Preface

SOME PEOPLE work with the Circular Economy every day .... But many of us have lots to questions! A simple question that we often hear is WHAT is the Circular Economy? We also consider other questions to be important .... we shall be addressing many throughout this compendium ...... just as we do throughout the Massive Open Online Course: Circular Economy: Sustainable Materials Management. You can access the course at www.coursera.org/learn/circular-economy. This compendium directly supports that course.

As a starting point, consider the following related to the ‘what’ question above.

• Have you ever wondered why so many people believe the Circular Economy is important?
• How is it linked to the function of natural resource production systems?
• Why is the Circular Economy so important for developing countries?
• How will it benefit society?

Other questions we think are important are related to HOW do we go about it?

• How can business, industry and society move the Circular Economy forward?
• What are the technologies involved?
• What issues and incentives motivate businesses?
• How do companies make money in the Circular Economy?
• Can policy and politicians help the Circular Economy?
• Does society have to change?

Please read on to find out more!

We have structured this compendium to closely follow the MOOC, and intend that this will serve as an aid to your understanding of the course and as a ‘ready reference’ source describing many aspects of the Circular Economy and sustainable management of materials.
The scope of the compendium covers many parts of the emerging circular economy. We choose to place considerable focus on some of the substances that we extract from the ground – in particular raw materials and critical materials. We focus on circularity in these areas, because presently we use too much, too fast, and we are not re-using nearly enough. Simply stated, not enough of our materials are derived from the resources that we’ve already extracted. This approach in turn demands that we look at the technologies that rely on such materials, and how businesses are innovating to make circularity of materials a reality.

This document provides many concrete examples of what we mean by “sustainable materials management”. We present cutting edge insights on topics such as the following:

- **why raw material supply chains are important to society;**
- **how circularity can benefit us;**
- **where changes in our economies are required;**
- **who needs to be involved;**
- **what businesses are doing to make the circular economy a reality; and**
- **how governments and regulators can support the circular economy.**

At the start of every subsection in this compendium we provide a brief ‘take home messages’ of each lesson presented throughout the MOOC.

### Why do we need a circular economy and how do we pursue it?

Governments and businesses are becoming increasingly concerned about the growing pressures on our global resources due to human activities. Our economies, and our systems of production and consumption, are stressing and damaging Earth’s natural systems. We use enormous amounts of raw material and energy to create the billions of products that sustain our lives. At the same time, we send huge volumes of waste into the very atmosphere, waters, land and ecosystems that are vital to our existence. The richer we are, generally the more we pollute.

An overarching challenge is that billions of people in less developed countries have the same right to live long and comfortable lives as people in developed countries have. This is directly linked to becoming wealthier. But if everyone consumes resources, and emits wastes, at the level that developed countries do at present, then our planet will simply be unable to meet the demands placed upon it.

The underlying problem lies with our linear economies – these have excessively high material and energy consumption, and eject large proportions of material as waste. Something has to change! One thing we can do, is to make our economies much more circular – so that we achieve more using less. Advances are needed in many areas to achieve a circular economy – and a picture of what a circular economy is, or could be, is becoming clearer as more practical real-life examples emerge.

Generally, strategies can be seen as seeking to keep resources and products at as high a value as we can, for as long as possible, and extending their lifetimes so that they function for longer.

To demonstrate how a circular economy can be developed, this document showcases many of the ways that society works towards the ‘slowing’, ‘narrowing’ and of course, ‘closing’, of resource flows. Importantly, the creation of a circular economy is about much more than resource flows. It is also about circular product design, business models, and policy formulation. These must be interlinked with social changes to evolve a circular society.

### Scope for Circular Economy: Sustainable Materials Management

This compendium document describes the first steps of a journey towards circularity. The journey will be different for all countries of the world, but this text is intended to share knowledge so that many more of us can create a path forward.

For this introductory section, our highlights appear as follows:

- **Key challenges arising as a result of the excessively high material and energy consumption – and the way we eject large proportions of material as waste to the environment – demand that we pursue a Circular Economy.**
- **Damage to natural systems and shortages of key resources – both renewable and non-renewable – will negatively affect the development of less wealthy countries unless we achieve a Circular Economy.**
- **The creation of a Circular Economy is about much more than resource flows. It is also about circular product design, business models, and policy formulation. These must be interlinked with social changes to evolve a circular society.**

### What are the benefits of a circular economy?

The circular economy can help us do much more, with much less. It can help reduce the burdens on the Earth caused by our material and energy consumption. It can help protect ecological goods and services from the pollution and wastes we generate.

It can also help us limit our overall demand for resources per capita so that there are enough for the wellbeing of all. Many countries are still developing, and they need the resources to do so. The circular economy can help ensure that we secure enough resources for our societies to function and develop.

Achieving a circular economy needs the engagement of society. And it will need plenty of invention and innovation. It will also require the creation of new forms of business; new technologies and processes, and new forms of governance. Such changes offer the potential to generate value to society. For example via stimulation of employment, and an increased demand for educated and skilled workers. This evolution also needs new thinking, new social systems, new forms of engagement, and new institutions. This demands an evolved society.

### Exploring five areas of the circular economy

This compendium describes five important areas that need work as we look to the future and achievement of a circular economy to replace the linear economy that dominates today.

- **Chapter 1** explores where metals and other key materials come from, and outlines some of the key arguments for why society needs more circularity.
- **Chapter 2** presents a range of circular business models and showcases a range of ways for business to create economic and social value.
- **Chapter 3** introduces you to circular design. Here you will explore topics such as functional materials and eco-design; methods to assess environmental impacts, and networks where best practices can be shared.
- **Chapter 4** provides details of why policy is important for progress towards the circular economy. It explores where we need help from governments, and how policy interventions can help the circular economy.
- **Chapter 5** our final chapter then allows you to examine aspects of circular societies. You will learn of things like new social norms, forms of engagement, systems, and institutions that are needed by the circular economy. You will also explore how individuals can help society become more circular.

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**For more information and resources, visit:**

- [Circular Economy Knowledge Hub](https://www.circular-economy.com)
- [Global Circular Economy Coalition](https://www.globalcircularity.org)
- [Circular Economy Academy](https://www.circularacademy.com)

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Materials are mined, transformed and used throughout their life cycle, within various political, societal and business contexts. This section covers the basics of the material supply chain, including its social, environmental and economic consequences, and explores how the original form of materials management is reimagined in a circular economy model.

1.1 MINING

What, when and where?

We use many non-renewable raw materials in our society. These include metals, like iron and gold, fossil fuels such as coal and lignite, and ornamental stones like marble and granite. All of these raw materials are extracted by different forms of ‘mining’.

But the extraction, use and recycling of raw materials is not a new thing. In fact, we have mined for thousands of years to obtain metals and minerals that we use to make products crucial for the survival of humanity. The development of human societies through the Bronze Age and the Iron Age has even been described according to those products of mining that defined the key technologies of the time. Some sort of recovery and recycling has also always been performed. Some materials are inherently suited for circularity and have always been considered too valuable to throw away. But this was not the case for all materials, and even today, the average recycle rate recorded is not as high as it could – or should – be.

Mines are located where mineral-rich ores are located! Sometimes they are far away in remote places, and sometimes they are close to places where many people live. The Avlapakan open-pit gold mine in the Russian Far East is an example of a remote mine – it’s more than a thousand kilometres from the nearest town. Many cities and towns were actually started as places of mining, and there are often communities attached to mines. The town of Laurion in Greece, got its start due to mining some 5000 years ago.

Exploration and Extraction

There is a lot of work to be done before a mining operation actually begins extracting minerals. The very first step in mining is the search for mineral deposits. For thousands of years, humankind has looked for ‘ore bodies’ to mine. And this search has led them far into remote areas, and essentially to every part of the globe.

Exploration includes a number of steps, from examining a geological map, to site investigations, non-destructive geophysical surveys, and of course drilling holes into the ground to find and define how big and how valuable the deposit is. Exploration activities can last years and cost millions. An important issue is that even before the creation of a mine, this process of looking for minerals also has the potential to result in significant environmental or social implications.

Mining and minerals processing operations can take many forms and these differ depending upon mineral, metal, ore type or mining location.

Mine site and minerals processing facility activities – and their wastes – must be carefully managed to prevent environmental degradation or negative social impacts.
impacts. For example, access roads can open up sensitive areas to human exploitation, and test pits can disrupt ecosystems. It is important that such issues are also given consideration.

After mineral exploration has found a promising mineral body, and depending on the value of the minerals, a model of the sub-surface is developed, and this model is used to figure out which parts are economically viable to mine. Then a mine design and a plan to extract the minerals can be developed. The mine plan should meet all the three objectives of sustainability: economic viability, environmental protection and societal support.

A mine can be deep underground with only small surface entrances (for example when the deposit extends to great depth), or it can be an open pit if the deposit is very close to or reaches the surface. Sometimes such mining pits are so big that they can be seen from space. (Fig 1.1)

Such a large operation of course has the potential to cause many impacts on ecological and hydrological systems, and on the stability of the landforms. Because of this, the mine plan must also address issues like the protection of flora and fauna, water resources, geotechnical stability and so forth. It is very important that such aspects be considered at the design stage.

Once a mineral deposit has been ‘developed’ into an actual mine, mining typically involves the extraction of huge volumes of rock or soil. For example, in a large iron ore mine, annual production can total tens of millions of tonnes per year. At times, very large volumes of ‘waste rock’ must also be moved to access the ores that contain the minerals that we want. (Fig 1.2)

Once mineral ores are extracted, mining companies process ores to separate the valuable minerals. This often starts with physical processes such as crushing, grinding, and a sieving process called screening. After this, other physical and physicochemical separation methods are applied based on differences in properties such as specific gravity, magnetism, or colour. Thus, a concentrate or metal is then transported to places where it’s smelted or further refined, or both. Smelting aims to treat the concentrate and recover the contained metal, and refining is used to further improve the quality of produced metals and remove any remaining impurities.

Mining Footprint

For many mineral ores, the concentrate may be just a tiny fraction of the ore. Very large volumes of ore and rock are often excavated, processed and then placed in waste management areas around a mine site for every small portion of concentrate produced. Thus it is no surprise that we often talk about the (large) ‘footprint’ of mines. A mine may create large, physical voids in the ground, as well as large waste deposits. These must be properly planned for, managed and then remediated when mining is finished.

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Figure 1.1 Sidewall of a large open pit copper mine.

Figure 1.2. An unprotected waste rock stockpile of approximately 120 million tonnes rich in copper.

Figure 1.3 Flotation process to obtain metal concentrate.

Minerals are composed of the same substance throughout and there are more than 1000 different minerals in the world. Minerals are made of chemicals – either a single chemical element or a combination of chemical elements.

Rocks are made up of 2 or more minerals. For example, the rock called granite is a mixture of the minerals quartz, feldspar, and biotite.

Ore – A mineral or an aggregate of minerals from which a valuable constituent, especially a metal, can be profitably mined or extracted is an ore.

Amine Footprint

Over decades, the price of many metals and minerals have increased or new, improved processes for extracting minerals from ores have been developed, or both. With these advances, there are many tailings deposits that can now be profitably recycled and reprocessed to recover the residual minerals/metals. Hence, many old tailing deposit sites have now become mines again!

Mine Life Cycle

All mining operations have a life-cycle. This spans from exploration, through mine development and operation, to closure. And then very importantly, to the use of the post-mining site. The planning and design work for mining must consider much more than just the economic viability of a mine during its operational life. Careful management is required to protect ecosystems and society from potential negative impacts from mining, and this requires the consistent compliance of the principles of sustainability at all stages. In particular, the design of and application of land reclamation works, and ongoing management routines, is needed to make sure that the quality of the natural and manmade environment remains protected during both the mining stages, and then also when processing operations have closed.

For example, soils and water need to be carefully considered. The protection of soil and water quality close to the mine is very important to sustain agricultural activities during and after the mining operations and to maintain a clean supply of drinking water for neighbouring communities. Post closure use of the site also needs to be considered. Mining is an activity related to the development of mankind and should therefore follow the needs of society, not only regarding a secure supply of raw materials but also a commitment for environmental protection. So, to minimize the footprint of mining, environmental protection measures have to be incorporated in the whole life-cycle of the mine, all the way from initial exploration to the closure of the mine. (Fig 1.4)
1.2 MINING AND SUSTAINABILITY

boundary conditions for sustainable mining
Throughout the history of mining all the way up to the 1960s, there was little or no consideration of its environmental and social consequences. Many parts of the world still bear the unsustainable legacies of pollution and disturbed land as a result. But since then, there has been an ever-increasing awareness of the environmental and social liabilities that can be caused by mining. While many legacy problems remain, a great deal of remediation has been performed, and this work continues today. Leading mining firms and international organizations now know how to prevent problems, and they share such knowledge freely. Governments, regulators and civil society have also learned how to challenge industry to keep improving.

A prime goal for sustainable mining is to achieve four ground conditions:
1. Maximize socio-economic benefits.
3. Ensure that environmental resources are not subject to physical and chemical deterioration.
4. Achieve after-use for the site that is beneficial and sustainable in the long term.

So-called ‘sustainable mining’ has certainly not been achieved around the world. But, a number of leading countries do support operations that meet these precursor conditions. Lessons from such activities need to be spread, entrenched, and improved upon everywhere if we are to achieve a global norm for sustainable mining.

Communities and mining
A mine is often a core component of a community. This is especially so when mining is conducted in remote areas or in less-developed countries, where they are commonly some of the first true industrial endeavours to deliver vital income. In these situations, mines are often the foundation for economic development, as well as for achievement of sustainable development goals. Even many advanced countries rely significantly on mining.

Therefore, it is very important to consider social, socio-economic, developmental, and inter-generational issues. Countries pursuing sustainable mining must develop and enforce innovative regulations for mining practices that reflect both present and future expectations for environmental and human health protection.

Mining companies and governments must consider how communities grow around a mine. And governments must ensure that the wealth generated by mining is transparently distributed among the present generation. However, we should never forget – essentially all mineral deposits eventually run out! This means that miners and governments must plan for what will happen to communities after the mine is gone. This requires that the land use for the mine area is beneficial to the community and sustainable for the long term – and that social and economic structures remain in place to support communities. Such planning should not be done close to the end of mining – at that stage it may be too late. Rather, planning for mine closure ideally should be done at the time of planning the start of mining.

Such issues must extend from the pre-mine planning phase, through construction, mining, and mine closure to post-mine stewardship. This requires an inter-generational time frame. Companies that practice sustainable mining plan many years in advance for what happens to communities, as well as the role of communities in the use or protection of land after the mine is gone.

Environmental constraints
A baseline requirement for environmental sustainability is that the management policies, field practices and technologies applied in mining reduce environmental harm to within ecological limits. At the same time, land must be preserved as a repository for biodiversity and for natural ecological services. With such conditions in mind, there is a number of fundamental physical and chemical issues that must be considered in order to achieve environmentally sustainable mining.

1. Rocks and ores are not in ‘equilibrium’ when brought to the surface and can become chemically and physically unstable when exposed to surface conditions. This bears with it that they can potentially release eco-toxic substances. Unless planned for, prevented, or contained, such processes can cause damage that lasts for very long periods of time.

2. Mining development often occurs on undisturbed land. When a mine is opened in some areas, access to nearby sensitive or undisturbed areas by other groups – for example loggers or farmers – may not be compatible with overall sustainable land use. For such reasons, access to a mine site must be restricted, and alternatives to mining should be explored.

3. Environmental and social impacts are cumulative. So-called ‘sustainable mining’ has certainly not been achieved around the world. But, a number of leading countries do support operations that meet these precursor conditions. Lessons from such activities need to be spread, entrenched, and improved upon everywhere if we are to achieve a global norm for sustainable mining.

4. Metals and other raw materials are essential to our global economy and our social development. But how do we go from mining to metals? After mining, a certain sequence of processing steps is needed to upgrade raw materials to produce marketable products.

Depending on their properties, their areas of application, or even their scarcity, metals are placed in different categories such as non-ferrous, base metals, technological, precious metals, or even critical metals. No matter the category, all of these metals are essential for the production of the ‘high tech’ devices and engineered systems that modern society relies upon. Each of these types of metals have their own mining and processing sequences, and their own systems that deliver the products – either in a raw form or as refined versions. This is called the ‘supply chain’.

Engineers have learned how to work with materials in supply chains, and a metal supply chain consists of both upstream (mining and refining operations) and downstream (smelting, casting, and metal working) processing. Mining and metallurgical engineers guide the processing of raw materials into metals, which can then be mixed with other elements to provide special additional properties. This is called alloying.

At each step the value of the material increases due to investment of time, effort and energy. From a scientific point of view, each step increases the cumulative energy input that has been needed for metal production. From an economic perspective, at each step the product cost increases.

Case Study – Aluminium
Aluminium is a light-weight and durable metal which mixes well with other elements and is thus used in a vast array of products and applications. These include transport, construction, packaging, electronics and electricity transmission, among others. Aluminium can also be recycled repeatedly – meaning that much of the economic value in the metal can be preserved for each cycle. (Fig 1.5)

The chain of activities called ‘primary aluminium production’ starts with the mining of bauxite ore. Then chemical refining follows to extract pure aluminium oxide – called alumina. The alumina is then smelted to primary aluminium. After this, production of alloys takes place. Finally, the metal is formed by a rolling and extruding processes, or cast into moulds and then machined to final products. And at the end of the product life, aluminium scrap can be collected and recycled.

It takes four tonnes of bauxite ore to produce just one tonne of pure Aluminium. The investment of energy, work and materials needed to achieve this is reflected in the market value. Consider the base value of raw bauxite ore of around 40€ per tonne; this amount increases to nearly 400€ per tonne for alumina. After smelting, the aluminium metal has an even higher value – around 2000€ per tonne. For many applications, further value adding may take place – for example, special aluminium alloys used in aircraft components are much more expensive than the aluminium foil that we use in the kitchen.
Aluminium also has a highly developed recycling system, because the recycling process requires only about 10% of the total energy used in primary production. This makes it both economically and environmentally attractive. Unsurprisingly, global aluminium recycling rates are high: approximately 95% for transport and construction applications, and about 60% for beverage cans. As an example, more than 90% of the aluminium used in a car is actually recycled into new products when a car has reached its end of life. It’s estimated that nearly 75% of all aluminium ever produced is still in use today!

Even though society obtains a lot of aluminium from recycling – the system to produce this is called secondary production – global demand for aluminium is constantly increasing. This means that we still need to rely on primary aluminium production to provide more than two-thirds of our aluminium demand. So even if we could recycle all of the aluminium we use, we would still need primary production. Very important to note is that this demand for primary production will continue to grow to meet global demand, and global demand is expected to increase for many decades to come.

There is strong global demand for materials to meet the needs of growing populations and the development of countries. That means that we will need production and supply systems that are constantly increasing. This means that we still need to rely on primary aluminium production to provide more than two-thirds of our aluminium demand. So even if we could recycle all of the aluminium we use, we would still need primary production. Very important to note is that this demand for primary production will continue to grow to meet global demand, and global demand is expected to increase for many decades to come.

1.4 VALUE AND GOVERNANCE

- The complexity of global material-supply-chains makes it difficult to trace the actors, the processes to transform materials, and transfer between geographical areas.
- We need to understand why and how materials flow, and how this benefits the different partners if we are to make our economies more circular and resource-efficient.
- Global value chain analysis – an approach that focuses on the coordination and control mechanisms of the supply chain has emerged as a way to better understand global flows of materials and value.

This focuses on coordination and control mechanisms – also described as the 'governance' of the supply chain. In other words, in addition to focusing on what is flowing in a supply chain, we look at the transactions and governance structures linking segments.

Governance arises from the transaction between a buyer and a supplier as they are coordinating and controlling the exchange. So it’s important to remember that any value visible in the form of traded materials, services or monetary exchanges is the outcome of a negotiation. Governance describes how this negotiation affects the buyer and the supplier; for example, one partner might be better off than the other due to the conditions or characteristics of the transaction.

When analyzing a supply chain, it’s important to pay attention to what is flowing from one segment to another. While we have materials flowing, there is also money moving from one segment to the next as the materials are sold and bought. The process of identifying and then drawing up which segments are part of a particular supply chain is called ‘mapping’. In essence, supply chain mapping helps us define the boundaries of the analysis: it details the processes and actors that are part of the transfer of materials and the processes to convert raw materials into more valuable products, also termed transformation here.

It’s also important to consider where the transformation processes take place. Are they specific to particular regions or nations, or are they undertaken across many regions or nations throughout a global value chain? The geographical focus is important because access to labour, energy, capital or land varies significantly between regions, and has a huge impact on costs. Laws and regulations also vary greatly between countries, and this also impacts how and why materials flow in a particular way.

Despite efforts to map actors and links between transformational processes, or segments in and across particular geographical areas, supply chain analysis can’t explain all the outcomes of trade. Difficult to answer questions remain such as: why some nations seemed to gain relatively more from trading than others? To explain this discrepancy, Gary Gereffi and Michael Korzeniewicz developed an approach called ‘global value chain analysis’.

The “Why” and “How” is Important

When we try to make our economy more circular and resource-efficient, answering why and how materials flow becomes crucial. Firstly, this information allows us to better understand the social circumstances related to the material flows, to reconnect materials with their human coordination and control mechanisms. In simple terms it helps us to explore the decision-making processes behind materials entering and circulating in our economies.
Secondly, it allows us to see value for what it is: a ‘moving target’. Value arises not only from the physical attributes of a material but also from the perspectives of different actors, such as buyers and suppliers. Such actors negotiate their values between themselves, but within the larger context of a system of actors at local, regional, national and global levels. All of these factors influence how the value of a material is constructed.

