Integration of material circularity in product design

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THÈSE

Pour obtenir le grade de

DOCTEUR DE LA COMMUNAUTE UNIVERSITE GRENOBLE ALPES

Spécialité : **Génie Industriel**

Arrêté ministériel : 25 mai 2016

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préparée au sein du **Laboratoire G-SCOP, Grenoble – Sciences pour la Conception, l'Optimisation et la Production, UMR 5272**

dans **l'École Doctorale I-(MEP)², Ingénierie – Matériaux Mécanique Energétique Environnement Procédés Production**

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Thèse soutenue publiquement le **12 décembre 2017**,
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Abstract

In the last decades, many tools have been developed to understand and manage the anthropogenic cycles of materials, with different approaches. Each handles the material flows in society in different ways and each possesses its respective databases that fuel their uses. Yet there seems to be no common ground of communication between design activities and cycling activities, as well as their respective stakeholders, which hinders the information exchanges required for a proper management of discarded products (and their materials). This thesis provides two original contributions to circular product design: a tool for the integration of material circularity in product design and a framework to characterize material cycling networks. The tool is composed of a multi-criteria indicator for circular material value that is used in the Design for Material Circularity method. The framework is based on an extensive literature review enhanced by industry experts' interviews and provides a basis for data collection and knowledge capitalization on cycling activities. The open-loop recycling networks of eight materials, from the three main material classes, are characterized using this framework (steel, aluminium, copper, precious metals, specialty metals, rare earth elements, plastics and glass). Two case studies detail the deployment of these contributions. The first focuses on the optimal choice of material and end-of-life scenario for a 1,5-litre bottle container. The second is aimed at identifying material circularity hotspots and ideal end-of-life scenarios for a vehicular lithium-ion battery pack.

Keywords

Product Design; Recycling; Material Selection; MFA; Circular Economy.

Résumé

Au cours des dernières décennies, de nombreux outils ont été développés pour comprendre et gérer les cycles anthropiques des matériaux, avec plusieurs approches. Chacune considère les flux de matière dans la société de différentes manières et chacune possède ses bases de données respectives alimentant leurs utilisations. Il ne semble toutefois pas y avoir de bases communes pour la communication entre les activités de conception et les activités de bouclage, ainsi que leurs parties prenantes respectives, ce qui entrave les échanges d'informations nécessaires à une bonne gestion des produits mis au rebut (et de leurs matériaux). Cette thèse apporte ainsi deux contributions originales à la conception circulaire de produits: un outil pour l'intégration de la circularité des matériaux dans la conception de produits et un cadre pour caractériser les réseaux de bouclage de matériaux. L'outil est composé d'un indicateur multicritères de la valeur circulaire des matériaux utilisé dans la méthode de conception pour la circularité des matériaux (*Design for Material Circularity method*). Le cadre s'appuie sur une analyse documentaire approfondie, enrichie par des entretiens avec des experts de l'industrie, et sert de base à la collecte de données et à la capitalisation des connaissances sur les filières de bouclage. Les filières de recyclage en boucle ouverte de huit matériaux, appartenant aux trois principales catégories de matériaux, sont caractérisées grâce à ce cadre (acier, aluminium, cuivre, métaux précieux, métaux de spécialité, terres rares, plastiques et verre). Deux études de cas détaillent le déploiement de ces contributions. La première porte sur le choix optimal du matériau et du scénario de fin de vie pour une bouteille de 1,5 litre. La deuxième vise à identifier les points chauds (*hotspots*) de circularité des matériaux et les scénarios de fin de vie idéaux pour un bloc-batterie véhiculaire au lithium.

Mots-clés

Conception; Recyclage; Sélection de Matériaux; MFA; Economie Circulaire.

A Edmond,
qui m'a appris la valeur des choses.

Acknowledgements

I would like to thank my supervisors Professors Peggy Zwolinski and Maud Rio, my reviewers and members of the jury Professors Tatiana Reyes and Nicolas Perry, my examiner and other member of the jury Professor Wilson Kindlein Junior, all the members of the CPP group and the Ecodesign team in particular, all the members of the G-SCOP lab and GI-NOVA platform, the interviewees, Kleber, Dani, Tom, Camille, Mathieu, Fred, Christelle, Thierry, Philippe, Hugo, Katyanne, Lucie, Lucile, Feng, Natalia, Guillaume, Guillaume, Guy, Cédric, François, Fadila, Marie-Jo, Myriam, my family and friends in Brazil, and most of all, Delphine. Thanks to each one of you for the support you have provided me along the meandering path of this thesis. The result is the sum of all your contributions; I was merely the prism through which they shone.

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INTRODUCTION

The intrinsic value of materials was commonly recognized and respected up until recently. Gathering discarded objects in order to retrieve some sort of economic gain from reshaping or regenerating the matter that constituted them was a typical and ubiquitous activity, sometimes even the primary means of survival of marginalized populations. It was only in the 20th century, especially after the Second World War, with the advent of mass consumption and the pervasive use of polymers in particular, that people began to lose sight of the effort and energy required to produce goods. This apparent disconnection from the lifecycle of the ingredients in our society's metabolism led to a disregard of materials when thrown away, creating first a troublesome abundance of waste and, subsequently, aggravating an already fast-paced depletion of non-renewable natural resources.

French chemist Antoine Lavoisier stated, back in the 18th century, that "in nature, nothing is lost, nothing is created, everything is transformed". While this affirmation is the basis of modern chemistry and thus much of present day industry, there is a concealed corollary behind it that went seemingly unnoticed for almost two centuries: planet Earth being a finite environment, every gram of dirt that is removed from it and turned into an object is going to live out its lifecycle and return to the ground in some way. A commodity, product or good is matter's fleeting moment of utility that society exploits before deciding to put that matter back to where it came from, in a Sisyphean struggle against entropy and the 2nd Law of Thermodynamics.

This ability to conceive materials from mineral resources grew exponentially in the last decades, albeit under a false premise of enjoying unlimited ingredients with which to fabricate new technological objects. There was little to no preoccupation of how materials were used and what happened to them at the end of their product life. But signs of this miscalculation started to show, as more and more predictions of future consumption and companies' ability to secure their material supplies indicated shortages were looming in the not too distant future. Waste, which had been initially touted and dealt with as an environmental issue, returned to its first definition: the palpable evidence of inefficiency in our technosphere.

Initially, the solution of this problem was to create systems to manage waste as an externality of industrial cycles, a haphazard mitigation of the symptoms that did nothing to attack the causes of the issue. This, in turn, led to the development of an entirely new industrial segment dedicated to recovering and regenerating discarded materials and products, which, counterintuitively, emerged almost completely disconnected from manufacturers, severely underfunded and operating virtually always at the brink of bankruptcy. And yet, an estimated 70 trillion euros were spent worldwide in 2008 to collect, sort and treat waste (35 billion euros on waste transportation only), according to (Pauli 2011).

With this challenging conjuncture of material preservation in mind, fuelled by a plethora of recycling experiments around the globe to inform it, this thesis was conducted with the conviction that production processes can be improved in order to encompass material use more efficiently across product and services lifecycles. This introduction thus presents the context, focus, scope and structure of the research that was conducted for this study.

Chapter 1: Context, objectives and structure

This chapter gives a short description of the contextual elements for including material circularity issues in product design decisions. It then introduces the focus and scope of this research. Finally, it is concluded by an explanation of the thesis structure.

1.1 Contextual elements for the rise of circular thinking

In the last 25 years, the array of materials synthesized in laboratories and present in industrial applications has expanded considerably. Not only has the economy become omnivorous in its consumption of elements from the periodic table (Greenfield and Graedel 2013), but scientists have also gone to great lengths to produce materials that are ever more sophisticated, complex and architected, down to the nano-scale. The advances in sectors such as carbon-lean energies, information and communication technologies have led to a steep increase in demand for materials whose reserves seem inadequate to fulfil future scenarios (Graedel and Erdmann 2012; Fromer, Eggert, and Lifton 2011; Erdmann and Graedel 2011). Yet, despite the economic and ecological need of preserving resources through recycling, by establishing what is called a closed-loop economy, most industries and material value-chains are still open-looped. This means that materials follow complex routes and change states. A wide range of end-of-life applications is currently in place, with potential material dissipation and environmental impacts as a result of each subsequent loop. Today, material lifecycles look more like a spiral or a coil than a circle.

In terms of demand, Binder et al. (Binder, Graedel, and Reck 2006) have indicated that metal use increases with income growth, a statement that could be generalized to other commodities such as ceramics and polymers. Thus, since global population and economy are growing, one could consider the consumption of some materials as ever expanding in the near future (Graedel and Cao 2010). This may not be true in some cases, where predictions have shown it may saturate (Müller et al. 2006). Still, adding a note of unpredictability to the mix, the innovation process itself can disrupt any forecasting model of demand, as technological innovations relying on new materials can quickly transform the demand of little-known, undervalued elements of the periodic table into overnight industrial favourites (Graedel and Erdmann 2012).

With a growing demand pull, production will continuously be pushed to its limit, whether they are technical or economic. The added pressure of regulations on material end-of-life has rapidly made secondary production an interesting and sometimes economically viable option. Nevertheless, hasty initiatives in material recycling, uncoordinated with product manufacturers have generated more harm than good in some cases: the recycling of large volumes of steel has been hindered by copper contamination for a long time (Björkman and Samuelsson 2014) and the indiscriminate use of fillers and additives in plastic formulation has also hampered the take-off of polymer recycling (Shen and Worrell 2014). In this sense, it is important to understand what makes a recycling chain shift from secondary option to the first choice and how this move can be fostered.

