# The Role of Design in Conserving Product Value in the Circular Economy

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ABSTRACT

Design is integral to human activity and has been practiced since humans first made tools to fulfil specific functions. It was formalised during the first industrial revolution since when it has evolved to become a multi-disciplinary profession. Before the industrial revolution products and buildings were ‘circular’ by default. However, the development of synthetic and composite materials, and product and component miniaturisation has encouraged linear economic practices in design and manufacture. This has raised concern in the EU about rising waste, demand on resources, and risk to supply. In this chapter we explore the role of design in the value chain through four industrial sectors and discuss their evolution to understand the potential for circularity and the extent to which design can influence and contribute to circular practice now and in the future.

## Design

### The History and Role of Design

The Oxford English Dictionary defines *design* as a noun and a verb. In this context, design is described as ‘the purpose, planning or intention that exists or is thought to exist behind an action, fact or material object’1; in the broadest sense therefore, ‘design’ is integral to human activity. Evidence of design dates from prehistoric times when artefacts such as cutting, digging, and hunting tools were fashioned to fulfil a particular function.

Since then, design has been - and still is - practiced across societies, and in many contexts and related activities, outputs have simultaneously developed alongside social, economic, and environmental change. While some design activity remains informal and intuitive, design has evolved, become increasingly sophisticated, and developed into a profession. Design activities have also become more specialised and distinct disciplines have emerged, examples of which include fashion, textiles, graphics, communication, furniture, interiors, film, exhibition, architecture, service, user experience (UX), product, and industrial design. Design is also integral to engineering, which is defined as ‘the branch of science and technology concerned with the design, building and use of engines machines and structures’ in the Oxford English Dictionary1. The evolution of engineering from an intuitive and informal activity to a profession, mirrors that of design. As engineering has become more complex for example, more specialist disciplines have emerged. The history of the profession is now discussed.

### The Concurrent Development of Engineering, Design, and Industry

Engineering was practiced in ancient civilisations, but ‘modern’ and formal engineering and the engineering profession began during the 1st and 2nd Industrial Revolutions in the 18th century. Engineering evolved concurrently with the various Industrial Revolutions, each of which simultaneously initiated and drove changing technologies. For example, the invention of the steam engine and electrical systems encouraged the first and second Industrial Revolutions, while the third (computing based) Industrial Revolution began in the 1950s and the fourth Industrial Revolution that integrates cyber-physical technologies is now underway. During the 1st and 2nd Industrial Revolutions the introduction of new manufacturing processes (including mechanisation), energy systems, and materials facilitated a shift from craft-based and batch production to one of higher volume and mass, as did changes to working practices such as the division of labour. Production rates and output were further accelerated during the 1950s and 1960s following the introduction of industrial robots and Computer Aided Design and Manufacture (CAD, CAM), since when their utilisation has become increasingly widespread and integral to many industries. Digital manufacturing technologies progressed to include processes such as additive manufacturing (3D printing), and a shift from centralised to decentralised local and domestic production, facilitated by increasing connectivity and the emergence of cyber-physical systems via the Internet of Things (IoT).

Formal design practice and the design profession also emerged and evolved from the 1st and 2nd Industrial Revolutions. Initially design practice was inherent to architecture, craft, and engineering activities; however, the introduction of new manufacturing processes, technologies, and materials encouraged the development of distinct applied arts (i.e., design). The importance of design as a driver of innovation was formally recognised when the Society for the Encouragement of Arts, Manufactures and Commerce (now known as The Royal Society for Arts – RSA) was founded in 1754 in the UK to stimulate industry. The need for specialist design training became apparent at this time which led to the establishment of the first design (Normal) schools near to manufacturing centres in 1836. Their mission was to simultaneously prepare students for employment in and support the industry, and to develop ‘good’ design2. Since then, the RSA has continued to promote and consolidate links between the arts, manufacturing, and society.

The design process is comprised of a series of stages which were formalised by the UK Design Council in 2005. The Double Diamond Design Method for Innovation3 shown in Figure 5.1 defines the stages as discover, define, develop, and deliver. The method is not linear and involves considerable iteration to ensure that the outcome meets all constraints. Like engineering, design has pushed and pulled development of technologies in response to the demands and requirements of industry and users, and design has become increasingly important as a mediator between technology and user in line with rising sophistication and complexity.

[Insert Figure 5.1 near here]

### Design, Society, and Economics

Design and engineering had major impacts on society. For example, at the beginning of the Industrial Revolution western societies were predominantly agrarian but rural labourers were encouraged with the promise of higher incomes to seek employment in industrial facilities and to move close to mines, mills, and factories. Because of this, urban population increased from 9% in 1800 to 62% in 1900. Improved diets4, antibiotics, and other developments in medical care, equipment, and products have also increased global average life expectancy from less than 30 in 1800 to 73 years in 2019. This has contributed to global population growth from around 1 billion in 1800 to 8 billion in 2022, and increased demand on resources.

Design and engineering have also been critical to economics and in 1776 Adam Smith stated that, in addition to agriculture, gold, and silver the ‘wealth of nations’ was grounded in ‘national production’, i.e., manufacture5. ‘National production’ was critical to and developed because of the demand– supply–income cycle6, and, as predicted by Smith national and personal wealth increased. In the UK, for example, between 1700 and 1871 Gross Domestic Product (GDP) increased 53% per capita7, and between the beginning and end of the twentieth century an even greater increase of 400% per capita was recorded8.

Design encouraged demand, consumption, and industrial activity, through aesthetic and technical interventions. For example, in 1932 Bernard London9, an American economist, stated that increasing demand for goods would stimulate the economy following the 1929 Wall Street financial crash and Great Depression. He proposed planned obsolescence i.e., that products should be designed to break to encourage replacement10. This phenomenon had already proved successful for the lighting industry, members of which formed a cartel and purposefully reduced the life of tungsten bulbs from 2500 hours to 1000 hours to increase their profits. Similarly in 1927 Harley Earl was employed to lead the newly established Art and Colour Section at General Motors to increase profits by increasing sales of new vehicles; this was achieved by changing colour and minor design details to encourage product replacement without the need for major changes to engineering and tooling11. At a time when there was little if any concern about resource supply and environmental degradation the predominant perception of design was as a key driver of consumption and economics. While the industrial designer Brooks Stevens defined his role as creating the ‘desire to own something a little newer and a little better, a little sooner than necessary’12, another renowned designer – Raymond Loewy – apparently stated that ‘Industrial design keeps the customer happy, his client in the black and the designer busy’ and that ‘The most beautiful curve is a rising sales graph’13. These strategies certainly encouraged and continue to encourage demand and sales, but they also generate waste and adverse environmental and social impacts.