1.5 CRITICALITY AND CIRCULARITY

- Raw material supply security has been central to economic systems since early civilization and the modern concept of ‘critical materials’ arose in the 1930s.
- Perceptions of ‘criticality’ based on the economic importance and supply risk of materials has become more pressing as global trade, and the material complexity of products, has drastically increased.
- Enhancing supply security for critical materials by reducing, reusing, recycling and remanufacturing is an important driver for the circular economy.

Mineral raw materials are essential components of all national economies, and complex decision-making processes define whether exploration or mining for minerals take place. Among other things, countries must first decide if they look for important materials within their territories. Then, among other things, countries must first decide if they source it from another country. Such issues have driven supply security questions, as mining, they must decide if they mine for it. Or whether exploration or mining for minerals take place.

For example, metal and alloy producers feed materials via component suppliers into the Global Value Chain for a wind turbine – even if they are not direct suppliers. So, the links and impact of raw material access goes much further than just to the ‘next customer’.

Some elements, like copper, zinc or gold, have been in use for a long time and we have a good understanding of how to find and trade them on an open market. Other elements, such as rare earth elements, are not traded on an open market, but instead mostly in direct business-to-business transactions. This makes accessing them more challenging. And it makes accessing information about their trade more challenging too.

Knowing where and how to access materials – and being able to access them is important for our economies – this is an issue addressed by the concept of ‘critical materials’. Bridging the challenges of accessing particular elements and judging their ‘criticality’ was first taken up in the late 1930s in the United States. A discussion of critical materials emerged when the issue of raw material supply became related to the politics of national security. At that time, the U.S. government authorized stockpiling of materials for national defence to mitigate potential supply risks. During the 1970s and 80s, amidst two periods of oil crisis that combined with relatively high commodity prices, the political discussion about criticality was revived.

Criticality

In recent years, the US began to consider non-energy minerals as critical, defining a critical mineral as ‘one which is subject to supply risk’. In Europe, the European Commission also acknowledged that many of its member states had high levels of import dependency on high-tech metals. In recognition of this, the Commission launched a European Raw Material Initiative that seeks to address such issues. Here, their experts defined critical raw materials according to ‘their economic value and high supply risks’. They visualize raw material criticality in a two-dimensional illustration. This has supply risk (‘the risk of a disruption to supply of the material’) on the horizontal axis and a measure of vulnerability and economic importance on the vertical axis.

Supply risk is defined as ‘the risk of a disruption in the EU supply of the material’. It’s derived from examining the extent to which the supply of raw materials is concentrated in a particular country. This occurs jointly with examining the governance performance and trade aspects of the country. For example, when determining EU import reliance, which is the extent to which the EU is dependent on imports of raw materials, both the global suppliers and the countries from which the materials are sourced are investigated. The supply risk parameter focuses on the segment of the global value chain where a high supply risk for the EU is detected. This could be, for example, the extraction of the raw material. A focus on reducing, reusing, recycling and remanufacturing, as well as, to some degree, substitution, of the critical materials could contribute both to reducing supply risks and to shaping a circular economy.

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Figure 1.6 The growing material complexity of technologies.

Figure 1.7 Raw material criticality matrix.

Figure 1.8 EU criticality assessment 2017.
Economic importance describes how important a material is for the EU economy. This importance is measured in terms of end-use applications and the `value added` to the relevant EU manufacturing sectors. An assessment of economic importance is conducted by examining a so-called `substitution index`, which looks at the technical and cost performance of substitutes for individual applications. Eurostat, the statistical database of the EU, is commonly used to derive this data.

It's important to consider at least three time periods for adjustment related to raw material criticality: the short-, medium- and the long term. Within all of these periods, access to a particular raw material could be restricted for a variety of different reasons.

The EU criticality assessments have been conducted three times so far: in 2011, 2014, and 2017. In the latest assessment, 61 candidate critical raw materials were examined, of which 26 were assessed as critical. For example, tungsten was assessed to be of high economic importance but with a relatively low supply risk, while both the light and heavy rare earths were identified as having lower economic importance but high supply risk, and magnesium was determined to be both high in economic importance and supply risk. (Fig. 1.8, previous page)

The criticality assessment can provide insights from a global perspective on which countries have the largest supply share of a particular raw material. (Fig. 1.9)

### 1.6 TRANSITION TO A CIRCULAR ECONOMY

- A product perspective instead of a material perspective is critical to achieving closed-loops where the complexity and functionality of a product is conserved.
- Product design, circular business models and a circular policy context are key enablers for circular economy.
- A society-wide transition to a circular economy requires changes to the way we live our lives with action at all levels of society.

Stopping from a materials perspective to a transition perspective

Up to this point, this compendium chapter has focused on issues and topics immediately connected to materials and the extraction of materials. It has been presented that these activities remain vital (critical) to the function of our modern economies, but it has also been shown that Circular Economy efforts will serve to reduce the impacts related to the delivery of materials to global value chains.

For each portion of materials value chains that have been addressed, an explicit link has been drawn to how working to embed activities that align with the Circular Economy can help to reduce the impacts related to the delivery of materials to global value chains.

For each portion of materials value chains that have been addressed, an explicit link has been drawn to how working to embed activities that align with the Circular Economy can help to reduce the impacts related to the delivery of materials to global value chains. Further, a number of lessons have detailed how materials increase in value (quite drastically!) as they move up value chains. Consider aluminium that went from ore to fabricated products with orders of magnitude increases in value along the way. Now let us relate this back to the very reason we are here – being a part of a broad social and economic transition to the circular economy – and as a scene setting for the chapters that follow, the concept of value and function preservation embodied in the Circular Economy, and the theme of transition are introduced.

Circular economy – preserving value and function

The circular economy is an economic system where products and materials are kept at their maximum value and functionality. A starting point is to take a product perspective instead of a material perspective, and the aim is to set up closed-loops in which the complexity and functionality of a product is conserved for as long as possible. This seeks to avoid breaking a product down into its basic materials after each use cycle. After all, is it the functionality and complexity of products where most of their value lies. (Fig. 1.10, 1.11)

Setting this new system up requires a systemic change: a disruption of the existing patterns and habits of both producers and consumers. We need different types of products and services, a new legislative framework and stronger interaction between people. Digitization and new technology help; it allows us to do things we could not do before, such as to produce things in new ways, manage products more sustainably, and reuse, repair and share.

A circular economy needs durable products that can be repaired, reused, remanufactured and recycled, while trying to use fewer and less scarce materials in the first place. Product design is key to enabling circularity. For example “Design-for-repair” and “Design-for-recycling” are design strategies that aim to integrate circular economy principles at the early stages of product design. An alternative angle is to maximize the functionality of materials, and whenever possible substitute in other materials that perform the same function but that are less scarce, or have less environmental impact. Some products can even be completely dematerialized and sold as a service instead. Music streaming is an example of such.

The circular economy needs new business models in order to translate circular strategies into competitive advantage, resilient company resilience and successful revenue models. Current business models focus on product sales, which makes it challenging to integrate longer use and reuse in the market approaches. How do you create value for your customers while using fewer materials and conserving resources? And how do you deliver this value if not through conventional sales? These are some of the issues that circular economy is trying to address.

Policy also needs to be adapted to support circular economies. Current policies are still rooted in waste management, but in a circular economy the very notion of ‘waste’ is phased out, as products are designed to prevent waste, and residues are transformed into new resources. Waste policies and product policies become linked to each other, and the resulting new policies need to facilitate circular material flows, and support the creation of circular businesses.

The transition to a circular economy will require changes in the way we live our lives. It will create new patterns of interaction between people, and change the way that we own
and consume products. Action needs to be taken at all levels of society: industry, citizens, policy makers and researchers. We will need to embrace a new mindset; shifting from our current take-make-dispose paradigm to a circular vision.

In the circular product life cycle there are material losses in each step of the chain. We can minimize the losses through recycling, either back to the front of the cycle or into other products. This means that we need to set up connections between various circular products. As such, the circular economy is not actually a circle; it is rather a dynamic system of interlinked products. This complexity demonstrates that implementing the circular economy requires strong interaction between different value chains and sectors.

Another important element is that we need to ensure that hazardous materials and pollutants are removed from the circular system. We must develop and maintain clean material cycles that do not generate health problems or environmental hazards. Therefore, the system needs safe sinks, such as incineration with energy recovery for combustible materials, or safe disposal for inert materials.

Inner and Outer Circles
Over the previous decades a lot of effort has been invested to reduce material losses and bring materials back into new material loops. Europe, for example, has become successful at recovering materials from industrial residues and reinjecting them in the production process. At the end of the product life, we can also bring materials back into the loop through, for example, waste collection systems and treatment facilities. Most of the solutions currently in use rely on waste collection and recycling, but material management is more than just recycling; we need to develop ‘inner circles’, where we manage the products and materials that we have in a different way, and dematerialize things.

The outer circles refer to breaking down end-of-life products and residues into single materials, which can then be used as raw materials for new products. Inner circles are a way to retain value by extending the lifetime of the actual parts and products so they can cycle longer in the economy before returning to their material basics. Inner circles are shorter inner loops, that can be achieved for example through repair, reuse and remanufacturing.

By repairing a product we can create a very small loop that feeds right back into the use phase; repairing can extend product lifetime and retain value in the loop for longer. When we are done with a product, but it can be reused, we can create a loop back to the distribution phase, and provide a second lifetime to the product. (Fig. 1.12)

A third way of setting up shorter loops is to refurbish or remanufacture a product. This allows us to create a loop back to the production stage. Remanufacturing involves taking the parts of a used product and reusing them in a new product, possibly after small repairs. By creating these inner circles, we can preserve value and the functionality of products in a circular economy for longer.

Figure 1.12 An economic system where the functionality (value) of a product or material is maintained at the highest value possible. www.reburg.world Photo:Lestat (Jan Mehlich)
In this chapter circular business models are explored in-depth and a range of ways for business to create economic and social value are discussed.

2.1 THE ROLE OF BUSINESS IN THE CIRCULAR ECONOMY

- Three key strategies help businesses keep resources and products at high value for as long as possible: ‘closing loops’, ‘slowing loops’ and ‘narrowing loops’;
- Approaches that pursue resource efficiency, longer product lifetimes, and material recycling are vital to closing, slowing and narrowing;
- The combination of the three strategies in circular business models is an ideal that companies must pursue for the Circular Economy to be achieved.

The concept of a circular economy allows us to focus on issues of resources and how they are used and managed in a business context. In our current linear economy, we are using too many resources, too fast, and we are not reusing enough of them. Here, we present three key approaches applied as we seek to address this – to strategies to narrow, slow, and close resource loops. The central goal is to keep resources and products at their highest value, for as long as possible, and to extend their lifetime to ensure that they can function for longer.

Three key strategies

Narrowing Loops
In a business sense, ‘narrowing loops’, is about reducing the amount of materials needed per product or service. Fulfilling the narrowing principle is something we’re already quite good at in the current linear economy. It is about ‘resource efficiency’, or ‘doing more with less’, which is also an opportunity to save costs.

Narrowing loops is an essential strategy in a circular economy, but narrowing strategies may not account for what happens with the product after it has been used. It may not include consideration of whether the product can be reused or remanufactured; or recycled. In the current linear economy, many efficiently manufactured products are thrown away after only being used once, but in a circular economy we try to retain the value of products and materials.

First and foremost this means we must create products that have a long life span, and which people will want to use for a long time. But there can be trade-offs between durability and resource efficiency in production – and building more durable products can actually increase the amount of resources needed for production. Thus, we must also try to design products that are easy to repair, maintain, upgrade, refurbish and remanufacture, so that extra resources used in production can be offset by the longer use-cycle of the product.

Slowing Loops
In order to put this into business practice, we also need to develop the business models and value chains to support continuous reuse over time. This is called slowing loops. Businesses that pursue the design of long-life goods, product-life extension and service loops of repair and remanufacturing can extend or intensify the use of products, resulting in a slow-down of resources used. Out of narrowing, slowing and closing loops, slowing is actually the most important strategy – and also the hardest. This is because it requires us to both change the way that we design and manufacture products, but also how we use these products in our everyday life. If we can slow loops we can decrease the amount of resources that we have to put into the loop in the first place, and then we can also reduce the amount of waste that has to be processed and recycled at the end! (Fig. 2.1)

Closing Loops
After many cycles of reuse we need to close the loop and recycle. Central to successful loop closing is to avoid the mixing, or cross-contamination, of materials. Braungart and McDonough in their seminal work on the Cradle to Cradle concept, already referred to separating technical materials from biological materials. When materials are not mixed, such as when glass is separated from plastic, they are much easier to recycle. Most of the clothes we wear are mixes or blends of different materials, which makes them difficult to recycle. But some companies are developing opportunities out of this challenge, the start-up ReBland for example spins new yarn out of these discarded mixed materials for use in new furniture and clothing.

Ideally, though, we want to be able to separate these materials and reuse them in their original form. Separating materials means that flows are not contaminated and products can easily be dismantled and remanufactured or recycled. These strategies of disassembly and reassembly will be instrumental in closing the loops.

How to narrow, slow & close
There are many ways we can narrow, slow, and close resource loops.

Narrowing loops can be achieved through using fewer resources per product and during the production process. An example of this is ‘lean manufacturing’, where the efficiency of production processes is constantly optimized, reducing both costs and environmental impacts. These benefits help explain why ‘narrowing loops’ is widespread in our current linear economy.

Another example is lightweighting cars, which saves materials in the production phase and fuel in the use phase. British automotive start-up Riversimple’s prototype car only weighs 580 kilograms, a fraction of the typical weight of a car. And, Riversimple actually combines narrowing loops with other operational strategies, moving from ownership of a car access to a car, which also helps with slowing and closing loops. (Fig. 2.2, next page)

Slowing loops can be achieved through the design of long-life goods and product-life extension. The time during which we use products is extended or intensified, resulting in a slowdown of the flow of resources. Perhaps the most classic ‘slowing loops’ example are businesses who design products to last. A watch or a piece of classic furniture may be designed to be passed on from one generation to the next.

Instead of focusing on product life extension, businesses can also focus directly on slowing consumption of products or resources, but this is very challenging. Consider the example of a government funded project started by the Dutch university TU Delft, which experiments with business models to slow consumption. This project aims to incentivize customers to reduce the impact of home appliances, starting with washing machines. Rather than buy a washing machine, consumers pay per wash in high quality machines provided by the project. The machines last a long time and are built to be reused and recycled. That which is really novel here is that this test project also seeks to change user behaviour by incentivizing fewer and lower temperature washes. Customers only pay when they use the washing machine and they pay less if they wash at cold temperatures.

Repairing, cleaning and maintaining products also help to slow down loops, as does making new products from old ones, or ‘remanufacturing’. This strategy is already being adopted for medical devices. Used devices are thoroughly checked and tested for compliance, worn parts are replaced and software is updated to current standards. In this way the life cycle of the product can be extended, decreasing wastes and delivering cost-savings for medical facilities.

Businesses that challenge current consumption models can also slow resource loops. Outdoor company Patagonia’s Common Threads Initiative encourages people to consume less, and instead repair, reuse and recycle clothing. The company’s famous ad in the New York Times, “Don’t buy this jacket,” is an example of an effort to create awareness for ‘slow consumption’. After the ad ran, many people still bought the jacket though, highlighting the practical complexity of slowing loops.

Businesses can pursue the closing of resource loops through recycling, where the loop between disposal and production is closed.
are instead recovered or recycled. This would mean that the products do not become a ‘waste’ in the first place, and if value chains and business models are designed so that new carpets out of old fishing nets, and they also work with ocean plastic into new garments. Interface Networks makes products. Nike Grind for example makes new sports fields for raw materials, as recycled materials can be used in new considered waste in one process can often be a resource for another. In the food industry, Gunter Pauli is famous for his work on the “Blue Economy” and creating multiple ‘value cycles’. For instance, mushrooms can be grown using coffee waste and salad crops can be fertilized with waste through an aquaponics process; in such ways waste can become ‘food’. In a perfect world, companies would combine strategies of narrowing, slowing and closing resource loops in a circular business model. While this is still an ‘ideal’ rather than a norm, some companies are already moving in this direction. One example is the start-up MUD Jeans, the first firm in the world to ‘lease jeans’ to customers, with an aim to stimulate a sustainable lifestyle through clothing reuse and recycling. Companies in a circular economy work to retain the value of resources by encouraging reuse, refurbishment and remanufacturing, followed by recycling; utilizing these service loops helps maintain the value of products. (Fig 2.3)

To achieve this goal, the circular economy requires innovations at the technology, business model, design and value chain level with clear circular intent, followed by assessment of actual impact. 2.2 THE NUTS AND BOLTS OF A CIRCULAR BUSINESS MODEL

What is a business model?

To help companies adopt circular strategies that can narrow, slow and close resource loops, business model innovation is essential. By taking a closer look at what a business model is, we can gain insights into what this actually means and why it is relevant.

A business model is a management tool that is used to present the company’s organizational structure and value creation processes. It describes the organizational and financial architecture by which an organization converts resources and capabilities into economic value. A widely used definition, created by analysts Osterwalder and Pigneur, describes the business model as the core logic of how a company creates, delivers, and captures value. (Fig 2.4)

A business model consists of different elements that can be adjusted in innovative ways to enable and integrate more circularity. These elements can be structured into three value dimensions:

- value proposition – describing the value provided and to whom;
- value creation and delivery – detailing how value is created and delivered;
- value capture – outlining how value is captured and turned into profit.

Each of these value dimensions consist of a number of business model elements.

An example of a fictitious backpack company, ‘Waterproof Bags Incorporated’ can be used to help clarify how these fit together.

A value proposition dimension consists of three elements:

- customer segments; customer relationships; and the actual value proposition. The value proposition being the value that the product or service creates for the customers.

In this instance, Waterproof Bags Inc.’s main value proposition is that its bags are 100% waterproof and the customer segment targeted is ‘adventurous people’ who spend a lot of time outdoors. The customer relationships strategy is ‘co-creation powered by social media’, where the company’s customers are involved in the development of upcoming models.

The value creation and delivery dimension consists of four elements:

- key resources and capabilities;
- channels;
- key partners, and
- key activities.

For Waterproof Bags Inc., the key resources and capabilities include the development of new, lightweight, waterproof materials. To establish channels with customers, they decide to focus on online sales to support their online community. Their key partner is a large cycling parcel delivery company that helps them promote the backpacks in action. Their key activities are lean manufacturing and sales. The value capture dimension consists of two elements: revenue flows and costs. In this case, the revenue model is quite simple: Waterproof Bags Inc. receives income from selling bags to its customers. Its main costs are incurred in manufacturing, retail activities, and management of the online community.

Innovating business models

Innovating business models can take two forms: the development of an entirely new business model, or the reconfiguration of existing business model elements. As such, innovating the business model can help coordinate technological and organizational innovations and secure partner networks or capabilities that are required to successfully preserve and utilize the embedded value in
resources. Business model innovation can help businesses devise an offer and value proposition that proactively embeds a circular strategy to prolong the useful life of products and parts or close material loops. By rethinking the three value dimensions; for example, how value is created, delivered and captured (Table 2.1), business model innovation provides a more holistic approach when seeking to align the value creation logic of the company with principles of circularity.

The Business Model Canvas

When we design ‘circular’ business models, we seek specific changes in our economy’s resource flows. We want to move away from linear patterns and implement actions that narrow, slow and close resource loops. This requires that companies innovate their business models. A key approach utilized in business model innovation has been the visualization of business models. Visual business model representations reduce complexity and reveal tacit structures. In turn, this helps actors to understand and communicate the current business model, generate and develop new business model ideas, and remove obstacles to innovation.

A framework for supporting work with business models that has been acknowledged for its practical relevance is the “business model canvas” by Osterwalder and Pigneur. The authors distinguish nine business model elements that describe three value dimensions (Table 2.1).

### Adding Circularity

When performing business model innovation in pursuit of a circular strategy, shaping and adjusting business model elements can make implementation of the strategy easier. This can also help overcome barriers and capture value.

For example, the value proposition can be designed to deliberately use a circular strategy and target customers that find the associated value appealing. A value proposition might be a ‘long-life product with low maintenance and lifecycle costs’. This can be appealing to customers with a high environmental awareness or to customers that are bothered by products that quickly become obsolete. For the same product or products, relationships with customer segments can be designed so as to encourage return of a product after its use, such as through establishment of closer and more service-oriented relationships, or by offering a financial reward upon return – or both.

Value creation and delivery elements can be devised to successfully create and deliver the value of a company’s circular offer. Operating a circular strategy requires specific activities, resources, technologies, capabilities, and partner networks to successfully prolong the life of products and close material loops. A company needs to shape these elements in a way that allows it to embed circular practices in its business model. This might require that it finds partners that have special capabilities that it doesn’t currently have. For example, partners that can test and certify quality of repaired products, or partners able to provide sufficient volumes of discarded products that are upgraded or reused.

Value capture elements in a circular business model might be adjusted to generate additional revenue by selling (essentially) the same product several times, or by capitalizing on environmental benefits associated with resource conservation. There may also be opportunities to reduce production costs via the use of cheaper secondary materials, or to avoid costs for end-of-life disposal.

### A note about value creation in circular business models

The sources and processes of value creation in circular business models differ from those in linear business models to some extent. To preserve and utilize the embedded value in products, parts, and materials for as long as possible, business models need to shift their focus beyond a single use cycle by enabling interventions such as resource recovery, and multiple use cycles. To effectively implement these, and create a net positive environmental and economic outcome, business model elements need to be devised with the respective circular strategies and interventions in mind.