1.1.1 The age of engineering materials

Materials are sought after and devised today to accomplish a myriad of functions, relying on their multiple physical and chemical properties. While 75 years ago, most materials and devices were composed of around 10 elements, now virtually all of the 92 stable elements of the periodic table are used. At an average of 1.4 tonnes of engineering materials per person each year, production and consumption are at an all-time high. 500 Eiffel towers in metal quantities are consumed each day around the globe, from computer chips to the skeleton of skyscrapers (Ashby, Balas, and Coral 2016).

In addition, the increasing complexity of products[1] has put a lot of pressure on certain specific resources. Supply-chain disruption has become a serious issue that material-dependent companies must face. Global markets have seen commodity prices rise at a rate of 8% each year on average since 1990 after having dropped 1% per annum approximately since 1860. Prices have also become extremely volatile and have been affected by the unilateral decisions of governments that hold a near-monopoly grip on certain resources, by conflicts affecting certain mineral-rich areas of the planet, but also because of evolving legislation and bans on specific elements as well as increasing societal demand for more responsible corporate choices in material sourcing. Moreover, certain materials are fundamentally rare in terms of their deposits in the earth's crust and, to complicate things further, some require large quantities of energy to expose, mine and transform the rock in

[1] A phone from the 1950s contained only 12 elements of the periodic table, while a current smartphone holds at least 60. In the same way, an early aircraft engine contained 9 elements whereas today's gas turbines hold 25 (Ashby, Balas, and Coral 2016).

which they lie, e.g. whereas 1 tonne of iron ore provides 330 kg of metal iron, 1 tonne of platinum ore only yields 0.0003 kg of metallic platinum (Ashby, Balas, and Coral 2016).

1.1.2 Growing concern over material risks

Economically speaking, material prices started to rise faster than inflation since the year 2000, with sharp increases in commodity prices seemingly erasing the real price declines of the 20th century (Figure 1). Manufacturing nations are now competing for worldwide mineral resources to feed their national industries (Ashby, Balas, and Coral 2016).

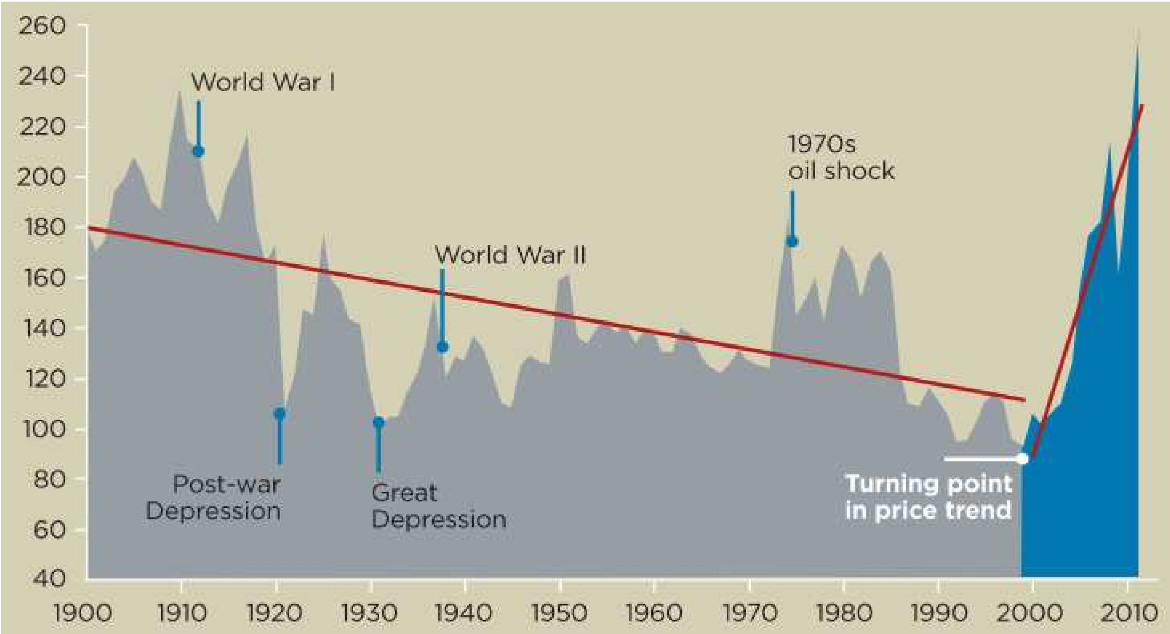


Figure 1: McKinsey commodity price index (years 1999-2001 = 100), based on arithmetic average of four commodity sub-indices: food, non-food agricultural items, metals and energy (Ellen Macarthur Foundation 2012)

Availability used to be considered simply as a function of the geological occurrence of a material and the economic viability of its production process. It was relatively simple to calculate the depletion time of a given material if its consumption or demand was known. However, routine use of some materials is now questioned due to geopolitical issues, increased extraction rates, poor recycling rates, ever more complex industrial processes needed to physically recover them, and the rapid changes in demand that a new technology can introduce (Graedel and Erdmann 2012).

Material-based companies strive to ensure that their supply chain is secure, complying with environmental legislation and aiming to strike a good bargain on prices as much as possible, whether they are producing raw materials from natural resources, intermediary components, or consumer products. Material sourcing has thus become an increasingly complex task. (Schneider et al. 2013) state that, in the German manufacturing industry, material costs are the highest cost pool by (44,3%) with more than double of labour costs (18%), while energy costs represent a mere 1,8%. Furthermore, technological innovation can, at the same time, make the mining of unattainable resources possible and profitable, and generate a demand for certain materials that is incompatible with their reserves (Wouters and Bol 2009). Figure 2 presents the different risks concerning material supplies summarized by (Ashby, Balas, and Coral 2016).

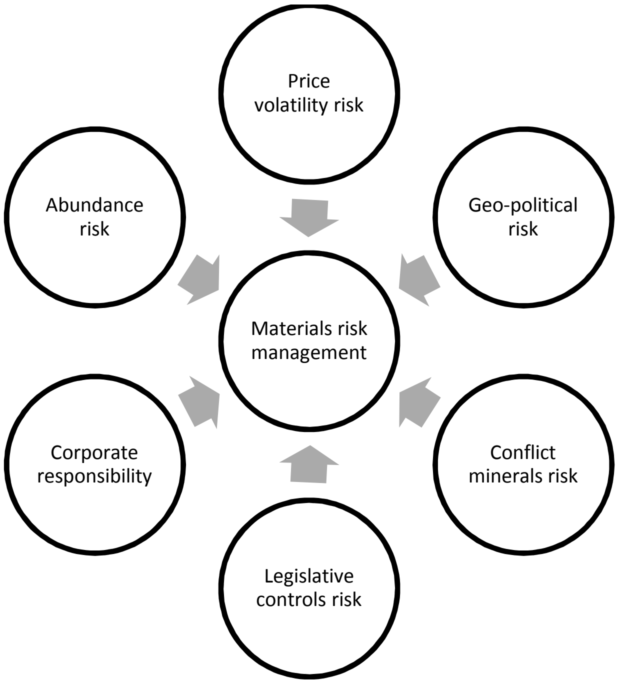


Figure 2: Constituents of material risk management (Ashby, Balas, and Coral 2016)

In their assessment of the risks to the supply chain associated with material availability, (Alonso et al. 2007) state that "over the long term, market forces and technology will effectively ensure that responses such as substitution and recycling will occur" in case of material scarcity or disruption. They also suggest that material selection decision-making is a means to develop a strategy to reduce vulnerability and mitigate material shortages. Nevertheless, integrating all the different variables at stake in the choice of materials has become a particularly complex task, often presenting contradictory trade-offs in regards to materials' value, availability and end-of-life management.

If certain studies are to be believed, the depletion of some resources seems alarmingly near. When depletion times are calculated by dividing current reserves (i.e. stocks that can economically be mined today) by current annual production (Graedel 2011), or by establishing peak production years (Sverdrup, Ragnarsdottir, and Koca 2015), data shows that several fundamental industrial metals only have a few decades of regular supply left. There is, therefore, a need to achieve material supply resilience by avoiding path dependence and sourcing lock-ins, anticipating, preparing, adapting and innovating in terms of material choices but also product design, so as to achieve greater resource efficiency. In this sense, the European Commission has defined resource efficiency as a key element of its sustainable development activities and describes it as “using the Earth's limited resources in a sustainable manner while minimizing impacts on the environment” (European Commission 2017).

1.1.3 From linear to circular thinking

Linear industrial processes can be summarized as the “take, make, dispose” paradigm and lifestyle that dominated economic development in the last two hundred years since the Industrial Revolution. Raw materials were extracted from the earth, transformed into products that were used and then disposed in landfills or incinerated. This open system that led resources to be discarded to the environment is consensually deemed obsolete.

In recent years, a lot of progress has been made in environmental awareness, from schools to businesses, with many environmentally-conscious practices becoming widespread. The public and private sectors started to recognize the importance of extending the use of materials beyond their first and sometimes only use. After a product is used and abandoned by its final owner, thus being considered waste, different waste management options are now envisioned such as reuse, remanufacturing, recycling, energy recovery and landfilling. A new paradigm, lifecycle thinking, has started replacing the linear model, especially in developed countries, and several tools and methods for its adoption by companies have since been proposed.

But taking into account all the impacts of a product’s lifecycle and establishing measures to mitigate them quickly proves to be insufficient since there are still losses due to waste. The next step forward is to consider waste as a resource for a new lifecycle and close material loops. This type of circular thinking is put forward as the most radical way of decoupling economic growth from environmental degradation (Webster 2013), even though the empirical and theoretical results (and the very notion of growth) are still in dispute (Paech 2013)[2]. It is the latest and most ambitious attempt to enhance the permeability of sustainable development in businesses by focusing on the positive effects it may have on profitability, competitive advantages and local job creation (Ellen Macarthur Foundation 2012; Webster 2013)

In what is known as a circular economy, industrial systems and flows become restorative and regenerative by intention and design (Ellen Macarthur Foundation 2012), in which “resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops” (Geissdoerfer et al. 2017). Figure 3 presents the flows envisioned by the circular economy.