### Sustainable Design

Not all designers and engineers agreed with the aforementioned strategies, however, and in 1938 Richard Buckminster Fuller – a ‘comprehensive anticipatory design scientist’14 – advocated resource efficiency by ‘doing more with less’, which he defined as Ephemeralization15. Similarly, during the 1960s, the designer Victor Papanek adopted a radical environmental and ethnographically sensitive approach to design. However, he was castigated by his peers and forced to resign from the Industrial Designers Society of America (IDSA) when he stated that they produced ‘shoddy, stylised work that wasted natural resources, aggravated environmental crises, and ignored their social and moral responsibilities’16 and that ‘There are professions more harmful than industrial design, but only a few of them’. Many designers were responsible for planned obsolescence and had created ‘whole species of permanent garbage to clutter up the landscape, and by choosing materials and processes that pollute the air we breathe, designers have become a dangerous breed’17.

Growing concern about the environment, social justice, and human needs led the United Nations to establish the World Commission on Environment and Development (WCED) in 1983, and in 1987 the group published a highly influential report, Our Common Future. It includes one of the most frequently cited definitions of sustainable development as ‘development that meets the needs of the present without compromising the ability of future generations to meet their own needs’18. This has significant implications for design and engineering practice, and output regarding, for example, use of resources, conflict minerals, waste, emissions, and pollution. Some designers and professional bodies responded to these concerns, as a result of which Buckminster Fuller and Papanek’s ideas gradually spread and in 1991 the UK Design Council published ‘Green Design’19 as part of the Design Issues series. Since then, Design for Sustainability (DfS) has evolved considerably as a discipline that can be integrated into other design and engineering specialisms. As shown in Figure 5.2, initially product/industrial design was solely object and technology focused and supported the environmental and economic dimensions of sustainability; it has evolved to be more systems-focussed, and to include socio-ethical factors in addition to addressing environmental and economic concerns, and therefore to support more radical change and transition to potentially more sustainable systems overall20. The inclusion of social dimensions also suggests that there is potential to align with more of the UN Sustainable Development Goals.

[Insert Figure 5.2 near here]

### The introduction of the Linear Economy and Design

Early mechanical products were easy to repair and upgrade because of the way in which the constituent parts were manufactured and assembled; for example, mechanical components such as gears, pistons, and belts found in steam engines or looms were exposed and could be removed and replaced. Similarly, mechanical fixings such as nails, screws, and bolts permitted relatively easy disassembly while welded, soldered, and joints that used animal-based glues could be reheated and separated. This in conjunction with the relatively high cost of producing goods and limited expendable income encouraged thrift and careful use of resources until the general level of expendable income rose and relatively inexpensive (e.g., plastic) goods were introduced. Changes in purchasing power and as previously discussed, built in obsolescence and aggressive marketing encouraged product replacement before necessary, increasing waste; this was exacerbated by changes in materials selection, assembly, and joining processes which limited or prevented easy repair. The second-hand market and ‘make-do-and-mend’ culture had thrived when expendable income was limited and during wars when resources were scarce or required for manufacture of defence goods. In addition to rising incomes, and more available and cheaper resources design strategies encouraged the linear economy which also increased disposal of unwanted and/or damaged goods and decreased interest in and market for second-life goods.

In a linear model of consumption, we take resources from the ground, make them into a product, use the product, then dispose of it. In this take-make-waste approach the product and materials it contains are considered waste at the end of its life. This is a problem not only because of the pollution created from waste disposal, but also from the continued extraction of virgin raw materials which have a finite supply. A model of consumption in which products and their components and materials have no value at the end of their first life is inherently flawed when planetary boundaries put limits on the resources available to us and the amount of pollution it can remove.

### The Circular Economy and Design

In contrast, a circular model of consumption takes a whole systems approach based on a fully renewables-based energy supply and in which no product or material ever becomes waste. The circular economy echoes natural systems where dead/redundant materials decompose and become nutrients for the subsequent year’s growth and/or generations. There are two main loops in the circular economy21 as shown in Figure 5.3 below: one includes technical ‘nutrients’ and the other biological ‘nutrients’. In this second loop, systems are designed to regenerate soil, by feeding nutrients released through composting and anaerobic digestion into the land on which renewable materials like cotton and wood are grown and fed back into the economy22. In the technical loop materials are circulated for as long as is technically and economically feasible, and products are designed to allow for reuse, repair, refurbishment, and remanufacturing; at end of life the materials are recycled, reclaimed, and reused. Closing the materials loop ensures that we do not lose resources from the system; rather they flow continuously within the loop at a product, component, or material level. By minimising or ideally removing the concept of waste altogether, pollution from disposal and raw material extraction can at least be minimised and ideally eliminated. A circular economy includes physical artifacts/goods and performance/functional services in which products are leased and/or shared. This practice supports dematerialisation and resource efficiency23. An example is the Rolls Royce business model in which the company does not sell aircraft engines but sells Power by the Hour and therefore maintains and controls all their products from design to and beyond end-of-life24.

[Insert Figure 5.3 here]

### Design and the Value Chain

According to the World Business Council for Sustainable Development (WBCSD) the value chain is ‘the full life cycle of a product or process, including material sourcing, production, consumption, and disposal/recycling processes’25. It differs from the supply chain because, in addition to economic factors, it considers ethical, social, and environmental factors which are added internally and externally throughout the lifecycle26. Furthermore, a sustainable value chain is one that ‘enables both business and society to better understand and address the environmental challenges associated with the life cycle of products and services’26. It is evident that informal and formal design decisions and related activities have always influenced impacts throughout the value chain. Impacts may be environmental, social and/or economic and therefore design can affect the overall sustainability or otherwise of a product.

Such is the power of design that it is said to determine up to 80% of the environmental impact of a product over its lifetime27. Although frequently cited28–31, there does not appear to be any empirical evidence to support this exact percentage. However, the figure may originate from an article which describes Green Product Design as ‘a proactive approach to environmental protection that addresses life-cycle environmental concerns in the product design stage. Decisions made during that stage profoundly influence the entire life cycle of the product and determine 80 to 90 percent of its total life-cycle costs’32. Whether 80% is accurate or otherwise, the influence of design on environmental impact and overall sustainability is indisputable.

To facilitate the move to a circular economy, designers need to consider positive and negative impacts at each stage of the product life cycle (i.e., down- and upstream). Factors include:

* **Design:** physical durability, cognitive and physical functionality, and emotions.
* **Resource efficiency:** materials selection and efficiency – their criticality, social, and environmental impact, cost, extraction/processing methods required, and ease of recovery from the product at end-of-life.
* **Operational energy** inputs and efficiency.
* **Manufacturing methods:** efficiency and waste reduction/elimination.
* **Ability to disassemble** products economically for life extension and end-of-life treatment.
* **Potential to extend life** through reuse, repair, component upgrade, and remanufacture – including modularity.
* **Treatment at end-of-life:** enable maximum recycling and minimal waste to ensure that little if anything goes to landfill.