Emerging research on managing value creation from prolonged life cycles suggests several unique characteristics of business model elements designed for preserving resource value. If additional life cycles of a product are enabled, it can be useful if the value proposition, from the beginning, is thought of as more fluid and subject to re-definition along the product life cycle. For value creation and delivery, different value networks for cycling resources need to be established; for example, partnerships for securing sufficient supply of secondary products. For value capture, some activities along the product life cycle will result in additional costs (e.g. collection), while others can reduce costs (e.g. substituting virgin materials with secondary materials). Revenue streams can be captured multiple times throughout the lifecycle; for example, through extended spare part and aftermarket services during a first use cycle or accessing new markets and customer segments in a second cycle.

Thus, in order to create and capture value from prolonging the useful life of products and parts and closing material loops, separate value creation architectures may need to be designed to create value from each cycle. Business model development needs to consider how business model elements are configured to support each of the envisioned cycles if value is to be preserved and utilized.

To seize opportunities for preserving and utilizing resource value in the business model, timely consideration and integrated planning of the required interventions for each cycle is pivotal.

### 2.3 Key Strategies for Circular Business Models

- There are 3 key ingredients for a company applying circular business models: engage in circular value creation; use value propositions that enable circularity, and be embedded in circular value network.
- Success of a circular business model depends on intelligent combinations of circular value creation strategies, value proposition strategies, and value network strategies.
- Providing services to the customer instead of selling the product is a key strategy to create a circular economy.

When asked to provide an example of a circular business, many people will likely respond “a recycling company”. Others might tell you of a “reuse shop”, and a few will probably refer to a “car sharing” platform. Despite these activities being quite different, they would all be correct! With such variety available, it is important to consider what is that makes us call a business circular. In this light, it can be observed that actors working with a wide range of circular business models and circular businesses have identified three key ingredients for a circular business model:

- the company should engage in some form of circular value creation;
- the business should make use of value propositions that enable circularity.
- the activities and the business should be embedded in a circular value network. (Fig 2.5, next page)

The first key ingredient, ‘circular value creation’, stands at the heart of a circular business model. Circular value creation means that the business model should include one or more ways to close, slow or narrow resource loops. Several strategies exist to create circular value, such as recycling, repairing, remanufacturing and reusing. We can also seek to increase the amount of use a good has during its lifetime (i.e. improve its ‘utility rate’), make products more resource efficient, or avoid the use of toxic substances. A solid ‘value proposition’ is the second key requirement. Circularity is important, but it also has to be a part of a viable business, and businesses need customers. The best
value proposition depends on the needs and motivations of your customers. If customers are interested in a product made from waste materials for example, then a firm could use a circular branding strategy. This is what a company called FlagBag does for its leisure bags and purses: the design clearly emphasizes the origins of the waste materials they use. (Fig 2.6 A)

For other customers, a premium brand strategy may be more attractive. Vitsoe, for example, produces furniture products that are intended to last a lifetime; they put product quality and longevity at the centre of their value proposition.

Another value proposition strategy that can enable circularity is a product-service offering. Here, a company delivers the product as a service rather than selling a good directly. In this configuration, as the company still owns the product, it is now in their interest to make sure that it lasts as long as possible, which makes repairing, reusing, or remanufacturing more important. This strategy is applied in “pay-per-copy” models, that allow companies like Ricoh to manage their copy machines like assets.

Other value proposition strategies can focus on reducing costs for the customer. For instance, by offering a product or service that is cheaper than the linear alternative, providing a platform to share undeniably capacity, or by eliminating product inventories via production on demand systems. Some companies have also demonstrated that you can use circular business models to increase business without necessarily branding yourself as a circular business. Nearly New Office Facilities, for example, focuses on customer needs for affordable office furniture combined with a healthy work environment. The fact that they use materials from old furniture in the manufacturing of new furniture is something many people may not even notice.

The third and last key ingredient for a circular business model is the ‘value network’ that surrounds the company. Such collaboration can be set up with customers or suppliers in the value chain, or with companies, governments, or civil society in a wider value network. Such collaboration can be set up with customers or suppliers in the value chain, or with companies, governments, or civil society in a wider value network.

Circular strategies and the Business Model Canvas

Though no official link exists, it is possible to connect the three ingredients to the Business Model Canvas components, helping identify potential strategies to increase circularity:

• Circular value creation strategies are typically linked to the key activities, key resources and capabilities, or key partner elements in the Business Model Canvas.
• Value proposition strategies are linked to the product offer, customer segments and customer relationships elements.
• Value network strategies can be linked to the delivery channel, customer relationships, key partners or key resources and capabilities elements.

While the Business Model Canvas, in combination with the circular strategies, is a highly valuable place to start designing a circular business model, it is less suitable to use in mapping circular value networks, a crucial part of any successful circular business.

The importance of a circular value network

The success of a circular business model depends on the creation of smart combinations of circular value creation strategies, value proposition strategies, and value network strategies.

Consider a company that produces repairable and recyclable smartphones. While the design for repair and recycling the smartphone is key to creating circular value, such circular value is actually only realized when the product is in a repair shop or recycling facility. As such, the producer needs to create incentives for their customers to return the phones when they are damaged, or when the customer has finished using them. The producer also needs to work with repairers and recycling companies to make sure the smartphones are repaired when broken, and recycled when repair is no longer possible.

There are a number of combinations of circular strategies that can make these situations technically and economically feasible. A first, and very common one that can be found in Europe, is the creation of an extended producer responsibility (EPR) scheme. This is a collective, government-controlled mechanism in which producers are required to finance the collection and recycling of end-of-life products – including end-of-life smartphones.

Although this value network strategy has been shown to support increased recycling, many smartphones still end up in consumers’ drawers at home, as at present there is no real incentive for them to have their phones repaired or collected. The producer of the smartphone, also generally has no direct benefit of its design-for-circularity efforts, as there is no direct link between producers and recyclers. In simple terms, the value of the design efforts gets lost.

However, such challenges can be overcome if actors in the system improve aspects of the circular business model design. For example, the producer can directly cooperate with its customers by offering a discount on new products when an old smartphone is sent back. The producer may then re-market the collected smartphones in other markets, or capture residual material value by sending the phones to a recycler.

An even more effective circular strategies combination that can capture all the circular value of smartphones designed for circularity, can be to introduce a “smartphone-as-a-service” as the value proposition. This scenario allows the producer to keep control over its product both during and after the use phase, and it also creates leverage to maximize the reuse, repair and recycling value of their products. As the owner of the products, the smartphone company can engage in partnerships with repairers and recyclers within its business model. Providing information such as product disassembly guidelines, or the detail bill of materials for the product, or by jointly organizing reverse logistics, can also help these partners to improve their own activities – in turn improving the overall viability of the system.

The role of Products-as-a-Service in the circular economy

Providing services to the customer instead of selling the product is a key strategy to create a circular economy. A ‘product-service’ offering, or ‘Product-as-a-Service’ (PAAS), is one type of value proposition that can be used to achieve circular value creation.

Viewing this as a value proposition, where a combination of product and service elements are offered to the customer, is one way to understand how this functions. Such models are by no means new! Libraries and cable television for example, have applied this model for many years. With the advent of digital technologies it has become increasingly easy and interesting to use a PAAS strategy for a wider range of products. PAAS has completely changed the music industry in recent years. Start-ups such as Spotify have brought the value of music to its customers without ever having to produce, distribute, or play a hardware form of music such as a CD. PAAS exists in many forms and variations, but for circularity, it is relevant to make the distinction between three types of PAAS; ‘product’, ‘use’, and ‘result’ oriented PAAS (Fig 2.7).

A product-oriented PAAS still closely resembles a conventional sales offer in that the ownership of a tangible product is still transferred to the consumer. However, it differs because there is an addition of a service offering to provide
The circular business model planning tool is a visualization tool to map circular business models. It offers a standardized representation of the elements and possible cycles of circular business models, that can prolong the useful life of products and parts, and close material loops. The tool integrates the three value dimensions discussed earlier (‘value proposition’, ‘value creation and delivery’, and ‘value capture’, and their business model elements).

Further, it applies four lifecycle interventions:
1. collect and reintegrate;  
2. first sale (enabling prolonged useful life);  
3. additional sale(s) of the product or parts;  
4. material recovery. (Fig 2.9)

As the tool is built from the principles within the business model canvas of Osterwalder and Pigneur introduced earlier, the circular business model planning tool, is also referred to as a ‘canvas’ – but it is now essentially a ‘circular business model canvas’.

It is important to note (see Figure 2.10) that collection and reintegration is mapped twice in planning tool. This is because these processes can take place both upstream and downstream in a company’s value chain.

The tool maps business model elements for each of the enabled interventions. It can help you recognize which interventions for circularity are currently utilized and which are not. This can reveal innovation opportunities to embed more circularity in the business model. It can also help you analyse if the business model elements are configured to effectively support each of the envisioned cycles. Lastly, it can help recognize interdependencies between the enabled cycles and how shaping business model elements to support one cycle, enables value creation from another cycle (e.g. customer relationships and partners).

As an aid to business model innovation, visualization tools that depict circular business models can be used to help plan product life cycles that can create and capture value from multiple use cycles and closed material loops. A visualization tool can also highlight how business model elements may be adjusted to effectively implement each cycle.

The ‘Circular Business Model Planning Tool’ is a visualization tool to map circular business models. It offers a standardized representation of the elements, and possible cycles of circular business models, that can prolong the useful life of products and parts, and close material loops. The tool integrates the three value dimensions discussed earlier (‘value proposition’, ‘value creation and delivery’, and ‘value capture’, and their business model elements). Further, it applies four lifecycle interventions:
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As the tool is built from the principles within the business model canvas of Osterwalder and Pigneur introduced earlier, the Circular Business Model Planning Tool, is also referred to as a ‘canvas’ – but it is now essentially a ‘circular business model canvas’.

It is important to note (see Figure 2.10) that collection and reintegration is mapped twice in planning tool. This is because these processes can take place both upstream and downstream in a company’s value chain.

The tool maps business model elements for each of the enabled interventions. It can help you recognize which interventions for circularity are currently utilized and which are not. This can reveal innovation opportunities to embed more circularity in the business model. It can also help you analyse if the business model elements are configured to effectively support each of the envisioned cycles. Lastly, it can help recognize interdependencies between the enabled cycles and how shaping business model elements to support one cycle, enables value creation from another cycle (e.g. customer relationships and partners).
The Fairphone circular business model
Filling out the Circular Business Model Planning Tool using details from a mobile phone manufacturer and distributor named Fairphone, provides an example of how it can be applied in practice.

Fairphone offers a modular long-life phone and both replacement modules and repair guides can be accessed via the Fairphone website. Their customers are presented a value proposition of competitive performance standards, reparability and low lifecycle costs, as well as access to a website community where Fairphone users can – among other things – discuss repair techniques. (Fig. 2.10)

As part of their business model, Fairphone has an intertwined relationship with a collaboration partner named Teqcycle; a repair and recycle company. Fairphone offers Teqcycle a resale opportunity and thus the value proposition for Teqcycle includes the modular design of the Fairphone.

This in turn makes repair and resale of phones relatively easy: Fairphone also collaborates with Teqcycle for the take-back system. Customers for the re-purposed phones are in fact not direct customers of Fairphone, but are customers of Teqcycle, so they are not mapped in this version of the model.

Filling in the model canvas highlights interdependencies between the interventions, and how shaping business model elements in one intervention enables value creation through other interventions. In the case of Fairphone, the relationship established with users when selling the phone helps them reach out to users and inform them of repair possibilities, and to promote the return of phones. The design for repair and recycling facilitates value creation after use for its partner Teqcycle.

Not all of the interventions have to be addressed in a circular business model. Examination of the last two interventions represented on the canvas, demonstrates that the responsibilities between Fairphone and Teqcycle are more and more divided. And not all business model elements of the focal company Fairphone are filled in. Typical reasons for this are that some interventions may not be more resource efficient or economically desirable, or that they can rarely be realized by one company alone, but are reliant upon networks of companies that align their business models, to each other. In the case of Fairphone, no integration of secondary materials in their own products is happening as yet. The blank columns in the circular business model canvas, however, send signals that there may be an opportunity for embedding more circularity in the business model, and that is worth exploring.

Explore further – ‘The Circulator’
To help you with the design or analysis of a circular business model, the Circulator has been developed. This can be found at www.circulator.eu. This web-based tool allows you to explore circular strategies, and to combine them according to your own preferences. (Fig 2.11)

2.5 MAPPING THE BUSINESS AND SOCIAL ENVIRONMENT:

The transition to a circular economy is not expected to be an easy, gradual evolution. It requires a profound change in the way we live, travel, work and do business. For this change to succeed, radically new ideas must gain momentum and find a ‘window of opportunity’ to change the mainstream system. These windows of opportunity emerge when different trends and events in society suddenly come together and point in a similar direction, making room for a new mindset, or helping to make a place in markets for products or services that offer something different. When this happens, a new product or a new service may suddenly break through and contribute to a profound change in our way of thinking and acting.

The right idea at the right time is what entrepreneurs are looking for. Unfortunately, the process of creating ‘the right time’ is largely out of our control. Changes in technology, market conditions, social trends, government policies and regulations, and other factors combining generally define such points in time – and it is difficult, if not impossible to influence so many things. Such parameters have a large impact on whether a great idea can actually turn into a real business opportunity or not. Companies must react and accommodate the changed conditions into their value propositions, company policies, and their marketing strategy. This means that understanding what these external factors may be, and how they work together, is key to recognising ideas that are most likely to be successfully developed.

The PESTEL framework, which is often used in marketing, is a useful tool for this. It lists key external (macro-)influences that can affect a business’ strategy and success. They are listed according to the following 6 factors ascribed to the acronym PESTEL:

P for Political – These factors determine to what degree the government and government policies intervene in the economy or a specific sector. This can include government policy, and political stability or instability in local as well as overseas markets, trade restrictions, fiscal incentives and taxes, labour regulations, environmental law, and so forth. Companies must be aware of, and able to respond to, current and anticipated future legislation, and adjust their business strategy accordingly.

E for Economic – These factors have a significant impact on the economy, which in turn impacts the profitability of a company and the way in which it can do business. Factors include the level of economic growth, employment rates, interest and exchange rates, inflation, disposable income of consumers, raw material and energy costs, and more.

S for Social – Socio-cultural factors determine the customers’ needs and wants and are of particular interest to marketers. They include the characteristics, the shared beliefs and attitudes of the customer population. These are assessed by factors such as population demographics, education levels, general health status, lifestyles and attitudes.
T for Technological – Technologies change rapidly and can have a huge impact on the way products are made and marketed. Technical factors affect the way in which goods and services are produced and distributed, as well as the way in which customer communication is created and delivered. Factors include parameters such as changes in automation and robotization, and trends in digital and mobile technologies.

E for Environmental – These relate to the impact of ecological factors and constraints. Environmental factors have become important due to increasing environmental awareness by both governments and consumers. Concerns – and tangible impacts on businesses – related to issues such as resource scarcity, pollution, carbon footprint, and climate change are also notably influencing choices made by companies. In the context of the Circular Economy, the E for Environment parameter in the PESTEL framework is oftentimes stretched to include broader sustainability issues. One leading example is a shift towards more ethical and sustainable business policies. With more and more consumers demanding ethical and sustainably sourced products, corporate strategies that explicitly account for sustainability issues are also gaining importance.

L for Legal – Legal factors include parameters such as employment policies, consumer rights, health and safety standards, advertising rules, privacy, product labelling, warranties, liability, trade restrictions, and so forth. It is clear that companies need to understand the legal boundaries within which they must operate. This can become particularly challenging when a company operates on an international level, as each country has its own rules and regulations, and they often differ. There are also a range of legal issues with new forms arising related to circular economy activities – liability and intellectual property rights are just two of these.

By undertaking such as structured assessment of external factors that may affect an organization, a company can improve its resilience to external threats and identify windows of opportunity for new business strategies. This in turn may create a competitive advantage for the firm. In recognition of this, the parameters within a PESTEL analysis are often described as ‘drivers of change’ as can define issues that can create a competitive advantage for the firm. In recognition of opportunity for new business strategies. This in turn may improve its resilience to external threats and identify windows of opportunity for new business strategies. By doing this, a company can reduce its dependence on externally sourced products, and the materials they are made of. This can increase their resilience to market disturbances. Remanufacturing or refurbishment of used goods can also lower production costs, allowing a company to make their products more affordable, while keeping quality standards high. There are now numerous companies offering reconditioned industrial machinery, refurbished electronics and second-hand clothes.

S for Social – Drivers for circular business are linked to understanding and addressing customer needs. For example, people living in crowded city centers increasingly do not wish to own a car, particularly where there is well developed public transport. As global populations continue to move to cities, cars are becoming even more expensive and difficult to park in many urban centers. Adding to this is a greater societal awareness of the negative environmental and social impacts of cars – particularly in cities. Existing norms and practices for car ownership and use are being questioned in a number of countries. But even concerned people would often like (or need) access to a car from time to time, for example, to visit friends in the countryside. If given the opportunity, they would only want to pay for the days or kilometres they are using a car. Such social conditions and drivers help explain the success of car sharing services in urban settings. The focus on access rather than ownership also makes expensive goods accessible to a broader range of customers.

Another social aspect of circular business models is that they often entail service activities, such as maintenance, repair or remanufacturing; and quite a number of these also involve the development of online communities for sharing knowledge and experiences. Such factors strengthen the relationship between providers, customer and communities. They also generate local employment.

T – Technology is also a key enabler – and the rate of technological change at present is extremely high when viewed in a historical perspective. Right now, many technologies are being developed that will improve the resource efficiency of production processes. For example, 3D printing allows us to locally print fully customized products and spare parts when and where we need them. This can also remove the need to produce and store large amounts of goods and parts that may never be used. Digitization is a pivotal technology for circular business. The new digital environment supports a broad range of new business models that connect suppliers of goods and services to potential customers. Some services, such as access to music, can now be fully dematerialized and delivered directly through ‘the cloud’ as a service.

E – For a range of customer segments, environmental considerations can be an important driver when choosing a product or service. Circular business models that keep products and materials in use for longer. Reuse and recycling can reduce waste, replace the extraction of new primary materials, and reduce the need to produce new products – and thus reduce material and energy use. By providing information on the environmental performance of their products, companies can both differentiate themselves and make it easier for customers to make environmentally conscious choices.

L – There is a strong link between environmental considerations and legal drivers for circular business models. Stricter environmental standards, policies such as extended producer responsibility and higher recycling targets often provide incentives to shift to more circular business models. The extension of legal product warranty periods can also contribute to design improvements to make products more durable and easier to repair.

Barriers

Having posed a range of drivers, it is reasonable that a question be posed: Why aren’t all companies transitioning to circular business models if there are so many good reasons to do so? The simple answer is that companies may face a range of barriers when trying to apply circular thinking to their organization.

These barriers are often dependent on firm size, location, and product or service. In this application of the PESTEL framework, internal issues are also considered. This is largely in recognition of the fact that many structures within the firm – as well as external to the firm – have been formed over a range of barriers when trying to apply circular thinking to their organization.

Examples of barriers that external, meaning they are driven from within the firm, can include things such as the way that a company judges the value of an investment. There may not be established practices to fairly judge the value offerings. Or, they can also drive from external, meaning they are difficult in building a new system or practices comes from outside the firm. For example in the form of regulatory or policy-related structures that disadvantage a new set of circular economy initiatives.

Again we can compare the PESTEL framework to a range of commonly observed internal and external barriers to circular business models in order to demonstrate the application of the tool.

P – Policies, legislation, or regulations may influence a firm’s ability to implement a circular business model. These types of political barriers are most often external and dependent on the location of the firm.
Existing policies that incentivize recycling, incineration, or disposal over other circular strategies, such as reuse and refurbishment, have real potential to negatively affect firms looking to base their value proposition on product life extension. Recent research from the Information and Communication Technology (ICT) field provides several tangible examples. A first is how existing extended producer responsibility policies can create competition between ICT reuse organizations and recyclers or manufacturers. A system has been built to support recycling – in the face of waste problems – but now when activities focused on reuse enter the market competition is set up between two systems.

Tax and labour regulations can also make it challenging for firms to make the business case for repairing, refurbishing or remanufacturing products, as these activities can be labour and cost intensive. Policies are usually country specific, so firms wishing to expand internationally must comply with all relevant regulation and provide documentation, which can be a challenge, especially for smaller firms.

- Greater upfront investment, higher costs, and return on investment uncertainty are three main types of economic barriers faced by firms attempting to transition to more circular business models. Many circular business models require greater upfront investment, influencing a firm’s cash flow and lengthening the time of return on investment. In addition to these expenses, circular business models may also require additional resources, leading to higher costs. Undertaking activities such as repair, refurbishment, and remanufacturing often means an increase in firm resources, including additional skilled employees. And in countries with high taxes on labor, firms may find it difficult for this to be economically feasible. Like any business model innovation, circular business models do not guarantee a return on investment. Remanufacturing and resale of existing products may cannibalize new product sales. External economic factors like high costs associated with product take-back, or the low price of virgin materials, may also discourage firms from implementing circular business activities.

S - On the social side, success of circular business offerings is shaped by consumer acceptance. Customers’ desires and pre-conceived notions largely influence their willingness to adopt circular offerings. Customers may for example purchase a new product over a remanufactured product if they believe the remanufactured product is inferior. For example, depending on the type of product, some consumers may have concerns about data security or hygiene when products are reused. In many cases, consumers are open to circular offerings but are simply unaware of their existence. As a result, many organizations and governments have moved to create more awareness of such business opportunities.

- Technical barriers can and do hinder a company’s ability to adopt circular offerings. For example, it may not be technically possible to reuse, refurbish, or remanufacture existing products to meet current performance demands. There are also often concerns about the technical performance properties of materials that have been recovered and recycled.