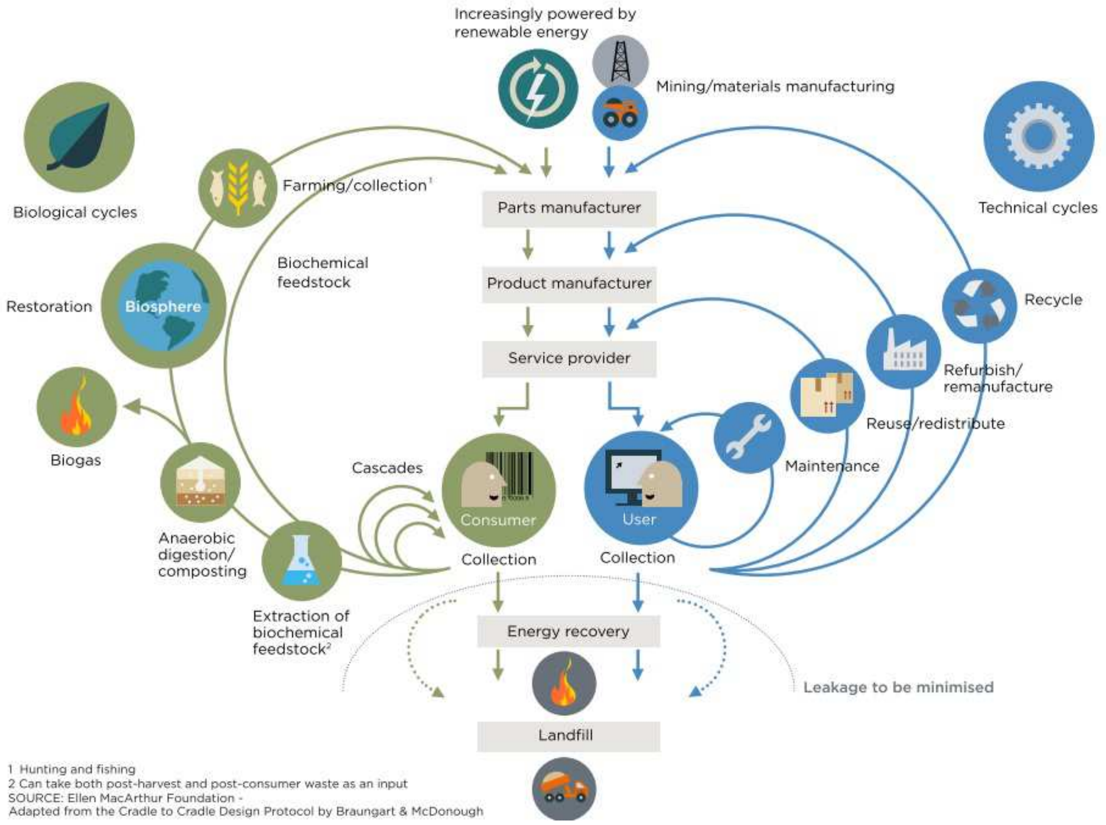


Figure 3: The flows envisioned by circular economy for the biosphere and the technosphere (Ellen Macarthur Foundation 2012)

[2] There are indeed critics of circular thinking that deem it another pointless remediation of a broken system, that shifts the focus from the real issue, i.e. that the consumption behaviours of industrialized society are unsustainable. To these critics, economic growth is a delusion that should not be used as a goal or a driver. This thesis does not take sides on this debate and concentrates on following a pragmatic point of view regarding production processes. For an interesting perspective on this, see Bihouix, P. *L’âge des low tech*. Editions Seuil, 2014; and Latouche, S. *Le pari de la décroissance*. Fayard, 2007.

The circular economy is a new concept that encompasses several previous efforts in lifecycle thinking and provides a holistic framework for companies, governments and society as a whole to understand the urgency and benefits of adopting this as a reference. Its origins stem from several schools of thought such as Regenerative Design, Performance Economy, the Cradle-to-cradle framework, the whole field of Industrial Ecology, and Biomimicry (Ellen Macarthur Foundation 2012). It focuses on showing that businesses can generate financial, social and environmental gains when managing their product cycles more thoroughly, especially regarding their materials after products are discarded. For that to be accomplished, it is now the object of initiatives from research centres and organizations, which are looking to operationalize this notion into tangible tools to be applied in the industry.

The permeability of the concept seems to be following a top-down approach, with the proposals of major think tanks and government agencies being transmitted to companies in the hope that they incorporate them. These initiatives started out at a more strategic level, with general concepts being put forward, and have progressively moved towards a more grassroots approach, with the day-to-day activities of the stakeholders in mind.

Though it is a relatively young field, with little to no research before the year 2000, there has been a recent surge in circular economy research, with China leading in country-specific studies, probably due to their 2009 circular economy strategy (Figure 4).

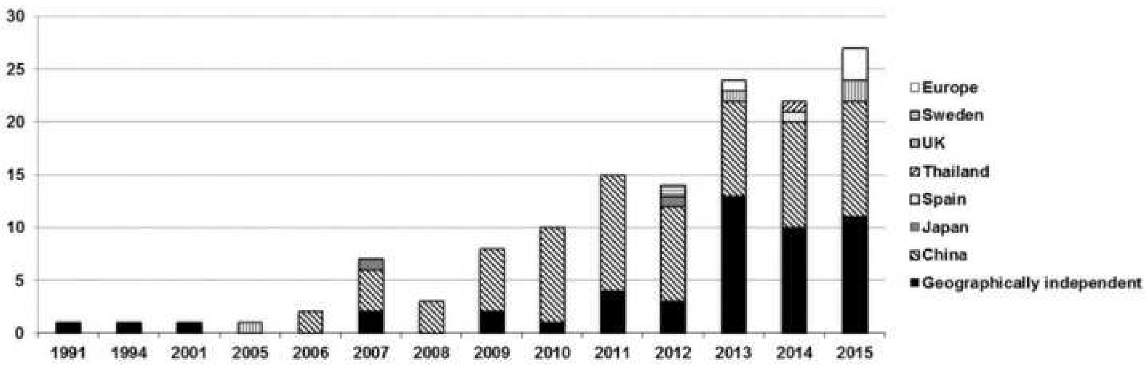


Figure 4: Distribution of academic publications including geographic focus in which circular economy has been published without specified research perspective (Lieder and Rashid 2016)

In this context of material uncertainties and impending scarcity, adopting circular economy strategies and Design for Recycling guidelines is important not only for the preservation of natural resources but also for the long-term economic well-being of companies in a world of global flows. Circular economy has served to reframe the waste and resource debate in order to encompass resource life-extending strategies to the way waste and resources are managed, thus facilitating additional value extraction and reducing value loss and destruction (Blomsma and Brennan 2017).

1.2 Focus and scope

The dynamics between the anthroposphere and the ecosphere have indeed become increasingly destructive and have provoked serious issues to both ecosystems and human health. These issues are quite serious and have been addressed in countless studies. However, the viewpoint of this thesis is not on the pressing environmental crisis but on another impact of industrial activity: material scarcity. With rising demography and the accompanying demand increase for energy and goods, the risk of material availability falling short has become very real and potentially very serious (Graedel and Erdmann 2012). This thesis thus focuses on understanding human industry and its use of the planet's resources, the so-called anthropogenic cycles of materials (as opposed to the natural, geogenic cycles).

This is the subject of different fields of expertise and grasped by different skill sets such as geological, environmental, geopolitical and economic specialists. In this thesis, it is tackled in the context of industrial engineering, based on its capacity to make several disciplines converge in the accomplishment of technical projects. In this research, product designers are seen as the first line of defence against material scarcity and towards a circular economy. They are the ones who decide which materials shall be used in producing the objects that compose our everyday life.

According to (Ciacci et al. 2015), "material dissipation is often by design, it is precisely in the design and manufacture of products that the most effective actions can be undertaken to avoid or reduce material losses". These material losses are intrinsically connected to the final stage of the product's lifecycle, its end of life or, as some have called it, its grave. This, however, is not consensually defined since it can mean both the final landfilling of discarded materials or include recycling and energy recovery operations (Domingo 2013). **The end of life is characterized in this research by the material cycling processes that return the materials into the economy to achieve circularity.**

Although a substantive amount of knowledge has been accumulated after decades of material cycling experiences, the information on the evolution of these ventures has not been thoroughly capitalized to inform design decisions for the benefit of all concerned industries. Yet, a separation remains among the actors of the different stages of material lifecycles (intervening from the beginning until the end of product or material lifecycles): designers do not know the stakes of recyclers and the latter cannot always accomplish full material recovery. Also, material selection tools often used in the design phase do not take into account the evolution of a chain's capacity to cycle materials and do not render the impact that material choices can have on the supply chain of a sector or a territory. Designers are not always made aware of the relative ease or difficulty in recovering these materials, which sometimes is a direct consequence of their choices. Product designers' lack of information comes up in the final stage of a product's lifecycle and feedback about material choices and the consequences to the end of the lifecycle rarely travels back the line to the designers.

Depending on different factors such as the industry sector, the size and culture of the company, the type of product and the local industrial network, design decisions are made by individuals working alone or in a design team. In this study, no distinction is made of these configurations and it is aimed at the decision-makers of the design process that have a say in material selection in particular, whether they are internal or external to the company. Likewise, decisions related to the material end-of-life are referred to the corresponding expert in the design process.