In addition to influencing physical factors such as materials selection, design also influences users who decide how, where, and for how long the product is used. These factors can be encouraged or discouraged by stimulating emotion, which is another key role for design in the value chain.

### Emotional Design

Design has significant influence on the quality of user-experience and can decrease or increase physical and cognitive ease of use33. It can also make products inclusive and enable easy use across generations and genders like OXO Good Grips products. These were developed for use by people with limited dexterity and grip because of arthritis for example. Some products for users with different abilities appear alienating or cumbersome and different from mainstream products; however, Good Grips products have a distinct visual brand identity that was created to appeal to and be used by everyone, and therefore the products do not look out of place alongside other mainstream products. While product aesthetics give brands visual identity, research shows that users also find aesthetically pleasing ‘beautiful’ products and interfaces easier to learn how to use than less visually appealing products or interfaces34 and consequently ‘attractive things’ may even be perceived as working better35. Making interfaces more comprehensible and guiding users through processes, is increasingly important as products and their functions become more complex. While visual beauty may be overt, other more covertly ‘beautiful’ design features such as surface finish, appeal to sense of touch which, alongside sound and smell can also provoke an emotional response. A user is more likely to develop an emotional bond with a product that they find pleasing even if they are unable to explain why. This emotional bond encourages the user to keep the product, extending its lifetime and helping to reduce waste.

## The Role of Design in the EU Circular Economy Action Plan and UK Circular Economy Package

Concern about climate change and other environmental factors and increasing waste and supply chain security encouraged the European Commission to devise and publish various guidelines and policies to increase the design and manufacture of more resource efficient consumer27,36 and capital goods37. The initial focus was energy efficiency, which was rated, and goods and properties were labelled from A\* to E accordingly. In 2020 the EU extended this incentive to include embodied energy and physical resources in the Circular Economy Action Plan for a cleaner and more competitive Europe27; the UK also published a similar Circular Economy Package in 2020. Some of the initial guidelines for better practice in the Action Plan – e.g., the right to repair (with emphasis on consumer goods) - are already being developed into policy and it is expected that in time all 35 recommendations will become mandatory. Several key product groups are prioritised in the Action Plan because there is significant potential to increase circularity and reduce negative impact throughout the value chain. These are textiles, furniture, high impact intermediary products (steel, cement, chemicals) and electronics and ICT equipment. Some proposed actions are beyond the role of design and will depend on legislative action; these include introducing a ban on the destruction of unsold durable goods, restricting single-use plastics and products, countering premature obsolescence, and rewarding products based on their different sustainability performance, including by linking high performance levels to incentives. However, design can directly influence many other proposed actions. These include increasing product energy and resource efficiency by improving durability, reusability, upgradability, and reparability, and enabling remanufacturing and high-quality recycling; increasing recycled content in products, while ensuring their performance and safety; reducing carbon and environmental footprints and addressing the presence of hazardous chemicals in products. A combination of design and legislation will drive other actions including the incentivisation of product-as-a-service; other models where producers keep the ownership of the product or the responsibility for its performance throughout its lifecycle; and mobilising the potential of digitalisation of product information, including solutions such as digital passports, tagging and watermarks. We now consider the challenges presented by and opportunities for change through design and the value chain for the four priority areas.

### Textiles

The global textile industry is well-established and creates yarns and fabrics that are essential to different sectors including clothing, footwear, and household textiles. Products from these sectors are essential to well-being and in addition to creating privacy, protecting wearers from injury, maintaining comfortable environmental and body temperature, for example, they also offer wearers and users a sense of cultural and social identity38. Currently 175m tonnes of primary raw materials are used to produce textiles annually for the EU, 40% of which become clothing, 30% household textiles, and 30% footwear39,40.

Textiles can be composed of natural and/or synthetic fibres and the global fibre market is split into four categories of which synthetic fibres, and in particular polyester, account for the greatest proportion. The global split of production in 2021 was41:

* **Synthetic fibres** made from crude oil (64%) – polyester, polyamide (nylon), polypropylene, acrylics, elastane.
* **Plant (natural cellulose) fibres** (28%) – cotton and others like jute, flax, and hemp.
* **Manmade cellulosic fibres** (6.4%) extracted from plant-based materials (like wood and bamboo), processed into pulp and extruded (6.4%) – viscose, acetate, lyocell, modal, cupro, and rayon.
* **Animal fibres** (1.6%) – wool (sheep, goats, rabbits, alpaca), down and feathers, silk (from the cocoons of insect larvae), leather, and other fibres.

Polyester accounts for 54 percentage points of the 64% synthetic fibre production, driven in large part by fast fashion. Many qualities have led to its dominance, for example it is relatively low cost, easy to dye, and weave and blend with other fibres, lightweight, strong, and wrinkle-free42.

#### Problems Faced by the Textiles Industry

Fibre mixing is commonplace and while 100% natural textiles may be composed of (for example) cotton, wool, and silk, 100% synthetics may be composed of mixed acrylic, nylon, and elastane yarns/fibres. Natural-synthetic hybrid mixes (such as polyester cotton and mixes of three and more types of fibre) are also common as are ‘performance’ textiles, which may be coated for fireproofing, waterproofing and/or to block out light.

From 1975 to 2020, global fibre production almost tripled from 34 to 109 million tonnes. In 2021 around 8.5% of production was from recycled fibres, of which less than 1 percentage point derived from textiles. In the case of polyester for example, most of this content was from open loop recycling of bottles rather than textiles. Low recycling rates of polyester are partly due to a lack of infrastructure for textile-textile recycling, but also because of the degradation in quality over successive cycles of recycling, and combination with other materials like cotton (polycottons) which make recycling impossible. This pattern is typical to other textiles. Many textiles end in landfill or incineration in countries outside of the EU and are often discarded rather than donated43. Furthermore, cheaper clothes mean that more are being bought, worn for shorter periods, and discarded in less responsible ways.

Natural virgin fibres require a lot of land and water for cultivation and energy for materials production. Textile production is heavily reliant on chemicals and utilises 25% of those produced globally per year44. Water consumption is also very high, and it takes 100-150 litres water to produce 1 kg of fibre depending on type, while the fashion industry alone uses about 93bn m3 water per year 45. The textile industry is also responsible for 20% water pollution from dyeing and finishing and 10% of global greenhouse gas emissions per year43, while the washing and laundering of synthetics creates microplastics and water pollution.

These criteria make identification and separation of constituent yarns/fibres for reuse and recycling very challenging at best, and at worst impossible, resulting in very high adverse impacts. At present less than 1% are recycled into new products; some textiles are exported from EU, and some of the non-reusable fraction is downcycled into industrial rags, upholstery filling, and insulation, however, 87% of textile products are sent to landfill or incinerated at end-of-life43. Consequently, textiles have the 4th highest impact on the environment and climate change after food, housing, and mobility in the EU39.