- Circular business models must contribute to the cycling of products and materials and replace primary production in order to contribute to environmental sustainability but at present there remains uncertainty in some situations about whether there are actually environmental benefits associated with circular offerings under all circumstances. Even though it is expected, that environmental benefits dominate, studies have shown that this is not guaranteed. Such uncertainties have been observed to slow the adoption of circular business models.

- Like many of the barriers previously discussed, legal issues surrounding adoption of circular business models differ from country to country, and can also differ according to firm location and type. In circular business models where product ownership is not transferred to the customer, firms must internalize legal risk – for example, taking on some liability for performance. As a consequence, some companies may hesitate to extend responsibility from beyond point of sale. The potential for legal action from other firms can also act as a barrier to circular business models. Intellectual property and other design rights may, for example, hinder or limit companies from reusing other firm’s products.

- In many cases, consumers are open to circular offerings but are simply unaware of their existence. As a result, many organizations and governments have moved to create more awareness of such business opportunities.
This chapter presents functional materials, eco-design and methods to assess environmental impacts.

3.1 DESIGNING MATERIALS FOR A CIRCULAR ECONOMY: OPPORTUNITIES AND CHALLENGES

- Humankind has always developed new materials, but the rates of new design and synthesis – and the number of applications for materials – have rapidly accelerated in recent times.
- Modern demands stimulating new waves of innovation are many – and increased circularity also places new demands.
- Traditionally non-degradability and eco-toxicity was largely ignored in material design, but now this has increasing importance for society and it has great implications for circularity.

The types of materials that have been available to society have had enormous importance for the development of societies throughout time. This fact is well recognized in human history, with key epochs such as the bronze age and the iron age being named after the key material of the era.

In the past, humans essentially collected ‘natural’ materials based on them fulfilling specific functions, or simple criteria such as strength, hardness and weight in structural applications. However, the number and complexity of selection criteria rose dramatically when people discovered that the properties of natural materials can be altered significantly by changing their structure. Importantly, we learned how natural oxides like iron oxide (commonly known as ‘rust’), can be extracted into relatively pure metals, in this case iron.

Understanding that metals can be cast, cut and shaped into specific final products was a huge step forward in material engineering. We also learned that strength can be increased and other properties altered dramatically by mixing one element with others, and such mixtures became known as alloys. For instance, bronze is an alloy of copper and zinc, while steel is an alloy based on a mixture of iron and carbon. In essence, the advancement in making new structural and functional materials in this way was the beginning of an industrial revolution. It was a paradigm shift; instead of collecting natural materials and relying on their natural properties, we began designing and synthesising our own materials. The sophistication of modern engineering technologies now allows the fabrication of a large variety of ‘man-made’ materials that can fulfil a larger number of selection criteria simultaneously. The material selection criteria of today have expanded from the functions of materials alone to also include the characteristics of fabrication technologies, their cost, and the availability of natural resources.

Today, we can fabricate materials that range from oxide ceramics and semiconductors, to metals and polymers, to compose and hybrid materials, and even to living biological tissues. The advances have great significance for parameters such as functionality and resource-efficiency. For example, new strong lightweight material-based structures allow aircraft to fly further and faster while using less fuel, and even allow them to reach space. New semiconductors now provide clean solar electricity, and new composite materials form the vanes of the turbines used to generate power from the wind. These are just a few examples of how society can benefit from materials innovation.

However, a common ‘side effect’ of fabricating artificial materials is significantly reduced ability to decompose or degrade ‘naturally’ within a reasonable period of time. When we invest a lot of effort into materials taken from nature in order to tailor their properties, it also oftentimes embarks a need to apply additional effort to make the materials safe if they are to be returned to nature. This ‘effect’ has been ignored by society for a very long time, but as modern scales of production grow along with population and consumption, the pollution arising from discarded complex materials has grown to levels that pose an existential threat to ecological systems, human health, and society in general. As a result, it has now come into the technological spotlight.

Of course, there are alternatives to the discarding of materials. Instead, additional effort can be applied to make the materials suitable for their original functions again, thus closing ‘material cycles’ and reducing overall consumption and pollution. This brings us to a more circular society where material technologists face new challenges. While the fundamental challenge is to continue innovating to provide new materials with improved functionality, an increasing demand is to deliver materials that are also recyclable. This defines a new paradigm for materials engineering where materials that both deliver a function desired by society and are recyclable are increasingly preferred. Beyond demands such as ‘environmental friendliness’ or ‘recyclability’, the capacity to be a chain link in the emerging circular economy is becoming crucial in material design and selection processes.

This situation is well illustrated by the use of materials in the transportation industry, in particular in car bodies. Steel was an unrivalled structural material until the late 1970s when demands to reduce vehicle weight became stronger. An underlying reason at that time was to decrease (expensive) fuel consumption. Later, that was reinforced by demands to reduce CO2 emissions. These factors spurred the replacement of some steel body components with lightweight alternatives – and consequently many non-load-bearing panels have been replaced by plastics. More critical components were replaced gradually by aluminium, then by magnesium alloys, and now increasingly by carbon-fibre composites as well. These special materials deliver significant weight reductions. The use of aluminium alloys delivers approximately 65% in weight savings, while magnesium and carbon fibres save another 30%. But these light materials have their own drawbacks, beyond the increased cost of car production. These are related to the new material alloy and structure complexity required to achieve such performance.

But aluminium and magnesium as pure metals are very soft, so performance targets are achieved by creating alloys of each. For example, without special additions, magnesium is notoriously difficult to fabricate – and it degrades too quickly during service. Aluminium alloys are extremely difficult – or simply too expensive – to recycle to their original grades. Therefore, they are ‘downcycled’ to lesser quality and value products. New composites such as carbon fibres have similar challenges.

This brings us to the most interesting part of this example. The competition from light-weight materials has now stimulated accelerated development of better-performing steel grades. In this case, the weight savings are achieved by reducing component thicknesses. In addition, steel recyclability received an important stimulus as more valuable possibilities for ‘closing material cycle loops’ with steel were recognized.

In turn, the revival of research in steel industries has further stimulated the development of light-weight materials. This has created more demands for the analytical capacities of sophisticated tools like electron microscopy, synchrotron radiation and neutron scattering. These tools allow us to design new materials satisfying the dual challenges of improved functionality plus circularity. Materials engineering thus has an important role to play in creating pathways that bring the visions of the circular economy to reality.

3.2 ECO DESIGN STRATEGIES

- product design strategies can be formed to support circularity.
- there are a range of dilemmas to deal with and tradeoffs to consider when pursuing circular design;
- it is important to match specific product design processes to relevant circular business models.

Why ecosign? Ecosign is an umbrella term that incorporates several sub-strategies that companies can use to improve the environmental performance of their products. Ecsign takes a product-centric view with focus on reduction or elimination of environmental and human health-related impacts and resource depletion. Smarter design can increase the eco-efficiency of many products, for example by reduction of materials and energy needed for production or the use-phase energy consumption. There are numerous reasons why businesses engage with ecosign. One is to comply with present or upcoming regulations. Another is to save costs by being able to use recycled materials. Businesses might also attract customers willing to pay a premium price for environmentally superior products.

Building on the idea of ecosign, a product’s entire lifecycle must also be examined in the design phase when designing for circularity. To help ensure the reuse of products and their parts, products should be designed to align with the value propositions of circular business models, which typically include this.

Six design strategies

Researchers have identified six different circular design strategies that may be chosen. Which strategy, or combination of strategies, to choose is highly dependent upon the business model being applied.
Strategy 1: Design for attachment and trust – This design approach encourages users to bond with the product and can help extend product lifespan, as the user is less likely to discard a product for which they have a strong emotional attachment.

Strategy 2: Design for durability – Products are designed to be durable, reliable, and have reduced likelihood of failure. However, when defining a product’s durability, designers need to also match the economic and stylistic life span of the product.

Strategy 3: Design for standardization and compatibility – This typically involves designing product parts to be interchangeable and compatible with multiple products. This enables repair and can extend the life of the product. When compatible replacement parts are readily available products may be more easily refurbished or reused. This can also help reduce overall consumption as one product can be used for different purposes. An example is where phones and tablets can be charged with the same charger instead of requiring a unique charger or each.

Strategy 4: Design for maintenance and repair – This design strategy extends product lifetimes by increasing the ease of product maintenance. Repair for many products is often time-consuming and in countries with high labour costs, it can oftentimes be more expensive to repair a product than purchasing a new one. Reducing the number of components in a product and the number how parts are joined – for example, by avoiding adhesives – can help companies decrease repair time and cost. And, it can also enable users to more easily repair things themselves. The availability of repair manuals and spare parts is of course also a key enabling factor.

Strategy 5: Design for adaptability and upgradability – Here, allowance is made for future product modifications. Functional updates can allow a product’s function to change over time, such as a child’s high chair that can be turned into a dining room chair as the child ages. Technical updates such as the update of a computer with a new operating system allow products to adapt to technological change. Sometimes however, the speed of technological development limits upgradability possibilities. Thus, the rate of technology change in a product segment is a key factor for designers to consider.

Strategy 6: Design for ease of disassembly and reassembly – The design of products and parts so they can be taken apart and reassembled not only enhances the reparability and reusability of products and components but it also makes the products easier to recycle.

Parallel strategies

In addition to these six strategies, two other strategies are often discussed in parallel with circular design and sustainable materials management. These are design for recycling and design for dematerialization.

Design for recycling focuses on using specific design techniques that can increase the rate of material recoverability in the recycling process. A prime example within this that makes products easier to recycle is the avoidance of the use of mixed-materials.

Finally, product design can also pursue dematerialization. Examples of approaches are the reduction of packaging or the application of high-performance materials that allow less total material to be used, while maintaining or even improving functionality. In some cases of dematerialization, the product may actually be replaced by a service – and approach that typically consumes much significantly less resources. One example of this is the move toward streaming films instead of producing DVDs or Blu-ray disks.

3.3 INTRODUCTION TO NANOTECHNOLOGY

The word “nano” means “dwarf” in Greek, and many people associate nanotechnology with something that is small. People, now many see how nanoscale is used – for example, by avoiding adhesives – can help companies decrease repair time and cost. And, it can also enable users to more easily repair things themselves. The availability of repair manuals and spare parts is of course also a key enabling factor.

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Most of us know that the tip of a pen is about 1 mm, but it is not very often we measure everywhere distance in millimetres. Making the scale yet 1000 times smaller we reach the length of micrometre (also known as microns), which are a million times smaller than a metre or ten to the power of minus six metres (10⁻⁶m). Structures measured in microns can still be seen with the naked eye; for example, mites can be a couple of 100 microns across, and human hairs are typically 50 micrometres wide, but often microscopes are required to study micron sized structures. Other examples of micrometre sized structures are red blood cells, around 8 micrometres wide and 2 micrometres thick, and bacteria, which often have a size of between half a micron to five microns. But to reach the scale of nanometres we have to make it yet another 1000 times smaller, which is a billion times smaller than a metre or ten to the power of minus nine metres (10⁻⁹m). A common definition of nanotechnology is the generation and manipulation of materials and objects that consist of some components that are in the size range of 1-100 nanometres. Structures on the nano-scale can no longer be seen by the naked eye, so advanced microscopes are needed. Two examples of nanoscale objects from nature are viruses, which can be around 50-100 nanometres, and our DNA, which is 2 nanometres wide. Today there are also many man-made structures with nanometre sized dimensions. A transistor, which is the core component in our computers, consists of structures with nanometre dimensions. Other examples include graphene, carbon nanotubes, nanowires and nanoparticles, all with one or more dimensions smaller than 100 nanometres. Although many of us are familiar with some nanometre sized structures, not many of us can easily relate to and have an intuitive feeling about the nanometre length scale.

To help put nanometre in perspective; consider a piece of paper, which is 100 000 nanometres thick, and that your fingernails grow about 1 nanometre per second.

Nanomaterials: properties and applications

In addition to their amazingly small size, materials with nanometre dimensions can have different properties compared to larger pieces of the same material. This is of course a major reason for the substantial interest in nanotechnology. A natural consequence of nanosstructured materials is a much, much larger surface-to-volume ratio compared to larger objects, which simply means that the surface plays an important role. This is utilized in nanobiosensors, for example, where binding of molecules to the surface of the biosensor affects its electronic properties that generate a signal, which can then be detected.

An important part of nanomaterial development is to modify the surface of a material to give it specific properties, and such modifications are often inspired by discoveries from nature. An example is adhesive structures made without glue, similar to the feet of a gecko. Geckos can easily climb walls due to a large number of small nanostuctures on their feet, each one giving rise to a tiny force, that when added together creates a force strong enough to carry the weight of the gecko. A product that has the potential to provide adhesion without toxic chemicals often found in adhesives clearly has environmental implications.

It is not only the surface effects that are important for nanomaterials. Graphene, for example, is a nanomaterial that is made of pure carbon, and it exhibits completely different properties on a nanoscale than larger forms of carbon. Compared to these larger forms, graphene has different and better mechanical, electronic, optical and thermal properties, and it’s also stronger and lighter. Nanomaterials like graphene can be added to other materials to create composites with improved properties compared to the pure material. There are now many products that are made with graphene enhanced materials so that they are stronger, lighter and more flexible than traditional materials. Such nanomaterials offer opportunities to do ‘more with less’ – or in other words they can contribute to ‘narrowing material loops’.

Nanomaterials can also be used in the design of new electronic and optoelectronic materials. Since nanomaterials have dimensions on the same order as the wavelength of an electron, they exhibit quantum effects. One example is the quantum dot, where electrons can only move between certain discrete energy levels that are closely related to the size of the quantum dot. This means that quantum dots will emit light of specific frequencies or electricity or light is applied to them, a feature that is utilized in quantum dot...
televisions – these offer much clearer and brighter colours at significantly lower energy consumption. Other types of nanostructures where quantum effects can be used are carbon nanotubes, graphene and nanowires. These make it possible to create new types of transistors, light emitting diodes, lasers and solar cells – these applications all have important roles to play in technologies required for resource efficient and clean development.

Nanotechnology is not only interesting to material science; in the field of medicine, for example, people hope to use nanotechnology to create faster diagnostic tools, directed delivery of pharmaceuticals and improved contrast agents.

In addition to its size (very very small) and its special properties, the third thing to remember about nanotechnology is that it is a truly multidisciplinary field, ranging from physics and electronics to chemistry, biology and medicine.

Nanotechnology and the Circular Economy

Nanotechnology is sometimes referred to as “crafting with atoms”, which basically means building up materials atom by atom. It is a bottom-up approach that mimics natural processes, for example how a seed eventually grows into a large tree. The conventional manufacturing approach is the top-down approach, which starts with bulk material, from which the desired structure may be carved or etched out. The bottom-up approach can lead to a more efficient use of materials and less waste, and is therefore a promising way to help narrow material loops. Innovative bottom up approaches becoming established in the field are described here. Even at such tiny scales, and dealing with specialized substances, efforts are being pursued to create low waste, energy efficiency production techniques.

Semiconductor nanowires are rod-shaped, one-dimensional structures with a nanoscale diameter, and they have the potential to radically improve future electronic devices. In the production of nanoparticles and nanowires a bottom-up approach to creating nanoparticles with a physical method called aerosol generation is applied. This approach starts with a small piece of bulk material that is evaporated in a carrier gas; this can be done by a laser, in a furnace or with a spark or arc process. This vapor is then transported away from the hot zone by the carrier gas, and starts to form a nucleus, which continues to grow in size into nanoparticles. The size of the particles can be carefully tuned, and the carrier gases can be recycled and reused. The small amount of waste that is created is in the form of material condensation on surfaces in the system, and it can be easily collected and recycled.

The nanowires are formed atom layer by atom layer in a process called epitaxy. Instead of a thick bulk semiconductor, the process starts with a thin semiconductor substrate where either seed particles or a mask is deposited. After that, the growth material is supplied and the nanowires are formed under the seed particle or in the hole in the mask, atom layer by atom layer. Another way that can be even more material efficient is an aerosol process called aerostaxy. Here the nanowires are grown in a gas stream, with only a seed particle to initiate the growth. The two main advantages of aerostaxy are that the nanowires are grown in a continuous process, and that there is no substrate. This makes it an extremely material efficient production route. (Fig. 3.1)

In addition to narrowing material loops, nanotechnology can also help slow material loops, by prolonging the lifetime of products – for example using coatings enhanced with nanoparticles. There are nano-based coatings that can make a structure withstand wear better, or make it more resistant to corrosion. One example is self-healing materials, that are designed to heal themselves from thermal or mechanical damage, with full or partial recovery of their mechanical strength. Common types of self-healing materials are based on polymers that are designed to self-heal their broken bonds. Among different promising materials, researchers have developed both self-healing rubber and self-healing glass.

There are also coatings that can make surfaces super hydrophobic. This property creates surfaces that resist water, and they are based on materials that are not affected by water. This can be built up in a bottom-up approach.

The research on nanotechnology-based materials has grown significantly in recent years. And there is a wide variety of different applications where nanomaterials can have a huge impact this area of material science is considered likely to offer much to the circular economy.

3.4 ASSESSING THE ENVIRONMENTAL SUSTAINABILITY OF CIRCULAR SYSTEMS: TOOLS AND METHODS

- Environmental life cycle assessment can be used to assess whether a new product or process can contribute to a more sustainable society.
- Circular systems do not by default lead to environmental improvements.
- LCA practitioners face several challenges when it comes to assessing circular systems, with recycling as a prime example.

Introduction to life cycle analysis

Just because a product is circular does not necessarily mean that it is sustainable, and innovations with new materials may improve some environmental characteristics, but not others. Tools need to be used to assess whether or not a new product or process can contribute to a more sustainable society.

Let us examine a situation where a company wishes to assess the environmental impact of its newly developed circular product system. They need to analyse the product in a structured way, so that they can better understand its environmental impacts, and evaluate if it is actually more environmentally sustainable than the current alternative.

A first step is to examine the process level to see if this process consumes more or fewer resources or emits more or fewer emissions than a non-circular alternative. (Fig 3.2)

When doing so, efforts are made to quantify all the inputs such as electricity, water and chemicals, and all the outputs such as effluents and emissions arising from processes. To assess the impact of a process on the environment, it is necessary to apply a risk assessment method. This assesses the potential for impact of emissions in the environment surrounding the process plant. To assess the impact of a process on resource use, it is possible to perform an efficiency analysis, such as an energy analysis, which will provide insights on the resource efficiency of a process.

Such work provides a basis for analysis, but the possibility always exists that the energy or material inputs needed in order to make the product, may have a higher impact on the environment than inputs used in the non-circular alternative. These cannot be seen when focusing at the process level. Therefore, analysts must look at another level called the life cycle level. This level is analysed by conducting a life cycle assessment (LCA). Instead of just considering the process of producing the circular product, it considers all processes throughout the entire life cycle of the product. The assessment starts from natural resource extraction and ends with...
Environmental LCA

Life cycle assessment is a process framed by ISO standards, which define the four steps of an LCA. (Fig 3.4)

The first step, Goal and scope. The first step in an LCA is to define the goal and scope of the assessment. The goal includes the intended application, the reason for the study and its intended audience. The scope includes:

• The selection of the product for assessment. In this instance, a product can be either a physical product, or a service.

• A functional unit is a certain ‘measure’ of the amount and the quality of service delivered by the studied product.

Or in other words, the functional unit is a measure of product’s functions. The choice of a relevant functional unit allows consideration of different characteristics including the durability of a product. This is important when establishing the amount of product(s) needed to deliver a chosen amount of service. Note that delivering a service is the actual function of a product! Choosing a functional unit is not always straightforward and can have a large impact on study results. For example, when comparing two light sources (lamps), their light output as well as their lifetimes might differ. Thus, comparing one lamp to another using a functional unit of ‘1 lamp’, might not be a suitable way of comparing their performance. A functional unit expressed as an equal number of lumens-hours’ considers both the performance of the products, and their durability and it is much more suitable for comparing them. So it is very important to remember that the functional unit should reflect the real value and functionality of the product.

Second step. Inventory analysis. The second step of an LCA is an inventory analysis. This consists of inventorying all inputs that used along the product’s life cycle, and resulting outputs. These include inputs such as raw materials and energy, and outputs such as by-products and waste. This step is the most time-consuming and data intensive. Data can be collected based on measurements, information received from companies, literature, modelling, and more. As this data collection can be quite labor intensive, databases have been created to provide the life cycle inventory data of certain products. For example, if a product requires 1 kWh of electricity for its production, databases can provide the complete life cycle inventory for electricity from many possible sources. Such includes all steps from resource extraction via generation activities through to delivery of the electricity via power grids. Examples of databases are the Ecoinvent Database, the Agri-footprint Database and the European Reference Life Cycle Database. Data quality may vary rather significantly so it is important that an analyst always validate the data chosen by comparing it with literature, or similar studies.

Third step impact assessment: The third step of an LCA is the life cycle impact assessment. It translates the inventory into an estimate of the impact on the environment by multiplying the amounts of emissions and resources emitted and consumed by a characterization factor. However, the various flows that have been inventoried do not have the same effect on the environment. For example, carbon dioxide and methane emitted to air contribute to climate change while phosphate emitted to water contributes to eutrophication of water bodies. These environmental concerns are called environmental impact categories, and for each impact category, characterization factors are defined for each contributing flow.

