type of product, consumer needs, and maintenance operations.

Circularity phase: the circularity phase begins when the product reaches the end of its useful life. In this phase, operators disassemble the product and send its components to recovery centres, where they transform them into new raw materials. This process is essential to promoting the reuse and reduction of resources, thus contributing to a circular economy that reduces the need for new resources and minimises environmental impact.



Open Living Lab

As defined by the European Network of Living Labs (ENoLL), an Open Living Lab is a user-centered, open-innovation ecosystem integrating research and innovation processes in real-life settings. In this spirit, Living Lab functions as a collaborative platform where academia, industry, public institutions, and local communities co-create design solutions for the ecological transition of the built environment.

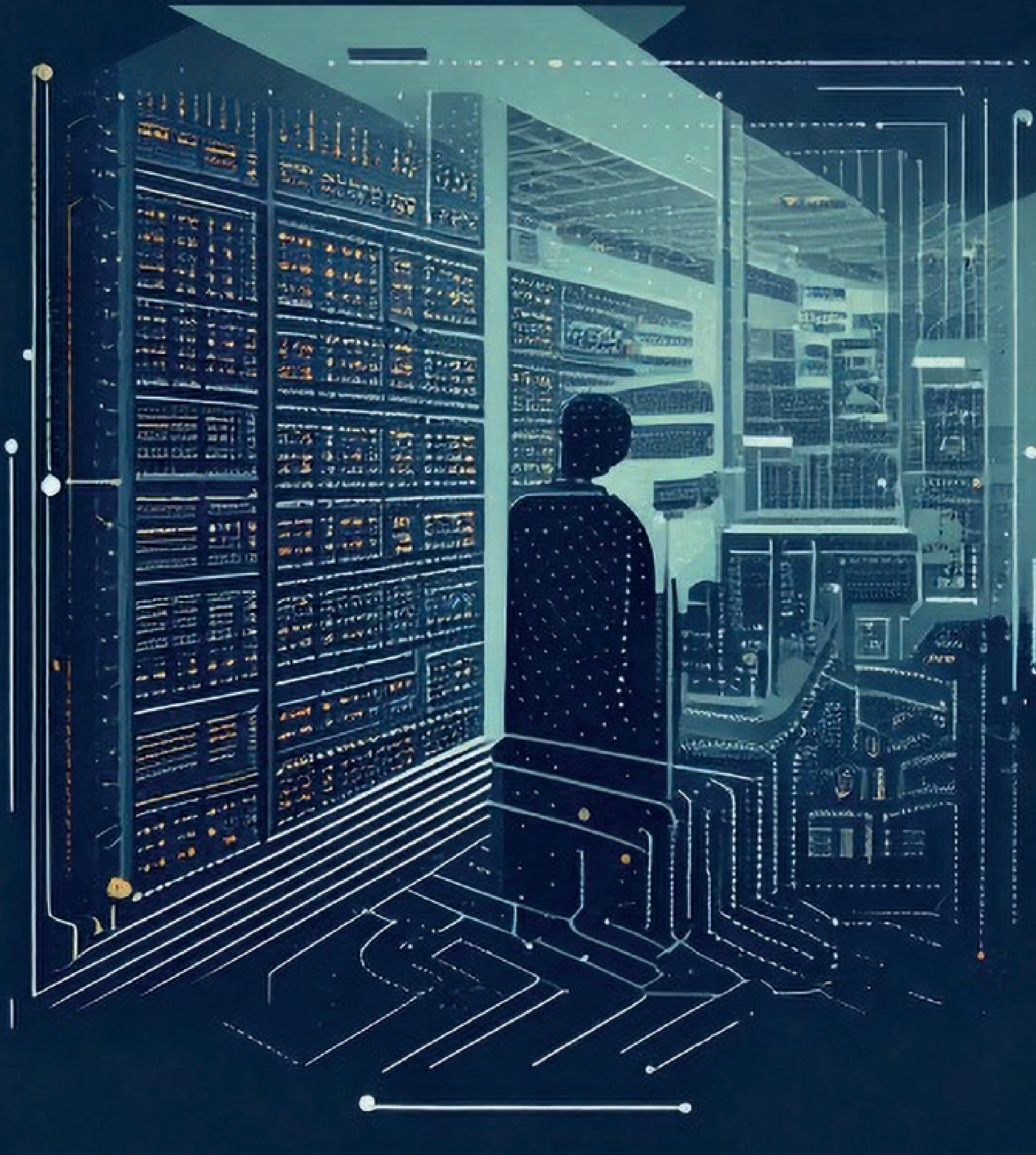
With a strong focus on material circularity, low-impact construction, and environmental performance, the lab encourages the adaptive reuse of building components, the rethinking of design processes, and the implementation of cross-sectoral strategies aligned with the principles of the circular economy and the EU Green Deal. By combining scientific research, design prototyping, and territorial engagement, Living Lab fosters the development of resilient, regenerative, and culturally aware spatial practices.

Performance class

The performance class is a classification that groups products according to their performance levels, using specific parameters that allow users to compare them uniformly. This classification system is mainly used in European legislation, such as in ecodesign and energy efficiency, to differentiate products according to their efficiency and ability to meet certain requirements. In this context, performance requirements represent the quantitative and qualitative requirements that a product must fulfil to achieve the expected level of performance. These requirements define the minimum standards that a product must have to qualify as suitable for its intended use, ensuring that it meets the required efficiency and functionality. Together, the performance class and performance requirements provide a basis for evaluating and comparing products consistently, helping consumers to make informed choices and promoting the competitiveness of products in the marketplace.

Processing

Any operation or set of operations which is performed on data or sets of data in electronic form, whether or not by automated means, such as collection, recording, organisation, structuring, storage, adaptation or alteration, retrieval, consultation, use, disclosure, dissemination or making available, and the comparison, interconnection, restriction, erasure or destruction of data.



Product

The European Union uses the term "product" to refer to a physical good placed on the market or put into service[1]. Design is a strategic player in the transition towards regenerative economic models. Whereas past studies emphasised that 80 per cent of a product's environmental impact was determined at the design stage[2], today, the focus has shifted to the transformative power of design: not only as a reduction of impact but as a driver of systemic change.

Therefore, the design approach must go beyond linear logic and fully embrace the complexity, uncertainty, and plurality of actors and relationships involved in circular systems. Designers are called upon to create more efficient objects or services and to imagine and enable alternative life scenarios, including new forms of production, distribution, use, and post-use.

The required skills go far beyond traditional technical mastery: systemic, speculative, collaborative, and material skills are needed[3], as well as the ability to dialogue with technology, public policy, local communities, and existing infrastructure.

However, the methods to implement this change are still evolving. The challenges are manifold and may concern design for multiple life cycles[4], material literacy – a deep understanding of the transformations, implications and potential of materials[5] or, more

1. European Union (2024), *Directive 2024/1781 of the European Parliament and of the Council on Ecodesign for Sustainable Products Regulation (ESPR)*.

2. European Commission (2014), *Ecodesign your future: how ecodesign can help the environment by making products smarter*, https://data.europa.eu/doi/10.2769/38512.

3. Sumter D., de Koning J., Bakker C., Balkenende R. (2020), *Circular Economy Competencies for Design*, in «Sustainability», 12, 1561, https://doi.org/10.3390/su12041561.

4. Franconi A. (2020), *Multiple design perspectives for the transition to the circular economy: Managing design strategies between systems, designers and time*, University Iuav of Venice.

5. De los Rios I.C., Charnley F.J.S., Sundin E., Lindahl M., Ijomah W. (2017), *Skills*

recently, the use of artificial intelligence in the creative process. Design, in this context, becomes a cultural practice, not only requiring an integrated and transdisciplinary approach, capable of imagining not only the evolution of products but also new relationships between communities, materials, technologies and territories.

and capabilities for a sustainable and circular economy: The changing role of design, in «Journal of Cleaner Production», 160, pp. 109-122.

Product

Product Service System (PSS)

The Product-Service System (PSS) is an innovative model that integrates products and services into a single offering. It aims to satisfy specific user needs without necessarily implying ownership of the physical good. In this approach, the value lies not so much in ownership as in the functional use of the product, fostering collaborative and sustainable modes of consumption.

As Thomas Rau[1], an architect and visionary thinker in the field of sustainability, claimed, what really matters is not owning things but being able to use them when one needs them. An emblematic example is lighting as a service: instead of buying light bulbs or fixtures, a user can pay for the amount of light provided, while the supplier remains the system's owner, thus incentivised to guarantee durability, efficiency, and ease of maintenance.