#### Design and Change in the Textiles Value Chain

As previously explained, textiles fulfil several important functions; however, it is evident that current practices in the sector are not sustainable. Design needs to mitigate or eliminate the adverse impacts of natural and synthetic fibres used by changing technologies and behaviours. Technical change includes use of materials that can be easily recycled (including single rather than composite yarns), and use of recycled as opposed to virgin materials, which will be expedited by an increase in the rate of recycling. Clothing and household products also need to be designed for durability, longevity, and repair as and when appropriate. However, these changes must be supported by change in user behaviour, some examples of which are already taking place. Examples include clothing hire and purchase of ‘pre-loved’ items. Nonetheless, one of the biggest challenges is ‘fast’ (and low cost) fashion which is also encouraged by on-line business and social media. Design could encourage ‘slow fashion’ although this will be a challenge because the fashion industry is built around two seasonal design collections every year. Consumption could be reduced by increasing the perceived, emotional, and actual value of items through use of textiles that wash well, and retain shape and colour, for example.

Several initiatives have been established in response to the status quo to encourage better practices across the value chain. One initiative 46 recognises that ‘design continues to play a significant role in the damaging impacts on natural systems and human populations throughout the textile supply chain’ and is undertaking research to address this by developing circular systems for fashion and textiles that are already in circulation. Example projects include use of post-consumer waste, the development of associated materials production technologies, and a sustainable design toolbox. A second initiative is focusing on future fashion and household textiles challenges by turning waste bio-feedstocks into functional and regenerative textiles designed for circularity; by developing better tools to facilitate Circular Supply Chains; and by improving links between resource flow and human wellbeing and changing consumer experience47.

### Construction and the Built Environment

The human-made buildings, roads, infrastructure, service networks, and public spaces that support our home and working lives are collectively known as the built environment and is underpinned by the construction industry. In the UK in 2022 the construction industry accounted for 6% of employment, 6% of the total GVA (Gross Value Added)48 and 10% of the total EU GVA49. The industry is a driver for social and economic growth and is one of the most important industries to the EU economy.

The construction industry also adds a heavy burden to the environment. It is the world’s largest consumer of raw materials50, accounting for 50% of all extracted material27, and one of the biggest sources of waste in Europe51. In the EU in 2020, construction accounted for 37.5% of the total waste stream, whilst mining and quarrying for 23.4%52. In the EU the industry creates 9.4% of total domestic carbon footprint, and buildings consume 40% of total energy consumption, whilst the cement, steel, aluminium, and plastics industries – used extensively in the industry – account for 15% of total EU carbon emissions49. Globally, cement alone accounts for 8% of total CO2 emissions. In the UK this equates to 5-12% of all GHG emissions originating from materials extraction, construction product manufacturing, construction, and renovation27.

The main materials used in construction are:

* metals like steel, aluminium, and copper (structural elements, pipes, and ductwork)
* cement (mortars and concrete)
* ceramics products (bricks, tiles, conduits, and electrical insulators)
* glass for windows
* wool insulation
* glass fibres (composite products like cladding, and insulation)
* wood (including composites like glulam and CLT (cross laminated timber)), and
* plastics

The choice of material depends on the function of the element. For example, concrete works well in compression, is strong, durable, relatively cheap, and fire-resistant. However, it does not perform well in tension and is therefore used with aluminium reinforcement bars or mesh. Steel is fast to erect on site, generally leads to lighter super structures and therefore a reduced sub-structure (foundations) and can be used to create longer column-free spans, however, it requires fire protection which concrete does not. Often composite metal decking with a slimmer concrete slab is used to reduce the depth of material use, and the need for temporary formwork.

#### Problems Faced in Construction and the Built Environment

The industry still relies heavily on a linear – take-make-dispose – model of consumption. It consumes huge volumes of virgin raw materials for construction, and energy for operation, and accounts for one of the biggest waste streams globally. To reach the EU 2030 goal of reducing CO2 emissions by 55% below 1990 levels53 and 2050 targets for reaching carbon net zero, the industry must reduce its global emissions by 2.1 billion tonnes54 - a target the industry is currently not on track to achieve55.

There are several barriers to the slow implementation of a circular economy which would reduce these impacts. Globally, investment in building energy efficiency is low, alongside a moderate move to renewable sources of energy, and there is a lack of mandatory energy codes in many countries55. Policy is needed to incentivise circularity as will be set out in the European Commission’s Strategy for a Sustainable Built Environment56, for example the setting of required recycled content for construction products27, EU material recovery targets, and less prescriptive waste regulations57.

Contractual barriers between different stakeholders in the building lifetime create a silo effect, making it hard for the industry to collaborate and share knowledge on circular designs and solutions. In addition, teams that could improve outcomes later in the project – such as commissioning and demolition engineers – are often not included early enough in the design process to be able to influence outcomes and support a paradigm shift, and lessons learned are often not fed into future designs. In addition, the industry has substantial inertia, meaning the positive effects of any systemic and behavioural changes take longer to appear.

Underdeveloped infrastructures make material recovery hard. Steel can be recycled almost indefinitely without degradation to its performance. Globally 85% of steel is recycled58. However, the highest embodied impact is retained when it is reused. To support reuse the industry needs initiatives like take back schemes, secondary markets, mechanisms to guarantee quality (for example methods of demolition that retain the structural integrity of elements), and initiatives that can help eliminate the 15% of construction materials that leave site as waste without having been used54. Although many other construction products are recyclable – like cement and plastics – reuse and recycling rates are much lower (with huge EU variance) due to poor recycling infrastructure and disassembly outcomes. Concrete can contain recycled aggregates such as PFA (pulverised fuel ash) and GGBS (ground granulated blast-furnace slag), however, in the UK in 2020 they only accounted for 28%59 of total aggregates used.

#### Design and Change in the Construction and Built Environment Value Chain

The Ellen MacArthur Foundation describes three Circular Economy (CE) strategies that provide the biggest opportunities for reducing emissions from the built environment. The first is to make better use of existing buildings54, by building nothing and reusing and renovating existing buildings, or increasing the utilisation of already underused spaces.

The second strategy is to design new spaces in ways that eliminate waste54 and allows for better outcomes from the first strategy. Although typical design lifetimes for buildings are over 60 years, buildings are often demolished after 30 when they are no longer deemed desirable or fit for function58. To improve CE-outcomes, new buildings should be designed for longevity using durable and maintainable materials that are repairable, and with spatial consideration of the needs of different users to increase building utilisation through concurrent use of spaces by multiple tenants. Modular designs should be used to allow for future adaptability and reconfiguration which can meet the needs of new occupants as well as any future implications of climate change such as change in space heating and cooling requirements. Design complexity, building spans and building dimensions should be minimised, and high strength materials (resulting in smaller elemental masses) used to avoid overspecification and reduce material use. Simplified designs are also easier to construct, reducing risks of error and wastage during construction. Wherever possible, prefabricated elements should be used to reduce raw materials consumed and waste generated. By lengthening lifetimes and reducing construction volumes this effectively circulates products and materials to retain their embodied impact54.

