Buildings

Peck, David

DOI
10.1016/B978-0-323-85514-3.00034-8

Publication date
2024

Document Version
Final published version

Published in
Handbook of Recycling

Citation (APA)
Peck, D. (2024). Buildings. In C. Meskers, E. Worrell, & M. A. Reuter (Eds.), *Handbook of Recycling: State-of-the-Art for Practitioners, Analysts, and Scientists* (2 ed., pp. 235-247). Elsevier. https://doi.org/10.1016/B978-0-323-85514-3.00034-8

CHAPTER

15

Buildings

David Peck

Circular Built Environment and Critical Materials, Faculty of Architecture and Built Environment, Delft University of Technology, Delft, The Netherlands

15.1 THE WHY: BUILDINGS AND CIRCULARITY

Buildings are an essential part of living for everyone in the world. They provide at the most basic level shelter and safety. Buildings are where people live, work, and play.

The construction sector in the European Union is, however, the highest producer of waste when compared to other economic sectors, accounting for 35% of the total waste generated (Eurostat, 2018). At the same time the creation, running, maintenance, and refurbishment of buildings are highly resource and energy intensive. Up to 50% of globally extracted resources are used to construct buildings and associated infrastructures (UNEP, 2020). Greenhouse gas (GHG) emissions from material extraction, manufacturing of construction products, construction, and renovation of buildings are estimated at 5–12% of total national GHG emissions. Construction and demolition material (CDM) efficiency and construction and demolition waste (CDW) prevention could significantly reduce those emissions.

As the world population grows and becomes wealthier, the challenge for all the stakeholders working in the building and construction sector is to respond to the global demand for building and infrastructure needs, while significantly reducing environmental impacts. The EU has committed to reducing emissions by 55% by 2030 and this can only be achieved by close collaboration between all stakeholders, including the whole value chain, from mining to design, through multiple life cycles to recycling. The building sector has difficulties in reintroducing CDW into new construction cycles, as the level of reuse and recycling of these materials is still very low (see Chapter 26—Concrete and aggregates and Chapter 16—Construction and demolition for details). The reasons for this low reuse and recycling rate are, according to the building stakeholders, a lack of training and knowledge, the loss of construction material quality, and the limited availability of final products that can replace traditional primary material-based ones. Another very important aspect is that in most new construction and refurbishment projects there is a lack of consideration of design for deconstruction principles, which are discussed in Durmisevic (2010) and US EPA (2015), for example.

Much of the material demand for the construction sector is from primary mined material sources. This demand and primary supply have

Handbook of Recycling. https://doi.org/10.1016/B978-0-323-85514-3.00034-8

seen an exponential rise in the twenty-first century. This is driven by developments such as growing world population, aging populations, growing wealth in many economies, increasing expectations of places to live and work, and changing family and relationship patterns. The world is becoming increasingly urban as people are increasingly living in cities, also leading to the rise in the number of megacities, which are cities with a population of over 10 million people. The embodied carbon in building materials and components also increases as the primary material demand increases.

Importantly, there is the urgent need to lower the environmental and societal impacts of running buildings. Energy consumption comes from cooking, lighting, heating, cooling, and ventilating buildings as well as providing digital services. Buildings have become "smarter" and demand more sophisticated technologies (UNEP, 2020). Besides smarter, buildings will also be more connected with other systems: for example, through interaction with the electricity grid (using, storing, and providing energy), with mobility systems by providing charging infrastructure, and with district heating systems, as shown in Figure 15.1. This in turn drives the demand for a wider palette of technology materials. At the same time, the demand for the more conventional bulk materials such as concrete, bricks, steel, aluminum alloy, wood, and glass, etc. continues to increase too. In mass terms, the bulk materials form the majority, while the rise in technology material use poses new challenges, such as supply chain and criticality aspects, discussed in Chapter 36—Geopolitics of resources and recycling.

The current predominant pattern for building construction and refurbishment tends to follow the linear economic model of "take-make-waste," where primary resources are "taken" or extracted, via primary mining and harvesting. These raw materials are then processed into usable materials, which are used on the construction site directly. It is often the case that materials are used to manufacture components and products in factories, which are then directly installed and used in the building. At the point of refurbishment or complete building demolition, materials can be recycled; however many materials are then downcycled, and some critical materials are lost, being placed beyond economically realistic recovery.

This chapter aims to explore the importance of buildings as a secondary resource for materials while exploring the material complexity of buildings. The focus is on not just the bulk building materials, but also the technology and critical materials that are essential for the future functionality.

The chapter looks at current state-of-the-art of building waste recycling, to show what approaches work and what leads to missed opportunity. An overarching approach is taken, where the how, who, when, and what are considered (Hassi et al., 2009). In this, reuse, repair, refurbishing, remanufacturing, and recycling strategies are used to extend the life of buildings and enhance flows into eventual recycling activities.

15.2 THE HOW AND WHO: A FRAMEWORK

Researchers at Delft University of Technology, Faculty Architecture and Built Environment, "Circular Built Environment Hub" collaborated to develop a framework to help explain and better understand materials in the Circular Built Environment (CBE) context.

The method used was cocreation workshops by experts. A cross-disciplinary group of experts from the Delft CBE hub came together to develop solution pathways in on-line workshops. Their backgrounds and expertise covered domains such as materials, architectural design, building engineering and technology, product design, management in the built environment, urbanism, education and learning, societal, food and water, business, policy and climate, and environment.