Materials are seen as the fulcrum of all engineering specialties, the physical embodiment of their concepts. As expressed by (Kindlein Jr, Ngassa, and Dehayes 2006), materials are the point of convergence and allow a dialogue between all actors of the product's lifecycle. Focusing on materials can open discussions about raw materials extraction, material properties and fabrication, the trends and evolutions of products, consumer behaviour, waste treatment strategies, among other issues.

1.3 Structure of the document

This thesis is structured in three parts, preceded by this introduction and followed by a general conclusion. In Part I, the research foundations are presented and examined in order to position the contributions of the thesis. Two areas of interest are explored: the flow of material cycles in the world economy, how they are observed and the main information they provide, particularly in regards to waste and the final stage of products' lifecycles; and the current state of material end-of-life (or cycling) expertise that is contemplated in product design. This state-of-the-art literature review is based on the macro and micro levels of circular economy implementation. A thesis statement is then made, with a research question formulated from two integration gaps that were identified in the literature review and the hypotheses for answering the research question.

In Part II, the contributions to the integration of material circularity in product design are exposed. First, the Design for Material Circularity method is introduced based on an indicator for circular material value that was conceived so as to follow the flow of materials beyond the first lifecycle. Then, a framework for the characterization of material cycling networks is proposed, laying the foundations for the systematization of data on material cycles for practical use on the aforementioned method but also to promote a better communication among stakeholders. This framework was applied to identify and analyse the pertinent parameters for the evolution of the open-loop recycling of eight different material flows.

In Part III, the Design for Material Circularity method is applied to two different and complementary case studies that illustrate and validate its use by product designers at different stages of the design process. The first case study consists in the evaluation of a simple monomaterial product – a 1,5-litre bottle container – at an early stage of the design process. In the second case study, a multi-material product comprising metals that are considered critical and important to carbon-lean energy technologies for future industrial use – a vehicular lithium-ion battery pack – is examined in order to find potential circularity hotspots as well as the best end-of-life scenario for value conservation after the first lifecycle.

Finally, the general conclusion provides a synthesis of the thesis with its limits and perspectives for future research. It shows how this study is a step towards integrating circular economy principles in product design by means of a dedicated method and framework to capitalize knowledge, opening up a new field for further research projects.

Part I: RESEARCH FOUNDATIONS

A long road has already been trodden since engineers and manufacturers started reflecting upon their production paradigms. From a strictly linear thinking, a new model began to take place in the industry in the last decades, encompassing what was first considered as an externality, i.e. parameters that were thought not to belong to the concerned issues. Thus, social and environmental matters were included into businesses. The straight line that ran from extraction to the landfill was bent and turned circular, as the lifecycles of products and their materials became a topic of interest for both researchers and industrialists.

(Allwood 2014) affirms that the aspiration for a circular economy is the new axiom and technical fix promoted in political and mass media discourses to simultaneously solve the environmental problems of current production systems while allowing economies to continue growing. It runs in parallel with the "(failing) search for the miracle of unlimited renewable energy supplies and the (forlorn) creating approaches to hiding (sequestering) undesirable outputs underground".

In this Part, the subject of circularity is analysed in light of the state-of-the-art literature in this field. First, in Chapter 2, the macro-level issues of circular economy are defined from the studies of material cycles in the anthroposphere. The notion of socioeconomic metabolism is introduced along with the recent material stock and flow assessments that have ultimately led to the identification of what are known as critical materials. Waste management (WM) networks are also described, as they are a major agent in creating the loops that are so desirable in circular thinking.

Chapter 3 explores circular economy from a micro-level perspective, rooted in manufacturing companies and the product design activity, focusing on the existence of a cycling expertise. The tenets of material sustainability in companies are first presented and the links between product design and material end-of-life are investigated, focusing on the present state of knowledge regarding the consideration of material cycles by product designers.

This literature review is concluded in Chapter 4, in which the gaps for the integration of material circularity in product design are identified, leading to the formulation of the research question that guided this research. Hypotheses and requirements for answering this question are then proposed.

Chapter 2: Macro-level circular economy – Material cycles in the anthroposphere

Economy and ecology share the same etymology, from the Greek root *oikos* meaning "house". In a sense, both fields are concerned with safeguarding and maintaining rare resources. Never before has the definition of these concepts been so important since the conservation of material resources is considered, alongside climate change mitigation (related, among other things, to carbon emissions into the atmosphere), the key environmental and economic challenge of this century (Flasbarth 2013).

Humankind's ability to transform and bend Nature to its creative will has never ceased to grow. It even seems to have accelerated in recent years, in such a way that concerns regarding the consequences of the age of science and technology began taking shape. According to (Allwood 2014), "reduce, reuse, recycle" (3R) is a critical and intelligent mantra for the future of material management but, in reality, the preference still seems to be "redouble, replace, recycle-a-bit-if-it's-easy, reject". Also, while material costs fell (mostly due to large-scale mining) and labour costs rose, the three Rs became uneconomic (Ashby, Balas, and Coral 2016).

In his seminal essay that is considered to have first introduced the notion of a circular economy (then called the "spaceman" economy in contrast to the previous, "cowboy" economy), back in the 1960s, (Boulding 1966) already touched on the apparent paradox between recycling and circularity objectives and proposed that, to counter society's insatiable demand for more goods, the measure of economic success should shift from annual flows (such as Gross Domestic Product) to stock-based material flows. In this sense, "lightweight, low-energy products over a long duration, with individual measures of success derived from quality of life, leisure, creativity, and other constructive values" should supersede the generation of economic growth and income alone (Allwood 2014).

This chapter presents the dynamics of material cycles in the economy. It begins with the basis of material flow accounting and its contributions to understanding the engine that drives anthropogenic cycles. Then, the concept of material criticality is introduced, a particular yet very troubling discovery from material flow analyses that affects certain strategic industries. Finally, waste management networks are described, considering that they are the fulcrum of circular material flows.

2.1 Socioeconomic metabolism: keeping count of human activity

According to (Fischer-Kowalski 1998), the concept of metabolism in biology refers to "a highly complex self-organizing process that the organism seeks to maintain in widely varying environments" and it "requires certain material inputs from the environment and it returns these materials to the environment in a different form". This definition, though originating from biological sciences, can be expanded to the material and energetic exchanges between entities in an ecosystem, their consumption of certain materials and subsequent transformation and production of other materials[3].

2.1.1 Material stocks and flows: a global view of material resources

Following the flows of materials in society is the first step in establishing a model for material availability and understanding the dynamics that drive material cycles. The main tool used in these studies is Material Flow Analysis (MFA) and, more recently, Dynamic Material Flow Analysis (DMFA). MFA is considered a fundamental industrial ecology tool and has many applications due to its very synthetic display of an element's transformations and exchanges in society or with the environment. It provides a quantitative partitioning of a material in its different life stages for a given region or time period and may serve as a solid basis for sustainability assessments (Dittrich, Bringezu, and Schütz 2012; van der Voet et al. 2009), urban planning (Müller 2005; Cherubini, Bargigli, and Ulgiati 2009; Obernosterer and Brunner 2001) or policy-making (Reimann et al. 2010). When performed on a local level, they offer information on the social mechanisms of management systems and the economic interactions with neighbouring regions, whereas analyses performed on a global scale – usually collected from several more local studies – portray general tendencies for material consumption and scarcity (Ermelinda M. Harper, Johnson, and Graedel 2006).

MFA can focus on elemental, molecular, substance and material flow analysis. The information stemming from MFA requires the analysis of energy, space and socioeconomic issues to be interpreted and put to use. MFA allows the identification of depletion and accumulation of material stocks, the estimation of waste flows and internal recycling loops, and the detection of

[3] The field of industrial ecology has brought this analogy to the forefront of industrial sustainability since the late 1980s by inserting an ecosystem *ethos* in all areas of human activity, becoming "the science of sustainability" (Graedel and Lifset 2015). It encompasses many concepts including circular economy and can be seen as the systematic optimization of industrial society (Allenby 1999).

environmental loadings and their respective sources. Classical uses range from resource management, waste management (by determining the composition of waste flows cost-efficiently) and environmental management. In industrial ecology, it can assist in controlling pathways for material use and industrial processes, creating loop-closing industrial practices, dematerializing industrial output, systematizing patterns of energy use and balancing industrial input and output to natural ecosystem capacity (Brunner and Rechberger 2005). The general model for a MFA is presented in Figure 5.