The final strategy is to reuse and recycle materials54. Currently only 20-30% of construction and demolition waste is reused or recycled58. Designs need to take a whole life approach which increases recycled content and reduces the use of virgin materials, critical raw materials (e.g., recycled aluminium reduces the consumption of primary bauxite from which it is extracted), and hazardous materials. Designs should allow for disassembly, using methods like reversible mechanical fixings, and limiting composite materials that cannot be reused in their initial state or separated. On practical completion, buildings should be handed over with repair, maintenance, adaptability, and disassembly manuals in digital logbooks27, and material passports60 to ensure improved circularity of materials and retention of embodied impacts54. Finally, it is imperative that the construction process and building operation transition to renewable sources of energy and eliminate the use of fossil fuels.

### Furniture

Traditionally most furniture was made from wood because it was an abundant resource and, unlike metals, it could be harvested, shaped, and joined relatively easily. Accurately cut joints also rely on friction fit and do not require glue. Traditional glues were made from animal parts, which was very sustainable because the parts used - skin, bone, hooves, and horn - were unfit for human consumption. Although glues were not used for some highly skilled furniture and building manufacture (like those found in Japan) they were often used by batch and mass-manufacturers, particularly for lower cost items61. Metal furniture and components were introduced concurrently with the development and evolution of metal manufacturing processes for the construction and transport industries. Early examples from the 1830s include cast iron tables and benches which were used in gardens and parks. Tube bending processes were originally developed for bicycle handlebars, but the technology was imaginatively transferred to furniture production by members of the Bauhaus (Modernist German design school and movement) during the 1920s; the new processes and materials allowed for new lighter weight forms such as the Model B3 Club Chair designed by Marcel Breuer in 1925-26 and the MR10 cantilevered chair designed by Mies van der Rohe in 1927. Both chairs can be easily disassembled for repair, component reuse, and recycling.

While solid wood furniture can also be repaired and disassembled relatively easily if joined with animal-based glues, it is subject to shrinkage and swelling in certain humid conditions if it is not cured properly. Cutting planks from tree trunks can also generate considerable waste although this is frequently reduced to particles or fibres and used to manufacture chip, strand, and medium density fibreboard (MDF). Temperate hardwoods like oak, beech, walnut, poplar, cherry, and ash are used to make furniture62 while softwoods from managed plantations (pine and spruce) are also used in the furniture and construction sectors.

Although wood is regarded as a renewable resource and some woods (eucalyptus, pine, and spruce) are relatively fast growing, other temperate woods are much slower growing and therefore regeneration is slow. Many forests are managed and certified as sustainable by the Forest Stewardship Council but almost 100 types of trees are listed as (critically) endangered, threatened, vulnerable or in need of conservation63. This is a point of concern because the supply chain lacks transparency, and it is difficult to identify the exact origins of timber without extensive due diligence and therefore wood used could be from unsustainable sources. Many imported products are not covered by EU Timber Regulations. At present over 50% of furniture and components are imported from outside the EU, 42% of which are from Chinese forests and 50% by volume come from countries with illegal logging/trade issues62. These issues are compounded by the fact that import partners don’t necessarily represent the origin of the timber62 and retailers are not doing enough to understand or validate their supply chains all of which damage local ecosystems and societies and reduce potential carbon sequestration.

Examples of engineered timber by-products include chip (particle) board, MDF and HDF (high density fibreboard or hardboard), laminated wood where the grain of successive glued layers is parallel, and plywood where layers/veneers of wood are glued together with the grain of each layer at right angles to the next, providing strength and stiffness in both directions. The manufacture of by-products from timber processing reduces waste, which is positive. However, these materials are bonded with synthetic resins and are heated and pressed into boards. Resins used include polyester, vinyl ester, epoxy, and polyurethane resins which are thermoset and converted from liquid to solid through polymerization (cross linking). Consequently they cannot be returned to their former liquid state, which makes economic and/or simple recycling impossible. Melamine - another thermoset plastic - can be made in sheets; it is available in a wide range of colours and surface patterns, and it is frequently used to face chip and fibre boards. Being water- and heat-proof it protects the engineered timber and prolongs product life. However, it is glued to the timber, which in conjunction with being a thermoset material, compounds the challenge of recycling. In addition to adhesives inexpensive flatpack and mass-produced furniture is often joined using knock-down fittings. Some of these devices can be unfastened to allow for component separation, but many are made from plastic and designed to click fit one way, which prohibits disassembly. It is not surprising therefore that in 2018 the North London Waste Authority found that 22 million furniture items were thrown away each year, 11% of which ended up in household rubbish64. Some of these items would have been incinerated at energy from waste plants but others would have been sent to landfill. Not only is this a waste of resources but use of polymer-based resins and adhesives means that decomposition is slow. Finally, formaldehyde can ‘off gas’ and leak into the atmosphere but levels tend to be so low that any adverse effects are rare, and most will occur prior to delivery of boards or furniture to homes.

It is evident that current furniture design and manufacture methods are simultaneously environmentally and socially advantageous and disadvantageous. For example, use of solid timber can increase durability, and perceived and actual product value, but unless it comes from an approved supply chain it contributes to the destruction of forests. Melamine faced chip and fibre board furniture can be more economical and available to more consumers, but it is less durable which limits life in service, it cannot be recycled, and contributes to a growing waste stream. Once again design decisions will have a considerable impact on environmental, social, and economic factors throughout the value chain and designers need to consider and balance all factors to develop products that simultaneously meet users’ requirements and minimise adverse impacts.

Design features could increase product life. Examples include adjustable furniture that ‘grows’ with children, supply of repair and customisation kits to update and refresh tired products, and design for disassembly to encourage and enable easy reuse of components and recycling at end-of-life. Designers also need to identify and consider less energy intensive manufacturing processes and use of low impact and alternative materials. For example, by-products like walnut shells reduce the need for virgin materials, significantly reduce formaldehyde emissions, and improve water resistance in fibre and particle board at the same time as reducing stress on forests and creating jobs and a second income stream for farmers65.