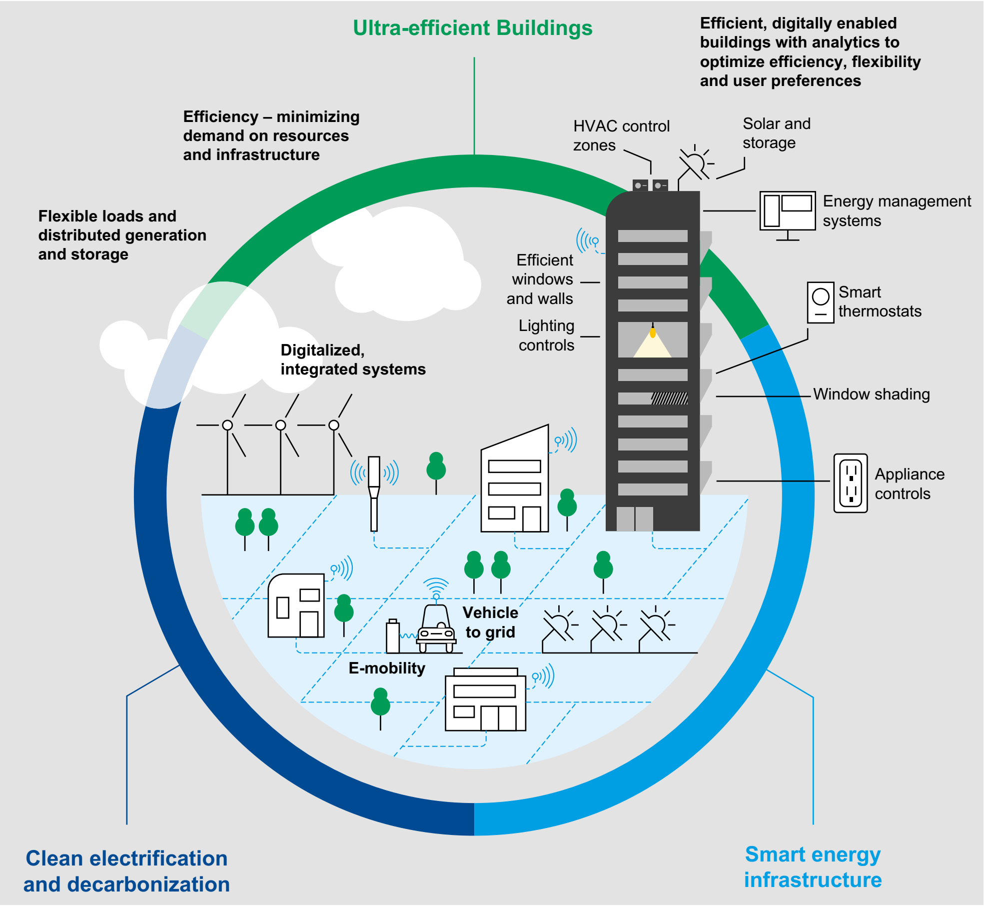


FIGURE 15.1 Buildings as part of integrated energy systems in cities. *From* World Economic Forum (2021).

The group was typically 10–12 people, meeting on-line over 3 months, a total of five times, and using a video call platform and an online collaborative whiteboard platform that allowed visual and interactive cocreation workshops. The collaborative whiteboard platform became the information storage repository. This section is partly derived from some of the information on the whiteboard platform.

The group of experts first developed a framework upon which they could work. The full framework (Figure 15.2) covers different scales in the inner circle of the figure, so that it scales from the smallest part of the built environment (materials) to the largest, systemic part (regions). The latter goes beyond the scope of this work and is therefore excluded. On the outer ring the six interrelated domains (or aspects) are listed.

Together they make up the (draft) definition of CBE (TU Delft, 2022):

> The Circular Built Environment (CBE) is a system designed for closing resource loops at different spatial-temporal levels by transitioning cultural, environmental, economic & social values towards a sustainable way of living (thus enabling society to live within the planetary boundaries).

FIGURE 15.2 The Delft "Circular Built Environment Hub" framework used by the Circular Built Environment hub. The scales (materials, components, buildings, neighborhoods, cities, and regions) are represented by the inner circle. These interact with the interrelated domains (technology, design, resource flows, stakeholders, economy, and management) shown in the outer circle. *Reproduced with permission from TU Delft (2022).*

The interaction between each scale and the domains are explained next.

15.2.1 Materials

First the scale of materials is discussed across the domains of technologies, management, design, stakeholders, resources, and economic aspects.

Technology: A CBE transition requires technologies, which require materials. The new technologies offer solution pathways, be they data, energy, new designs, etc. It is challenging for primary supply alone to meet the CBE demand for these materials. The fundamental approach of a CBE requires that primary materials use be minimized.

Management: Materials are managed from either a primary or secondary perspective. Circular management strategies generally fall into either material (product) life extension (PLE) or recycling. PLE strategies often require additional materials.

Design: This domain has two aspects at the materials scale:

- the design of new materials *and*
- the design of products/components and systems to facilitate PLE and/or recycling.

Both these design activities can facilitate a CBE. Design plays a key and transformative role in addressing materials challenges and opportunities. Both material design and product/component design are closely interlinked.