The example of the impact category ‘climate change’ can be used to demonstrate differences within an impact category. A wide range of substances like carbon dioxide, methane and nitrous oxides contribute to climate change, but they do not all have the same potency in their contribution to the warming effect upon the climate. Their potency is usually compared to the one of carbon dioxide, which is defined as a reference substance. For example, the potency of methane to contribute to climate change is known to be some 25 times higher than carbon dioxide (CO2), so its characterization factor is 25 kg CO2 equivalent per kg methane. The amounts of greenhouse gases emitted by the product system are multiplied by their associated characterization factors to obtain the final impact of the product. (Fig 3.5, next page)

Such calculations are performed for all impact categories. In practice, environmental impact assessment is usually done using a software tool which assigns the different flows of the system to the impact categories that must be studied for the product.

Last step: Interpretation & reflection. The last step of an LCA is the interpretation of the results. During this step, analysis is performed to find areas where improvements may be possible, or to support recommendations for the most environmentally desirable product in the case of a comparison. This is also where an analyst can suggest design modifications to improve the environmental performance of a product. Here it is also necessary to critically interpret the results of the study by taking into account the limitations of LCA, and reflecting on the assumptions made when performing the analysis.
It is important to keep in mind that in each of these four steps, important, sometimes even subjective choices have to be made. All of these influence the final outcome in some way and need to be clearly communicated.

### How to deal with recycling and multi-functionality in LCA

LCA practitioners face several challenges when it comes to assessing circular systems. A high-profile example is the case of recycling, which is a difficult issue to deal with in LCA but is also a key process in many circular systems. Recycling requires re-processing of a material so it can fulfill another service to society. A material can be recycled to fulfill the same function as in its previous life, which is called closed-loop recycling. It can also be recycled to fulfill another function – often at a lower quality. In this case we talk about open-loop recycling. One common approach in LCA is to assume that the recycled product replaces a product produced from virgin raw materials. An example can be taken from when a phone is designed so that the parts and components can later be recycled to other products. In this case, the benefit from recycling can be considered by assuming that the system will avoid the production of these other products from raw materials. An example is given below, from a fictive case of the environmental impact assessment of a new phone. (Fig 3.6)

It can be seen that the impact of the phone’s production (extraction of raw materials, transport, and manufacturing) is 30 kg CO2 equivalent per phone, the impact of the use phase is 2 kg CO2 equivalent per functional unit and the recycling process is 3 kg CO2 equivalent per functional unit (in total, 35 kg CO2 equivalent per functional unit). Recycling the phone at its end of life enables the recovery of its reusable materials, replacing the use of raw materials like copper, iron, or zinc in future product production. These raw materials have an impact of 10 kg CO2 equivalent per functional unit. Hence, the recycling withdraws this impact from the phone production, use and recycling. The total net impact of the functional unit is therefore reduced to 25 kg CO2 equivalent per functional unit with recycling. It should also be noted that there is a subjective aspect in the choice of the avoided products – and this should be carefully identified and made clear to readers of the analysis.

Another important difficulty arises if a system (a collection of unit processes) of the life cycle has more than one function or, an output of two or more (co)products. For example, the unit process of recycling of a phone produces several products which can be used in different applications. It is important to decide how the flows and impacts of the process (recycling in the case of the phones) should be attributed to these co-products.

Different options exist to deal with this matter, although there is no ideal solution. The three main options are:

- Subdivision of the considered processes into smaller unit processes, of which none have more than one function or, one product. This is often not possible for basic unit processes.
- Partitioning (also termed ‘allocation’) of the process flows and impact between the different functions or products based on a certain partitioning coefficient, for example mass or economic value. Substitution (also called ‘avoided burden approach’) may be performed. The approach is the same as when dealing with the recycling issue described above. It is often applied in LCA, as it is a way to avoid the partitioning coefficient factor option, which again is often subjective.

### Limitations and assumptions of LCA, software tools, and life cycle thinking (streamlined LCA)

#### Limitations of LCA

Even though LCA is the most recognized tool to assess the environmental sustainability of products and services, its limitations should be recognized while interpreting the results of the assessment.

One important aspect is the subjectivity of the choices that need to be made at several stages of an LCA, including the definition of the functional unit and the approach selected to deal with multifunctional issues. The choice of whether to apply the system expansion approach or partitioning is an example of such. And in the case of partitioning, choices must be made regarding which partitioning coefficient to use. Moreover, practitioners often lack data, and data which are not necessarily representative are sometimes chosen.

The conclusions of an LCA also depend on the impact categories that are analysed. Take the example of a comparison of the environmental sustainability of product A and product B. The carbon footprint of product A might be higher than product B, while its eutrophication potential might be lower. If only one impact category is analysed, the conclusions and thus the measures resulting from the analyses (e.g., change of consumer behaviour) might be different as well. Practitioners must keep such issues in mind and understand that there is no single complete impact assessment method or combination of indicators.

All of these issues need to be dealt with and kept in mind when conducting an LCA. It is important for all to recognize that while the results of such studies do have real value and support decision-making, the respective outcomes must be regarded as estimates and not as certain facts. Thus, despite the uncertainties, these assessments provide valuable information for decision-making and product stewardship. They allow environmental issues to be evaluated strategically, throughout the entire product life cycle. The challenge is to take advantage of these valuable features of life cycle assessments while bearing in mind the difficulties and uncertainties.

#### Software for LCA

Since conducting an LCA is a time-consuming task, software programs have been developed to help in this matter. Simaprio and OpenLCA, which is freeware, are two examples. In these programs, databases and different impact assessment methods can be developed. Through the software interface, life cycles, optionally linked to the database, can be constructed and their impacts assessed.

#### Streamlined life cycle assessment

The use of life cycle studies falls along a spectrum that runs from a level where practitioners pursue a complete spatial and temporal assessment of all the inputs and outputs over to the entire life cycle (which may never be accomplished in practice due to effort and expense) to efforts that constitute...
Life cycle thinking

Life cycle assessment

Figure 3.7 A spectrum of life cycle analysis.

only an informal consideration of the environmental stresses that occur over a product or process life cycle. This spectrum is illustrated in the figure above. (Fig 3.7)

The further a study positions itself to the right side of the spectrum, the more expensive and time-consuming the study will be. An analysis that includes an inventory of all inputs and outputs and all life-cycle stages (including an assessment of which ones are significant enough to be included in the inventory), an impact assessment, and an improvement analysis can be considered a life cycle assessment. A study that falls to the left in the spectrum of complexity will be said to ‘involve the use of life cycle concepts’.

Studies in between the two extremes are referred to as ‘streamlined life cycle assessments’. Streamlined life cycle assessments are conducted in order to provide insights into the most important life cycle stages, or type of inputs and outputs, in a product life cycle. These stages, inputs, or outputs may then be targeted for more detailed study. Also, they can be used to identify where the most significant environmental issues occur. The intensive data collection process for a complete life cycle assessment study is one of the main reasons why streamlined life cycle assessments or studies with only life cycle concepts are applied.

3.6 ASSESSING RESOURCE EFFICIENCY

- Environmental life cycle assessment can be used to assess whether a new product or process can contribute to a more sustainable society;
- Circular systems do not by default lead to environmental improvements;
- LCA practitioners face several challenges when it comes to assessing circular systems, with recycling as a prime example.

Many parts of the world face a huge challenge related to the supply and efficient use of resources. The global population is growing and market are becoming more competitive. This makes it difficult for industry to predict market prices and the availability of valuable resources. This is the case for ‘critical raw materials’ – materials that are important for the economy and have a high risk of supply disruption.

This challenge has become a priority for several countries and regions around the world and many programs have been launched to increase the self-sufficiency of nations. Examples are the Resource Efficiency Program of the United Nations Environment Programme (UNEP), Finland’s National Resources Strategy and the Critical Materials Strategy in the United States. In Europe, the European Commission launched the resource-efficient Europe Flagship Initiative in 2011 and a Roadmap to an Efficient Europe. It presents several milestones to be achieved by 2020 on the use of resources such as minerals, metals, water, marine resources, land and soils. The EU strategy places circular systems at the front line of solutions to increase European self-sufficiency.

To encourage the development of such systems, the EU is funding research and innovation programs such as the Horizon 2020 program. Horizon 2020’s call for projects explicitly states that the new technologies or products developed should contribute to increasing the resource efficiency of Europe. For example, it states that project developers are expected to increase “the resource and energy efficiency for the process industries by at least 20%”, or to contribute to “gains in productivity, in material and energy efficiency”.

While increasing the resource efficiency of the economy as a whole is one of the core aims of circular systems, ensuring such a result requires measurements. Apart from the fact that measure helps the management of such efforts, it is also a vital input to avoid “green-washing”, a practice that can create consumers doubt and distrust. It also helps prevent unexpected side-effects that could negatively affect economic sectors regarding access to specific resources. To measure progress at the European level, a system of indicators called the Resource Efficiency Scoreboard was developed. It begins with focus on “Resource Productivity”, which is the ratio between the Gross Domestic Product and the Domestic Material Consumption.

The Domestic Material Consumption can be estimated for each country based on a Material Flow Analysis, which consists of a thorough analysis of the fate of materials within a defined geographic area. The results of a Material Flow Analysis can be represented in a Sankey diagram. In Figure 3.8, below is the example of the Domestic Material Consumption of Denmark, where the flows of materials going in and out of the country be estimated. The materials that enter the Danish economy are those that are imported and those that are extracted within Denmark. They are represented here on the left-hand side of the consumption box, with the width of the arrows proportional to the flow quantity.

The flows that leave the country are those which are exported, as represented by the flow to the right of the domestic consumption box. (Fig 3.8)

Hence, the Domestic Material Consumption of Denmark is the amount of materials imported and extracted in Denmark, minus the amount of materials exported.

However, when a research department or a company wants to develop an innovative circular product, resource efficiency indicators other than those defined at macro-level for Europe are necessary. Unfortunately, there can be confusion about the term “resource efficiency”, and unfortunately, companies can choose an interpretation and evaluation method which favours their new product – a situation that can lead to confusion.

It’s therefore important to understand the different concepts behind the term as well as the ability to choose a resource efficiency evaluation method in the most scientific and objective way possible.

What are resources and what is resource efficiency?

The definition of resource efficiency starts first with the definition of resources, specifically environmental resources in this context. There are two ways of looking at environmental resources: in the broad sense and in the strict sense. The broad sense considers resources as “inputs” into a system but also the environment itself as a sink; this perspective accounts for the environment’s role in absorbing emissions. Resources defined in the strict sense only consider “inputs” specifically entering an anthropogenic system, for example materials consumed by a city or water consumed at an industrial plant. The broad sense is primarily used in a policy context and the strict sense is mainly used in industry and engineering, as resource consumption is the starting point for all economic production and consumption activities. (Fig 3.9)

As a developer of a new circular product, following the strict definition of resources makes more sense. Of course, even if it does not fall into the term of resource efficiency evaluation,
Methods available to quantify resources

The numerator of the RE equation; in this case, the benefits obtained from resources, is often easier to quantify than the denominator. Broadly speaking, this is because benefits are generally delivered to end users and can often be expressed in tangible units: kg, MJ, money, etc. However, this is not always the case, especially when benefits have a social function. The denominator requires additional calculations and discussion. While there is no universal consensus on exactly how this should be done, in recent times, it has been proposed that there should be a classification of methods to evaluate resource use in Life Cycle Analysis (LCA) according to two principles:

- A physical accounting of resources: the quantity of resources consumed by the studied system is systematically accounted for based on a physical property (mass or volume, energy, exergy\(^1\) or area); or
- An assessment of the impact from resource use: this is done by considering one of the following elements: the amount of resources available in the Earth’s crust, predefined targets, future consequences of resource extraction, or willingness-to-pay (WTP).

Resources can be classified as renewable or non-renewable and as biotic or abiotic as shown in Table 3.1. Renewable resources are able to regenerate within a human lifetime but can be exhausted if they are consumed beyond their regeneration capacity. They can be biotic (i.e., ‘derived from presently living organisms’, e.g., wood) or abiotic (i.e., ‘a product of past biological or physical/chemical processes’; e.g., air, wind, sunlight and water). On the contrary, non-renewable resources cannot be renewed in the natural environment, or can be renewed but not within a human lifetime (e.g., metals or natural gas). The methods used to quantify resources do not all consider these resource sub-categories in the same way.

Resource accounting method

Resource accounting methods can be used in both gate-to-gate and life cycle-based analyses. Each method accounts for resources based on a specific physical property. Four main properties are considered by existing methods: mass/volume, energy, energy and area. Because not all resources have the same properties, resource accounting methods do not necessarily account for the same resources. For example, energy-based methods do not account for water and land, whereas exergy-based methods are considered to account for these resources. Similarly, area-based methods neither account for non-renewable material resources nor for abiotic renewable energy resources. However, some area-based methods, such as the Ecological footprint, account for bio-productive land necessary to absorb CO\(_2\) emissions, as well as for the amount of consumed nuclear energy carrier. Moreover, some methods are only able to account for a fraction of a resource “category”. For example, mass accounting methods are not able to account for all energy carriers, typically only wind energy and electricity. Current energy-based methods account for the largest number of resources.

Impact assessment methods

Impact assessment methods are applied in life cycle-based analyses (Table 3.1, next page). Similar to gate-to-gate analysis, they do not all cover the same resources (for example, some cover nuclear energy whereas others do not). Most developed methods are derived from calculations using one of the parameters detailed below – there are thus several approaches classified.

- Quantity/quality of reserves: these methods take into account the decreasing quantity and/or quality of resources available in the natural environment. Thus, they acknowledge that the consumption of resources has an impact on resource availability. Methods based on the quantity/quality of reserves are only able to account for non-renewable resources.
- distance-to-target: these methods compare the quantity of resources consumed to previously defined targets. The most used distance-to-target LCA method is called the

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\(^1\) Exergy is a measure of the energy available to do work that can be obtained from a system through its exploitation with the surrounding environment. It is based on the second law of thermodynamics, which states that all energy in an isolated system can only increase over time or remain the same in ideal processes. While energy is never destroyed, energy is always destroyed in irreversible processes. The impact of energy is categorized into two: heat (it has no effect on the quantity but also on the quality of the energy embodied in process flows).
Some tips to calculate resource efficiency
Several choices need to be made when calculating the resource efficiency ratio. These choices are subjective but there is commonly agreed advice to help analysts make the most informed decisions in this regard.

First, the numerator of the resource efficiency ratio should be carefully defined. It represents the benefits obtained from resources. Thus it essentially defines the functionality of a product. It can be done by taking into account the quality and the lifetime of the products. This is the same principle used in Life Cycle Analysis (LCA) studies.

Secondly, an LCA should always be performed to calculate the denominator of the resource efficiency ratio. For developers of a new circular product, the aim is to create a product that has a solid business plan and contributes to increasing the resource efficiency of the economy as a whole. Life cycle thinking is the only approach that empowers this goal and should therefore be pursued. Gate-to-gate analysis is a limited approach but can be very useful when calculating intermediary indicators and integrating resource efficiency evaluation during the project's development.

Third, attention should be given to the resource coverage of the method chosen to quantify the resources consumed. As discussed above, each method covers different types of resources. However, lowering the consumption of one specific natural resource can induce higher consumption of another. As an example, a recent study examined the sustainability of two ways of converting algae grown on aquaculture wastewater into a saleable product (also called valorization): valorization as shrimp feed and valorization as biogas via anaerobic digestion. The study compared the results of the resource efficiency ratio when the denominator was calculated using three different methods: the CEENE method of Ghent University in Belgium, the ADP method of Leiden University, and the Eco-Indicator 99 method, developed by the firm Pre Consultants. (Fig 3.12)

These methods do not cover the same resources, and the conclusion on which scenario is the most resource efficient is a matter of the method used. Therefore, you should consider one method or a set of methods that cover all resource categories: energy, primary and secondary raw materials, land and water.

Finally, the integration of resource efficiency considerations more systematically during the course of product development can help project developers achieve higher resource efficiency goals. However, a drawback in real-life is that most project developers evaluate the resource efficiency or even the overall sustainability of their products at the end of product development; at this stage, the product has already been conceived and there is little room for improvement. Therefore, it may be more effective to implement an iterative resource evaluation process during product development, starting with preliminary indexes and using more elaborate indicators at the end of the project. Simple indicators, such as gate-to-gate analyses, can be conducted early as they require less time and data. An LCA approach, which doesn't necessarily require quantification, should be followed throughout the project, with a full life cycle analysis conducted at the end.

Even though a universally applicable assessment of resource efficiency and consumption impact does not exist, these key methods can be used in product development to calculate the resource efficiency of new products in the most scientific and objective way. Such work is vital to effective pursuit of the circular economy.
3.1 MATERIAL SCIENCE INNOVATIONS Dmytro Orlov – Materials Engineering, Faculty of Engineering, LTH, Lund University, Sweden.
3.2 ECODESIGN STRATEGIES Katherine Whalen – IIIEE, Lund University, Sweden.
3.3 NANOTECH DEVELOPMENTS Maria Messing – Solid State Physics and Nanolund, Lund University, Sweden.
3.4 ASSESSING THE ENVIRONMENTAL SUSTAINABILITY OF CIRCULAR SYSTEMS: TOOLS AND METHODS Sophie Sfez, Green Chemistry and Technology, Ghent University, Belgium.
3.5 ASSESSING CIRCULAR SYSTEMS Sophie Sfez, Green Chemistry and Technology, Ghent University, Belgium.
This chapter explores the role of governments and networks and how policies and sharing best practices can enable the circular economy.

4.1 FROM WASTE TO MATERIALS

- Over time, there has been a transition in governance from command & control approaches, through efforts to eliminate uncontrolled landfilling, and now towards a multi-stakeholder platform facilitation approach.
- Facilitation approaches include a range of different policy domains and a suite of new societal actors.
- A number of societal actors have also had to adopt new roles as governance of 'waste' has evolved towards governance of 'materials'.

To better understand evolving policy frameworks for the circular economy, it is useful to examine the recent history of waste management policy in Western Europe. Policy follows a wave-like pattern, with a steep increase in effort and attention in the initial years. Over time, this effort levels off as policies settle into place and are enforced and monitored. As new policies develop, the pattern repeats itself. (Fig 4.1)

Before the 1970s, waste was managed locally, and usually this meant it was collected and deposited in local dump sites. This posed a risk for the environment and public health. Waste management policy in the form of national laws regulating collection and disposal emerged in the early 1970s as waste began to be considered a problem. The authorities responded by developing a policy that was based on containment and risk remediation to secure the health of citizens. This ‘command and control’ policy limited the operation of landfills and their emissions. Sites that clearly had negative impacts on the environment were forced to close and remediate.

This second wave of policy was also driven by the sheer volumes of waste. The authorities became aware of the scale of the volumes of waste materials produced every year, and also that many of these materials were recyclable, such as paper, glass or construction and demolition waste. The second wave aimed to extract these materials from the waste stream and recycle them. This resulted in the introduction of separate waste collection systems and recycling targets for specific waste streams, in an attempt to reduce the overall volume of waste produced. The policy was characterized by collection and recycling targets in the form of amounts or percentages. For example, Flanders, Belgium has set a target of maximum 150kg residual waste per inhabitant, and since 2008 the EU aims for 70% recycling of construction and demolition waste.

These targets led to unique collection strategies, in which the high-volume materials were collected separately, close to the point where they were produced. Collection could generally be in the form of ‘door to door’ collection or via centralized collection systems. Centralized systems were often applied for materials such as glass containers or paper. The second wave led to the development of waste treatment facilities – as distinct from the earlier ‘dumps’. These were also controlled by permit-based policy. In addition, legislation increasingly controlled the shipment of waste and regulated the treatment of hazardous materials. In 2006, the European Waste Framework directive introduced a “waste hierarchy” and set recycling targets for 2020 for implementation in each member state. The second wave had resulted in the creation of a waste management sector focused on collecting and recycling waste. Initially, this activity was largely subsidized but as it grew it became a private market activity, and with the introduction of the waste hierarchy the focus of recycling activities shifted from processing large volumes of waste towards the creation of value – the third wave of waste policy.

As the third wave developed, it subsequently led to a shift in focus from large volume, low value materials to low volume, high value materials included in broader societal waste streams, such as metals like copper or gold. Typical of these streams are flows for used products such as electronic waste or used cars. These types of material flows need thorough processing in order to extract the metals. Evolving to cater for such flows, waste treatment activities became more complex and capital intensive. At the same time, this resulted in a tension between waste regulation and market drivers for material recovery and recycling. Waste was no longer necessarily processed close to the source, but increasingly at locations of higher market price or lower cost.

The fourth wave of waste management is underway, and here is referred to as the wave of circular economy. It is no longer only driven by the value or the recycling in itself, but also by constraints on the stable supply of materials that are important to our economies and technologies.

This enfolds the concept of critical materials, the idea that our economy needs of certain materials that will be harder to purchase or more expensive to get as the global economy grows and expands. This wave is driven new policy, which looks not only at how we can use more recycled materials, but also examines the use phase of materials and products. It sets demands on societal actors to increase the lifetime of products and keep materials at a high value throughout their life cycle.

This fourth wave, demands that the role of the policy maker has moved from a controlling function in waste management, to an enabling factor in materials management and product policy.

Policy actions need to focus on waste prevention and on the responsibility of producers, and this requires an approach that stimulates evolution via communication campaigns for consumers and the promotion of responsibility amongst manufacturers and industry players.

In addition to the changing role of the legislator, it is interesting to also review the changing role of the waste sector. In the first wave, the waste sector was considered part of the problem; their waste disposal activities required control and limitation by the government. In the second wave, the responsibility for treating wastes, and therefore limiting the burden on public health and environment, shifted from the authorities to the waste management sector. As owners of the waste problem, they increasingly explored and developed the possibility of recovering the residual value of the material flows that they now controlled. This value capture began to drive waste processing, so much that primary producers and larger service companies, also became more interested in waste management activities.
This led to the third wave, where small local waste treatment companies were taken over by larger groups and major industrial players entered the market.