### Electronics and ICT

#### Electricity

The Industrial Revolution saw the transition from an economy based on hand production to one of industrial and machinery-based production. This was due to technological advances which included new energy sources such as coal, steam engines, and electricity66. The development of electricity-based technology began in the 1750s when Benjamin Franklin noticed that power could be generated from sparks emitted from lightning strikes67,68. Other pioneering scientists subsequently extended knowledge, and developed components, products, and systems including electric batteries, motors68, and incandescent light bulbs as well as coal-fired, hydro and wind generation plants66,68 and distribution networks from the 1880s. The number of suppliers increased in line with the growing demand for electricity and reliable transmission and in the UK by 1937 all local grids were combined and run synchronically with the same 132 kV voltage and 50 Hz frequency without failure69. By 1950 the network could no longer meet demand and work started on a 175kV supergrid which has subsequently been extended with most of the UK now connected to the grid and/or with access to an off-grid electricity supply.

The growth of mass power generation and distribution encouraged rapid developments in the design and production of commercial and domestic electrical equipment. Manufacture was also accelerated by the invention of Bakelite - another synthetic thermoset plastic made from phenol (and later urea) formaldehyde by the Belgian chemist Leo Baekeland in the early 1900s. The materials were excellent insulators and ideal for electric lighting fixtures, plugs and sockets, as well phonographs, kettles, irons, washing machines, and vacuum cleaners which became popular because they enabled entertainment in the home and alleviated some of the drudgery of housework. Electricity also initiated changes in machinery and manufacturing processes although early products were assembled in the same way as non-electrical goods i.e., plastic components tended to be bolted/screwed together with those made from the same and other materials. This meant that product repair, replacement, and reuse of parts was straightforward, and the purchase and use of second-hand goods was commonplace. Electrical and other metal components were separated and recycled, and waste was usually limited to the thermoset plastic housings. Telephones and wireless radio sets also benefitted from plastic casings and cabinets; they also proved very popular and changed communication permanently. The earlier invention of cinema had already transformed entertainment, and this was further transformed by the introduction of television in the 1930s, which, like telephony and radio70 were enabled by the discovery of the electron and gradual development of electronics.

#### Electronics

The evolution of modern-day electronics dates from 1897 when the British physicist Sir Joseph John Thomson discovered the electron. Various subsequent discoveries led to the development of the thermionic valve, which converted AC radio signals to weak direct currents detectable by telephone receivers and radios70,71 and were more reliable than early ‘cat’s whisker’ radios72 comprised of fine wires in contact with a crystal of semiconductor material which could not be amplified70. A semiconductor (like germanium and silicon) conducts electricity to a degree between that of conductors (like copper and aluminium) and insulators (like glass and diamond), and to which trace amounts of other elements can be added to alter the electrical properties. These materials proved incredibly important as the predecessor of modern-day solid-state components. Further discoveries led to the amplification of radio signals and advances in radio broadcasting, long-distance telephony70, and television68. Transistors, invented in 194870,71, comprised of semiconductors which were originally made from germanium73 and subsequently silicon70. Research found it was more abundant, cheaper, and better able to perform at higher temperatures. Transistors soon replaced vacuum tubes and valves because they were very reliable73 and because it was possible to create tiny transistors in silicon, all of which contributed to the development of modern computing.

Like other technologies, computing was (and is) simultaneously led and driven by scientific discoveries, technical and conceptual innovation, and development. Modern computing began in the 1820s in the UK when Charles Babbage developed his mechanical calculation machines - the Difference Engine and the Analytical Engine - with support from Ada Lovelace; she was the first person to recognise that a universal computer could do anything providing that it was given the right data and instructions, and therefore, she is often referred to as ‘the first programmer’74. Development continued slowly through the 19th and early 20th centuries with the introduction of electro-mechanical machines until 1937, when the British mathematician Alan Turing made a significant conceptual breakthrough and published a paper describing an imaginary machine that performed simple mathematical tasks by following precise logical steps75. At the time, reuse of scavenged components was commonplace and processing speed was increased through use of thermionic valves from telephone exchanges, which in 1943 facilitated development of the world’s first completely programmable, electronic, digital computer.

Other notable innovations include use of binary language to produce the first electronic calculator in 1938 and the first high level programming language around 1944. During and since the 1950s developments in programming, manufacturing, and other technologies have further transformed the computing sector; examples include keyboard input capability, transistor-based technologies, and integrated circuits (IC) which were invented to address the growing need for lightweight electronics. These components are assemblies of interconnected miniaturised devices like transistors, diodes, capacitors, and resistors embedded into a thin layer of silicon. Miniaturisation continued and a chip that could accommodate several components in the 1950s was able to accommodate 1000 components by the 1970s. In 1971 Intel developed the first microprocessors76, which integrate the arithmetic, logic, and control circuitry necessary to perform the functions of a computer’s central processing unit (CPU) and link the various distinct parts of a computer system. Early computers were large stand-alone mainframe products; however, these various advances led to streamlined computing in the 1970s and then to microcomputers which could perform more than just data processing or scientific calculations, paving the way for computing as we know it today. The resulting demand for microprocessors led to high-volume production and reduced costs, allowing for entry into the household appliance market which previously couldn’t afford the inclusion of such technologies. For the first time, personal computers became a financially viable option and by the mid-1980s cheap computerisation of home appliances like microwaves and thermostats was more widespread, whilst industry benefited from automated factory-lines and shops, and retail from point-of-sales systems.

In addition to miniaturisation and lower costs, the ubiquitous use of computing technologies was encouraged by the development of networks that linked computers for data exchange. The first were internal but in 1984 external networks for business and academia were introduced. During the 1980s, the British engineer and computer scientist Sir Tim Berners-Lee also developed a new digital information and communication language and network, which subsequently evolved to become the World Wide Web in 1989. Such is the popularity of this technology that over 4.95 billion people and 62.5% of the global population were ‘connected’ via the internet in 2022. Of these individuals, 97% owned a smartphone, 64% a laptop or desktop PC, and 34% a tablet77.

#### Materials and Manufacturing Processes Used for Electronics and ICT

Early computers were room-sized ‘mainframe’ entities, and although large their functionality was very limited. The term mainframe now refers to large non-movable machines that support thousands of applications and input/output devices simultaneously to serve thousands of users. Expansion of digital communication and computing capability has transformed societies around the world by enabling access to information, education, health, commerce, and entertainment by individuals for whom access would otherwise be difficult or impossible. However, it has also increased demand for resources which will continue as more digital technology is embedded into products (including clothing), automation increases in industry, and the internet expands.