Stakeholders can include citizens, policy makers, companies, not-for-profit organizations, and NGOs. Organizations outside the company—for profit loci—tend to be less engaged and understanding is typically lower. Citizens, covered under the term of "wider society," tend to be less involved and included in the stakeholder dialogue on materials, although their involvement is higher on secondary materials. Different (time and geographical) scales apply across the materials value chain, both primary and secondary. The aims of stakeholder engagement can be many and varied, including across the Global South and Global North. The societal aspects of complex material chains are not well addressed across the spectrum of stakeholders in relation to primary material supply from the Global South.

CBE material **resource flows** break down into a variety of material resources, with material types such as: plastics, biobased materials, e.g., wood, metals, and minerals. The analysis of the materials can differ, but common tools can be used. Current systems of resource flows are, in the context of sustainability, broken. The demand and supply of materials are, over the near-term period up to 2030, unsustainable at present rates of increase and at the present balance of primary and secondary supply.

"Circular" **economy** is strongly influenced by linear economic approaches, such as financial pricing, markets, economic growth, macro- and microeconomics, etc. Actual circular economic approaches require a radically new approach. Merely enhancing end-of-life recycling, in a CBE context, in the short to medium term, cannot address the challenges societies face. Nevertheless, it remains highly important and must be rapidly enhanced.

Summarizing the materials aspects, a CBE transition demands a wide range of technologies, which require materials supply, both primary and secondary. The CBE demand for materials is challenging to manage and supply, and thus requires a more systemic perspective.

The deployment of new technologies, circular business models, policy shift, and societal engagement in a CBE offers solution pathways when the design of materials, *and* of products and systems, is done at the same time. Although materials differ, common tools can be used for analysis.

Circular economic approaches require a radically new approach, leaving linear economic approaches behind, and include engagement of the material stakeholders across material value chains, geographies, and perspectives.

Materials do have to be applied and it is in the components and building scale (Figure 15.2) where this application happens. These aspects are addressed in the following sections.

15.2.2 Components

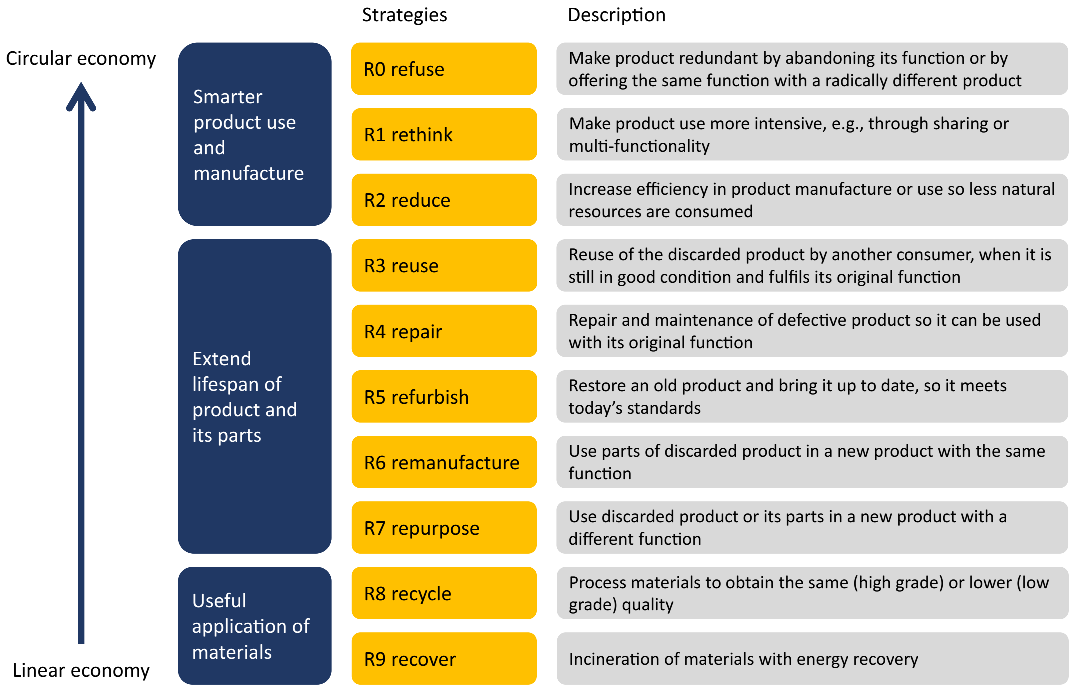
The CBE Hub workshops undertook a review at the scale of components across the domains of technologies, management, design, stakeholders, resources, and economic aspects. This section looks at each of those domains in turn.

Technology on the component scale concerns production technologies and processes and component hardware, but also digital technologies. R-strategies (Figure 15.3) such as reuse, repair, refurbish, remanufacturing, and recycling (Kirchherr et al., 2017), are typically proposed when it comes to component technologies.

Management of the component lifecycle and the reverse supply chain, but also (inter)organizational company operations, e.g., knowledge and expertise, fabrication facilities, outsourcing, sales, and marketing, are important factors to be understood.