The PSS model is central to the circular economy because it allows companies to extend the life cycle of goods, reduce waste, and encourage solutions oriented towards durability, reparability, and reuse. It also facilitates a more dynamic relationship between producer and user based on service quality, customisation, and resource optimisation.

From a regenerative perspective, the PSS becomes a tool for redesigning economic models, promoting shared responsibility, systemic innovation and distributed value within communities and value chains.

1. Rau T., Oberhuber S. (2019), *Material matters. L'importanza della materia: Un'alternativa al sovrasfruttamento*, Edizioni Ambiente.

Product Service System (PSS)

Prosumers

The term prosumer, coined by Alvin Toffler in 1980, describes individuals who combine the roles of producer and consumer, actively contributing to the creation of goods and services both for personal use and within communities. This hybrid figure redefines traditional economic models, integrating consumption with productive activities and requiring a revision of value creation processes, consumer behaviour and market dynamics[1].

Technological developments and the spread of digital platforms have enhanced the role of prosumers, facilitating content generation, collaborative innovation and peer-to-peer interactions[2]. In particular, social media and online platforms have amplified their ability to influence product development, marketing strategies and service delivery[3]. Through these practices, prosumers contribute significantly to creating and sharing knowledge[4].

In recent years, their impact has proven to be particularly relevant in the sustainable sphere: By being directly involved in business activities, business relations, and knowledge transfer, consumers can play a key role in developing more responsible economic models[5].

1. Halassi S., Semeijn J., Kiratli N. (2019), *From consumer to prosumer: A supply chain revolution in 3D printing*, in «International Journal of Physical Distribution & Logistics Management», 49, pp. 200-216, https://doi.org/10.1108/IJPDLM-03-2018-0139.

2. Ciasullo M.V., Lim W.M., Manesh M.F., Palumbo R. (2022), *The patient as a prosumer of healthcare: Insights from a bibliometric-interpretive review*, in «Journal of Health Organization and Management», 36, pp. 133-157, https://www.emerald.com/insight/1477-7266.htm.

3. Chan H., Zeng K.J., Yang M.X. (2022), *Review platforms as prosumer communities: Theory, practices and implications*, in «European Journal of Marketing», 56, pp. 2698-2720, https://doi.org/10.1108/EJM-10-2021-0819.

4. Hamari J., Sjöklint M., Ukkonen A. (2016), *The sharing economy: Why people participate in collaborative consumption*, in «Journal of the Association for Information Science and Technology», 67, pp. 2047-2059, https://doi.org/10.1002/asi.23552.

5. Maciaszczyk M., Kocot M. (2021), *Behavior of online prosumers in organic product market as determinant of sustainable consumption*, in «Sustainability», 13(3), pp. 1-14, https://doi.org/10.3390/su13031157.

Provenance

Provenance refers to the origin and traceability of a product or material, including all information related to its life cycle, from its creation or extraction to the transformations it has undergone to its use and transfer throughout the supply chain. This concept has established itself as a key element in promoting transparency, responsibility, and sustainability in production and distribution processes[1].

Detailed knowledge of provenance makes it possible to assess the quality and conformity of products against environmental, ethical or regulatory standards and to support circular economy strategies, particularly those related to recycling, reuse and design for durability. In the digital sphere, technologies such as blockchain or digital product passport tools are expanding the possibilities of reliably tracking information throughout the life cycle of goods, helping to create more transparent and sustainable production systems.

1. Kebede R., Moscati A., Tan H., Johansson P. (2024), *A modular ontology modeling approach to developing digital product passports to promote circular economy in the built environment*, in «Sustainable Production and Consumption», 48, pp. 248-268, https://doi.org/10.1016/j.spc.2024.05.007.

Raw material

Raw material is the basic, unprocessed material used to manufacture or produce a product. This concept is particularly relevant in the circular economy, where the extraction and use of raw materials are among the main environmental impact factors.

From a circular perspective, the approach promotes a more conscious and sustainable use of resources, favouring the reuse and recycling of materials to reduce dependence on virgin resources. In this context, many companies are developing alternative materials or innovative solutions that can replace traditional raw materials, which are often carbon-intensive or difficult to source.

For local communities, access to raw materials can translate into using locally available resources, reducing transport-related emissions and strengthening the local economy. If well structured, this approach can foster the creation of autonomous supply chains, stimulate employment, and make communities more resilient.

However, not all communities have the appropriate resources to meet their production needs. Moreover, the initial costs associated with developing local supply chains can be significant in economic, organisational and time-related terms. For this reason, promoting access to local resources requires a strategy attentive to territorial specificities, supported by targeted investments and partnerships between public and private actors.

Recover, Recycle, Repair and Reuse

In the circular economy, recovering, recycling, repair, and reuse are key strategies for extending products' life cycles, reducing waste, and limiting the extraction of new resources.

Recover refers to extracting value from materials or products that can no longer be reused or recycled. This value can be energetic, e.g., through the incineration of waste to produce heat, electricity or material or through chemical or physical processes that recover useful components (e.g., metals from electronic waste). However, within the waste hierarchy, strategies such as reuse or recycling are preferred over energy recovery[1].

Recycling is reprocessing waste materials into new products, materials or substances with the same or a different purpose. Recycling requires a design vision in which designers conceive the object or material in a transformative way, enabling it to retain value even after its initial use[2]. The concept of recycling potential assesses the ability of a material to be recycled while maintaining quality and functionality, thus contributing to a closed and sustainable production cycle[3].

Repair refers to all activities aimed at restoring a product's original functionality through maintenance or replacement of damaged components. It is a practice that extends the useful life of objects, avoiding premature replacement[4].

1. Gharfalkar M., Court R., Campbell C., Ali Z., Hillier G. (2015), *Analysis of waste hierarchy in the European waste directive 2008/98/EC*, in «Waste Management», 39, pp. 305-313.
2. Olivastri C. (2018), *Con temporaneo. Design per il riuso di spazi abbandonati*. Gangemi.
3. Thormark C. (2001), *Recycling Potential and Design for Disassembly in Buildings*, Lund University e Sun Q., Huang Q., Duan Z., Zhang A. (2022), *Recycling Potential Comparison of Mass Timber Constructions and Concrete Buildings: A Case Study in China*, in «Sustainability» 14, 6174.
4. ISO (2020b), *ISO 6707-1:2020 – Buildings and civil engineering works – Vocabulary –*

Reuse means the repeated use of a product or its components for the same original purpose or even a different function. This practice can occur without modification or prior preparation (cleaning, minor repairs). Reuse reduces environmental impact and can generate social, cultural and economic benefits, especially when integrated into local communities[5].

The growing focus on reuse has generated global initiatives that support circular and innovative business models. These initiatives involve investors, companies, and institutions in projects that aim to reduce environmental impact and promote more responsible and resilient practices.

Part 1: General terms, International Organization for Standardization, Ginevra, https://www.iso.org/obp/ui/en/#iso:std:iso:6707:-1:ed-6:v1:en.

5. De Carlo G. (1981), *Del ribaltamento del termine riuso nella prassi architettonica*, in Belgioioso L.B. *et al.* (a cura di), *Riuso e riqualificazione edilizia negli anni '80*, FrancoAngeli, pp. XX-XX.

Recover, Recycle, Repair and Reuse

Refurbishment

Refurbishment refers to all operations aimed at restoring the original functionality, performance, and appearance of a discontinued product or component, making it fit for its intended use again. These operations may include cleaning, testing, maintenance, and, if necessary, repair[1].

In building design and management, the term has a specific meaning: it indicates modifications and improvements made to existing buildings or infrastructures to bring them to an acceptable functional and performance condition without necessarily intervening on their supporting structure[2].

Refurbishment is part of the circular economy strategy as a virtuous practice that extends the life cycle of products and buildings, reducing the need for new resources and limiting the environmental impact of production and disposal. Unlike simple repair, refurbishment can also include aesthetic or technological upgrades, improving the overall value of the refurbished object or building.

1. European Union (2024), *Directive 2024/1781 of the European Parliament and of the Council on Ecodesign for Sustainable Products Regulation (ESPR)*.

2. ISO (2020b), *ISO 6707-1:2020 – Buildings and civil engineering works – Vocabulary – Part 1: General terms*, International Organization for Standardization, Ginevra, https://www.iso.org/obp/ui/en/#iso:std:iso:6707:-1:ed-6:v1:en.

Refurbishment

Regenerative sustainability

Regenerative sustainability represents an evolution of sustainability concepts. While conventional sustainability merely recognises environmental limits and the damage resulting from the uncontrolled exploitation of resources, and contemporary sustainability integrates considerations of ecosystem resilience, social justice and the balance of socio-ecological systems, regenerative sustainability goes beyond both, proposing a radical paradigm shift.