Electronic equipment can contain more than 50 different materials including ferrous and non-ferrous metals, precious metals (PM), platinum group metals (PGM), rare earth elements (REE) – which are all finite resources – plastics, and ceramics. In addition to the IT sector demand for these resources is increasing in sectors of strategic significance including renewable energy, e-mobility, defence, and aerospace78 . The EU has identified a list of Critical Raw Materials (CRM), which are of high economic and technical significance to the EU, and have high risk supply chains79 because of the limited amount of material that remains in the earth’s crust and current low recycling rates. Furthermore, their specific properties mean that substitution is either very difficult or impossible at present; some are located in politically volatile areas and/or in countries with poor human rights records; and they are often concentrated in one main location. Consequently in 2008, as part of the Raw Materials Initiative the European Commission committed to compiling and regularly updating a list of Critical Raw Materials. In 2011 the first list contained 14 CRMs. This grew to 20 in 2014, 27 in 2017, and 30 in 2020. The 2020 list of CRMs to the EU is shown below80.

[Insert Table 5.1 near here]

#### Design in the Electronics and ICT Value Chain

Electrical components vary in size according to type, function, and the product in which they are used, and dimensions range from millimetres to metres. The case of electronic components is rather different because they are comparatively small and material value per item is low. For example, a single silicon wafer may be 0.13 **µm** thick while surface mounted capacitors for use with printed circuit boards may be 0.4 mm x 0.2 mm (although some are larger at 7.4mm x 5.1mm). Capacitor composition depends on type and application, but they are comprised of metals (such as aluminium, tantalum, niobium, palladium, or silver), oxides of metals, and insulators (waxed paper, mica, ceramic, or plastics such as polypropylene (PP) or polyethylene terephthalate (PET); the surface of the metals/oxides may be etched and sintered, and the various material layers wound together81. Another example – printed circuit (or wiring) boards PCBs/PWBs - are also comprised of several materials. These include a substrate (base) layer, which may be rigid (and made from glass fibre and epoxy composites) or flexible polyimide (a thermoplastic elastomer). The second layer is copper, and the third - solder mask - and fourth - silkscreen ink - layers are usually epoxy82. The various components either sit on top of (surface mounted) or poke through holes in the boards and all are soldered into position to ensure connectivity. Traditional solder – a fusible metal alloy – is comprised of tin and lead; lead is a hazardous substance and consequently use in consumer electronics has been restricted in the EU since 2006, as a result of which use in the global market has also been reduced83. Lead-free solder is now widely used and may include tin, copper, silver, bismuth, indium, zinc, antimony, and traces of other metals84.

Electrical and electronic components were developed to perform specific functions and changes to design have been implemented to improve their functionality and performance as well as to reduce physical size. This has increased the portability of consumer products like mobile phones, tablets, and laptop computers, which have become ubiquitous. Electrical and electronic components are also embedded in numerous household products and vehicles and there is a growing interest in the creation of wearable electronics which may be embedded into products – e.g., cycle lights on or in helmets – and clothing. The scale, scope, and capability of digital manufacturing technologies has also grown as has connectivity and data transmission between products and manufacturers to enable monitoring of the frequency of product use and performance, for example.

The design and manufacture of electrical and electronic equipment can be separated into two distinct categories: external housing/casings and internal components. The external casings are the interface between user and technology and should be designed to facilitate accessibility, easy interaction, and use. In addition to size and manufacturing processes, the ease and difficulty in disassembly and the value of the embodied materials determine the economic viability of reuse and recycling at end-of-life. Early electrical products were screwed and/or bolted together using ‘off the shelf’ mechanical fixings that were exposed and easy to reach; recent safety regulations mean that many fixings are now concealed and require special tools to access and open them. Some manufacturers also produce unique fixings to prevent access to the internal components and opening products negates the guarantee85. This could be for safety reasons, but it is also to prevent interventions by anyone other than OEMs. While miniaturisation benefits product users, it has increased use of adhesives rather than mechanical fixings to save space which prevent easy separation of components and materials and deters repair and recycling. This means that the products are not fit for a circular economy and at end-of-life (in use), unless they are donated or sold via a secondary market, they contribute to the growing e-waste stream for example by being either stockpiled or added to domestic waste by owners. Designs of these products and components could be changed to facilitate repair and upgrade by users and/or non-OEM businesses, and recycling and reclamation of materials at end-of-life. Several companies have already proved that it is possible to design for circularity and develop electronic consumer products that meet the above criteria; the most notable examples are Framework (laptops)86 and Fairphone (mobile phones)87 who also avoid use of conflict and unethically produced materials and are exemplars of good practice.

The second design category is internal components, which, as described above, is extremely challenging, although there is evidence of research into components with lower impacts than those on the market. Examples include materials substitution such as use of paper88 and biopolymer substrates in PCBs and biodegradable capacitors89; 3D printed PCBs where the boards and components are printed as one entity90; nano-sized circuits to reduce embodied materials; and use of inks loaded with conductive materials91. Some of these proposals will reduce energy use and waste from manufacture and others will facilitate component separation for recycling. However, none of these proposals have been commercialised yet and there is a real need to design, develop, and test whole systems to ensure that a positive impact in one area doesn’t create a negative impact in another area. Unfortunately, the possibility of developing more circular electronic components at present is remote because of the physical properties and behaviour of the materials involved, the performance of which is determined at atomic level. This is very problematic because only 17% of e-waste is formally collected and sustainably recycled; the rest is either sold on informal secondary markets and/or exported and recycled using unregulated, hazardous, and toxic processes92. The current recycling infrastructure is under-developed, and materials reclamation and reuse are either poor or non-existent and the only recycled metals are ferrous, aluminium, copper, and gold (although research into reclamation of other critical raw materials and metals is ongoing); consequently, many millions of tonnes of potentially useful resources are wasted, and while many cause environmental damage as they downgrade and leach into water supplies for example, the mining of many materials to replace those that are lost is also environmentally and socially damaging. Furthermore, as demand for resources grows, the lack of closed loops for materials is a potential threat to supply, which will affect the transition to green technologies and could lead to conflict.

## Conclusion

This chapter opened with a definition of design and brief history of design and engineering, which revealed how design has always had a significant impact throughout the value chain. Several priority areas - textiles, construction and the built environment, furniture, electronics, and ICT – were specifically identified in the EU Circular Economy Action Plan and their history and evolution was discussed in order to understand the challenges and opportunities for change through design now and in the future.

Electrical and electronic equipment is unlike the other materials and product groups discussed in that textiles, buildings and civil infrastructure, and furniture all originated before the first industrial revolution. At that time, they were manufactured from natural and renewable resources and fabricated using processes that enabled easy disassembly, repair, and remanufacture. At end-of-life organic materials were composted, timber was sometimes used as fuel, and metals were recycled. In other words, the pre-industrial world was based on circular systems which could be replicated now by using the same or similar materials and manufacturing processes. This is not the case for many materials, manufacturing processes, and technologies that developed during and after the Industrial Revolution which accelerated the development of many new materials which were engineered to fulfil specific functions. Examples include plastics, polymers, and composites which may perform very well during use phase but were not developed with any consideration of what happens to them after use. The chemical composition of thermoset plastics prevents degradation like organic/biomaterials in air, on land or in water. Those that can be reprocessed – e.g., thermoplastics – lose their inherent properties within the process and rather than being recycled and (re)made into the same product they are generally downcycled or used with virgin material because of changes in their performance. At present many composites are comprised of glass or carbon fibres and a thermoset matrix; therefore, at best they are very difficult and at worst impossible to recycle successfully and/or economically and although they may be ground up as filler, many are incinerated or dumped. Pre-industrial structures and products were not consciously developed to be circular; rather they happened to fit circular systems because of the nature of available materials, manufacturing, and assembly processes.