Design by application of frameworks that allow for:

- regeneration,
- narrowing, e.g., through material choice, design optimization,



	Strategies	Description
Smarter product use and manufacture	R0 refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1 rethink	Make product use more intensive, e.g., through sharing or multi-functionality
	R2 reduce	Increase efficiency in product manufacture or use so less natural resources are consumed
Extend lifespan of product and its parts	R3 reuse	Reuse of the discarded product by another consumer, when it is still in good condition and fulfils its original function
	R4 repair	Repair and maintenance of defective product so it can be used with its original function
	R5 refurbish	Restore an old product and bring it up to date, so it meets today's standards
	R6 remanufacture	Use parts of discarded product in a new product with the same function
	R7 repurpose	Use discarded product or its parts in a new product with a different function
Useful application of materials	R8 recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9 recover	Incineration of materials with energy recovery

FIGURE 15.3 The 9R framework or R-ladder listing circularity strategies within the production chain, in order of priority. *Adapted from Kirchherr et al. (2017) and Potting et al. (2017).*

- slowing, through product life extension using, e.g., Design for Disassembly, reversible design,
- closing loops, e.g., design for recycling.

This is discussed in more detail in Chapter 2—The fundamental limits of circularity and Chapter 4—Material efficiency of this book.

Stakeholders are mostly related to industry and design such as product suppliers, builders, architects, engineers, and facility managers, but also standardization and norming bodies.

Complex **resource** and value chains must be programmed into components, considering a potential building's use, before the building design has actually started. Flows need to be tracked (i.e., through material flow analysis) and organized to a certain level of granularity (see Chapter 3—Maps of the physical economy to inform sustainability strategies, and Chapter 46—Process simulation).

The circular value chain requires new **economic** and business models that promote the circular use of components. Complex economic and relational structures emerge, as local supply chains are preferred over today's global supply chains.

15.2.3 Buildings

At this scale, components come together to form buildings through physical connections that should enable potential future disconnections, to facilitate a CBE. This can be enabled through the use of building information modeling (BIM) **technologies** at an early stage. It also includes digital technologies to support, for example, system monitoring, building maintenance, and system performance (Meyer, 2018).

The **management** of building actors and processes, building company operation, and procurement is an important factor. On the level of the construction system this requires laws and norms with building specifications, as well as fiscal and financial policy stimuli.

In a Circular Built Environment, buildings are **designed** as carbon neutral, with temporary configurations of component assemblies, creating flexible spaces for multiple and varied future uses and at the same time stimulating the well-being of its users. The buildings can educate and inform their users through their design and appearance. The temporality of configurations is designed using frameworks, which can focus on slowing and closing of loops across the lifecycle of the building, its components, and materials.

Stakeholders are currently investors and clients, product and component suppliers, builders, architects, engineers, and facility managers, but also the building users that aim to realize circular ambitions on a project-to-project basis. Building stakeholders providing essential, but "transient" resources, like energy, water, and food, are also involved.

Circular buildings, from an **economic** perspective, require an approach based on constraints and sufficiency, rather than excess. This needs business models that include the pricing of circular material use, and revolve around true costs, residual value, and social functions. True costs will include the cost of environmental and societal impacts.

15.3 THE WHEN: SHEARING LAYERS

It is important to understand the movement of materials and components in buildings. Much of the current thinking on buildings and materials is focused on building demolition and the recovery of materials via recycling of the bulk materials. This section shows that there is not a single point in time when buildings release products, components, and materials for circular activities. Rather, buildings continuously release a variety of products, components, and materials that change over time as a function of the lifetime and composition of each (see Chapter 2—The fundamental limits of circularity and Chapter 5—Material and product-centric recycling

The concept of "shearing layers" is useful to understand the time aspects of buildings. The concept was developed by Stewart Brand in his book *How Buildings Learn: What Happens After They Are Built* (Brand, 1995), which expands the concept of Duffy (1992). As shown in Figure 15.4, the layers start with the site, which is normally the ground upon and into which the building is located. The structure is then created. A skin of a building is then attached to the structure. Services and a space plan are then put into and onto the building. Finally, users of the building bring stuff into the building.

The materials that make up the different layers can cover a wide spectrum of material types and combinations such as plastics, bio-based materials (textile, wood), metals, minerals, etc. in a wide range of components and such as a products. In terms of elements, buildings, including the "stuff" occupants bring in, cover the entire spectrum of elements in industrial use, with even elements like uranium used in buildings such as nuclear power stations or research labs.

In any circular built environment, a range of R-strategies takes place. The 9R framework (Figure 15.3) provides an overview of the type of circular activity that can be applied when a material or component becomes available. Businesses cannot operate with any circular activity unless they can be certain of when a material or component will "supply" their operations. A combination of the building layers' expected