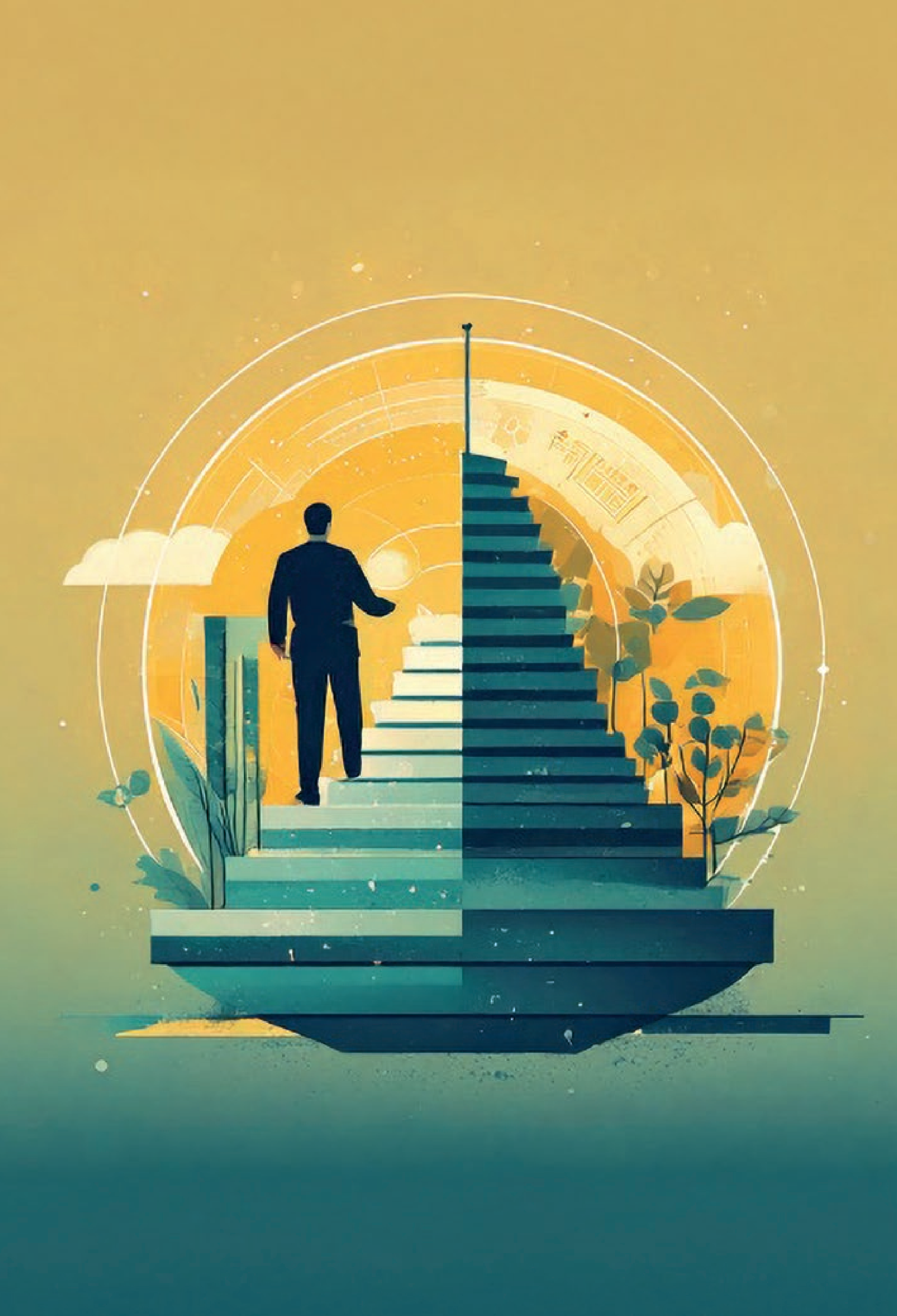
This approach considers human beings not as separate entities from the natural system but as an integral part of an autopoietic system – that is, one capable of self-generation, self-organisation and self-regulation – in which each place, community or environment possesses a unique potential to be expressed through processes of evolution and transformation[1].

Regenerative sustainability takes a holistic and systemic view of reality. The goal is not simply to reduce the negative impact of human activities but to regenerate ecosystems, strengthen social bonds, and encourage life to flourish in all its forms. It calls for conscious living, aligning with the fundamental principles of living systems such as relationships, continuous change, and wholeness[2].

1. Gibbons L.V. (2020), *Regenerative—The New Sustainable?*, in «Sustainability», 12(13), 5483.
2. Du Plessis C. (2012), *Towards a regenerative paradigm for the built environment*, in «Building Research & Information», 40, pp. 7-22, https://doi.org/10.3390/su12135483.

Reliability

The reliability of a product represents the probability that it will function as intended under certain conditions and for a set period without failures compromising its primary or secondary functions. Although it may seem obvious, reliability is a fundamental and measurable parameter in product design, manufacture and maintenance, particularly in sectors where safety, durability and performance are crucial. A reliable product reduces the risk of failure, optimises maintenance and replacement costs, and contributes to sustainability by extending product life and reducing resource consumption. Moreover, reliability is closely linked to quality standards and safety regulations in many industries.



Remanufacturing

Remanufacturing refers to the process of making a new product using objects discarded, manufactured or used components. This process involves making substantial changes that affect various aspects of the product, such as safety, performance, purpose or product type. Unlike recycling or repair, remanufacturing involves a significant transformation and rebuilding of the product to a state comparable or superior to that of a new product, improving functionality and overall quality. In practice, a used product, such as an engine or an electronic device, is disassembled, its parts refurbished and re-assembled, often with additional or improved components, to obtain a product that can be placed back on the market as a "second-life product", but with performance and standards comparable to those of a new product.

Repurposing

Repurposing refers to the act of using an object that is obsolete or considered as waste by its owner for a totally different use than the original one[1]. Repurposing implies a function change unlike other practices such as recovering, recycling, repairing or reusing. Users give a new function to an object originally designed for a specific purpose, reusing it in a completely different way. This process makes extending the useful life of materials or objects possible, contributing to sustainability and reducing waste while maintaining an innovative perspective on their reuse. In particular, unlike recycling, which refers to the process in which a material or product is transformed into new raw material to create a new object, or reuse, which implies the reuse of an object or material in its same function without changing it, repurposing, therefore, explores new possibilities of use.

1. Cruz P.J., Sieffert Y., Daudon D., Huygen J.-M. (2013), *Structures and architecture: New concepts, applications and challenges. How to build the future with limited and finite resources*, Taylor & Francis, https://www.taylorfrancis.com/books/e/9780429159350.

Resilience

The term "resilience" refers to a system's ability – an individual, a community, an environment or an infrastructure – to cope with critical events, adapt to new conditions and transform itself to ensure its continuity and functionality over time. In the context of the climate crisis, we specifically speak of climate resilience, which is the ability of a community or environment to anticipate and manage climate impacts, minimise damage, and recover and transform itself after the initial shock[1]. This type of resilience is not limited to responding to extreme events (such as floods, fires or heat waves). Still, it implies a structural and cultural change towards systems that are more flexible, adaptive and aware of their ecological limits.

In the territorial and social sphere, community resilience manifests itself in the collective capacity to cope with environmental, economic and social transformations without compromising internal cohesion, well-being and cultural continuity. Strong relationships, shared resources, participatory governance, and equitable access to services and opportunities form its foundation. Resilient territories do not simply 'resist' but can learn from crises and innovate in response to them, thus becoming generative spaces of new possibilities.

From a circular economy and regenerative design perspective, resilience becomes a key principle that guides decisions considering the interdependencies between resources, communities, ecosystems, and infrastructure, promoting more sustainable, durable, and inclusive life cycles.

1. United Nations Development Programme (2023), *The Climate Dictionary. Speak climate fluently*, cit.

Social footprint

The concept of social footprint generally refers to a product, service or organisation's impact on people and communities throughout its life cycle, including aspects such as working conditions, human rights, equity and social justice. Incorporating social footprint assessment into design and production strategies can help ensure that business practices are environmentally sustainable and socially responsible.

Storytelling & Narration

Narration and storytelling are two terms that are often confused or misused. While the first refers to the action of narrate, the structure that constructs meaning, the latter should be translated as “affabulation”, more precisely, the art of persuading the reader or viewer. Storytelling is thus how narratives engage and build trust with audiences. Compared to narration, storytelling has a more marketing orientation.