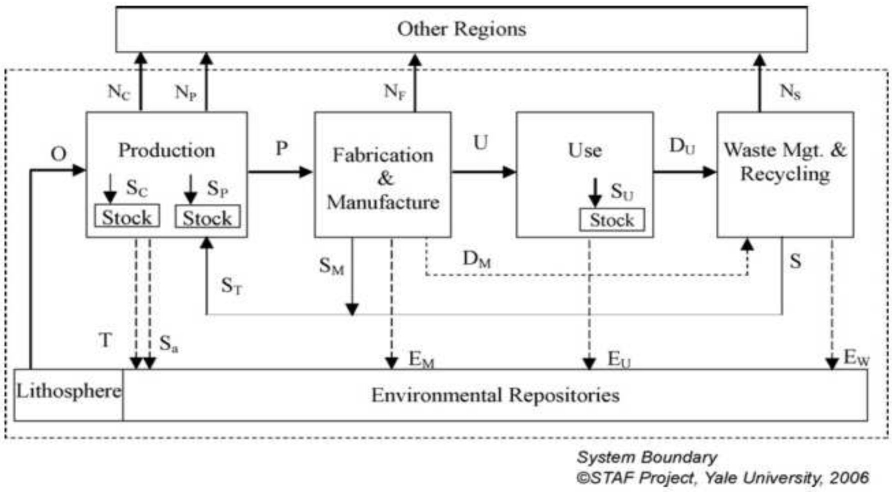


Figure 5: MFA general model (Mao, Dong, and Graedel 2008)

In this model, the environment provides ore from the lithosphere represented by the flow O. It receives different flows such as T (material contained in tailings), S_a (material in slag exchanges with the environment), E_M (material in emissions from fabrication and manufacture), E_U (material in use emissions) and E_W (material contained in waste management and recycling emissions). The production phase is characterized by the inputs from O and S_T (total material scraps in production, which one could consider to be total secondary production). Other than T and S_a, outputs from production are N_C and N_P (respectively, material in net export concentrates and material in refined net exports) as well as P (refined material). Stocks that remain in the production phase are represented by S_C (concentrate stock) and S_P (refined material stock). Here, fabrication and manufacture is a stage that only receives P as an input and does not accumulate stocks. It provides outputs in flows U (material entering use), S_M (scrap from manufacture), D_M (material contained in discards), N_F (material in net exports of semi- or finished products) and E_M. In the use phase, the input is U, stocks are represented by S_U (in-use stocks) and outputs are E_U and D_U (end-of-life material headed to waste management and recycling). Finally, the waste management and recycling phase receives D_U and D_M and provides S (scrap from waste management and recycling), N_S (material in net export of scrap) and E_W. This model, taken from a global MFA of lead (Mao, Dong, and Graedel 2008), can be adapted to fit other material cycles in which some flows appear, such as stocks in waste management and recycling or fabrication and manufacture, and others disappear. It serves as an example of the many flows that define a material anthropogenic cycle.

According to (Brunner and Rechberger 2005), MFAs have been applied in general to:

- Environmental impact statements;
- Remediation of hazardous waste sites;
- Design of air pollution control strategies;
- Nutrient management in watersheds;
- Planning of soil-monitoring systems;
- Sewage-sludge management;
- Modelling elemental compositions of wastes;
- Evaluating material management performance in recycling/treatment facilities.

But MFA can have different objectives and goals depending on the type of decision they support. Table 1 presents the general objectives of MFA, the goals for decision support in waste management, its dynamic forecasting goals, as well as the possible result evaluation.

Several MFA have already been conducted, constituting an extensive albeit not exhaustive database, each time reaching a handful of the complex objectives presented in Table 1. Many studies exist for specific materials, regions and timeframes and some attempts at a systematic and complete inventory have been undertaken such as the Stocks and Flows Project led by Prof. Graedel from the Center for Industrial Ecology at the Yale School of Forestry and Environmental Studies, which has been studying the anthropogenic cycles of many metals. However, the MFA database is still incomplete and, although studies exist for hazardous chemical substances (Long et al. 2013), plastics (Kleijn, Huele, and van der Voet 2000) and building materials (Müller 2005), it is quite concentrated on metal cycles. Analyses are also mainly focused on developed countries, perhaps due to information availability and reliability as the flows in these areas are generally more controlled and formally registered.

Table 1: MFA objectives, goals and result evaluation

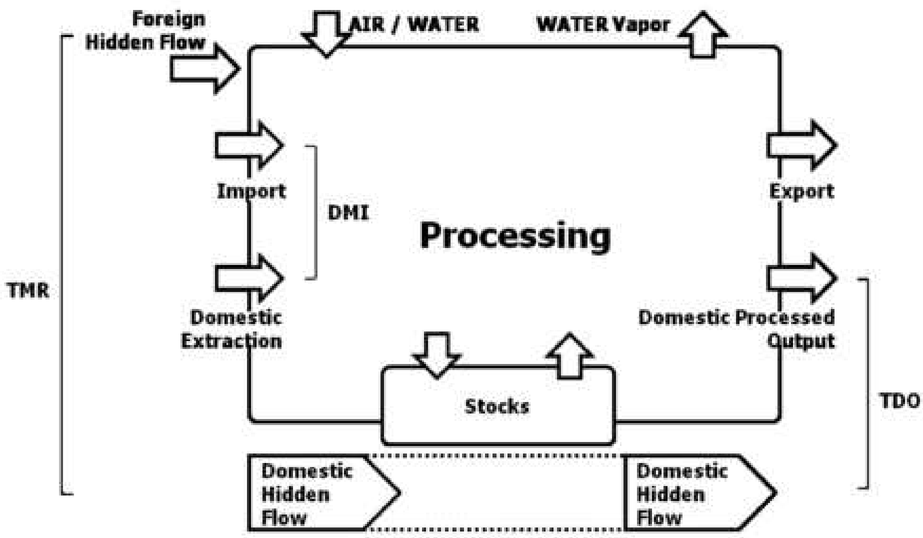
General MFA objectives (Brunner and Rechberger 2005)	**Goals for decision support in waste management** (Allesch and Brunner 2015)	**Dynamic forecasting goals** (Bertram, Martchek, and Rombach 2009)	**Result evaluation** (Brunner and Rechberger 2005; Allesch and Brunner 2015)
• Delineate system of material flows and stocks • Reduce system complexity while maintaining basis for decision-making • Assess relevant flows and stocks quantitatively, checking mass balance, sensitivities, and uncertainties • Present system results in reproducible, understandable, transparent fashion • Use results as a basis for managing resources, the environment, and wastes	• Assess and evaluate the performance of a current waste management system to obtain information about the distribution of materials (focus on related impacts and whether a system reaches set goals) • Describe and analyse a WM system for further assessments (focus on quantifying flows and stocks) • Compare different management systems or technologies • Early recognize beneficial or harmful changes of flows and stocks, for example, future accumulations or depletions of substances within a system • Evaluate and optimize WM systems	• Gain a better understanding of past and current material stocks and flows • Show change over time • Predict global future scrap flows and the extent to which future worldwide aluminium market demand will be met by recycling versus new smelter capacity • Develop scenarios for inventories of future industrial greenhouse gas emissions • Forecast the energy and ecological benefits of increased recycling rates, the use of aluminium products in energy-saving applications and potential improvements in industry efficiency	• Reveal the most important processes during the lifecycle of a material • Quantify resource potential to identify sources and pathways of valuable materials. Recycling potentials, reuse options, and reduction of landfill volumes are often investigated • Investigate environmental consequences by quantifying emissions to the hydrosphere, atmosphere, and pedosphere. Often, effects such as eutrophication and climate change are included • Evaluate the release of potentially hazardous substances to the environment or the incorporation of such substances in products to take into account risks for the environment and human health • The energy performance of WM and treatment is assessed to reduce energy consumption or to improve energy efficiency by new or advanced technologies

But MFA has shortcomings. (Hashimoto and Moriguchi 2004) state that, as a method for analysing material as product level, it has practical problems such as capturing by-products and used products, distinguishing between by-products and used products, and capturing product stocks. (J.-P. Birat 2012) proposes that in order to progress further in the future, the practice of MFA should be homogenized, possibly with a standardization procedure; layers of annual MFAs should be accumulated, with a more complex data collection to better encompass recycling and collection rates; and MFA methodology should extend beyond materials and substances (e.g. towards energy or consumer goods) to provide a global, geographical overview of any industrial flow of interest.

2.1.2 Major indicators of economy-wide material flows

Economy-wide material flow accounting is a method to analyse stocks and flows at a national level. They are usually employed to observe the effects of certain economic parameters on the consumption of material resources, sometimes even with international comparisons (OECD 2008a; OECD 2008b). It allows the direct and indirect calculation of several material flow-related indicators that describe the throughput and stock additions of material resources in a national economy, shown in Figure 6. According to the OECD, "while these material flow analysis based indicators are considered to be pressure indicators, they have proved to correlate closely with environmental impact potentials at the macroeconomic system level" (OECD 2008a). Uncertainties regarding these indicators can be calculated in different ways, the most sophisticated being statistical approaches such as sensitivity, probabilistic or fuzzy analysis (Schiller, Müller, and Ortlepp 2017).

MFA is an effective information source to rapidly assess data regarding material flows such as the available stock volume, annual extraction and consumption, as well as waste generated and recycled. It fuels the historical analysis of the recycling chains, saving up time from gathering recycling data across different sources. Data is usually comprehensively compiled for a given location and time frame. The process chain analysis also provides insight into the evolution of the different material chains, especially for the technical enhancements and economic viability of the recycling processes. MFA is essential to quickly access an important volume of data, compiled in a comprehensive manner that quantifies import and export rates, primary and secondary material production, stocks in the economy according to the applications therein, different waste management strategies as well as material dissipation.



Inputs	DMI[2] = Domestic Extraction + Imports[1]
	TMR[3] = DMI + Domestic Hidden Flows[4] + Foreign Hidden Flows
Outputs	DPO[5] = Emissions + Waste = DMI – Net Additions to Stock – Exports
	DMO[6] = DPO + Exports
	TDO[7] = DPO + Domestic Hidden Flows
Consumption	DMC[8] = DMI – Exports
	TMC[9] = TMR – Exports – Hidden Flows from Exports
Balance	NAS[10] = DMI – DPO – Exports
	PTB[11] = Imports – Exports
Efficiency	Material Productivity = Input or Output/GDP
	Resource efficiency of materials extraction = Unused[12]/Used (DMI) materials

Notes:
1. Import: The flows/fluxes across system boundaries
2. DMI: Direct Material Input
3. TMR: Total Material Requirement
4. Hidden flow: The material flow which doesn't import into manufacturing process
5. DPO: Domestic Processed Output
6. DMO: Direct Material Output
7. TDO: Total Domestic Output
8. DMC: Direct Materials Consumption
9. TMC: Total Materials Consumption
10. NAS: Net Additions to Stock
11. PTB: Physical Trade Balance
12. Unused: hidden or indirect material

Figure 6: Economy-wide material flow analysis indicators (Zhang 2014)

2.2 Critical materials: when scarcity gets troubling

The study of material flows has served to analyse and anticipate material shortages, so as to better manage material scarcity in general. This issue has become increasingly pressing in recent years, with globalized supply chains revealing the frailty of material sourcing networks. A study by the National

Research Council of the USA has gathered a few cases of recent supply disruptions that are shown in Table 2.