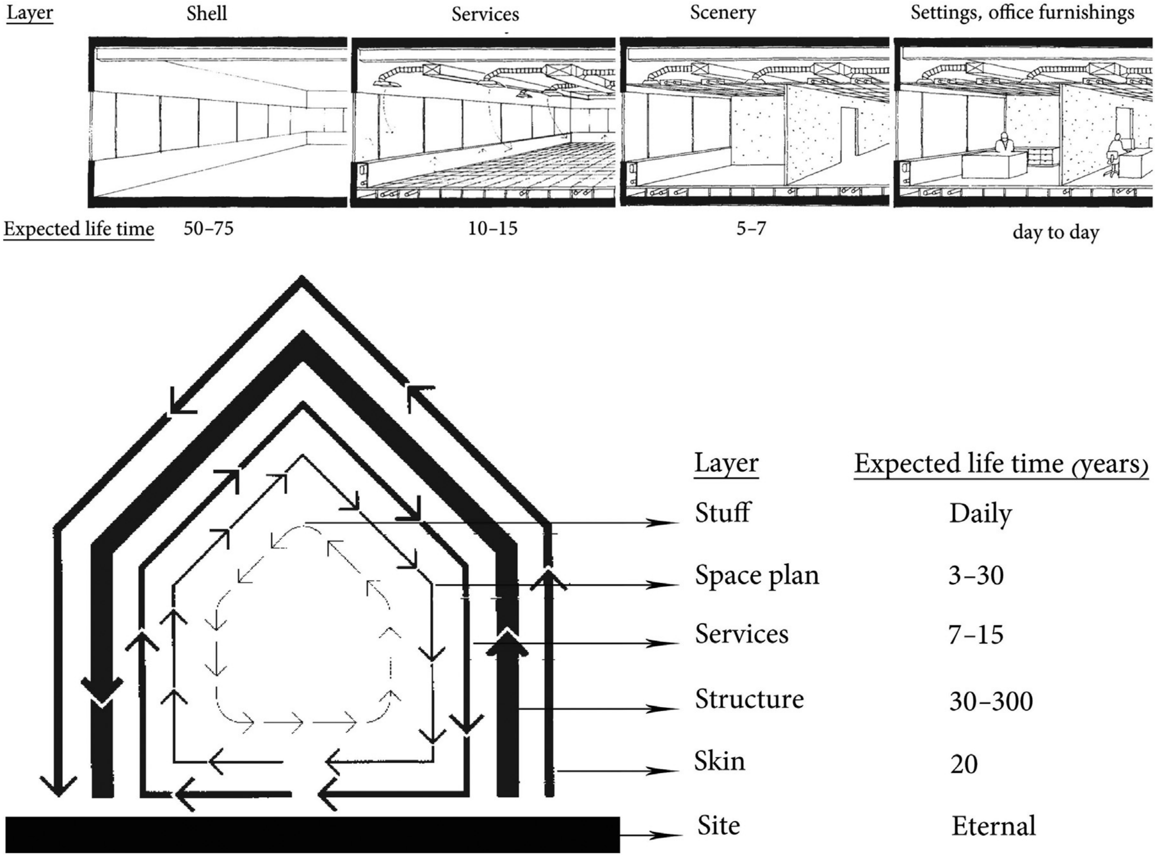


FIGURE 15.4 Building layers and their expected lifetime according to Duffy (1992) and Brand (1995), showing how components and materials flow through buildings over time. *From Salama (2017), who took the (original) figure from Durmisevic (2010).*

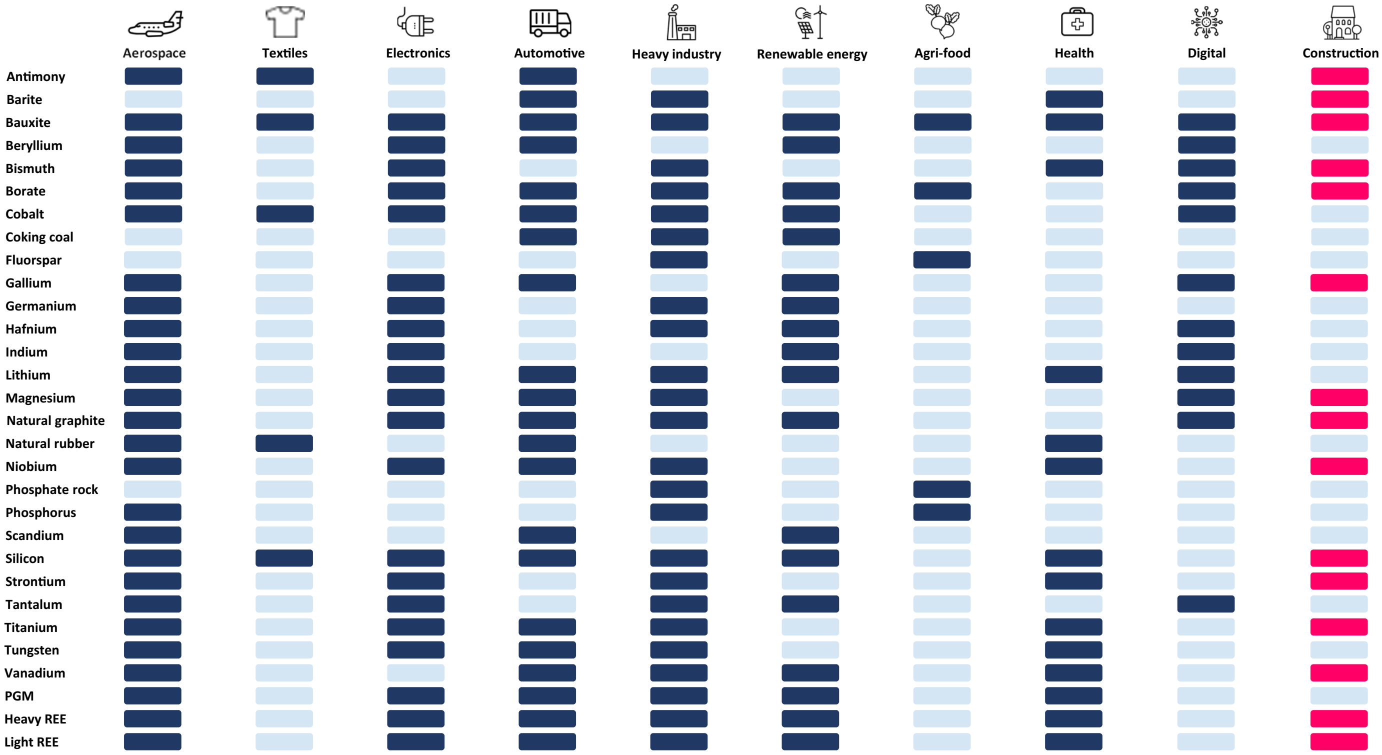
lifetime and R-strategies and activities provides a starting point for planning circular activities for buildings.