Substances of concern

Substances of concern' refer to any substance in a product that may risk human health or the environment. These are not only chemicals in the strict sense but also materials, compounds or additives that, due to their characteristics, pose risks during the product's life cycle – from use to disposal. Regulation (EU) 2024/1781 introduces an obligation for manufacturers to ensure the traceability and communication of these substances, including through digital tools such as the digital product passport. This obligation aims to improve transparency along the entire value chain and to support safer and more efficient recycling, reuse and disposal processes. Substances of concern may hinder disassembly, interfere with material recovery processes or pose risks to those who come into contact with products.

Supply chain

The supply chain encompasses all activities and processes that precede when a product reaches the end customer, i.e. all stages upstream in its value chain[1]. From the selection of raw materials to design, production to distribution, the supply chain represents the entire system that makes the realisation and delivery of a good or service possible. In a circular economy context, this network assumes a strategic role: it is precisely along the supply chain that fundamental choices can be made to reduce environmental impact, optimise resources and favour regenerative and sustainable production models.

Regarding the visual interpretation generated by AI, we can reason that the visual representation of 'value chains' often takes anthropomorphic forms to render complex concepts abstract. In many cases, the 'chain' is a connection between vital elements, a network, and a gestation of value. AI has presumably drawn on recurring cultural symbols, such as the female face, to convey origin, care, and transformation concepts.

1. European Union (2024), *Directive 2024/1781 of the European Parliament and of the Council on Ecodesign for Sustainable Products Regulation (ESPR).*

Traceability

Traceability refers to the ability to track a product along its entire value chain, from the production stage to its sale. This implies the ability to identify and monitor each stage of the product's life cycle and enable recording information regarding its origin, processing, distribution, and final sale[1]. Traceability must not be limited to a single starting point. To be effective, it must be applied at every stage of the production and distribution process, allowing the product to be fully and transparently traced throughout its entire chain.

A specific aspect of traceability is batch traceability, which refers to the ability to trace the complete history and path of a specific batch of products or materials within a company or supply chain. This approach allows detailed visibility and more precise management of a group of items (or materials) from the same production and/or process, having specific qualities or uniform characteristics, to improve the quality and safety of the final product.

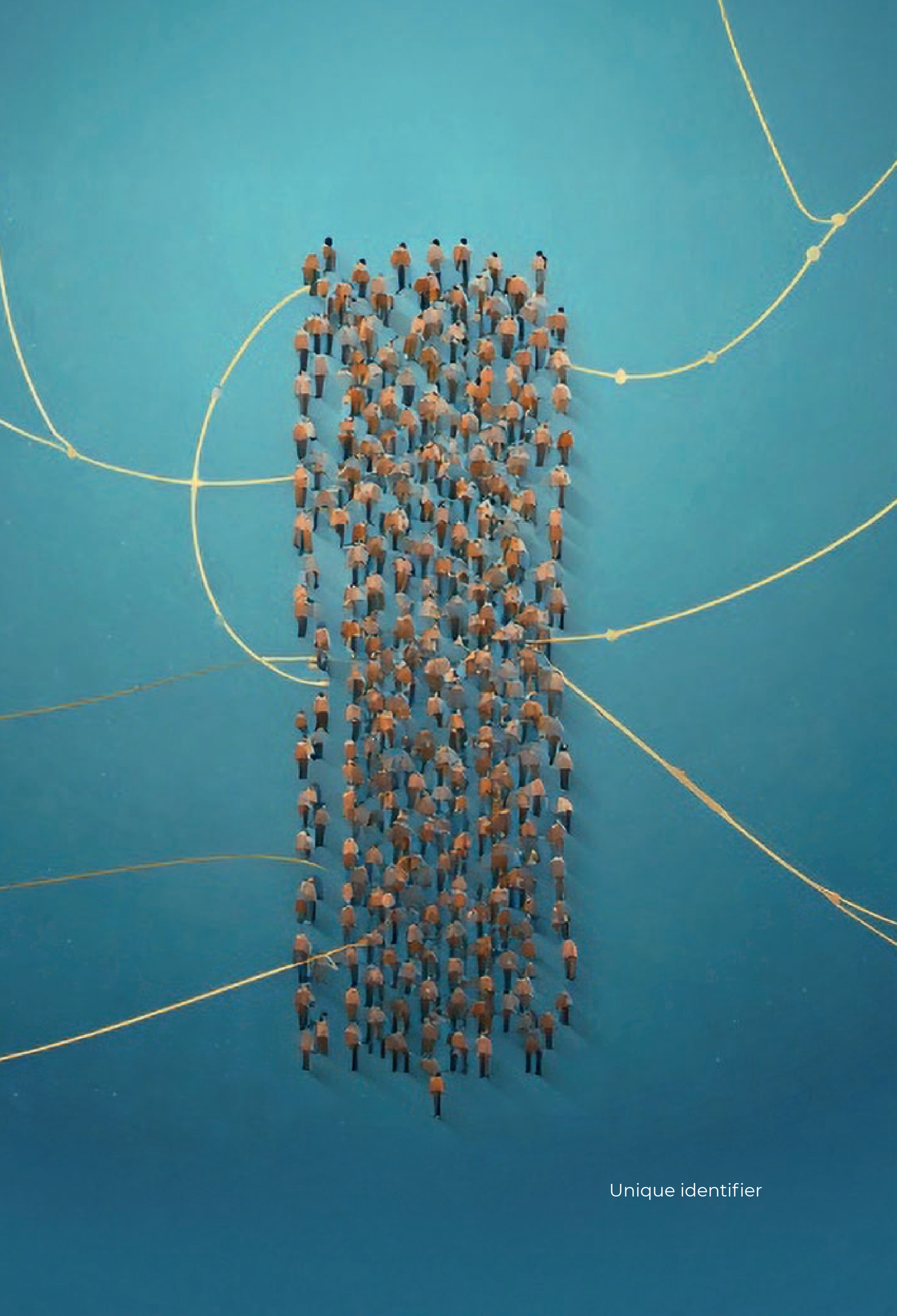
1. Bixio M.L. (2023), *Blockchain, tracciabilità e marchi di certificazione*, in «Il Diritto industriale», 2, pp. 117-124.

Unique identifier

A unique identifier is a string of characters used to precisely and standardise the identification of different entities involved in a product's value chain. In the context of the circular economy and industrial digitisation, these identifiers play a central role in ensuring traceability, transparency, and data interoperability throughout a completely product's life cycle[1].Among the main applications is the unique product identifier, which allows a specific product to be identified and linked directly to its digital passport. This passport contains key information on the composition, origin, environmental impacts and end-of-life management options. There is also the unique facility identifier, whose purpose is to uniquely identify the buildings or facilities involved in the production, distribution or treatment stages, and the unique operator identifier, which allows actors in the value chain, such as producers, distributors or recyclers, to be traced.

Integrating these identifiers into digital systems through technologies such as QR codes, RFID, or blockchain helps build a robust and transparent data infrastructure, essential to promoting accountability, facilitating the circular economy, and supporting the transition to more sustainable production models.

1. European Union (2024), *Directive 2024/1781 of the European Parliament and of the Council on Ecodesign for Sustainable Products Regulation (ESPR).*



Unique identifier

Upcycling

Upcycling is when the material's quality, future reuse potential and economic value are increased during the conversion process. This approach maximises the life cycle of raw materials, allowing them to be reused multiple times with increasing value at each stage of their use. Recent studies[1]. This approach maximises the life cycle of raw materials, allowing them to be reused multiple times with increasing value at each stage of their use. Recent studies[2] identify upcycling as an effective solution based on design and ecological practices, including using discarded materials, components and products that are no longer in use or destined for disposal. The process incorporates techniques of creative reuse, modernisation, redesign, reconstruction and advanced recycling, with the aim of minimising waste and toxicity, saving energy and water resources, and reducing pollutant emissions.

A practical example of upcycling is provided by rice bran, initially used as packaging material (a low-value product), and then reused for building insulation, increasing its value. Subsequently, they can be turned into bricks, a product with even greater value. Moreover, the bricks thus obtained could be further recycled in the future[3].

Each step in the upcycling process increases the value of the

1. Chini A.R. (ed.) (n.d.). *Deconstruction and materials reuse – An international overview* (CIB Publication 300, Final Report of Task Group 39 on Deconstruction), University of Florida.

2. Sung K. (2023), *Understanding Upcycling and Circular Economy and Their Interrelationships through Literature Review for Design Education*, in *Proceedings of the International Conference on Engineering Design (ICED23)*, Bordeaux, France, 24-28 July 2023, https://doi.org/10.1017/pds.2023.373.

3. Chini A.R. (ed.) (n.d.). *Deconstruction and materials reuse – An international overview* (CIB Publication 300, Final Report of Task Group 39 on Deconstruction), University of Florida.

original material, creating new products with a higher economic, aesthetic and environmental value than the original material. Upcycling, therefore, not only contributes to a more sustainable use of resources but also represents a form of conversion that encourages reuse with a positive economic and ecological impact.