Although some post-industrial inventions created during the 20th and 21st century were developed to prohibit intervention by anyone other than OEMs, the majority were not developed to prevent recycling or disassembly or degradation back to elemental level, rather development focused on functionality and performance during and up until the end of the use phase because materials were abundant and there was space for local landfill sites, for example. The ever-increasing demand on resources, in particular Critical Raw Materials which are essential to digital and clean technologies, potential threats to supply chain security, and rising costs and waste mean that current strategies are untenable.

We conclude that design has generated positive and negative impacts and that it also has the potential to conserve value in the Circular Economy in the priority sectors identified by the EU and therefore other sectors. However, design must encourage behavioural as well as technological change, which will prove more challenging in some areas than others. The extent to which societies, industries, and services around the world have become reliant on digital technologies and associated services means that the technology is here to stay but, for the foreseeable future, electronic components will remain difficult if not impossible to recycle, and reclamation and reuse limited; a problem compounded by under-development of recycling technologies and infrastructure. In an ideal world waste should be minimised and any that arises should be processed in the least environmentally and socially damaging way possible. Similarly, where there is no alternative to the use of virgin materials, any negative environmental or social impacts associated with mining and extraction processes should be minimised or eliminated and all supply chains should be ethical. The extent to which design and designers can influence these factors is unknown. Change will only come about with a collaborative approach which allows knowledge transfer between every stakeholder in the value chain, and which is supported by policy and legislation. However, it is clear there is huge potential to inform decision makers throughout the value chain about the benefits of these and other practices that will also have a positive impact on the UN Sustainable Development Goals, as indicated in Table 5.2.

Finally, although the extent to which design can influence choice of materials based on source location and supply chain diligence is unknown at present, in Table 5.2 we briefly consider the role of design in relation to the UN Sustainable Development Goals in an ideal situation:

[Insert Table 5.2 near here]

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Figure Captions

**Figure 5.1** The framework for innovation: Double Diamond design methodology. (Reproduced with permission from Ref.3 with permission from Design Council).

**Figure 5.2** Evolution of design for sustainability: From product design for system innovations and transitions. (Reproduced from Ref.20 with permission from Elsevier).

**Figure 5.3** The Ellen MacArthur Foundation butterfly diagram: visualising the Circular Economy. (Reproduced with permission from Ref.21 with permission from Ellen MacArthur Foundation).

Table Captions

**Table 5.1** 2020 Critical Raw Materials. Source (authors) adapted from Ref.80

**Table 5.2** The role of design in relation to the UN Sustainable Development Goals. Source (authors)

**Figure 5.1**



**Figure 5.2**



**Figure 5.3**



**Table 5.1**

|  |  |
| --- | --- |
| Antimony | **Lithium** |
| Baryte | Magnesium |
| **Bauxite** | Natural graphite |
| Beryllium | Natural rubber |
| Bismuth | Niobium |
| Borate | Platinum Group Metals\*\*\* |
| Cobalt | Phosphate rock |
| Coking coal | Phosphorus |
| Fluorspar | Scandium |
| Gallium | Silicon metal |
| Germanium | **Strontium** |
| Hafnium | Tantalum |
| Heavy Rare Earth Elements\* | **Titanium** |
| Indium | Tungsten |
| Light Rare Earth Elements\*\* | Vanadium |

**Key**

|  |  |
| --- | --- |
|  | New in 2020 CRM list |

\* Dysprosium, erbium, europium, gadolinium, holmium, lutetium, terbium, thulium, ytterbium, yttrium

\*\* Cerium, lanthanum, neodymium, praseodymium, samarium

\*\*\* Iridium, platinum, palladium, rhodium, ruthenium

**Table 5.2**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **DESIGN DECISION**  | Materials/component selection - due diligence along supply chain  | Materials selection - Durability – physical  | Materials selection - Durability – emotional design  | Manufacturing technology - safe and clean, proper disposal of waste  | Place of manufacture - energy sources  | Place of manufacture - respect for human rights, health and safety   | Place of manufacture - Job creation and employment, fair wages   | Disassembly, repair, remanufacture and recycling   | Formal, legal recycling  | Usability and inclusion  |
| **GOAL** |
| 1 | NO POVERTY |  |  |  |  |  | **x** | **x** |  |  |  |
| 2 | ZERO HUNGER |  |  |  |  |  | **x** | **x** |  |  |  |
| 3 | GOOD HEALTH AND WELLBEING |  |  |  |  |  | **x** |  |  | **x** | **x** |
| 4 | QUALITY EDUCATION |  |  |  |  |  |  | **x** |  |  |  |
| 5 | GENDER EQUALITY |  |  |  |  |  | **x** | **x** |  |  |  |
| 6 | CLEAN WATER AND SANITATION | **x** |  |  | **x** |  |  |  | **x** |  |  |
| 7 | AFFORDABLE AND CLEAN ENERGY |  |  |  |  | **x** |  | **x** |  |  |  |
| 8 | DECENT WORK AND ECONOMIC GROWTH |  |  |  |  |  | **x** | **x** | **x** |  |  |
| 9 | INDUSTRY, INNOVATION, AND INFRASTRUCTURE |  | **x** | **x** |  |  |  |  | **x** |  |  |
| 10 | REDUCED INEQUALITIES |  |  |  |  |  |  | **x** |  |  | **x** |
| 11 | SUSTAINABLE CITIES AND COMMUNITIES  |  |  |  | **x** |  | **x** |  |  | **x** | **x** |
| 12 | RESPONSIBLE CONSUMPTION AND PRODUCTION |  | **x** | **x** |  |  |  |  | **x** |  |  |
| 13 | CLIMATE ACTION | **x** | **x** | **x** | **x** | **x** |  |  | **x** | **x** |  |
| 14 | LIFE BELOW WATER |  |  |  | **x** | **x** |  |  |  | **x** |  |
| 15 | LIFE ON LAND |  |  |  | **x** | **x** |  |  |  | **x** |  |
| 16 | PEACE, JUSTICE, AND STRONG INSTITUTIONS |  |  |  |  |  |  | **x** |  |  | **x** |
| 17 | PARTNERSHIPS FOR THE GOALS | **x** | **x** | **x** | **x** | **x** | **x** | **x** | **x** | **x** | **x** |