15.4 THE WHAT: MATERIALS IN BUILDINGS

A building structure can be concrete and steel, which will contain a limited number of chemical elements, while the services, such as heating, ventilation, and air conditioning (HVAC), can contain 60–80 elements. This is even more the case when "controllers" and other digital technologies in HVAC systems are considered. In terms of mass, the rare earth elements in electronics, for example, will be very low.

It is interesting how buildings and the construction sector are viewed by different stakeholders. Figure 15.5 shows the critical materials used in Europe's industrial ecosystems.

This shows how the EU suggests construction uses a range of critical raw materials (CRMs), but the construction of buildings also requires the installation and use of the other ecosystems:



	Aerospace	Textiles	Electronics	Automotive	Heavy industry	Renewable energy	Agri-food	Health	Digital	Construction
Antimony	■	■	□	■	□	□	□	□	□	🟥
Barite	□	□	□	■	■	□	□	■	□	🟥
Bauxite	■	■	■	■	■	■	■	■	■	🟥
Beryllium	■	□	■	■	□	■	□	□	■	□
Bismuth	■	□	■	□	■	□	□	■	■	🟥
Borate	■	□	■	■	■	■	■	□	■	🟥
Cobalt	■	■	■	■	■	■	□	□	■	□
Coking coal	□	□	□	■	■	■	□	□	□	□
Fluorspar	□	□	□	□	■	□	■	□	□	□
Gallium	■	□	■	■	□	■	□	□	■	🟥
Germanium	■	□	■	□	■	■	□	□	□	□
Hafnium	■	□	■	□	■	■	□	□	■	□
Indium	■	□	■	□	□	■	□	□	■	□
Lithium	■	□	■	■	■	■	□	■	■	□
Magnesium	■	□	■	■	■	□	□	□	■	🟥
Natural graphite	■	□	■	■	■	■	□	□	■	🟥
Natural rubber	■	■	□	■	□	□	□	■	□	□
Niobium	■	□	■	■	■	□	□	■	□	🟥
Phosphate rock	□	□	□	□	■	□	■	□	□	□
Phosphorus	■	□	□	□	■	□	■	□	□	□
Scandium	■	□	□	■	□	■	□	□	□	□
Silicon	■	■	■	■	■	■	□	■	□	🟥
Strontium	■	□	■	□	■	□	□	■	□	🟥
Tantalum	■	□	■	□	■	■	□	□	■	□
Titanium	■	□	■	■	■	□	□	■	□	🟥
Tungsten	■	□	■	■	■	□	□	■	□	□
Vanadium	■	□	□	■	■	■	□	■	□	🟥
PGM	■	□	■	■	■	■	□	■	□	□
Heavy REE	■	□	■	■	■	■	□	■	□	🟥
Light REE	■	□	■	■	■	■	□	■	□	🟥

FIGURE 15.5 The critical materials used in Europe's industrial ecosystems. *Modified from European Commission (2020).*

digital, electronics, and textiles, even renewable energy technologies. Indeed, when the Brand model perspective is taken, all sectors, and therefore all materials, are covered at some point by buildings. The scope as to which product/component/building/infrastructure any material is in is poorly defined and, it can be argued, is hard to define.

For many stakeholders buildings are made of concrete, bricks, steel, wood, and glass. At that the differentiation ends. While those materials do make up the greatest mass of a building, they may not be the materials where the widest range of circular opportunities lies.

15.5 IMPROVING DATA ON MATERIALS

Digital technologies are essential for the transition to a Circular Built Environment and many other sectors (Pagoropoulos et al., 2017). Digital technologies can enhance and support various circular strategies, as shown in Figure 15.3, in particular understanding resource flows (Pagoropoulos et al., 2017) and the tracking and tracing of products and components for product life extension strategies.

To date much of the focus has been on building information modeling (BIM) and digital twins to support CBE actions. The geographical information system (GIS) is, however, used at an urban scale in the decision-making process (Wandl et al., 2019). BIM platforms have been identified to show how they can be utilized for even challenging materials such as critical materials, and this is explored in more detail next (Meyer, 2018).

Despite the acknowledged opportunities that these digital technologies offer, there are three main challenges in the application to the CBE.