Urban mining

Urban mining refers to recovering valuable materials from disused products, buildings and infrastructure in urban areas. This approach sees cities as resource mines, exploiting materials already in the urban environment rather than extracting new natural resources. Urban mining contributes to more sustainable resource management by reducing dependence on traditional mining and minimising the associated environmental impact.

Value chain

The value chain encompasses all the activities and processes accompanying a product throughout its life cycle, from design to production, use to end-of-life management, and any remanufacturing stages[1]. Within the circular economy, this concept is of fundamental importance because each stage of the cycle contributes to the creation, maintenance, or recovery of value.

The use of the term 'value' is by no means accidental but rather highly significant. It has its roots in the economic concept of value, understood as the capacity of an asset to satisfy a need and as the relative price that this asset assumes in the market. Translated to the building context, this implies designing buildings that not only meet functional and environmental needs but can generate a continuous increase in their value over time.

When considered dynamic and flexible entities, buildings become temporary repositories of materials and resources, capable of being disassembled, transformed, or used. In this sense, the value chain does not end with the end of a product's use. It continues through processes that extend the value of its materials and components, thus contributing to a more circular, resilient, and sustainable economy.

1. ISO 14044 (n.d.), *Environmental management – Life cycle assessment – Requirements and guidelines*, British Standards Institution.

Waste footprint

The waste footprint refers to the total amount of waste generated during a product's entire life cycle, including the use, maintenance, and renewal phases. In other words, it measures the impact of waste from a product or service from the moment it is produced to its end-of-life, including all phases in which the product comes into contact with the environment and its post-consumer management.

According to the European Parliament Directive[1], waste is any substance or object that the holder discards, intends to discard, or is required to discard. This concept also extends to materials that, once the product's life cycle ends, are considered useless, regardless of their potential qualities or capacity to be reused or recycled.

In the current linear model, once a product or building reaches the end of its life cycle, the materials used automatically become waste, and any value related to their characteristics, composition or potential reuse is lost. This approach leads to a superficial waste treatment without considering the possibility of exploiting the properties of materials that might still have ecological or economic value if managed correctly. In practice, waste is stripped of its identity and often ignored in sustainability strategies[2].

A crucial aspect of waste management is waste minimisation, which focuses on reducing the amount of waste generated in the first place rather than treating waste once it has been generated[3]. Waste minimisation is considered a key strategy at industrial

1. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives.

2. Rau T., Oberhuber S. (2019), *Material matters. L'importanza della materia: Un'alternativa al sovrasfruttamento*, Edizioni Ambiente.

3. Cheremisinoff N.P. (2003), *Handbook of solid waste management and waste minimization technologies*, Butterworth-Heinemann.

and household levels. At the industrial level, it can be achieved through changes in production processes, continuous quality surveillance and the integration of recycling and prevention practices into waste management. Source reduction involves preventing waste production before it is generated, reducing the use of natural resources and minimising waste through efficient process design and management. This approach not only reduces environmental impact but also helps companies save economic resources and improve their competitiveness in the market. At the household level, waste reduction at source can be encouraged through the active participation of citizens, who are made aware of their consumption and disposal habits[4]. However, where waste generation is significantly higher at the industrial level, source reduction and waste minimisation become urgent priorities and more complex challenges to address[5].

4. Lober DJ. (1996), *Municipal Solid Waste Policy and Public Participation in Household Source Reduction*, «Waste Management & Research», 14(2), pp. 125-143.

5. Hussain C.M., Paulraj M.S., Nuzhat S. (2022), *Source reduction and waste minimization—Concept, context, and its benefits*, in *Source Reduction and Waste Minimization*, pp. 1-22, https://doi.org/10.1016/B978-0-12-824320-6.00001-0.

Waste footprint

References

Andrews D. (2015), *The circular economy, design thinking and education for sustainability*, in «Local Economy», 30(3), pp. 305-315, https://doi.org/10.1177/0269094215578226.

Assaad C.K., Devijver E., Gaussier É. (2022), *Survey and evaluation of causal discovery methods for time series*, in «Journal of Artificial Intelligence Research», 73, pp. 767-819, https://doi.org/10.1613/jair.1.13350.

Atta I., Bakhoum E.S., Marzouk M.M. (2021), *Digitizing material passport for sustainable construction projects using BIM*, in «Journal of Building Engineering», 43, 103233, https://doi.org/10.1016/j.jobe.2021.103233.

BAMB (2020), *Materials Passports. Buildings as Material Banks*, https://www.bamb2020.eu/topics/materials-passports/.

Bauwens T., Heyen D.A., Strupeit L. (2021), *Digitalization and the circular economy: Bridging the knowledge gap*, in «Journal of Industrial Ecology», 25(6), pp. 1436-1449.

Berger K., Scöggl J.-P., Baumgartner R.J. (2022), *Digital battery passports to enable circular and sustainable value chains: Conceptualization and use cases*, in «Journal of Cleaner Production», 353, 131492, https://doi.org/10.101/10.1016/j.jclepro.2022.131492.

Berger K., Baumgartner R.J., Weinzerl M., Bachler J., Preston K., Schöggl J.-P. (2023), *Data requirements and availabilities for a digital battery passport – A value chain actor perspective*, in «Journal of Cleaner Production», 4, https://doi.org/10.1016/j.clpl.2023.100032.

Berger K., Baumgartner R.J., Weinzerl M., Bachler J., Schöggl J.-P. (2023), *Factors of digital product passport adoption to enable circular information flows along the battery value chain*, in «Procedia CIRP», 116, pp. 528-533, https://doi.org/10.1016/j.procir.2023.02.089.

Bernardo G., Guida A. (2024), *Building Heritage Materials Passports (BHMPs) for resilient communities*, in «Colloqui.AT.e», 3, pp. 115-127, https://link.springer.com/chapter/10.1007/978-3-031-71867-0_9.

Bernardo G., Dall'Arche D., Manicone A. (2025), *Circular Data Flowchart for Sustainable Ecodesign*, in «Colloqui.AT.e», forthcoming.

Bixio M.L. (2023), *Blockchain, tracciabilità e marchi di certificazione*, in «Il Diritto industriale», 2, pp. 117-124.

Bjørn A., Hauschild M.Z. (2013), *Absolute versus Relative Environmental Sustainability*, in «Journal of Industrial Ecology», 17, pp. 321-332, https://doi.org/10.1111/j.1530-9290.2012.00520.x.

Blomsma F., Brennan G. (2017), *The emergence of circular economy: A new framing around prolonging resource productivity*, in «Journal of Industrial Ecology», 21(3), pp. 603-614, https://doi.org/10.1111/jiec.12603.

Bocken N.M.P., de Pauw I., Bakker C., van der Grinten B. (2016), *Product design and business model strategies for a circular economy*, in «Journal of Industrial and Production Engineering», 33(5), pp. 308-320, http://dx.doi.org/10.1080/21681015.2016.1172124.

Borrello M., Pascucci S., Cembalo L. (2020), *Three propositions to unify circular economy*, in «Sustainability», 12(10), 4069.

Braungart M., McDonough W. (2003), *Dalla culla alla culla. Come conciliare tutela dell'ambiente, equità sociale e sviluppo*, Blu edizioni.

Cambridge University Press (s.d.), *End product*, in «Cambridge Dictionary», https://dictionary.cambridge.org/it/dizionario/inglese/end-product.

CEN (2019), *EN 15804:2019 – Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products*, European Committee for Standardization, Bruxelles.

Charnley F., Lemon M., Evans S. (2011), *Exploring the process of whole system design*, in «Design Studies», 32(2), pp. 156-179, https://doi.org/10.1016/j.destud.2010.08.002.

Chaudhuri A., Wæhrens B.V., Treiblmaier H., Jensen S.F. (2024), *Impact pathways: Digital product passport for embedding circularity in electronics supply chains*, in «International Journal of Operations & Production Management» (advance online publication), https://doi.org/10.1108/IJOPM-01-2024-0012.

Cheremisinoff N.P. (2003), *Handbook of solid waste management and waste minimization technologies*, Butterworth-Heinemann.

Chan H., Zeng K.J., Yang M.X. (2022), *Review platforms as prosumer communities:*

Theory, practices and implications, in «European Journal of Marketing», 56, pp. 2698-2720, https://doi.org/10.1108/EJM-10-2021-0819.

Chini A.R. (eds) (s.d.), *Deconstruction and materials reuse – An international overview* (CIB Publication 300), University of Florida, https://www.irbnet.de/daten/iconda/CIB1303.pdf.