Table 2: Recent supply disruptions (Wouters and Bol 2009)

Year	Material	Major Source	Problem	Effect
1978	Cobalt	Dem Rep. Congo	Rebels invaded copper-cobalt mining region in Congo.	Rapid rise in price.
1993-1994	Antimony	China	Flooding was alleged reason though some industry sources believe Chinese suppliers withheld material to increase price.	Price per pound rose from USD 0.80 to USD 2.28 in 1995 and from USD 1.61 in 2005 to USD 2.25 in 2006.
1994	Titanium (rutile). Key in producing titanium metal.	Sierra Leone has one of the largest deposits of rutile.	Production suspended when rebels invaded mining sites.	Global shortage.
2001	Tantalite. Used for capacitors.	Australia	Closure of facility in Australia for long-term maintenance.	Shortage, price rise, and smuggling from central Africa.
2005	Tungsten	China dominates supply and restricts amount produced and exported.	Exports reduced due to alleged inadequate supplies within China, the largest consumer.	Steep price increase.
2005-2006	Rhenium. 65 percent goes to aerospace (jet engine blades and rocket nozzles).	75 percent from two companies—Molymet in Chile (50 percent) and Redmet in Kazakhstan (25 percent).	Redmet exports blocked due to dispute over debt with copper company that supplies Redmet.	Price rose from USD 1,000/kg to USD 6,000/kg. Known future production increases are already sold.

There is also the well-known case of the Chinese government's export quota of rare earth elements that generated an artificial shortage and a steep price increase in the late 2000s (Habib and Wenzel 2014).

The dynamics that define whether a resource is scarce or not are quite complex and involve a number of different metrics and estimations[4]. There are, nonetheless, several types of assessments that represent these dynamics in a straightforward manner. The ratio of reserves to annual extraction, known also as range, is the metric used to estimate the number of years that a certain

[4] See (Wouters and Bol 2009) for a deep dive into what composes material scarcity.

raw material will still be available (Wouters and Bol 2009). In addition, material scarcity is usually evaluated as the supply of a material versus its demand. (Wouters and Bol 2009) state that the demand of materials fluctuates more than its reserves and supply, roughly depending on:

- Present use of materials;
- Growth of the global population;
- Growth of the prosperity of people;
- Replacement of materials;
- Development of new products and emerging technologies.

With growing interest for materials with limited and sometimes very rare supply, some raw materials have become so scarce that they are considered critical. This notion of criticality also recognizes that there is a particular importance in these rare materials and that their affected markets are strategic to society. (Wouters and Bol 2009) quote a Dutch governmental report on material scarcity that provides a categorization for raw materials, dividing them into three categories:

1. Elements of hope, which are the most abundant elements in the Earth's crust;
2. Frugal elements, which should be used in a restrained manner, i.e. only utilized in mass applications if their unique properties are essential;
3. Critical elements, whose expected time period of availability is already quite short and are sometimes of great importance to society.

Several assessments of critical materials have been conducted, with different criteria being used to qualify material criticality (European Commission 2010; Erdmann and Graedel 2011; E.M. Harper, Kavlak, and Graedel 2012; Bustamante, Gaustad, and Goe 2014; Peck, Kandachar, and Tempelman 2015; Coulomb et al. 2015; Graedel and Reck 2015). The main concern regarding these elements is that critical and near-critical materials are usually applied in delicate or urgent applications such as clean energy, defence applications, electric vehicles, electronics and lighting (Gaustad et al. 2017).

In their review of criticality assessments, (Jin, Kim, and Guillaume 2016) identify the following dimensions in criticality determination methodologies:

- Demand (sometimes formulates as demand risk/growth, total annual purchase, raw materials demand of specific application);
- Supply (sometimes formulated as availability, supply risk, supply disruption potential, supply and price risk);
- Vulnerability/Exposure to supply restriction;

- Environmental implications/country risk;
- Importance or impact, which includes economic aspects (sometimes formulated as Importance in use or impact of supply restriction, importance to clean energy, impact of an element restriction on the company, economic importance);
- Recycling restrictions;
- Materials risk;
- Innovation.

(Mason et al. 2011) mention substitutability and society's addiction, which also seem important when evaluating the criticality of materials. Figure 7 presents a table of critical elements based on several criticality assessments.

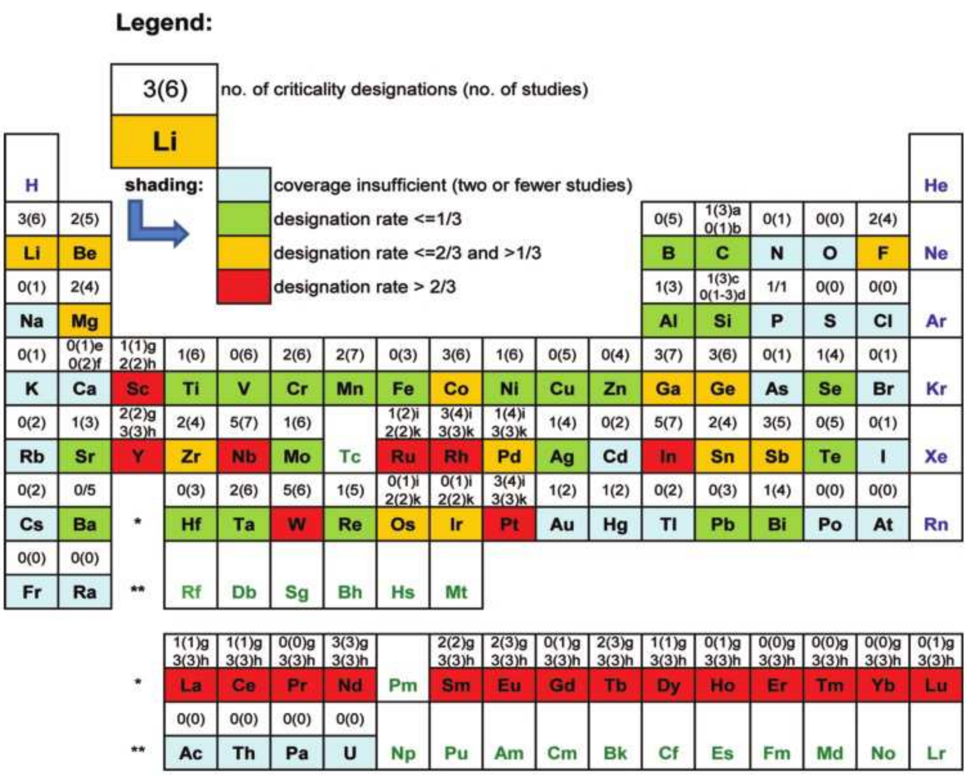


Figure 7: Frequencies of criticality designations and of coverage (in brackets) for materials addressed in seven selected studies (Erdmann and Graedel 2011)

(Gaustad et al. 2017) suggest that data information, recycling technology, substitution technology, and regulation are required elements for managing mineral and metals scarcity at a company level. They propose the following strategies to mitigate material criticality in businesses:

- Recycling, remanufacturing and reuse;
- Collection;
- Lean principles;
- Dematerialization;
- Diversity.

2.3 Waste management networks: it's not the end of the line

Material consumption in the USA exceeds 10t/person/year and averages 5t/annum on a global scale (Worrell and Reuter 2014). Managing waste is not only a way of improving resource efficiency from a material accounting point of view, but also a means of preventing or remediating material criticality. It is therefore important to understand what are the issues involved in avoiding these material inefficiencies.

The general model of an industrial lifecycle considers four main phases: material extraction, product manufacture, use, and end of life. This has been applied to both product flows (through lifecycle assessments) and material flows (in material flow analyses). However, the boundary between material and product flows in the lifecycle is not as clearly definable. Some mono-material products can be confounded with the material they are made of, such as firewood or a nickel coin. Some products have their own specific end-of-life industrial sectors and treatments so that they can almost be treated as a single "material" flow, as with tires and glass.

An open debate exists whether a product-centric approach to waste management should be favoured over a material-centric view. (J. P. Birat 2015) considers that the only kind of recycling that can be monitored over the long term and which will deliver measurable sustainability results is material-to-material. On the other hand, this is viewed as a complement to the preferred product-centric approach that considers the structures and joinings of complex designer minerals in products (UNEP 2013).

2.3.1 Extended Producer Responsibility

From a regulatory standpoint, there are specific laws that can enforce the collection and treatment of hazardous chemical compounds such as the RoHS Directive (Restriction of Hazardous Substances).

But the biggest waste management legislative overhaul came with the advent of Extended Producer Responsibility (EPR) in the early 1990s. By implementing administrative, economic and informative instruments, EPR implementation has effectively improved product design in encompassing lifecycle thinking, and enhanced collection, environmentally-sound treatment as well as reuse or recycling of discarded products (Rossem, Tojo, and Lindhqvist 2006).

The responsibility to properly manage waste flows can either be handled individually (when producers manage the end-of-life of their own products) or collectively (when a product group is managed regardless of brands, by producer groups). Although less frequent and facing tougher scrutiny, individual responsibility fosters design change more efficiently because the feedback loop to the manufacturer is more cost-effective, whereas collective responsibility dilutes the efforts of producers who invest in reducing environmental impacts and thus does not reward their investments (Rossem, Tojo, and Lindhqvist 2006).

Even though EPR systems exist throughout the world, they are much more developed in OECD countries[5]. However, even inside the European Union, there are large discrepancies in application and results (European Commission 2014).