First, from a digital perspective, not a single integrated digital approach has been developed supporting CBE throughout the building layers and their lifetimes so far; therefore providing a comprehensive overview of materials movement through the entire supply chain is not possible. In a building construction process, the management of materials can be considered a vital part of managing the project. Failure to do so will cause losses and increase waste generation. It requires supervision at the entry and exit of material in a construction process that calls for monitoring material circulation aiming to prevent material loss.

Secondly, from a practical perspective, to develop the systemic change a CBE needs, it is also crucial to change behaviors. The construction industry in Europe currently has:

- A difficulty in finding and developing enough skilled workers,
- a lack of both awareness and understanding of digital technologies,
- a lack of knowledge on how to shift toward circular business models while maintaining competitiveness, and
- a lack of incentives such as the use of recycled materials via public sector procurement.

Thirdly, from a technical perspective, one of the biggest challenges in materials management in a CBE is the variety in size and properties of materials, products, and components, which makes it difficult to sort them automatically with standard equipment.

As highlighted earlier, a positive development in the circular built environment transition is the increasing development and use of building information modeling (BIM). A BIM model makes it easy to collect data of the whole life cycle of a building and share it among all involved stakeholders in the process. This data can be easily exported to other formats for further use.

In 2018 Charley Meyer conducted research to test if BIM is compatible to facilitate knowledge of, and solutions for, critical materials in buildings (Meyer, 2018). BIM was assessed to see if there was an approach that could process CRM information into standardized datasets to make it easily accessible and comparable.

As a case study, Meyer selected an electronic component, a sensor, to assess the current use and composition of objects containing CRMs. Meyer demonstrated that the recycling rate of critical materials in such electronic components in buildings is low. More efficient use of the materials can be achieved through technical changes, in designing for a longer lifetime, and new business models summarized as product life extension strategies. Then enhanced recycling at the end of the final use cycle could be achieved.

Meyer went on to show how documentation of all the required information to lengthen the lifetime of CRMs, via circular strategies, in BIM appears to be an appropriate solution through the use of so-called IFC files. Herein standardized datasets could be created and exported into many formats for further use. Based on specified information in IFCs, objects in a BIM model can be found by searching for instance for "critical materials," "gallium" or "Ga," and schemes can be exported outlining this information.

Meyer concluded by showing a framework that provides information on critical materials, material selection processes, optimized used of the materials, and finally converts this data into the so-called "property sets" suitable for IFC. The sensor example used by Meyer does highlight the complexity of materials in buildings and shows the technology convergence, where digital, electronic, advanced HVAC, and low carbon energy generation technologies converge to produce a very low carbon or net zero building. At the same time, the embodied carbon in the structural materials of buildings, in particular of buildings using mainly steel and concrete in the structure, need enhanced recycling when they are beyond any further safe use.

The challenge of data availability and data accuracy on CRMs, however, presented the work with challenges. If the framework is implemented with data on both "bulk" materials and CRMs, interested stakeholders could have a holistic overview of not only what is in a building, but also the optimal circular product life extension strategy and eventual optimal circular recycling strategy.

Platforms are being developed that draw on the idea to integrate different existing monitoring tools for materials in a CBE, including:

- Building Information Modeling (BIM),
- Material Flow Assessment and Material Passport,
- GIS-based material stream, and
- Industrial Symbiosis platform.

These approaches can be optimized by utilizing real-time on-site progress data and AI sensor technologies, where a system could automatically capture and trace on-time and on-site material movements. Consequently, by automating registration processes and reintroducing materials management systems, this is beneficial for both circular product life extension strategies and for circular recycling.

15.6 THE HOW, WHO, WHEN, AND WHAT

As buildings in a low carbon, sustainable, circular built environment become power stations, farms, biocooling constructions, and much more, there is an increasing diversity in the material choice, construction methods, and types of buildings. Buildings using wood as the main material is nothing new, but recent innovations on the design and joining of timber is producing new opportunities.

At the same time, modular buildings that are built in factories are reemerging as a sustainable alternative. These modules can be new build and used as renovation or refurbishing components. These designs can revolutionize product life extension and, at eventual end of final use cycle, recycling.

One important opportunity for closing the loop on building components and even modular building sections, is, as shown in Figure 15.3, remanufacturing (Boorsma et al., 2019). Even though there is no single definitive definition of remanufacturing, the elements used to construct the available definitions have commonalities. The definitions are generally constructed of three elements, which are:

- the use of a previously used product as an input for the remanufacturing activity.
- an industrial production process where varying emphasis is given to different operational activities, such as inspection, cleaning, disassembly, inspection, testing, coating, parts replaced, reassembly, testing, and dispatch.
- the intended outcome, referred to as at least equal to original product grade, even "better than" the original.

Remanufacturing can take a product or component and return it back to a factory where it will be processed to a condition that is as good as, or better than, new, in a box, with a warranty. The new user cannot tell the difference between a newly manufactured product and a remanufactured one. The "better than" new can be realized by the incorporation of modifications and upgrades during the remanufacturing process.

Remanufacturing is not repairing, reconditioning, or refurbishing. This is important, as a remanufactured product can meet all the applicable regulatory and safety requirements in a building, because it is as good as (or better than) new. This ensures it meets all the requirements.

The suitability of a product for remanufacturing depends on the physical product design, as well as the success of its interactions with the system it operates in. Typical criteria suggest that a remanufacturable product should be long-lasting, failing functionally, constructed of highly standardized parts with stable technology, and containing remaining useful life after use.