Ciasullo M.V., Lim W.M., Manesh M.F., Palumbo R. (2022), *The patient as a prosumer of healthcare: Insights from a bibliometric-interpretive review*, in «Journal of Health Organization and Management», 36, pp. 133-157, https://www.emerald.com/insight/1477-7266.htm.

Circularise (2024), *Transparency and traceability for a circular economy*, https://www.circularise.com.

Cirpass (n.d.), *About CIRPASS*, https://cirpassproject.eu/about-cirpass/.

Costa A.R., Hoolahan R. (2024), *Material Passport: Accelerating Material Reuse in Construction*, Lancaster University and Orms Designers & Architects Ltd, London, https://doi.org/10.5281/zenodo.10472214.

Corbellini G. (2013), *Progettare l'amnesia*, in Marini S., Santangelo V. (a cura di), *Recycland*, Aracne.

Council of the European Union (2024), *Building materials: Council adopts law for clean and smart construction products*, https://www.consilium.europa.eu/it/press/press-releases/2024/11/05/building-materials-council-adopts-law-for-clean-and-smart-construction-products/.

Council of the European Union (2024), *Proposal 11312/24 for a Directive of the European Parliament and of the Council on substantiation and communication of explicit environmental claims (Green Claims Directive) – General approach*, https://data.consilium.europa.eu/doc/document/ST-11312-2024-INIT/en/pdf.

Cruz P.J., Sieffert Y., Daudon D., Huygen J.-M. (2013), *Structures and architecture: New concepts, applications and challenges. How to build the future with limited and finite resources*, Taylor & Francis, https://www.taylorfrancis.com/books/e/9780429159350.

De Carlo G. (1981), *Del ribaltamento del termine riuso nella prassi architettonica*, in Belgioioso L.B. *et al.* (a cura di), *Riuso e riqualificazione edilizia negli anni '80*, FrancoAngeli.

De los Rios I.C., Charnley F.J.S., Sundin E., Lindahl M., Ijomah W. (2017), *Skills and capabilities for a sustainable and circular economy: The changing role of design*, in «Journal of Cleaner Production», 160, pp. 109-122, https://doi.org/10.1016/j.jclepro.2016.10.130.

den Hollander M.C., Bakker C.A., Hultink E.J. (2017), *Product Design in a Circular Economy: Development of a Typology of Key Concepts and Terms*, in «Journal of Industrial Ecology», 21, pp. 517-525, https://doi.org/10.1111/jiec.12610.

Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008L0098.

Dokter G., Thuvander L., Rahe U. (2021), *How circular is current design practice? Investigating perspectives across industrial design and architecture in the transition towards a circular economy*, in «Sustainable Production and Consumption», 26, pp. 692-708, https://doi.org/10.1016/j.spc.2020.12.032.

Durmisevic E. (2016), *Reversible Building Design Guideline*, BAMB document, University of Twente.

Du Plessis C. (2012), *Towards a regenerative paradigm for the built environment*, in «Building Research & Information», 40, pp. 7-22, https://doi.org/10.3390/su12135483.

Ellen MacArthur Foundation (s.d.), *The circular economy in detail*, https://www.ellenmacarthurfoundation.org/the-circular-economy-in-detail-deep-dive.

Ellen MacArthur Foundation (2020), *Financing the circular economy: Capturing the opportunity*.

Ellen MacArthur Foundation (2023), *Unlocking a reuse revolution: Scaling returnable packaging*.

Elmashtawy A., Salaheldeen M. (2024), *Green sustainability: Definition, context, and application*, in «Reference Module in Social Sciences».

Ertz M., Cao X., Barragán Maravilla J.M. (2024), *The Prosumer*, in «Encyclopedia», 4(3), pp. 1263-1278, https://doi.org/10.3390/encyclopedia4030082.

European Commission (s.d.), *Circular economy action plan*, https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en.

European Commission (s.d.), *Environmental Footprint Methods*, https://green-business.ec.europa.eu/environmental-footprint-methods_en.

European Commission (s.d.), *European Platform on LCA | EPLCA*, https://eplca.jrc.ec.europa.eu/lifecycleassessment.html.

European Commission (2008), *Waste Framework Directive*.

European Commission (2012), *Ecodesign your future – How ecodesign can help the environment by making products smarter*, https://data.europa.eu/doi/10.2769/38512.

European Commission (2014), *Ecodesign your future: How ecodesign can help the environment by making products smarter*, https://data.europa.eu/doi/10.2769/38512.

European Commission (2020), *A new circular economy action plan for a cleaner and more competitive Europe* (COM/2020/98 final), Bruxelles, https://eur-lex.europa.eu/legal-content/IT/TXT/HTML/?uri=CELEX:52020DC0098.

European Commission (2020), *A Renovation Wave for Europe – Greening our buildings, creating jobs, improving lives* (COM/2020/662 final), Bruxelles, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52020DC0662.

European Commission (2021), *Raccomandazione (UE) 2021/2279 della Commissione del 15 dicembre 2021 sull'uso della Product Environmental Footprint per misurare le prestazioni ambientali dei prodotti*, in «Gazzetta ufficiale dell'Unione europea», L 471/1.

European Commission (2022), *Annexes to the proposal for a regulation of the European Parliament and of the Council laying down harmonised conditions for the marketing of construction products*, COM(2022) 144 final, Bruxelles, 30 marzo 2022.

European Commission (2023), *Digital Product Passport: The gateway to circular value chains*, Directorate-General for Environment, Bruxelles.

European Environment Agency (s.d.), *Glossary: Life-cycle assessment (LCA)*, https://www.eea.europa.eu/help/glossary/eea-glossary/life-cycle-assessment.

European Parliament (s.d.), *Environment policy: General principles and basic framework*, https://www.europarl.europa.eu/factsheets/en/sheet/71/environment-policy-general-principles-and-basic-framework.

European Parliament and Council (2004), *Directive 2004/17/EC of the European Parliament and of the Council of 31 March 2004 coordinating the procurement procedures of entities operating in the water, energy, transport, and postal services sectors*, in «Official Journal of the European Union», L 134/1.

European Parliament and Council (2008), *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain directives*, in «Official Journal of the European Union», L 312/3.

European Union (2023), *Digitalisation in Europe – 2023 edition*, https://ec.europa.eu/eurostat/web/interactive-publications/digitalisation-2023.

European Union (2024), *Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for products*, L 178/1, Publications Office of the

European Union, L 178, 1-62, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32024R1781.

European Union (2024), *Regulation (EU) 2024/3110 of the European Parliament and of the Council of 27 November 2024 laying down harmonised rules for the marketing of construction products and repealing Regulation (EU) No 305/2011*, Publications Office of the European Union, L 310, 1-62, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202403110.

Floridi L. (2023), *The Ethics of Artificial Intelligence: Principles, Challenges, and Opportunities*, Oxford University Press.

Franconi A. (2020), *Multiple design perspectives for the transition to the circular economy: Managing design strategies between systems, designers and time*, University Iuav of Venice.

Geissdoerfer M., Savaget P., Bocken N.M.P., Hultink E.J. (2017), *The circular economy – A new sustainability paradigm?*, in «Journal of Cleaner Production», 143, pp. 757-768, https://doi.org/10.1016/j.jclepro.2016.12.048.

Gharfalkar M., Court R., Campbell C., Ali Z., Hillier G. (2015), *Analysis of waste hierarchy in the European waste directive 2008/98/EC*, in «Waste Management», 39, pp. 305-313.

Ghisellini P., Cialani C., Ulgiati S. (2016), *A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems*, in «Journal of Cleaner Production», 114, pp. 11-32, https://doi.org/10.1016/j.jclepro.2015.09.007.

Gibbons L.V. (2020), *Regenerative—The New Sustainable?*, in «Sustainability», 12(13), 5483.

Gieß A., Möller F. (2025), *Exploring the value ecosystem of digital product passports*, in «Journal of Industrial Ecology», pp. 1-13, https://doi.org/10.1111/jiec.13621.

Giorgi A. (2025), *Generazione AI: Come potenziare creatività e produttività con l'AI generativa*, Hoepli.

Gong C., Yao D., Zhang C., Li W., Bi J. (2023), *Causal Discovery from Temporal Data: An Overview and New Perspectives*, in «arXiv», https://arxiv.org/abs/2303.10112.

Guidetti E., Ferrara M. (2023), *Embodied energy in existing buildings as a tool for sustainable intervention on urban heritage*, in «Sustainable Cities and Society», 88, 104284, https://doi.org/10.1016/j.scs.2022.104284.

Habash R. (2022), *Building as an energy system*, in *Sustainability and Health* *in Intelligent Buildings*, Woodhead Publishing, pp. 59-94, https://doi.org/10.1016/B978-0-323-98826-1.00003-X.