2.3.1 Cycling strategies

(Rose 2000) provides a definition of end-of-life strategies[6] (Table 3) and (Movilla 2016) proposes a hierarchy that adds a dimension of material circularity in three levels: prevention of material waste, recovery and disposal (Figure 8).

(Bauer, Brissaud, and Zwolinski 2017) distinguish the different end-of-life or cycling strategies between those that preserve and those that destroy product and material added-value. Incineration and landfilling destroy both material and product added-value; recycling destroys the product's added value and only recovers its materials; remanufacturing maintains added-value but requires

[5] The existing networks and objectives are reviewed in depth in (European Commission 2014).
[6] The strategies to reinsert material resources in the economy after the products in which they were used are discarded are usually called end-of-life strategies or scenarios but can sometimes be referenced as schemes (Webster 2013), networks or programs (Movilla 2016). This study does not distinguish the specificities of each terminology.

standard remanufacturing operations to be performed in order to obtain a product with at least the same guarantees and performances of a new one; and reuse, which retains a high added-value and demands only a light remanufacturing process.

Table 3: Definitions of end-of-life strategies (Rose 2000)

NAME	DEFINITION
Reuse	Reuse is the second hand trading of product for use as originally designed.
Service	Servicing the product is another way of extending the life of a durable product or component parts by repairing or rebuilding the product using service parts at the location where the product is being used.
Remanufacture	Remanufacturing is a process in which reasonably large quantities of similar products are brought into a central facility and disassembled. Parts from a specific product are not kept with the product but instead they are collected by part type, cleaned, inspected for possible repair and reuse. Remanufactured products are then reassembled on an assembly line using those recovered parts and new parts where necessary.
Recycling with disassembly	Recycling reclaims material streams useful for application in products. Disassembly into material fractions increases the value of the materials recycled by removing material contaminants, hazardous materials, or high value components. The components are separated mostly by manual disassembly methods.
Recycling without disassembly	The purpose of shredding is to reduce material size to facilitate sorting. The shredded material is separated using methods based on magnetic, density or other properties of the materials.
Disposal	This end-of-life strategy is to landfill or incinerate the product with or without energy recovery

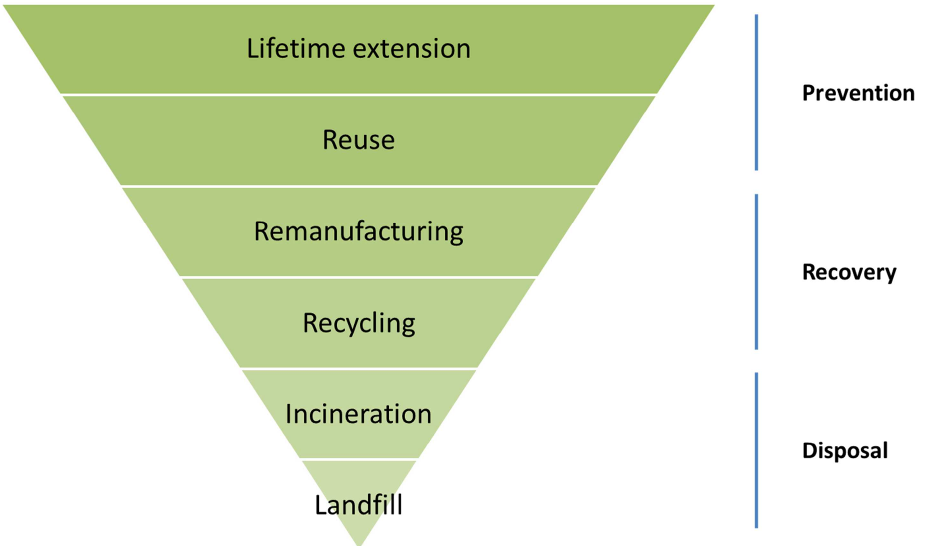


Figure 8: Waste management hierarchy (Movilla 2016)

There is also a distinction between **closed-loop and open-loop scenarios**. Closed-loop consists mostly of reuse, remanufacturing and closed-loop recycling, in which products or materials are not lost beyond the boundaries of the system. Open-loop involves products and materials flowing to different lifecycle systems (Yellishetty et al. 2011). This distinction is adopted throughout this research.

(Allwood 2014) proposes the following reuse strategy typology (in which remanufacturing is a special case):

- Reusing products as a whole via second-hand sales;
- Reusing components thanks to product modularity;
- Reusing materials from large components to make smaller components in the future;
- Diverting manufacturing scrap to an alternative use instead of recycling it.

2.3.2 Focus on recycling

For some decades, recycling activities have been increasingly promoted in the world first and foremost to reduce the amount of waste generated in urban areas that had begun occupying and posing sanitary issues everywhere. It is, by and large, the most widespread cycling strategy.

In an analysis of recycling models from the viewpoint of the technological process of economic systems in industrial societies, (Washida 1998) states that "recycling activities inevitably and irreversibly disperse some material, that is, complete recycling is impossible in industrial societies" even with "the best coordination of the economic system". Due to its energy-intensive processes, recycling is not free of impacts nor is it a universal panacea when compared to reducing demand or reusing materials. It generally involves property and quality losses, can sometimes require more energy than virgin production (in the case of certain alloys or in electronics applications), and is often at a stage of lesser technical optimization and economies of scale in order to effectively compete with virgin production (Allwood 2014).

According to (Gaucheron 2000), who was analysing the automotive plastic parts recycling sector, a component in a product will be recycled if:

- There is a sufficiently large collectable waste deposit from which to draw;
- There is a network that accepts this component;
- It can be liberated with minimal pollution;
- Its apparent density allows a financially feasible transportation.

These statements still hold true to this day and can be extended to all types of materials (Washida 1998) proposes the feasible condition of recycling in a given recycling sector and industrial sector, considering their interactions, to be met if the inequation below is satisfied:

$$a_{rk} < \frac{1 - a_{kk}}{a_{kr}}$$

in which a_{kk} is the amount of industrial product required to produce one unit of itself in the industrial sector, a_{rk} is the amount of recycled resources required to produce one unit of an industrial product, and a_{kr} is the amount of industrial products required to produce one unit of recycled material. If the above condition is satisfied, it is always worthwhile to activate the recycling sector.

Waste recycling usually consists of four steps: collection, sorting, shredding and regeneration. In the collection stage, waste may still follow a product stream through Extended Producer Responsibility legislation. It may also already be a distinct material flow (e.g. glass when specific collectors are available). The collection of recyclable materials is usually designed to avoid unnecessary stream complexity. Eventually, waste products are separated into their individual material components, if possible. Pre-sorting is usually optimized by “the collection system costs and structure, location and process capabilities of treatment facilities, and economic incentives available for different actors” (Heiskanen 2014). At this point, the value of waste is addressed in terms of the materials it contains and only elements and compounds that merit the high cost of final processing are regenerated. This entails a particle size reduction allowing a more efficient (and automatized) separation based on the physical property differences between the particles. Further purification by chemical or metallurgical means can then be applied (Heiskanen 2014).

While recycling as an industrial activity has grown constantly in the last decades (van Beukering 2001; Eurostat 2010), in some cases there seem to be limitations to its progression given by technological and institutional constraints (van Beukering 2001).

(Hagelüken 2012) proposes seven conditions for effective recycling:

1. Technical recyclability;
2. Accessibility of the material in the product;
3. Economic viability;
4. Collection mechanisms;
5. Material input (or loss) in the recycling network;
6. Optimization of technology and organisational configuration;
7. Sufficient capacity.

The geogenic (primary winning) and anthropogenic (secondary recycling) process chains of metals are not always clearly separated from each other according to (Rombach and Friedrich 2014), i.e. metals recycling processes are essentially the same as extractive processes that use ore as an input. Thus, the waste of electric and electronic equipment (WEEE) can be considered a complex form of man-made mineral, for instance (van Schaik and Reuter 2014a). However, while concentrations are already higher in waste than in mineral deposits (Johnson et al. 2007), there are significant differences in terms of industrial optimization and scaling that can hinder recycling activities.

A great effort has been made by the United Nations Environment Programme to collect and compile recycling indicators on metals based on their lifecycle and flows (Figure 9). These indicators include:

- old (post-consumer) scrap collection rate (CR), i.e. the volume of collected waste (e) divided by the volume of discarded material (d): CR = e / d
- recycling process efficiency, i.e. the volume of recycled material (g) divided by the volume of collected waste: g / e
- end-of-life recycling rate (EOL-RR), i.e. the volume of recycled material divided by the volume of discarded material (if the recycled material is reinserted in the same lifecycle it is deemed functional, otherwise, it is non-functional): EOL-RR = g / d or f / d
- recycling content (RC), which can be assimilated to the recycling input rate, i.e. the fraction of secondary metal in the total metal input: RC = (j + m) / (a + j + m)
- old scrap ratio (OSR), i.e. the fraction of old scrap in the recycling flow: OSR = g / (g + h)

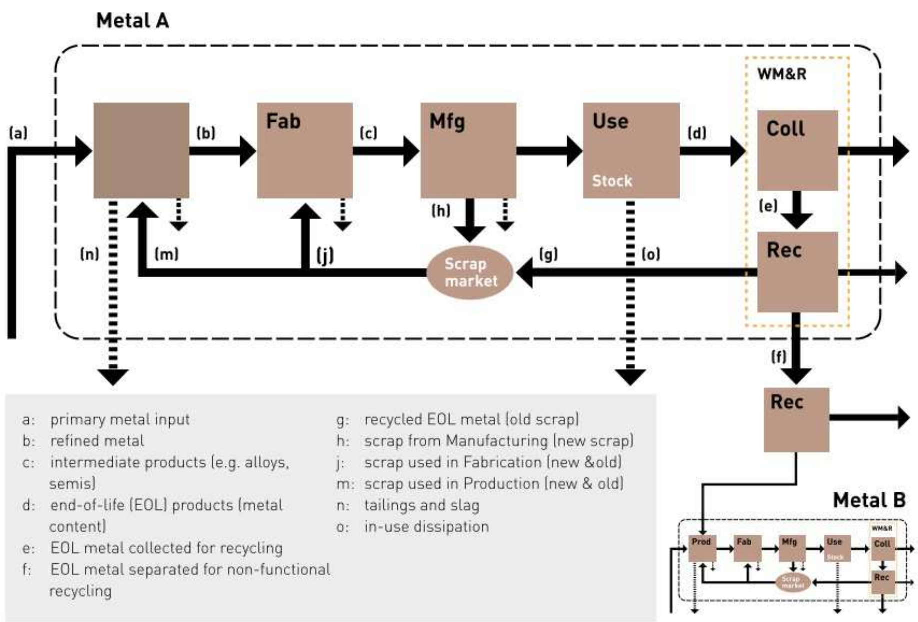


Figure 9: Metal lifecycles and flows (UNEP 2011)

Unfortunately, there is no compilation as extensive as this one for other material classes than metals.