In the emerging circular economy, the distinction between raw materials, products and waste continues to become increasingly unclear. Material management is part of the product value chain, and producers remain responsible for the product and material that they place on the market. In leasing models for example, the producers even keep the ownership of the product and provide only a service to the customer. Such developments will drive fundamental changes in the waste sector, and existing players will need to continually redefine their role in this complex system of material management.

4.2 Past Policy Solutions

Policy solutions: scarcity and the case of WWII

Material shortages have always been a problem for societies throughout human history. The technologies and the materials may change, but the problem of material availability stays the same. Analysis of historic periods of material shortages can help us understand the challenges and develop new policies in the future. For example, Britain experienced extreme material scarcity during the Second World War (WWII), and they developed a variety of policies to help deal with the shortages. (Fig 4.2)

Of course, many of the critical materials and technologies we use today did not exist during the Second World War, and a wartime material shortage situation cannot provide an exact blueprint for circular materials policy today. Nevertheless, it is a successful example of how society dealt with material access challenges, and we may be able to learn from it.

As the international situation worsened in the mid 1930’s, and war looked likely, the British government developed materials strategies in preparation, and a new Ministry of Supply began operating in August 1939. From the start, this department developed schemes to deal with the expected changes in global materials supply. Their approach included the careful use of scarce materials and the development of substitutes using alternative materials. Production was based on a system of priorities: the higher the priority, the more material allocated. Legal powers were also introduced to control prices, product volume and product use, and government controls were imposed on most materials.

One example is how furniture production was handled. During this time, timber supplies were halved, many pieces of furniture were lost in the bombing of towns and cities, and second-hand furniture prices were rapidly increasing. This fuelled a growing black market, but the government was keen to show they were in control of all aspects of the ‘home front’. So they acted, and in 1942 they launched the Utility Furniture Scheme. (Figure 4.3) Under this scheme a committee was formed that had complete decision-making powers over the design of furniture. To reduce material use they introduced a standard furniture range; the design of this furniture was very tightly controlled, and manufacturing firms had no freedom to adapt the limited range of designated designs. Consumers only had these designs as options to purchase! (Figure 4.4)

From the start, this department developed schemes to deal with the availability of materials in times of crisis. While the context is different to today, this shows that if true emergency situations arise, society act and solve overwhelming material supply related challenges.

Material scarcity experienced by Britain during the Second World War provide a range of learning opportunities regarding how society can act to ensure the availability of materials in times of crisis.

Severe material access challenges were met with combinations of government-led action – these included actions related to circular economy approaches including careful use of scarce materials and the development of substitutes using alternative materials.

While the context is different to today, this shows that if true emergency situations arise, society act and solve overwhelming material supply related challenges.

Policy instruments have a very important role to play in the shaping of future socio-economic regimes such as the Circular Economy.

There are a range of instruments available and in use – and more are proposed to build a mix that can lead to a transition from the linear economy.

At times policies can result in conflicts within a circular system and both care in design and monitoring of performance is required to deliver effective policy. Moving from a linear economy to a circular economy requires fundamental changes to current production and consumption systems. We have to change how materials are used and how our products are designed, and we need new business models. However, the circular economy also needs enabling conditions.

Figure 4.2 Severe supply chain disruption to Britain during WWII.

Figure 4.3. Product design approaches to address materials scarcity in 1943 compared to the EU’s 2017 Circular Economy Package.

Figure 4.4. Examples of British ‘utility furniture’ from 1943.
If the goal was to be growing potatoes, then sunshine, water, rich soil, and a lot of care would be enabling conditions for growth. Enabling conditions for the circular economy include the need for an appropriate policy framework. This needs to remove existing barriers in circular operations and enable the increase of material circularity in the economy.

There are a number of tools and approaches that governments can apply to scale up the circular economy. These include a wide range of policy instruments that can be used to achieve certain goals. The most commonly used distinguish between three types of policy instruments: administrative, economic and informative.

Administrative or regulatory instruments can be, for example, bans, standards, licenses and voluntary agreements between government and industry. Economic instruments can be taxes, fees, subsidies and charges. Examples of informative instruments include labelling, reporting requirements, certification schemes, awareness raising campaigns, etc.

All three types of policy instruments are important and can stimulate the uptake of a desired outcome in different ways. The more all three types of policy instruments are used in a complementary way, the higher the effect can be towards catalysing change.

The way policy instruments are used sparks change by enabling, engaging, encouraging and ultimately, enforcing. Policies can enable the circular economy by, for example, removing barriers, supporting the development of skills and capacity, and providing information; they can engage through media campaigns and voluntary industry agreements either within the sector or across the supply chain. Policies can encourage through tax cuts, subsidies, and reward schemes, and they can enforce through, for example, penalties and fines. (Fig 4.6)

Past and present EU initiatives towards the Circular Economy

In the period since the early 2000s the strategic resource policy direction of the European Union has increasingly pursued measures towards the sustainable use of natural resources, increased resource efficiency in the economy, and the scaling up the recycling and prevention of waste. At the same time, the Union has also sought economic growth. (Fig 4.6)

The EU promotes the circular economy with a package of proposals, including a comprehensive Action Plan (COM (2015) 614 final) and regulation amendments. The aim of the Circular Economy Package is to improve the competitiveness of EU businesses by shedding industries against potential resource scarcities and price volatility, and to help create new business opportunities and innovative ways of production and consumption. The circular economy is expected to create local jobs in the EU at all skill levels in the work force, as well as present opportunities for social integration.

It is particularly stressed in the Action Plan that economic actors, such as businesses and consumers, are to be the key drivers in the transition process. However, local, regional and national authorities are encouraged to act as catalysts in this transition. The EU is to play a fundamental but supportive role, ensuring that the right regulatory framework is in place for the development of a circular economy in the market. The EU Circular Economy Action Plan outlines potential policy interventions that would enable this development. (Fig 4.7)

The number and complexity of interactions among actors in a circular economy create a complicated policy landscape. This inevitably extends across the different parts of production and consumption systems and affects, directly or indirectly, several other parts in the value chain. Such interacting networks might also extend in different geographic locations within or between Member States.

In Table 4.2, current legislation relevant to the circular economy at the EU level, both mandatory and voluntary, is categorized by life cycle stage. There is a high concentration of mandatory EU legislation towards the end-of-life cycle.
phases. These aim to limit resource loss and increase the circulation of materials, mainly through recycling. In contrast, policies targeting consumption are rather limited and mostly indirectly affect resource efficiency – a clear gap! While there is a plethora of directives and regulations governing production processes at the EU level, the majority do not explicitly target material resource efficiency, and as a result a policy gap is observed at this life cycle stage as well. This stated, the fact that some policies do exist at that level is considered by many as positive. This, as material resource efficiency considerations can still be added to an existing policy, an easier pathway than seeking to create an entirely new policy framework from scratch. As an example, there is clearly scope for improving criteria for public procurement and eco-labeling so that material resource efficiency becomes more prominent. (Table 4.2)

At the Member State level, individual countries have the freedom to devise their own resource efficiency agenda as long as they do not counteract EU regulations. Recently, some Member States decided to take resource efficiency policies a step further, leapfrogging far beyond the existing EU policies. Table 4.3 summarizes a number of ambitious policies at Member State level, that aim to increase resource efficiency.

When policymaking intervenes in systems, there is always potential for both conflict or synergy. When applying a single policy instrument there is always a risk prompting unintended outcomes that change other drivers, particularly when the policy field spans several parts of the economy. For this reason, a more complex approach is needed in a circular economy context, and policymakers are working with a mix of policies and consider a wide range of related issues that consider:

1. the full range of available policy instruments targeting resource efficiency
2. the full cost of policies, including implementation costs, transaction costs and compliance costs
3. how to avoid negative interactions between single policies (i.e. instruments already in place vs. new ones), but emphasize mutual benefits with existing policies
4. how to carefully combine the instruments to mitigate side-effects

To place these issues in context, a hypothetical example of a synergistic policy mix relevant to the circular economy can be drawn. In this example, mandatory eco-design rules for reparability, together with material and parts certifications, may be put in place to facilitate increased reuse of a product. However, by themselves, these changes may not stimulate changes in the market – there may be limited demand for the product group, or there might not be collection systems that ensure enough of the products are collected to support repair and reuse, or it may be simpler for waste management systems to scrap the products for material recycling. Here additional policy interventions might act synergistically. One addition may be to better public purchasing criteria that favour, or even require, the purchase of repairable and reusable products – thus creating a base market. A second may be the implementation of novel extended producer responsibility rules that support the refurbishment of products over and above recycling. This intervention helping to ensure that such products could retain additional value from the item and maintain the resources embedded in the product, either intact or with minor modifications.

The Circular Economy Package
In past decades, policymaking in the European Union most often took an end-of-pipe approach, aiming to fix a problem rather than to prevent its cause. Thus, when examining the product lifecycle, most mandatory policies we find today target the end-of-life and waste phase. At other lifecycle stages the majority of policies are of a voluntary nature. Although significant improvements have occurred in recent years, the old approach is clearly reflected in existing resource efficiency policies.

After a series of discussions around progressive resource efficiency strategies the European Commission adopted an ambitious Circular Economy Package in 2015. This package includes legislative proposals on waste, and a detailed action plan. Apart from introducing more stringent targets for reuse and recycling and streamlining waste rules, the Action Plan includes a complete set of policy proposals targeting all stages of the product life-cycle. (Fig. 4.8)

Particular focus is given to instruments that could influence resource efficiency from the beginning of the life cycle, such as eco-design, and extended producer responsibility policies, which aim to change the way products are designed. Other areas of intervention might include utilization and certification for increased durability, reparability and recyclability of products. Public procurement is another policy approach that can significantly pull the uptake of circular solutions.

Table 4.2: Existing policies in the EU related to products, materials and resources.

<table>
<thead>
<tr>
<th>Life cycle stage</th>
<th>Production/Product design</th>
<th>Use/Consumption</th>
<th>Waste management</th>
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<td></td>
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<td>Packaging and waste packaging Directive 94/62/EC</td>
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<td>Shipments of waste Regulation (EU) No 663/2014</td>
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<td>REACH Regulation (EC) No 1907/2006*</td>
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Table 4.3: Existing policies in EU Member States promoting the circular economy.

- France
  - Act on consumption and preventing planned product obsolescence: Mandatory
  - The Act (Law no. 2014-344) addresses product durability and aims to prevent planned obsolescence. The law includes articles related to theWeapon of consumer goods, including the introduction of extended product guarantee from six months to two years; and the obligation of retailers to inform customers about the time horizon that spare parts will remain available for a product in question (I.EA. 2016).

- Spain
  - Reuse targets for Waste Electrical and Electronic Equipment (WEEE): Mandatory
  - In its new Waste Management Plan 2016-22, Spain sets a target of 50% municipal waste to be prepared for reuse or recycled, followed by a specific target of 2% for preparation for reuse in certain waste streams including textiles, WEEE, furniture and ‘other suitable waste streams’ (Ruiz Said-Aja 2016).

- Sweden
  - Value Added Tax (VAT) reduction in repair services: Mandatory
  - The Swedish government suggested a VAT reduction in repair services for a selected group of products (bicycles and shoes). In addition, the government proposed a tax deduction for repair services performed in relation to home renovations (I.A. 2016).

- Norway
  - Public procurement of refurbished ICT equipment by Swedish municipalities: Voluntary
  - Two Swedish municipalities (Gällivare and Laholm) apply specific criteria in public procurement, tendering the provision of refurbished ICT equipment for use in municipal services (Arfall Sverige 2015).

Figure 4.8 Indicative weighting of EU policy pre-2010.
A broader perspective for future Circular Economy policy

The systemic nature of the transition towards a circular economy implies that policy measures targeting the waste phase, while necessary, are insufficient to achieve circular products. In this context, two elements are essential: (1) the focus of the policy should encompass more than just waste management; and (2) policy actions throughout the product’s life-cycle need to be aligned to avoid negative side-effects and lock-in situations.

Initially, waste-related policies were introduced to tackle environmental and health problems related to landfill. Over time, the policy focus shifted towards stimulating recycling as an environmentally and economically sound way of managing waste. Product policies initially focused on the energy efficiency of products and the labelling of products with lower environmental impacts. With the policy focus now being on the transition towards a circular economy in which the value of products is maintained for as long as possible, a new phase in policy-making has been initiated. However, the change that is needed now is a widening, rather than a shift, of the policy focus. Stimulating markets for recycling is an important part of the transition, but the inner circles of circularity (i.e. reuse, repair and remanufacture) also need significant stimulation. At the EU level, durability, reparability, upgradeability, design for disassembly and ease of reuse and recycling will play a bigger role when setting eco-design requirements according to the Eco-design Directive.

In general, a wide range of possible policy instruments to improve product circularity can be applied throughout a product’s life-cycle (Figure 4.8). It will be essential, however, to ensure the alignment of policy measures throughout the life-cycle, not only to avoid conflicting incentives for businesses and consumers, but also to capitalise on synergies resulting from concerted action aimed at different product circularity strategies. For example, the collection rate of end-of-life products from consumers could be increased if collection initiatives not only make use of recycling as an argument for consumers to hand in their old products, but also include the opportunity to reuse or repair. Another issue that should be tackled is the aspect of liability when the repair of a product is undertaken through an informal interdependent economy approach (such as repair cafés).

Streamlining policy measures is, however, a significant challenge. This is not only because different policy actors are responsible for different stages in a product’s life-cycle, but also because it is difficult to predict all the possible impacts of a policy before it is implemented.

To place these issues in context, a hypothetical example of negative side-effects related to conflicting incentives can be presented. In this case, a policy measure is to provide economic incentives to improve the recycling of a composite waste material (e.g. electronics). These have many different parts and materials. Logically, recyclers will respond with investment in, and development of, sorting and recycling technologies and infrastructure that will enable increased recycling. However, as it becomes easier to recycle, product designers and manufacturers may be provided with lesser motivation to innovatively design products that are easier to recycle (a process that may be costlier). The may follow a logic, that the advancing sorting technologies will take care of them anyway. Such situations can also happen in reverse. For example, a situation can also arise that when incentives are given for better product design, then there will be less incentive, motivation and need for recyclers to improve their sorting and recycling processes. This then resulting in lower quality recycled materials despite the better product design.

Such examples, versions of each that have been observed in practice, highlight the need to use a systemic monitoring framework allowing the identification of systemic impacts of policy action, and appropriate adaptations. (Fig.4.9)

4.4 EXTENDED PRODUCER RESPONSIBILITY

Extended producer responsibility (EPR) is a policy principle that promotes efficient waste management and environmentally sound management of waste and products. EPR conceptually can be traced back to the late 1980s when many industrialized countries were struggling with their waste management, landfill capacities were filling up and it was difficult to open new ones. Waste incineration was becoming more common, but it also met a lot of opposition. Household recycling had started, but the results of most initiatives were not very impressive. One reason for the limited success was that municipalities often lacked the money needed to build convenient and effective infrastructure for recycling. Municipalities are also normally reluctant to increase fees and taxes – and when they do so, there are competing issues for how to use the money. Society also began to pay attention to the fact that products were typically designed and manufactured without any plan for how they should be treated as waste. All this led to the development of a new strategy for how to approach the waste management and recycling of products. In 1990 the principle of Extended Producer Responsibility was formulated and gradually introduced in various countries.

The essence of the EPR principle is that producers are incentivized to consider the end of life of their products when designing them. This is achieved by making the producers responsible for the end-of-life management of their products. In addition to financial responsibility, producers are also often assigned responsibility for organising the collection of the discarded products. It makes it possible for them to control the costs for end-of-life product management. In practice, producers typically form collectives called Producer Responsibility Organizations and these organizations collect fees from producers and then hire waste management companies to collect and recycle the products. Producers, of course, seek to recover these costs when selling the products so in the end, it is the users of the product that pay. This means that the cost of taking care of the product at its end-of-life will be reflected in the price and will also influence the purchasing decisions.

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<tr>
<th>POLICIES AND NETWORKS</th>
<th>CIRCULAR ECONOMY</th>
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<tr>
<td>Reuse, Repair, Redistribute, Refurbish, Remanufacture</td>
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<td>PRODUCTION AND DISTRIBUTION</td>
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<td>• Financial support for cleaner production initiatives</td>
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<td>• Regulations on liability for waste prevention requirements</td>
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<td>• Extension of warranties, leading to more durable products</td>
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<td>EXTRACTION OF RESOURCES</td>
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<td>MATERIALS</td>
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<td>• Specific reuse targets and guaranteed access to discarded products for actors in the reuse sector</td>
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Figure 4.9 Overview of potential policy instruments affecting product circularity throughout the product life-cycle.
countries however, such as Japan, prominent producers run at least one recycling plant themselves. WEEE legislation has led to a development of collection systems for discarded electronics in most OECD countries, but the existing systems are not always very convenient for the citizens. In many instances, this has resulted in low collection rates, especially for small appliances. In Europe, reused legislation now calls for easy-to-access collection systems for very small electronics, like mobile phones and light bulbs. The legislation mandates that large retailers have to accept very small electronics without consumers buying a new product. This is one way of reducing the likelihood that these products are thrown into the mixed residual waste and thus end up in landfills and waste incinerators. Another challenge for the collection systems has been that many discarded products actually still work and there is a potential second-hand market. While continued use is preferable in most cases (as it extends the lifetime of a product), there is also a very real risk that these products end up in countries that don’t have functioning recycling systems and that ultimately, they are discarded without any environmental controls. Some discarded products containing valuable metals are also exported for recycling in other countries. They are often disassembled as products for “reuse” in order to avoid more stringent and expensive recycling requirements at home. These products then often end up in recycling markets where primitive recovery methods are used, recovering only a limited portion of the useful metals and creating devastating environmental and health hazards. This has seriously affected impoverished people around the world, mostly in Africa and Asia.

In most OECD countries there are state-of-the-art recycling facilities that are able to recover almost all metals, including minute amounts of so-called critical elements such as rare earth metals. Such facilities also emit extremely little, if any, hazardous elements to the environment. The fate of phones. Mobile phones are definitely part of the challenges when it comes to collecting discarded products. This is a market that has grown extremely quickly, and many mobile phones are still very much fit for use after the first owner has upgraded to a newer model. The shift of owners may be repeated several times as the phone gets older. With repair and dedicated design adjustments it is technically feasible that the lifetime of a mobile phone could be extended even more. But due to so-called ‘style obsolescence’, the cessation of software updates, and so forth, such older phones most often end up in landfills, and do not have good recycling systems or technologies. Another limiting factor is the cost of repair and varying quality of repair works, due partly to the limited availability of authorized repair parts.

Moving forward with EPR

The present EPR systems still face many challenges, but the development of collection and recycling systems has advanced a lot during the last decades. Many countries now collect and recycle the majority of discarded electronics, and we are witnessing a rapid development in the technology systems that treat or process the materials within them. But, more progress is required. In particular, collection systems need to improve, especially for smaller electronic equipment, so even more products can be recycled. We also need better treatment systems and technologies for the contained substances where primitive recovery methods are used, recovering only a limited portion of the useful metals and creating devastating environmental and health hazards. This has seriously affected impoverished people around the world, mostly in Africa and Asia.

One way to reduce material use is to encourage people to use products longer. The product lifetime is dependent both on the product design and the potential for repair of a damaged or otherwise non-functional product. Repairability is in turn dependent upon the availability of spare parts and access to reasonably priced repair services. Unfortunately today, it often makes more economic sense to the consumer to buy a new product than to repair the old one. So in order to promote longer product lifetimes, European governments have adopted different policies to provide incentives for manufacturers to increase the product lifetime. For instance, some EU countries have reduced the Value Added Tax for repair services in order to stimulate the repair sector and make repair a more attractive option for consumers. Several European countries have also recently changed the legal warranty time for many products. In some countries consumers can now claim a right to repair or replace a product for up to six years after the purchase.

France has adopted perhaps the most progressive policies; they have now criminalized planned obsolescence, sending a clear signal to the market. Further, France has also started to look at the practices of some corporations seeking evidence that planned obsolescence is actually taking place. France has also introduced a scheme to provide incentives for manufacturers to ensure spare parts are available for a number of years after the purchase of the product.

Policies for Ecodesign

There are many different initiatives in European countries seeking to provide incentives for the design of more durable products and to reuse, repair or remanufacture products. However, none of the national policies actually regulate product design. As the EU product design directive does not make design mandatory, it is very difficult to get any clear incentives for producers to redesign their products to have less environmental impact, and to ensure that the legislation is implemented with effective and honest monitoring. The reuse of products and the design for optimal life times also needs to improve – and this demands sound systems and good control. Last but not least, although based on the same concept, the design and implementation of EPR programmes varies significantly. There are big differences between different product groups, and also between different countries. When discussing EPR programmes, it is very important to pay attention to the specifics of each program – the devil is in the detail!

4.5 THE ECODESIGN DIRECTIVE FOR CIRCULAR ECONOMY

- The ecodesign directive promotes product attributes such as longer product lifetimes and improved product reusability. Indeed, this has already been the case in, say, dishwashers, washing machines, refrigerators, freezers, water boilers, TVs and electric motors. In most product groups the product design is usually adapted by the energy efficiency of the products. However, now there are also ongoing discussions on how resource efficiency can also be considered within legal frameworks. For instance, the European Union’s Circular Economy Action Plan promotes “the reusability, upgradability, durability, and recyclability of products” and new legislation is now being considered for such.