Halassi S., Semeijn J., Kiratli N. (2019), *From consumer to prosumer: A supply chain revolution in 3D printing*, in «International Journal of Physical Distribution & Logistics Management», 49, pp. 200-216, https://doi.org/10.1108/IJPDLM-03-2018-0139.

Hamari J., Sjöklint M., Ukkonen A. (2016), *The sharing economy: Why people participate in collaborative consumption*, in «Journal of the Association for Information Science and Technology», 67, pp. 2047-2059, https://doi.org/10.1002/asi.23552.

Heisel F., Hebel D.E., Webster K. (2022), *Building better – less – different: Circular construction and circular economy fundamentals, case studies, strategies*, Birkhäuser.

Hoang K.-M., Böckel A. (2024), *Cradle-to-cradle business model tool: Innovating circular business models for startups*, in «Journal of Cleaner Production», 467, 142949, https://doi.org/10.1016/j.jclepro.2024.142949.

Homrich A.S., Galvão G., Abadia L.G., Carvalho M.M. (2018), *The circular economy umbrella: Trends and gaps on integrating pathways*, in «Journal of Cleaner Production», 175, pp. 525-543, https://doi.org/10.1016/j.jclepro.2017.11.064.

Honic M., Kovacic I., Aschenbrenner P., Ragossnig A. (2021), *Material passports for the end-of-life stage of buildings: challenges and potentials*, in «Journal of Cleaner Production», 319, https://doi.org/10.1016/j.jclepro.2021.128702.

Honic M., Fink D., Passer A. (2023), *Circular construction and material passports: Digital tools for the transition to a circular built environment*, in «Circular Economy and Sustainability», pp. 95-111. Springer, https://doi.org/10.1007/978-3-031-39675-5.

Hussain C.M., Paulraj M.S., Nuzhat S. (2022), *Source reduction and waste minimization—Concept, context, and its benefits*, in *Source Reduction and Waste Minimization*, pp. 1-22, https://doi.org/10.1016/B978-0-12-824320-6.00001-0.

IBM Research (2022), *Causal AI: The Next Frontier in Artificial Intelligence*, https://research.ibm.com/blog/causal-ai.

ISO (s.d.), *ISO 19650-1 – Building Information Modelling – BIM – Part 1: Concepts and terminology*, British Standards Institution, s.l.

ISO (2017), *ISO 17738-1:2017 – Thermal insulation products – Exterior insulation and finish systems – Part 1: Materials and systems*, International

Organization for Standardization, Ginevra, https://www.iso.org/obp/ui/#iso:std:iso:17738:-1:ed-1:v1:en.

ISO (2006a), *ISO 14040:2006 – Environmental management – Life cycle assessment – Principles and framework*, International Organization for Standardization, Ginevra, https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en.

ISO (2006b), *ISO 14044:2006 – Environmental management – Life cycle assessment – Requirements and guidelines*, International Organization for Standardization, Ginevra.

ISO (s.d.), *ISO 14000/44 – Environmental management – Life cycle assessment – Requirements and guidelines*, British Standards Institution, s.l.

ISO (2011), *ISO 15686-1:2011 – Buildings and constructed assets – Service life planning – Part 1: General principles*, International Organization for Standardization, Ginevra, https://www.iso.org/obp/ui/#iso:std:iso:15686:-1:ed-2:v1:en.

ISO (2020a), *ISO 20887:2020 – Sustainability in buildings and civil engineering works – Design for disassembly and adaptability – Principles, requirements and guidance*, International Organization for Standardization, Ginevra, https://www.steelconstruct.com/wp-content/uploads/ISO-20887_2020_01.pdf.

ISO (2020b), *ISO 6707-1:2020 – Buildings and civil engineering works – Vocabulary – Part 1: General terms*, International Organization for Standardization, Ginevra, https://www.iso.org/obp/ui/en/#iso:std:iso:6707:-1:ed-6:v1:en.

Jæger B., Myrold S. (2023), *Textile Industry circular supply chains and digital product passports. Two case studies*, in Alfnes E. *et al.* (eds), *Advances in Production Management Systems. Production Management Systems for Responsible Manufacturing, Service, and Logistics Futures*, vol. 692, Springer, pp. 350-363, https://doi.org/10.1007/978-3-031-43688-8_25.

Jansen M., Gerstenberger B., Bitter-Krahe J., Berg H., Sebestyén J., Schneider J. (2022), *Current approaches to the Digital Product Passport for a Circular Economy: An overview of projects and initiatives*, in «Wuppertal Paper» No. 198, https://epub.wupperinst.org/frontdoor/deliver/index/docId/8042/file/WP198.pdf.

Jensen S.F., Kristensen J.H., Adamsen S., Christensen A., Waehrens B.V. (2023), *digital product passports for a circular economy: Data needs for product life cycle decision-making*, in «Sustainable Production and Consumption», 37, pp. 242-255, https://doi.org/10.1016/j.spc.2023.02.021.

Jensen S.F., Kristensen J.H., Christensen A., Waehrens B.V. (2024), *An ecosystem orchestration framework for the design of digital product passports in a circular economy*, in «Business Strategy and the Environment», 33(7), pp. 7100-7117, https://doi.org/10.1002/bse.3868.

Joint Research Centre (JRC) (2022), *Preliminary study for the Ecodesign for Sustainable Products Regulation working plan*, Publications Office of the European Union, Luxemburg.

Kebede R., Moscati A., Tan H., Johansson P. (2024), *A modular ontology modeling approach to developing digital product passports to promote circular economy in the built environment*, in «Sustainable Production and Consumption», 48, pp. 248-268, https://doi.org/10.1016/j.spc.2024.05.007.

Kibert C.J. (2003), *Deconstruction: The start of a sustainable materials strategy for the built environment*, in «Industry and Environment», pp. 84-88.

King M.R., Timms P.D., Mountney S. (2023), *A proposed universal definition of a Digital Product Passport Ecosystem (DPPE)*, in «Journal of Cleaner Production», 384, 135538, https://doi.org/10.1016/j.jclepro.2022.135538.

Kirchherr J., Reike D., Hekkert M. (2017), *Conceptualizing the circular economy: An analysis of 114 definitions*, in «Resources, Conservation and Recycling», 127, pp. 221-232, https://doi.org/10.1016/j.resconrec.2017.09.005.

Korhonen J., Nuur C., Feldmann A., Birkie S.E. (2018), *Circular economy as an essentially contested concept*, in «Journal of Cleaner Production», 175, pp. 544-552, https://doi.org/10.1016/j.jclepro.2017.12.111.

Langley D.J., Rosca E., Angelopoulos M., Kamminga O., Hooijer C. (2023), *Orchestrating a smart circular economy: Guiding principles for digital product passports*, in «Journal of Business Research», 169, 114259, https://doi.org/10.1016/j.jbusres.2023.114259.

Leal Filho W., Trevisan L.V., Salvia A.L., Mazutti J., Dibbern T., Ruiz de Maya S., Bernal E.F., Eustachio J.H.P.P., Sharifi A., Alarcón-del-Amo M.-d.-C., Kushnir I. (2024), *Prosumers and sustainable development: An international assessment in the field of renewable energy*, in «Sustainable Futures», 7, 100158, https://doi.org/10.1016/j.sftr.2024.100158.

Lober D.J. (1996), *Municipal solid waste policy and public participation in household source reduction*, in «Waste Management & Research», 14(2), pp. 125-143, https://doi.org/10.1177/0734242X9601400203.

Maciaszczyk M., Kocot M. (2021), *Behavior of online prosumers in organic product market as determinant of sustainable consumption*, in «Sustainability», 13(3), pp. 1-14, https://doi.org/10.3390/su13031157.

Macozoma D. (2002), *Understanding the concept of flexibility in design for deconstruction*, in *Design for Deconstruction and Materials Reuse*, pp. 118-127.

Madaster (s.d.), *What's in it for me?*, https://madaster.com/madaster-benefits.

Mestre A., Cooper T. (2017), *Circular product design: A multiple loops life cycle* *design approach for the circular economy*, in «The Design Journal», 20(sup1), pp. S1620-S1635, https://doi.org/10.1080/14606925.2017.1352686.

Microsoft Research (2023), *Causal AI: Learning and Reasoning About Interventions and Counterfactuals*, https://www.microsoft.com/en-us/research/project/causal-inference.

Morganti L., Esnarrizaga P.E., Pracucci A., Zaffagnini T., Cortes V.G., Rudenå A., Brunklaus B., Larraz J.A. (2024), *Data-driven and LCA-based Framework for environmental and circular assessment of Modular Curtain Walls*, in «Journal of Facade Design and Engineering», 12(1), pp. 9-42, https://doi.org/10.47982/jfde.2024.305.