It is important that the cost to obtain the return product, known as cores, should be economically viable and the target market should be aware of what is on offer. Logistics plays a part too. The timing of incoming cores and the distance and cost of transportation, for example, are influenced by core management activities. Cores need to return when needed. A service-based business model may facilitate remanufacturing.

As a product is disassembled, inspected, and parts replaced, the old worn/defective parts are placed into the recycling stream. A recycler has a cleaned and monomaterially separated stream of "waste." Even better, it will arrive on a schedule. When the core can no longer be remanufactured, it can be fully disassembled, and all the parts go into recycling. It is everything a modern recycler wishes for.

15.7 OUTLOOK

This is the future of the built environment: to yield the greatest positive impact in closing material loops. It requires a combination of understanding the timings when things come out of buildings, their exact material composition, their value in terms of life extension, a steady stream of separated materials for recycling, and business models that make sense for all stakeholders. The result will be securing *both* critical and bulk materials in appropriate quality and lowering climate emissions by a significant factor, far beyond the current goals set for 2030.

The how, who, when, and what can help stakeholders develop circular built environment pathways to address the resource and climate challenges we face. The when, the time challenge, is key. The demand and supply of critical and other materials presents the built environment and its stakeholders with unprecedented challenges in the short term. The climate challenge will not wait. The key is a reduction in demand via circular strategies, as outlined in this chapter.

References

Boorsma, N., Tsui, T., Peck, D., 2019. Circular building products, a case study of soft barriers in design for remanufacturing. In: Ijomah, W. (Ed.), Proceedings of the International Conference of Remanufacturing 2019, Amsterdam, The Netherlands, pp. 1–17.

Brand, S., 1995. How Buildings Learn: What Happens After They're Built. Penguin Books. Paperback, October 1, 1995.

Duffy, F., 1992. The Changing Workplace. Phaidon Press Ltd. ISBN: 978-1854541208.

Durmisevic, E., 2010. Green Design and Assembly of Buildings and Systems, Design for Disassembly a Key to Life Cycle Design of Buildings and Building Products. VDM Verlag Dr. Müller, Saarbrucken, Germany. ISBN 978-3-639-11262-7.

European Commission, 2020. COM (2020) 474 Final Communication From the Commission to the European Parliament. The Council, The European Economic and Social Committee and The Committee of the Regions; Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0474.

Eurostat, 2018. Eurostat Statistics for Waste Flow Generation 2016. European Commission. ec.europa.eu/Eurostat/web/waste. (Accessed January 2022).

Hassi, L., Peck, D., Dewulf, K., Wever, R., 2009. Sustainable innovation – organization and goal finding. In: Andersen, R.D., Lehmann, M. (Eds.), Joint Actions on Climate Change. Aalborg University, Denmark. ISBN: 978-87-91830-30-3.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127 (2017), 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.

Meyer, C., 2018. Optimizing the Use of Critical Materials in the Built Environment Using Building Information Modelling (BIM), TU Delft Architecture and the Built Environment; Contributors Peck, D (mentor) & Bähre, B (mentor), Delft University of Technology Repository. http://resolver.tudelft.nl/uuid:7bbca8cd-473e-44e2-b787-044a31df7831. (Accessed 22 June 2022).

Pagoropoulos, A., Pigosso, D.C.A., McAloone, T.C., 2017. The emergent role of digital technologies in the Circular Economy: a review. Procedia CIRP 64, 19–24. https://doi.org/10.1016/j.procir.2017.02.047.

Potting, J., Hekkert, M., Worrell, E., Hanemaaijer, A., 2017. Circular Economy: Measuring Innovation in the Product Chain. https://www.pbl.nl/sites/default/files/downloads/pbl-2016-circular-economy-measuring-innovation-in-product-chains-2544.pdf. (Accessed 22 June 2022).

Salama, W., 2017. Design of concrete buildings for disassembly: an explorative review. Int. J. Sustain. Built Environ. 6 (2), 617–635. https://doi.org/10.1016/j.ijsbe.2017.03.005.

TU Delft, 2022. Circular Built Environment Hub. Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, the Netherlands. https://www.tudelft.nl/en/architecture-and-the-built-environment/research/research-themes/circular-built-environment/. (Accessed 22 June 2022).

United Nations Environment Programme (UNEP), 2020. 2020 Global Status Report for Buildings and Construction: Towards a Zero-Emissions, Efficient and Resilient Buildings and Construction Sector. Nairobi https://globalabc.org/resources/publications/2020-global-status-report-buildings-and-construction. (Accessed 22 June 2022).

US EPA, 2015. Design for Deconstruction Manual. United States Environmental Protection Agency. https://www.epa.gov/sites/default/files/2015-11/documents/designfordeconstrmanual.pdf. (Accessed 30 June 2022).

Wandl, A., Balz, V., Qu, L., Furlan, C., Arciniegas, G., Hackauf, U., 2019. The circular economy concept in design education: enhancing understanding and innovation by means of situated learning. Urban Plan. 4 (3), 63–75. https://doi.org/10.17645/up.v4i3.2147.

World Economic Forum, 2021. Net Zero Carbon Cities: An Integrated Approach. World Economic Forum, Geneva. https://www.weforum.org/reports/net-zero-carbon-cities-an-integrated-approach.