One approach among the strategies under consideration is to regulate lifetime or durability. Indeed, this has already...
been put in place for vacuum cleaners, where the motor lifetime and durability of the hose has been regulated. There have also been lifetime requirements set for lighting products such as lightbulbs. While setting standards on lifetime may at first appear straightforward, in practice it can be very complex. For example, ‘lifetime’ actually has several dimensions for lighting products. It includes the actual estimated useful lifetime in hours, but also how many switching cycles the lamp can endure and how the light output deteriorates over time. It is also necessary to test the legal requirements to ensure that manufacturers can comply with the laws. It is a challenge to ensure a product lasts for 15 years without actually testing it for 15 years!

A second type of requirement that can also be posed is that manufacturers must promote product reparability and guarantee the provision of spare parts for several years. In addition to improving reparability, guaranteeing the availability of spare parts will also make repair a feasible, and potentially more attractive option to the consumer.

A third type of requirement is to promote modular design. Modular design is considered to be good for availability of spare parts will also make repair a feasible, is that manufacturers must promote product reparability to ensure a product lasts for 15 years without actually testing it for 15 years!

A fourth type of requirement is related to design for recycling. One proposed example is that manufacturers must show that a product can be taken apart within a set time period, which makes recycling more cost-effective. Related to recycling, another category of rules could relate to declaration of content. If a manufacturer accounts for what materials are in a product and where they are situated, future recycling operations could be improved.

There are other options, too. But it is necessary to recognize that it is complicated to adopt such rules; and it is generally accepted that rules should not hinder desired innovations. A great challenge concerns the need to develop standards and test methods that enable authorities to ensure that manufacturers comply with the laws. Often, it is quite difficult to set requirements unless there are standards available to test them. If there are no such standards then they must be developed, and this is a time-consuming process.

Finally, one concern is that even if we make products durable, consumers may still change products before they have reached their useful lifetime. A prime reason for this is for reasons related to function or fashion, the latter which can be considered almost invariably to be a waste of resources. We must remember that reality is never straightforward. If we force manufacturers to develop more durable products, they may be incentivized to make them upgradeable and lease them to consumers instead of selling them, which could benefit its environmental performance. So, in some respects society may have to experiment with the policies to see what works and what doesn’t.

We should also bear in mind that the Ecodesign Directive is not the only possible instrument to promote product resource efficiency. Another option is to stimulate longer product lifetimes and reparability through consumer labelling initiatives.
of resource flows; this circulation implies that different stakeholders collaborate to exchange energy or material flows based on their needs. For example, a company in the UK might have ceramics that they want to get rid of. At the same time, a company in France might need ceramics as a raw material for building, which would decrease the amount of virgin raw materials used. So, the organizations discarding and those demanding material and energy to be reused or recycled need to somehow get in touch.

Stimulating circular economy systems also implies thinking outside of the box and imagining new systems that reduce resource consumption and overall emissions in the environment. Innovation takes place when people and companies meet to brainstorm, network and exchange knowledge. This helps them identify what is needed, what is feasible (or not), and if an idea can actually contribute to creating a circular economy. Several initiatives around this topic have been launched by public authorities and independent organizations to promote the circular economy agenda.

One example of an initiative launched by public authorities is the European Circular Economy Stakeholder Platform launched by the European Commission in 2017. This platform aims to gather existing networks focusing on the circular economy and to stimulate collaboration and knowledge sharing on opportunities and challenges. The platform gathers experts in the field of circular economy, organizes stakeholder discussions via conferences, and shares knowledge, strategies and best practices via a website. The European Commission is also funding a consortium of actors in the sector of raw materials in Europe called EIT Raw Materials, initiated by the European Institute of Innovation and Technology. EIT Raw Materials gathers more than 100 partners in academia, research institutes and businesses to find innovative solutions to secure and improve the supply of raw materials in Europe, including to a large extent the development of circular systems. The compendium you are reading has been produced within such an EIT Raw Materials initiative. (Fig. 4.8)

Yet another example is the initiative launched by the association ACR+, which was founded by a group of local authorities under the lead of the Brussels-Capital region. ACR+ launched the Circular Europe Network to share knowledge on efficient circular economy strategies implemented by cities and regions. One interesting output of the network is this map, which gathers successful circular economy initiatives from different regions in Europe.

Besides initiatives launched by public authorities, other actors such as academia and businesses also participate in creating networks. This is the case of the Ellen MacArthur Foundation and its programme Circular Economy 100. It aims to enable organizations around the world to innovate in the field of circular economy by bringing together companies, governments, cities, academia and emerging innovators. Members of the network have access to tools such as a matchmaking app, acceleration workshops and an Executive Education course. This initiative was recently extended with the creation of two specific programs for Brazil and the US.

Other types of initiatives gather specific technical information for social and environmental assessments of supply chains and resource management. The European Platform on Life Cycle Assessment was launched in 2014 by the European Commission to gather information and data for businesses and policy makers to make life cycle assessment studies. It hosts a registry called the Life Cycle Data Network for stakeholders to deposit life cycle inventory data and processes. It also frames the development of the European Life Cycle Database, which gathers life cycle inventory data for key products from EU business associations and others.

For example, if seeking information on aluminium extrusion, a complete description of one specific process can be found on this website, including materials and energy consumption necessary for the process.

These examples stress the importance of information sharing in the development of a circular economy as intended by regional policies. Initiatives are already ongoing, from the creation of networks for matchmaking to the creation of new communication tools and technical databases that can support innovators in their efforts to create new circular systems. These networks rely on the participation of all actors involved to transition towards a circular economy.

Other examples of initiatives to stimulate circular economy via information sharing and networking Many other initiatives aiming to stimulate circular economy via information sharing and networking are popping up around the world. They are led by a wide range of stakeholders, are implemented at different scales (from regional to worldwide levels) and have different levels of maturity. They can be a source of information and help project developers reach circular economy experts or future collaborators. A number of examples are introduced in the following subsections.

The Circular Economy program of the WBCSD (world) The World Business Council for Sustainable Development (WBCSD) has launched a circular economy program. Several outcomes of this program aim to inform businesses on circular economy practices and bring them together to create synergies. One example is the Circular Economy Practitioner Guide launched in 2017. It presents several circular economy practices as well as case studies, tools and publications from other organizations such as the Ellen MacArthur Foundation.

Another output of the program is the Marketplace2UR, an online platform that maps initiatives that promote the use of secondary resources around the world. The platform mainly lists marketplaces allowing businesses to publish their offers and demands for secondary materials (e.g., the North Carolina Waste Trader in the USA or the Belgian Waste Stock Exchange).

The Circular Economy Club (world) The Circular Economy Club (CEC) is an international non-profit network of over 2600 professionals around the world. It aims to connect members to create synergies, for example via the voluntary activities of CEC local organizers who can organize networking events in their city, and to provide professionals with open tools and resources via their website. Resources and tools promoted include: information on funding opportunities; new publications on circular economy guidelines to apply the circular economy principles, and examples of circular systems applied in different sectors.

The Raw Material Information System of the European Commission (EU) In the EU, the Raw Material Information System (RMIS) was developed by the European Commission Joint Research Commission (JRC) as a web-based knowledge platform on non-fuel, non-agricultural raw materials from primary and secondary sources. The website aims to gather information on raw materials, including critical raw materials and secondary materials (e.g. definitions, policy and legislation, environmental and social sustainability, etc.). In terms of the circular economy, the RMIS will provide information for specific industrial sectors such as Electric and Electronic Equipment (for which product sheets on product lifetime, recycling and eco-design opportunities will be available) and Mobility.
The European Innovation Partnership on Raw Materials (EU)
The European Innovation Partnership on Raw Materials (EU) is a stakeholder platform that brings together representatives from industry, public services, academia and NGOs. Its mission is to provide high-level guidance to the European Commission, Member States and private actors on innovative approaches to raw materials challenges. The EIP plays a central role in the EU’s raw materials policy framework. The EIP on Raw Materials has the aim to help raise industry’s contribution to the EU GDP to around 20% by 2020. It will also play an important role in meeting the objectives of the European Commission flagship initiatives ‘Innovation Union’ and ‘Resource Efficient Europe’. It will do this by ensuring the sustainable supply of raw materials to the European economy whilst increasing benefits for society as a whole.

The EIP targets non-energy, non-agricultural raw materials. Many of these are vital inputs for innovative technologies and offer environmentally-friendly, clean-technology applications. They are also essential for the manufacture of the new and innovative products required by our modern society, such as batteries for electric cars, photovoltaic systems and devices for wind turbines. With about 30 million EU jobs depending on the availability of raw materials, the EIP will have a clear, positive impact on European industrial competitiveness. The EIP’s Strategic Implementation Plan (SIP) sets out specific objectives and targets. Actions to achieve these include research and development, addressing policy framework conditions, disseminating best practices, gathering knowledge and fostering international cooperation.

The circular economy platform of the Americas (American continent)
The Circular Economy Platform of the Americas (CEP-Americas) is an initiative of the Americas Sustainable Development Foundation (ASDF). It aims to facilitate the transition to a circular economy in the Americas, especially in South American countries. It functions through the involvement of professionals in the sector, networking events to connect people and ideas, as well as the sharing of information on the latest advancements of the American continent toward a circular economy.

The economiecirculaire.org platform (France, Switzerland and Belgium)
The economiecirculaire.org platform is a French initiative that aims to explain the concepts of circular economy, connect local circular economy platforms, and facilitate experience sharing in France, Belgium and Switzerland.

AUTHORS and PRESENTERS CHAPTER 4: POLICIES AND NETWORKS
4.2 POLICIES FOR A CIRCULAR ECONOMY Leonidas Milios – IIIEE, Lund University, Sweden.
4.3 EXTENDED PRODUCER RESPONSIBILITY Thomas Lindqvist and Naoko Tojo – IIIEE, Lund University, Sweden.
4.4 ECODESIGN POLICIES Carl Dalhammar – IIIEE, Lund University, Sweden.
4.5 POLICY OUTLOOK David Peck – Delft University of Technology, The Netherlands
4.6 NETWORKS AND INFORMATION SHARING Sophie Sfez, Green Chemistry and Technology, Ghent University, Belgium.
This chapter presents an examination of new norms, forms of engagement, social systems, and institutions that are needed by the circular economy. It also discusses how we can help society become more circular.

5.1 SOCIETAL VALUE
Securing resources for social equity and development
The circular economy can create value for society in three major ways. The first way is to help secure global resource availability. The second is to help preserve the ability of natural systems to deliver goods and services to society. And the third way is related to the idea that we cannot achieve a circular economy without developing new technologies, new norms and new institutions, which can support and stimulate our society.

To start, we need to go back to a central argument: supporting the need for circular economy: we must reduce burdens on the earth’s ecosystems. However, this is a very significant task. We face a future where by 2050 there may be 10 billion people that can afford a healthy lifestyle with high levels of goods and services. A business as usual approach in this future – where we use too many resources, too fast, and don’t reuse them – will exceed global resource availability. If we want to maintain the earth’s ability to provide for our needs, then we need to change. We need to use too many resources, too fast, and don’t reuse them – will exceed global resource availability. If we want to maintain the earth’s ability to provide for our needs, then we need to change. We need to reduce the danger posed by the pollution, and the damage caused by waste and over-extraction is vital to preserving the ability of natural systems to support and supply society. One part of this is the danger pollution poses to health. Air pollution, for example, results in the loss of millions of human lives every year. Apart from the human factor of this, impacts on health along with lost productivity and the costs of health care also impact our economies negatively.

Pollution also threatens environmental systems that produce renewable resources. Clean air and water, timber from forests, and fish from the sea are examples of these. We call these ecological goods. Sadly, pollution from today’s linear, take-make-waste economy threatens many ecological goods. For example, crop yields are reduced – often times quite drastically – when air and soil are contaminated. Forests that produce valuable timber are damaged by acid rain. Fishes are damaged, or even destroyed, by the effects of pollution and overfishing. And all such systems are threatened by pests, resources that flourish in a warming climate that has more extreme weather events.

Such productivity losses can also be very damaging to our economies. By reducing threats to the environment, a more circular economy can benefit our economies and our society. In addition to providing society with ecological goods, we are deeply dependent upon ecosystems for the processes that they perform. The hydrological cycle delivers clean water, and photosynthesis in plants delivers the oxygen that we breathe. These processes are examples of ecosystem services. The ability of these natural systems to deliver are also threatened by our linear economy. Our oceans, rivers and landscapes, and their productive systems, are being clogged and poisoned by our wastes. Apart from taking away beautiful landscapes that we enjoy – in itself a service to society – such situations also reduce the ability of natural systems to deliver ecological services.

As an example, when a natural environment – producing clean water flowing in clean rivers – is polluted, then farms, towns and industry no longer have access to ‘clean’ water for ‘free’. There will probably still be water, but it must be cleaned before use. This being a process that generally requires additional investments in infrastructure. The process of cleaning then consumes energy, time and money. Further, other goods or services that the river provided such as fish, tourism, etc. may be lost. Such impacts constitute real costs and damage to society and its economy.

Examples of Ecosystem Services:
- decomposition of wastes,
- generation of soil and vegetation,
- pollination of crops,
- seed dispersal,
- recharge of groundwater systems
- greenhouse gas mitigation.

Taking too much from the environment, and releasing too much contaminated material back into it, threatens our very survival.

Creating a circular society
Broad economic, new ways of thinking, and lots of technological innovation are needed to make the circular economy work. They can also support and stimulate modern society. Likewise, new social norms and aspirations must emerge. As more people value products over consumption, speed up the shift of products-to-services, stimulate the sharing of goods, and lengthen product lifetimes.

In supporting the circular economy, these social shifts will also demand that we invent, innovate, develop new technologies, and create new businesses.

The circular economy requires stimulation of society’s research and development, and of the materials extraction and production industries. It demands the creation of new sectors to recover and process materials in circular ways, and it requires design innovation and the creation of new business models to operate everything that will make the circular economy function.

Nor should we lose sight of the fact that new policy priorities must also be put in place to support the emergence of the circular economy. Such work includes the design and negotiation of new policies and regulations to enable circularity. As well as supporting circularity, these policy frames must also impede value destruction and pollution in the first place. New institutional frameworks must be designed and implemented to support systems that share or remanufacture products.

There is also a general consensus among policy-makers and practitioners in the circular economy, that if the creation of new systems to regulate both the linear economy and the emerging circular economy will create skills and knowledge that are vital to meet other global challenges, such as climate change adaptation. That is, the skills and knowledge that we build as we seek a more resource efficient circular economy are also directly applicable when seeking to work with a range of other sustainability challenges.

But we need to evolve more than just new processes and technologies. We must pursue new social norms and forms of engagement; and we need new social systems and institutions.

If we are really serious about achieving a circular society then we must develop ourselves!

5.2 SOCIETAL IMPACT OF CONSUMPTION
Sustainable consumption and circular economy
Our current resource use is unsustainable; we’re consuming extracting and extracting more raw materials than our planet can provide in the long term. The environmental footprint of modern ‘middle-class’ lifestyle has steadily been increasing over the last century. And with business as usual, footprints are expected to increase even further during the coming decades: the size of the ‘global middle-class’ will increase from slightly under 2 billion in 2009 to almost 5 billion by 2030.

Analysis shows that in order to reduce our footprint, shifting to a more vegetable based diet, reducing waste and saving energy at home and in transport are the most important actions we can undertake. Buying more local products also reduces environmental pressures overall. The circular economy provides a way of using resources more efficiently. By using products longer, buying second-hand or recycled products, opting for dematerialized “services” rather than primary-material-based goods and by sharing products instead of consuming more, we can reduce our impacts overall, and result in a lower need for primary resource extraction activities such as mining. As such, circular economy strategies have the potential to contribute to a more efficient resource use and a reduction of primary resource needs. But, it is important to remember that it is not just a matter of making our consumption patterns more circular; we also need to think about the overall level of our resource use.

A vibrant social debate is going on about what level of consumption is needed for a good life and how much material, water, carbon, and land can be regarded as a ‘fair share’ for each person on Earth, within the sustainability limits of our planet. For many regions of the world, especially in Europe and the US, this will require a significant reduction in footprint per capita and thus profound behavioural changes. In modern society, such behavioural changes are often difficult to achieve in reality, as the ownership of material goods is deeply ingrained in our psychological and social identity. In fact, we tend to use goods as extensions of our own ‘self’, reflecting our social status and who we are. As a result, in order to make our consumption behaviour more sustainable, it’s vital to address the social logic of consumption as well.
Our environmental footprint

Our demand for goods and services drives the extraction of resources across the globe. The production and transport of these goods cause the emission of greenhouse gases and other substances into our air, water and soil.

Our consumption patterns have become more and more globalized. Only a few decades ago, products were mostly produced in the same country where they were consumed, and used materials and parts that were locally available. But today, in our global economy, products are made from materials from all over the world; supply chains have evolved into a complex and interconnected world-wide network of resource and money flows. For example, the steel in a car’s rear axle could have been fed with soy produced in Brazil, and mobile phones sold in the US are very likely to be assembled in Asia using minerals that were mined in Africa and South-America.

Because of these global supply chains, consumption in one part of the world now can trigger resource use and emissions in another part of the world much more than it did just a few decades ago. Take the example of an American-brand car sold in France: the emissions related to the burning of gasoline occur in France. However, the environmental impact of the extraction and refining of the gasoline was probably generated in the Middle East, and the impact of the car’s assembly was generated in America, while the impact of the life cycle of the car’s components was probably generated in South America, or Asia – depending on the material. All of these factors contribute to which we call our consumption related ‘footprint’.

The environmental footprint concept considers the environmental pressures that are associated with all the goods and services that are consumed by a person or a region. Like life cycle assessment, it takes the full life cycle of goods and services into account, including the emissions generated along the world-wide value chain for resource extraction, production, transport and use. In this way, environmental emissions generated abroad are also taken into account.

The most commonly used footprint in communication and policy-making is the carbon footprint. It expresses the amount of greenhouse gas emissions estimated to be emitted as a result of resource extraction, production, transport and use of all goods and services consumed. A carbon footprint can be calculated for specific goods or individual persons, but it’s mostly used to estimate the impact of an average consumption pattern in a region or a country, and it’s typically expressed in tonnes of CO2 equivalents per inhabitant.

By taking a closer look at which goods and services are responsible for the largest contribution to the overall footprint, we gain insight in the way our consumption habits affect the environment and which habits we should change in order to reduce our environmental impact.

The environmental footprint of a country can be defined as the environmental impact caused by the consumption of goods and services by its inhabitants. These environmental impacts are generated during the entire life cycle of these goods and services, i.e. during resource extraction, production, transport and use. This is called the ‘life cycle impact’ of the product. Often LCA-like methods are used to estimate this impact.

Expressed in a formula, the environmental footprint is the environmental impact from all goods and services produced in a region or a country (often called the ‘territorial flow’), minus the environmental impact from the production of exported products, plus the environmental impact from the production of imported products. Good knowledge of global value chains is needed in order to calculate the environmental footprint of a product, and by extension the consumption of a whole country. (Fig 5.1)

Carbon is not the only measure used however, and environmental footprints are estimated for various environmental concerns. Well established footprint measures, including carbon that has been presented, are listed below:

- **Carbon** – presents the amount of embodied carbon dioxide and greenhouse gas emissions as a result of the consumption (and hence, the production) of goods and services, expressed in tonnes of CO2-equivalents (hence, this includes non-C02 greenhouse gases, such as methane).
- **Water** – expresses the volume of freshwater consumed (or polluted) as a result of the consumption of goods and services, expressed in cubic metres of water. Distinction can be made between volumes of rainfall water (green water, e.g. by rain-fed agriculture or forests), surface and groundwater consumed (blue water, e.g. industrial process water or irrigation water) and volumes of water polluted (grey water, estimated as the amount of water needed for adequate assimilation of the pollutants).
- **Land** – calculates the amount of land use (rural, pasture and forest) needed to produce the amount of final consumption, expressed in km².
- **Material** – calculates the consumption of raw materials (metal ores, fossil fuels, biomass, minerals) of final consumption, expressed in tonnes. Material footprints can be made on an aggregated level, or for individual materials.

In contrast with the footprints presented above, the concept of the Ecological Footprint was developed in the early 1990s as an aggregated measure of the extent to which humanity used (or exceeded) the Earth’s carrying capacity. In the ecological footprint, all environmental pressures are converted to the “global hectare”, a unit that expresses the theoretical amount of land needed to absorb the exerted environmental pressure (e.g. to regrow resources, or to absorb CO2 emissions). Based on the ecological footprint concept, it was estimated that humanity used 1.5 times the carrying capacity of the Earth in 2015 (WWF, 2014). The ecological footprint is widely used in popular literature on sustainable consumption – in general it is found that the statement that “we currently need 1.5 Earths to sustain our global consumption” is a concept that is both attention-catching and relatively easy to grasp. Hence it helps communicate the seriousness of environmental concerns to broad audiences. This said, the concept is commonly criticized within the scientific community, not least because the methodology applied to calculate the ecological footprint very likely significantly underestimated the environmental impact of consumption; it only encompasses ‘available’ land area, while disregarding other very serious issues such as land degradation due to unsustainable land-use practices.

**Case Study: The environmental footprint of Flanders**

Carbon footprints are the most common footprints discussed in literature and used in policy making. The carbon footprint of a country or region is the total amount of greenhouse gases produced worldwide as a result of the consumption by its inhabitants.

As an example of how carbon footprints are applied for a country (the total amount of greenhouse gases produced worldwide as a result of the consumption by its inhabitants) it is useful to examine the carbon footprint of Flanders, a densely populated and highly industrialized region in Western Europe.

In 2010, the carbon footprint of Flanders amounted to about 20 tonnes per inhabitant. To limit the average global temperature rise to 2°C, global greenhouse gas emissions need to be reduced to an average of 2 tonnes per capita by 2050. The Flemish carbon footprint is therefore ten times higher than the nominal target. Important, in the context of this discussion is that much of this footprint is linked to consumption.