Murray A., Skene K., Haynes K. (2017), *The circular economy: An interdisciplinary exploration of the concept and application in a global context*, in «Journal of Business Ethics», 140(3), pp. 369-380, https://doi.org/10.1007/s10551-015-2693-2.

Neramballi A., Milios L., Sakao T., Matschewsky J. (2024), *Toward a policy landscape to support the product-as-a-service design process for a circular economy*, in «Journal of Industrial Ecology», 28(5), pp. 1045-1059, https://doi.org/10.1111/jiec.13535.

Olivastri C. (2018), *Con temporaneo. Design per il riuso di spazi abbandonati*, Gangemi.

Ompusunggu A.P., Tjahjowidodo T., Wicaksono H. (2024), *Causal AI-powered Digital Product Passports for enabling a circular and sustainable manufacturing ecosystem*. Proceedings of the 12th International Conference on Through-life Engineering Services (TESConf2024), Cranfield University, UK, https://doi.org/10.57996/cran.ceres-2579.

Ostapska K., Rüther P., Loli A., Gradeci K. (2024), *Design for Disassembly: A systematic scoping review and analysis of built structures Designed for Disassembly*, in «Sustainable Production and Consumption», 48, pp. 377-395.

Oxford English Dictionary (s.d.), *Raw material*, https://www.oed.com/.

Panyapatiphan D. (2020), *Empowering Consumers in the Circular Economy with blockchain-enabled storytelling* (Master's thesis), Faculty of Industrial Design Engineering, Delft University of Technology, https://resolver.tudelft.nl/uuid:cd41b015-7f76-457d-a108-71a7af217a53.

Paduart A., Heeren N., Durmisevic E. (2021), *Circular construction: Barriers and strategies for accelerating the transition*, in «Sustainable Cities and Society», 75, 103374.

PBL Netherlands Environmental Assessment Agency (2019), *Circular economy: what we want to know and can measure*, PBL, The Hague.

Pearl J. (2009), *Causality: Models, Reasoning, and Inference* (2nd ed.), Cambridge University Press.

Pidikiti V.S., Vijaya A., Valilai O.F., Wicaksono H. (2023), *An Ontology Model to Facilitate the Semantic Interoperability in Assessing the Circular Economy Performance of the Automotive Industry*. Procedia CIRP, 120, 1351-1356, https://doi.org/10.1016/j.procir.2023.01.231.

Plociennik C. *et al*. (2022), *Requirements for a digital product passport to boost the circular economy*, Gesellschaft für Informatik, https://doi.org/10.18420/inf2022_127.

Pomponi F., Moncaster A. (2017), *Circular economy for the built environment: A research framework*, in «Journal of Cleaner Production», 143, pp. 710-718, https://doi.org/10.1016/j.jclepro.2016.12.055.

Psarommatis F., May G. (2024), *Digital Product Passport: A Pathway to Circularity and Sustainability in Modern Manufacturing*, in «Sustainability» (Switzerland), 16(1), https://doi.org/10.3390/su16010396.

Platform CB'23 (2020), *Guide-Passports for the Construction Sector-Working agreements for circular construction*, https://platformcb23.nl/.

Rau T., Oberhuber S. (2019), *Material matters. L'importanza della materia: Un'alternativa al sovrasfruttamento*, Edizioni Ambiente.

Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC, art. 2, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32011R0305.

Reike D., Vermeulen W.J.V., Witjes S. (2018), *The circular economy: New or refurbished as CE 3.0?*, in «Resources, Conservation and Recycling», 135, pp. 246-264, https://doi.org/10.1016/j.resconrec.2017.08.027.

Rios F.C., Chong W.K., Grau D. (2015), *Design for Disassembly and Deconstruction – Challenges and Opportunities*, in «Procedia Engineering», 118, pp. 1296-1304.

Ruggerio C.A. (2021), *Sustainability and sustainable development: A review of principles and definitions*, in «Science of The Total Environment», 786, 147481.

Rovers R. (2004), *Existing buildings: A hidden resource*, in «Building Research & Information», 32(3), pp. 210-220.

Salgado M.S., Ferrari A.M., Settembre-Blundo D., Cucchi M., García-Muiña F.E. (2022), *Life cycle costing as a way to include economic sustainability in the circular economy: New perspectives from resource-intensive industries*, in «Circular Economy and Sustainability», pp. 161-176.

Schäfer M., Löwer M. (2021), *Ecodesign—A Review of Reviews*, in «Sustainability», 13, 315.

Schölkopf B. (2021), *Causal Representation Learning: A Review*, https://arxiv.org/abs/2102.11107.

Schroeder P., Anggraeni K., Weber U. (2019), *The relevance of circular economy practices to the Sustainable Development Goals*, in «Journal of Industrial Ecology», 23(1), pp. 77-95, https://doi.org/10.1111/jiec.12732.

Semeraro C., Lezoche M., Panetto H., Dassisti M. (2021), *Digital twin paradigm: A systematic literature review*, in «Computers in Industry», 130, 103469.

Singh J., Ordoñez I. (2016), *Resource recovery from post-consumer waste: Important lessons for the upcoming circular economy*, in «Journal of Cleaner Production», 134, pp. 342-353.

Stahel W.R. (2010), *The Performance Economy*, Palgrave Macmillan.

Stahel W.R. (2016), *The circular economy*, in «Nature», 531(7595), pp. 435-438.

Stahel W.R. (2019), *The Circular Economy: A User's Guide*, Routledge.

Sumter D., de Koning J., Bakker C., Balkenende R. (2020), *Circular Economy Competencies for Design*, in «Sustainability», 12, 1561, https://doi.org/10.3390/su12041561.

Sun Q., Huang Q., Duan Z., Zhang A. (2022), *Recycling Potential Comparison of Mass Timber Constructions and Concrete Buildings: A Case Study in China*, in «Sustainability», 14, 6174, https://doi.org/10.3390/su14106174.

Sundin E., Lindahl M., Ijomah W. (2017), *Product design for a circular economy*, in «Journal of Cleaner Production», 160, pp. 109-122.

Sung K. (2023), *Understanding Upcycling and Circular Economy and Their Interrelationships through Literature Review for Design Education*, in *Proceedings of the International Conference on Engineering Design (ICED23)*, Bordeaux, France, 24-28 July 2023, https://doi.org/10.1017/pds.2023.373.

Tabatabaei M.H., Vitenberg R., Veeraragavan N.R. (2023), *Understanding blockchain: Definitions, architecture, design, and system comparison*, in «Computer Science Review», 50.

Technopolis Group (2024), *Digital Product Passport: State of play and future design recommendations*, DG GROW, Bruxelles.

Terndrup M., Stella A., Pilcher N., Nilsson S. (2023), *Waterman Materials Passports Framework: Introducing a Standardised Approach to Materials Passports in the Construction Industry*, Woodbridge Publishers.

Thormark C. (2001), *Recycling potential and design for disassembly in buildings*, Lund University.

Tingley D.D., Davison B. (2011), *Design for deconstruction and material reuse*, in «Proceedings of the ICE – Engineering Sustainability», 164(3), pp. 195-204.

United Nations (2015), *Transforming our world: The 2030 Agenda for Sustainable Development*, https://sdgs.un.org/2030agenda.

United Nations Development Programme (2023), *The Climate Dictionary. Speak climate fluently*, https://www.undp.org/publications/climate-dictionary.

United Nations Economic Commission for Europe (2025), *Kick-off Meeting of ISO/PWI 25534-1: Digital Product Passport—Part 1: Overview and Fundamental Principles*.

United Nations Environment Programme (UNEP) (2021), *Building circularity into national climate commitments: A practical guide for governments*.

van Capelleveen G., Vegter D., Olthaar M., van Hillegersberg J. (2023), *The anatomy of a passport for the circular economy: a conceptual definition, vision and structured literature review*, in «Resources, Conservation and Recycling Advances», vol. 17, Elsevier, https://doi.org/10.1016/j.rcradv.2023.200131.

Webster K. (2017), *The Circular Economy: A Wealth of Flows*, Ellen MacArthur Foundation Publishing.

Wenning R., Papadakos P., Bernier C. (2024), *DPP system architecture*, https://cirpassproject.eu/wp-content/uploads/2024/04/D3.2-DPP-System-Architecture.pdf.

WifOR Institute (s.d.). *Case study: The Economic and R&D Footprint of the Graphene Flagship Project*, https://www.wifor.com/en/economic-footprint/.

World Green Building Council (2019), *Bringing Embodied Carbon Upfront: Coordinated action for the building and construction sector to tackle embodied carbon*.

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