Nearly three quarters of the Flemish carbon footprint, about 15 tonnes CO2-eq per inhabitant, are linked to goods and services purchased by households. The majority of these greenhouse gas emissions, roughly 80%, result from the production, transport and use of goods and services linked to housing, food, and personal transport. In addition to the emissions related to direct consumption of households, roughly half times CO2 eq per inhabitant can be linked to investments by businesses and governments in buildings and infrastructure, machinery, ICT equipment, etc. (slightly over 3 tonnes CO2-eq per inhabitant) and emissions linked to public services that are not directly used by consumers, such as education and defence (about 2 tonnes CO2-eq per inhabitant). (Fig 5.2)
When we dive deeper into the part of the footprint that is related to housing, we discover that energy use within homes is responsible for almost 80% of the carbon contribution. Most of the energy use is related to heating. Slightly over half of these emissions are generated during the production and distribution of heating fuel, natural gas and electricity, while the other half is caused during fuel combustion within the home itself. Based on this analysis, we can see that from an environmental point of view, reducing energy use in homes should be one of the priorities in order to reduce the carbon footprint of households.

When considering the global distribution of Flemish consumption emissions, over two thirds of the carbon emissions originate from outside the region of Flanders. Further, a large share of this is generated outside Europe in regions where environmental standards are less strict. This ‘export of carbon emissions’ explains partly why the carbon footprint of Flanders has increased between 2001 and 2010, while the carbon emissions within Flanders have decreased slightly.

Material footprint

Metals are essential for society and the economy. The material footprint for metals for the region of Flanders was calculated in 2007. When considering the metal use across the whole production value chain, about 10 million tonnes (10 Mt) of primary metal ore was needed in order to fulfill the consumption demand in Flanders. The metal demand mainly consists of iron ore (3Mt), non-ferrous metal ores (0.275Mt). While steel is an important base material for a diverse range of applications, non-ferrous metals are essential for many sectors, such as electronics, renewable energy, energy efficient products, medical appliances, automotive, chemicals, etc.

The per capita consumption of primary non-ferrous metals and their ores is illustrated in the material footprint in Figure 5.3.

Sustainable consumption in a Circular Economy

How can one define ‘sustainable consumption’?

Sustainable consumption means that the environmental footprint of consumption stays within the carrying capacity of the planet (the ‘planetary boundaries’), at global scale, and for some impacts at regional or local scale as well (e.g. water depletion). Unfortunately, the estimated maximum sustainable levels are difficult to estimate, highly uncertain, ambiguous and subjective. In 2014, two European analysts Hoekstra and Wiedmann estimated the global footprints and then compared them with their suggested maximum sustainable levels (Figure 5.4). The inner green coloured circle represents the maximum sustainable footprint, while the red wedges represent estimates of the current global level of each footprint. From the figure it can be seen that the ecological footprint (expressed in global hectares) exceeds the estimated maximum sustainable level of the human development index (expressed in global hectares) by a factor of 2.

Sustainable consumption and well-being

The ultimate goal of society is to increase the well-being of its citizens. However, the question is whether a higher consumption pattern always leads to a higher well-being. As you can see in Figure 5.5, well-being (expressed by the human development index of a country) levels off at a certain level of resource use (expressed by the material footprint of the country), showing that from a certain high level of well-being, additional resource consumption no longer improves the level of well-being.

Also, well-being encompasses much more than material concerns. As stated by Tim Jackson in his 2009 book ‘Prosperity without Growth’.

“Well-being” resides in the quality of our lives and in the health and happiness of our families. It is present in the strength of our relationships and our trust in the community. It is evidenced by our satisfaction at work and our sense of shared meaning and purpose. It hangs on our potential to participate fully in the life of society.

Prosperity consists in our ability to flourish as human beings within the ecological limits of our planet. The challenge for our society is to create the conditions under which this is possible. It is the most urgent task of our times.”

5.3 A GLOBAL VIEW

Mining elsewhere and sending our wastes away

Today’s material and product flows are truly global. Materials that make up complex products might be sourced from Africa, then shipped to Asia to be made into parts, and then move on to Europe for assembly. As a single product can contain materials from all corners of the world, this means that products such as computers and phones are associated with environmental and social impacts – both good and bad – across the globe. With inputs from so many places, it can become very difficult to know where the materials we use in products come from, or how they were produced. And similarly, it is also very difficult to know where our products end up when we discard them.

If we are concerned about sustainability, this means that we have to think more carefully about where we source our materials, and where we send our wastes.

Raw materials can have massive implications on a global scale, both for trade and for international diplomacy. For some particularly important materials, a few countries dominate the global supply. China for example, supplies the majority of rare earth elements, magnesium, tungsten, antimony, gallium and germanium. Metals such as Cobalt and Tantalum are mostly sourced from the Democratic Republic of Congo and Nigeria. And other countries like Russia, South Africa and the US supply the majority of materials such as niobium, beryllium, and the platinum group metals.

Many of these materials are vital for a sustainable future, as they are used in products such as wind turbines, solar cells, communication devices, batteries and electric vehicles. Supply situations where the sources of key materials are concentrated in a limited number of sourcing locations can be ‘risky’ for companies and economies – if demand or supply changes quickly, then shortages, or major price fluctuations can arise. Such risks become higher when the social, political or economic situations of source countries lack stability. Further, there are also some countries that have used their market dominance – apparently deliberately – in ways damaging to other economies.

Such risks are made worse by our low recovery and recycling rates. We may depend on these materials, but instead of seeking to recover, reuse and recycle, often we discard large proportions in our wastes.

More critically, our economies can help build resilience against supply restrictions. But that is not the only story. We need to ensure that both the start and the end of raw material life cycles do not poison the environment or threaten society. However, this is exactly what is happening right now in a number of places that supply large proportions of critical materials to global markets. Similarly serious environmental and health issues are being caused in a number of countries that receive waste products that contain such materials – that have been sent there by other countries.

Figure 5.4: 2008 global footprints vs. the maximum sustainable footprint (Hoekstra and Wiedmann, 2014).

Figure 5.5: Human development index (HDI) as a measure of well-being versus the material footprint of consumption (Tukker et al., 2014).
Rare Earth Elements and critical metals from countries with weak governance

There are a number of situations where global markets are dependent upon only one or two countries for the dominant proportion of supply for critical materials. Yet, we see a number of very problematic issues related to the mining and processing of such materials in some of the most important source countries. For example there has been significant international media attention for many years that has focused on human rights abuses, inhumane working conditions, and environmental degradation related to mining of metals in the Democratic Republic of Congo. There has also been similar attention given to catastrophic environmental degradation and human health impacts related to the extraction of rare earth elements in China’s Inner Mongolia Autonomous Region.

Generally speaking, the underlying reasons are inadequate environmental regulation or enforcement of regulation, unsafe working conditions, or limited levels of technical development. Or indeed – ALL of these factors. In such governance contexts, the result can be many operations that don’t want them produced anywhere near home! Under such conditions, maintaining a strong and responsible raw materials sector can be difficult.

As a result, we can end up with the apparently perverse situation where our societies demand the technologies and benefits that require special raw materials but our societies don’t want them produced anywhere near home! Under such conditions, maintaining a strong and responsible raw materials sector can be difficult.

Process end of life products containing hazardous materials at home? – or away?

Many of the products that we discard at the end of their useful life contain valuable Rare Earth Elements and other ‘critical raw materials’. A particularly important product category is Waste Electrical and Electronic Equipment (WEEE), also called E-Waste. Apart from potentially valuable materials, they can include hazardous substances like mercury, lead, cadmium and beryllium.

There are many good reasons to establish a good collection system for electronic waste, and to ensure that both valuable and hazardous materials, are captured and taken care of in the subsequent reuse and recycling process.

A challenge for us all, however, is that many materials and products often become more expensive when we take on the costs of good environmental and social practice. Avoiding the costs for clean and safe processes, waste management, and decent working conditions is one way to make materials cheaper, and hard to compete with. This is one part of why we see suppliers of cheap critical materials dominating world markets.

If we are going to extract materials in a responsible manner, then we need to find ways to make sure that regulations are strengthened in all countries where we source materials, or we need to ensure that we only source materials from countries that have effective systems to protect society and the environment.

But sometimes achieving mining in countries with the more sustainable conditions described above is hard to achieve. A contributing factor to this situation, is that stakeholders – particularly in wealthy developed countries – sometimes strongly oppose the presence of industries that they perceive as being ‘dirty’. In fact, many industrialized countries have developed systems to ensure that waste electronics are collected and recycled in an environmentally friendly manner.

We also have international rules to restrict the trade of hazardous waste. The most notable is the BASEL Convention, a global treaty that came into force in 1992. The BASEL Convention mandates that hazardous waste should be taken care of as close to its origin as possible, and that when a country wishes to export hazardous waste, that country must obtain a written consent from the importing country. There are also regional conventions that go a step further and prohibit the exporting of hazardous waste from developed countries to developing countries.

But despite the existence of these national and international policy measures, electronic waste still flows to countries that don’t have good systems for recycling. The two main reasons for this is economic interests of actors and lack of good enforcement in both importing and exporting countries.

What makes the situation even more complex is that much of the electronic products discarded in developed countries are still working, and are exported to developing countries as second-hand products. While the reuse of products is preferable in many ways, the problem is poor treatment of non-reusable parts and products in receiver countries.

When these products cannot be reused anymore and are finally discarded, many of these countries don’t have good infrastructure to take care of them in an environmentally friendly manner. And the recovery of the valuable resources is not done in an efficient way. This has resulted in serious environmental, health and social problems. Further, much less of the valuable material is recovered.

Taking responsibility for consumption of materials

Our common future requires large amounts of materials to build the infrastructure for equitable and clean development. But much of the pollution and damage that is caused by today’s supply chains, is a result of sourcing materials from unsustainable production systems – and then sending waste products that contain the materials away when they reach end of life.

Society needs more knowledge of the role of circularity in reducing resource dependencies, securing supply, and protecting communities. Sending our waste away to where it likely causes problems does not achieve this. In fact it causes multiple problems: first human and animal health are put at risk, second the environment is put at risk, and finally significant proportions of valuable materials that could have been recovered. This last item in turn results in a situation that additional materials must be extracted to make up for those lost.

There is also a need for a range of societal actors to demand that all key materials are sourced from countries that have effective systems to protect their societies and the environment. Some of the stakeholders that need to be involved are companies working on their supply chains, policymakers and concerned consumers. We may have to reconsider our role as consumers and citizens as part of a “society” that demands new ways of production.

But it is clear that there are no simple solutions – for one thing, it seems these approaches may not result in raw materials that are the ‘cheapest’ in the short term. A key part of a sustainable solution must be to help develop systems in less developed countries, so that both their raw materials production systems and their recycling systems become safe and beneficial. However, a second, and equally important part of a sustainable solution is to source from countries that already can and do conduct operations responsibly. The same can be said for the recovery of materials from end of life products. And this part of the solution very likely requires that wealthy industrialized countries – and their citizens – host more of these industries than they do today.
5.4 A LOCAL VIEW – CHANGE CLOSE TO HOME

The circularity principle has been applied at many different levels. We should remember that circularity (closing resource loops) and resource efficiency (narrowing resource loops) need to go hand in hand if we are to bring our consumption within global limits. This requires deep social shifts, such as re-organization of individual lifestyles by people joining, sharing and repairing communities. In this way collaborative consumption and production are fast entering our everyday lives. Examining a number of the underlying issues associated with our consumption patterns can cast light on why this is so.

Sharing

Many goods stay idle for most of their lifetime. For example, the average European car is used for only 29 minutes per day. This means that over an average 12-year lifetime the car is used in total for only 3 months. Households own an increasing number of products and equipment, much of which is rarely used. In the UK and the US the items that people use less than once a month amount to 80% of all appliances overall. As a result, the electricity consumption per household for large appliances was only slightly lower in 2009 than in 1997.

Environmental impacts occur not only in the production and use phases of these appliances but also in their end-of-life, when the old appliances need to be recycled or disposed of. In addition, some appliances like washing machines and dryers often have considerable idling time – for example, standing idle for a week or so, waiting for a new batch of laundry to be loaded. We also see some households owning an extra freezer, where people store frozen fruits and berries, pre-cooked food for parties etc. The net throughput, and thus effective use in this scenario is low, and thus equivalent to idling. (Fig 5.7)

If we owned fewer appliances instead, and could ensure that people get access to them when they need them, we could optimize the idling capacity of these appliances so that they are used more frequently. In addition, we could choose appliances of higher quality and efficiency, and the ones that have a longer lifetime. Having fewer, more efficient and more durable appliances would help keep production at lower levels. Such actions would save resources, and reduce environmental pollution and waste generation in the production phase. Since fewer appliances would be in use, this would also reduce the need for the end-of-life waste management and would decrease the associated environmental impacts. Overall, sharing appliances could help us contribute to a more circular society.

“Sharing”, “sharing economy”, ‘peer to peer economy’ and ‘collaborative consumption’ are just some of the terms used to describe a variety of bottom-up initiatives, public-private-people partnerships, business start-ups and local government schemes, all of which seek to utilize more of the available idling capacity of our material world. Sharing is seen as one potential answer to the unsustainable patterns and levels of production and consumption. It can also be attractive for individual consumers as they can get easier access to products that are normally difficult to find or very expensive to buy, such as higher quality products, luxury goods and rarely used products.

So if we know that many goods are already out there, and they have a large idling capacity, why do we need to produce more? Why not improve or optimize the use of goods that have already been produced instead? The whole idea of sharing is built around access-based consumption and functional thinking. Instead of viewing a product as a consumable, we can instead consider the function or value the product can deliver, and if we can get the same value by accessing the product instead of owning it, this is nothing new! Libraries full of books for example, have existed for a very long time – in such a case, a central actor (the library) mediates the ‘shared use’ of books. During a book’s library lifetime it may be read by many many individuals. What is now different is that we see more examples of sharing between strangers utilising new forms of mediation. Such “new sharing” is generally mediated by digital technology and occurs in a variety of consumption domains including fashion, mobility and accommodation. Some examples of these are swap shops for clothes and accessories, car sharing organizations like Driivy and Uber, and home sharing platforms like BedWelcome and AirBnB.

Sharing’s contribution to a circular society

Let’s look at an example of how accessing goods instead of owning them can contribute to a reduced environmental impact from our consumption. In the European Union over the last two decades, the average specific electricity consumption of all large appliances (except TV-sets) has been decreasing steadily since 1990. This is because appliances that are more energy efficient are now offered on the market. Energy efficiency improvements have reached almost 40% for washing machines and dishwashers, and around 30% for freezers, refrigerators and dryers. (For TV-sets, the increase has been offset by an increase in the equipment ownership sets). Large appliances are on average 25% more efficient than in 1990, with countries like Germany, Sweden and the Netherlands registering very strong progress. (Fig 5.6)

At the same time, almost all energy efficiency gains have been offset by an increase in the equipment ownership (Figure 5.6). In other words, even though people own more appliances that are energy efficient they also own more appliances overall. We should remember that circularity (closing resource loops) and resource efficiency (narrowing resource loops) need to go hand in hand if we are to bring our consumption within global limits. This requires deep social shifts, such as re-organization of individual lifestyles by people joining, sharing and repairing communities. In this way collaborative consumption and production are fast entering our everyday lives. Examining a number of the underlying issues associated with our consumption patterns can cast light on why this is so.

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Figure 5.6 Evolution of specific consumption of large appliances (the base is 100% in 1990) Source: Odyssee 2010.

Figure 5.7 Decomposition of change in the use of large appliances. Source: Odyssee 2010.
Repairing

While some goods stay idle, others are thrown away too soon. 99% of the material content of goods becomes waste within 6 weeks. Short product life cycles intensify the throughput of resources in the economy and aggravate environmental and social impacts. For every bin of waste that a household produces, 70 bins of waste were made upstream. So even if we could recycle 100% of our household waste, it does not get us to the core of the problem.

One of the reasons that products are thrown away is because they physically fail in some way. Often the faults are minor but the users are reluctant to consider repair options due the high cost of repair in relation to the low cost of a new good, or due to a desire to obtain the latest model of a product instead. Activities such as upcycling and repair offer valuable alternatives to the ‘dump culture’ that mostly wealthy societies have created. In addition to being consumers, individuals can assume an active role in co-production of utility by repairing and upcycling products, from upgrading electric and electronic equipment to co-production of utility by repairing and upcycling products, being consumers, individuals can assume an active role in production-consumption systems with the help of diverse innovation hubs. They reframe their everyday consumption practices to include serious leisure projects, repair services, and upcycling strategies. These often have a so-called pro-social purpose.

Sharing and repairing more

Despite the potential of sharing and repairing to foster circular societal shifts, these activities are still marginal, and unsustainable lifestyles continue to dominate. To make sharing and repairing normal and embedded in our everyday lives, our perceptions need to change. People will also need to accept that it is perfectly okay to wear someone else’s clothes or drive someone else’s car, and this can be equally as fashionable and comfortable as wearing new clothes or driving your own car. People will also need to accept that it is quite normal to repair their smartphones, laptops or bikes. You can do it yourself or, even more fun, with some help from your neighbours, colleagues, friends or co-citizens.

But how do we go about achieving such a norms shift? As a starting point, it is generally agreed that there is a need to better understand the potential contribution of sharing and repairing to environmental sustainability, economic prosperity and social cohesion, as well as the socio-economic and environmental risks that these activities might bring along. A balanced understanding provides proponents of the Circular Economy a basis for both action and communication.

From an economic perspective, by participating in sharing and repairing, individuals can save money since they don’t have to buy as many new products. They can also earn money if they rent out their possessions, or help others with repairs. Since sharing systems are mainly local, they have real potential to contribute to local community development and economic growth. However, this is not without controversy, as uncertainties remain on how the profits should be distributed, and in what ways these new models affect established businesses. There is also no universally accepted practice on how to incorporate profits created from sharing into the formal tax system, which often places them in a ‘grey’ legal area. Such areas remain ‘works in progress’ in many countries, and resolving such issues is important to the future progress with the Circular Economy.

From a social perspective, by participating in sharing and repairing, individuals can build social connections, improve communal well-being and in this way build social capital. On the other hand, concerns have been raised about, for example, public safety, privacy and limited liability of sharing organizations. Again, such areas need to be resolved.

5.5 WHO OWNS IT?

Responsibility for a manufactured product

Remanufacturing can extend the lifetime of a product, but there are challenges involved; for example, when a third party remanufactures a product, who made the product? The original equipment manufacturer certainly designed the product, made the parts and assembled it together, but the third party company remanufactured it again. We see controversy in this area with hard drives that are extracted from used computers and put through a factory process that takes the hard drive apart, replaces worn or failed parts, reassembles and tests it, puts it in a box and sells it for new with warranty.

Liability

When this remanufacturing process is undertaken the product can be upgraded to improve performance. In that case who is liable for the product if it fails? Is the warranty of the original equipment manufacturer still valid? Might this situation have the potential to damage the brand name of the original equipment manufacturer? The original equipment manufacturer may not be responsible for the quality of the remanufactured product so it might also have issues with the use of trademarks and brand name. This in turn leaves uncertainty about which logos or information can still be used on the product and packaging.
Intellectual Property Rights
Another challenge is that of intellectual property rights. This could be a barrier to the third party who needs information about the product or special tools in order to remanufacture it. Issues concerning liability, quality and warranty are also connected to the original equipment manufacturer and this is possibly extends to third party remanufacturers.

Market share
In some cases the third party develops a market that can be beneficial to the original equipment manufacturer, like opening up a new region. But in other cases the original equipment manufacturer sees the third party as stealing market share – what if people opt to buy the remanufactured products instead of buying new products?

Trademarks
Concerning trademarks, it is advised that the remanufacturer places their trademark on the product itself and not only the packaging. It should be clear that the product of the original equipment manufacturer has been remanufactured.

Patent infringement
In some countries, if a product is remanufactured, the original equipment manufacturer may have grounds for patent infringement. Therefore the remanufacturer is advised to check if a product is under patent protection. If a remanufactured product is defective the remanufacturer can face claims, therefore the remanufacturer is responsible for the product and should provide documents and support.

So there are tensions between third party remanufacturers and original equipment manufacturers, and in the worst cases this can lead to legal disputes. But there is a better, circular, way forward. This can be pursued by setting up networks and alliances between original equipment manufacturers and third party remanufacturers. This can lead to business partnerships to the benefit of everyone in our circular economy.

Product user communities for repair
There can be tensions between original equipment manufacturers and product users when they repair and upgrade their own purchased products. To have more access to the knowledge and specialist tools they need, many users join online communities, and friction between these communities and original equipment manufacturers can develop. There are many such communities all over the world.

One example is the Story of Stuff, a worldwide movement about sharing information with the aim to reduce the number of products. It focuses on slowing consumption by sharing and serving the community. The movement also raises awareness about harmful products.

A second example is Hackerspace. This group set up creative spaces to co-create. It is a repairing community, and has its own philosophy on society and products. The ‘hacker ethic’ is focused on freedom and open access of information. They embrace the concept of learning by doing and peer-to-peer learning.

A third example is Fablab, this community focuses on empowerment through new technologies, at the grassroots level and has a focus on the local community. Fablab is short for Fabrication Laboratory, and they are small-scale workshops offering digital fabrication, such as 3D printing.

Organizations such as IFIXIT provide support in the form of tools and knowledge, and support all communities in their repair activities.

We see an emerging and evolving topic in the tensions between people and companies. In a linear economy the situation is clearer, but the emergence of the circular economy is throwing up new challenges and tensions that we will need to sort out as we transition.