(Graedel and Reck 2014) state that recycling indicators can serve the following purposes, regarding resource efficiency:

- "Determine the influence of recycling on resource sustainability by providing information on meeting [material] demand from secondary sources;
- Provide guidance for research needs on improving recycling efficiency;
- Provide information for lifecycle assessment analyses;
- Stimulate informed and improved recycling policies."

However, the same authors assert that these promising attributes of recycling cannot always be achieved since data acquisition and dissemination for the quantitative efficiencies of recycling is not very well characterized nor vigorously pursued.

In their study of the Swiss waste management system, (Haupt, Vadenbo, and Hellweg 2017) conclude that collection rates and intermediate recycling rates (i.e. the input into the recycling process, without the collection impurities) are not suitable as a performance indicator for a circular economy. The former does not provide any insight into how much actually becomes a secondary resource or what the downstream applications will be, while the latter does not inform what are the recycling efficiencies or the quality of the secondary material. The authors state that open- and closed-loop recycling rates should be used in circular economy assessments of waste management systems.

The biggest motivation of these businesses is often the cost-effectiveness of the solution adopted for the treatment of waste (Grimaud, Perry, and Laratte 2017). This has detrimental impacts on recycling and closed-loop scenarios. The authors propose a database for evaluating and comparing recycling processes that can be used by product designers in their decision-making processes (Table 4).

Table 4: Parameters and technical performance indicators for elementary recycling processes, adapted from (Grimaud, Perry, and Laratte 2017)

Category	Parameters	Performance
Shredding	Size reduction Density Flow	Fineness
Separation	Particle size Composition Flow	Purity Capture
Transport	Particle size Density Flow	Rate of flow

2.4 Conclusions on the use of anthropogenic cycle information for product designers

MFA can be used by companies to understand their corporate and regional material flows, energy consumption, and the environmental impacts generated by their activity. It is especially important in the case of companies operating in regions with limited raw materials and expensive energy.

Most MFA studies are static and contained within a given region and timeframe, even if dynamic models are increasingly available. Moreover, static and dynamic MFA provide little to no contextual information and authors generally infer the circumstances that have shaped the flows and hypothesize their interpretations. To complement and confirm the inferences from the MFA, a comparison with historical data is needed. A look back to the origins of the material flows, and particularly of their end-of-life management, can clarify which contextual elements have an influence on the anthropogenic cycle and, ultimately, the availability of a given material. **Stakeholders such as government agencies, eco-organisms, waste collectors and recyclers can provide empirical information, both qualitative and quantitative, to and from the industry**.

MFA is considered a broader form of lifecycle analysis (Fritsche 2013). It reduces the complexity of a system but still remains a reliable, transparent and highly-visual quantitative tool. It allows the quick assessment of a considerable amount of data, compiled to translate the applications, stocks and flows of primary and secondary materials in a time and place. However, MFA as a tool for decision-making support, it is still more useful at a macro level (Reimann et al. 2010) and is often used to describe the evolution of a material as it crosses a given system, lacking indicators to detail the material's lifecycle inside that system (Hashimoto and Moriguchi 2004).

Moreover, if certain studies are to be believed, the depletion of some resources seems alarmingly near. When depletion times are calculated by dividing current reserves (i.e. stocks that can economically be mined today) by current annual production (Graedel 2011), or by establishing peak production years (Sverdrup, Ragnarsdottir, and Koca 2015), data shows that several fundamental industrial metals only have a few decades of regular supply left. There is, therefore, a need to achieve material supply resilience by avoiding path dependence and sourcing lock-ins, anticipating, preparing, adapting and innovating in terms of material choices but also product design, so as to achieve greater resource efficiency. In this sense, the European Commission has defined resource efficiency as a key element of its sustainable development activities and describes it as "using the

Earth's limited resources in a sustainable manner while minimizing impacts on the environment" (European Commission 2017). **Resource efficiency aims at dematerializing production and dissociating value from material input. The connections between material value and the product's lifecycle should, therefore, be highlighted to product designers, especially regarding the potential circular material flows**.

Chapter 3: Micro-level circular economy – Product design and cycling expertise

Designers are facing interesting times. They are expected to constantly provide technological innovations that enhance everyday life, improve production systems, create value and minimize environmental impacts such as material scarcity on a local and global scale. The increasing demand for manufactured goods and energy resources in developing markets in Asia, Africa and Latin America has led to an intensification of the consumption of commodities in general and some materials in particular. Many of today's information and communication technologies, as well as most carbon-lean energy systems, depend on materials whose future availability is uncertain at best. Moreover, industrial use and society may sometimes be "addicted" to a given material when it is present in a broad or key range of applications (Mason et al. 2011). In this case, if alternatives are not readily available, it is necessary to plan ahead so as to evaluate how sudden changes in supply and demand can affect future material availability.

This chapter discusses the implementation of circular economy strategies at the micro-level, i.e. in manufacturing companies. It focuses on establishing the relationship between product design and the expertise regarding material cycles. First, the notion of sustainability in its application to businesses is introduced. Then, product design activities are presented, highlighting the distinct viewpoints that are integrated into the decision-making processes of product designers when addressing the issue of waste. Finally, the recent steps toward circular design, i.e. the incorporation of circular economy principles in design methods, are identified and analysed.

3.1 Sustainability in businesses: when companies go green

Corporate social responsibility and sustainability have definitely become a part of businesses in recent years, being associated with brand value and trust, despite not always playing a pivotal role in company strategy. Previous management systems had the tendency to focus on site environmental compliance issues rather than natural resources, transportation, distribution and consumer behaviour, which would secure more benefits in terms of environmental and business performance (Kemp, Stark, and Tantram 2004). However, Environmental Management Systems standards (e.g. ISO 14001:2015 (International Organization for Standardization 2015)) are evolving from a general approach of impact mitigation within the company to a more detailed integration of product eco-design in ISO 14006:2011, which comprises lifecycle thinking and even value chain involvement, with a clear indication that information exchanges among stakeholders are required.

(Ashby, Balas, and Coral 2016) suggest a multi-layered approach to deal with complex systems involving many disparate entities and fields of knowledge such as sustainable assessment in companies, composed of 5 steps:

1. Problem definition (articulation statement)
2. Identification of stakeholders and their concerns
3. Fact-finding
4. Synthesis (interpretation of the facts)
5. Reflection

In practice, each subsequent layer should be informed by the previous one, even if the process does not always follow a linear sequence. Many other approaches can be found in the literature and within existing standards, and their applications vary from one context to the other. With the concept of material scarcity in mind, the contributions of sustainable supply chain management and material flow management are presented in the next sub-sections.

3.1.1 Sustainable supply chain management

Materials have properties that are used in products whose functions fulfil human needs. (Daigo et al. 2014) propose a framework based on material properties to more rationally assess how human needs can be met with the least environmental impacts. This obviously prompts many questions to material-dependent companies regarding the stability and sustainability of their supply chain.

Sustainable supply chain management is "the management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all dimensions of sustainable development, i.e. economic, environmental and social, into account, which are derived from customer and stakeholder requirements" (Seuring and Müller 2008). Its implementation is triggered by stakeholders in general, customers and government in particular, and passed on by the focal company to its suppliers (Seuring and Müller 2008). Table 5 presents the main pressures and incentives for sustainability in supply chains.

Table 5: Pressures and incentives for sustainability in supply chains (Seuring and Müller 2008)

Pressures and incentives	Number of papers (N=191)	Frequency (%)
Legal demands/regulation	99	52
Customer demands	96	50
Response to stakeholders	90	47
Competitive advantage	71	37
Environmental and social pressure groups	38	20
Reputation loss	30	16

This observation indicates that a large range of drivers exist for companies to adopt sustainable practices in their supply chain management, chief among them regulatory and customer demands as well as response to stakeholders. Competitive advantage, environmental and social pressure groups as well as reputation loss are nevertheless also present in the studies and should not be understated. Any contribution to the issue of material sourcing should consider this distribution of pressure points in company drivers.

3.1.2 Material flow management

(Lieder and Rashid 2016) point out that for circular economy implementation to succeed, there must be concurrent top-down, national-level efforts (from society, legislation and policies) and bottom-up individual company-level efforts (from manufacturing industries, looking for profitability and a competitive edge).

The material flow management approach developed in Germany by the “Material flow management and recovery systems” working group, which aims at providing a “new economically sound closed-loop supply chain option” by simultaneously reducing material-related environmental pollution and optimizing resource expenses, divides material flow stakeholders into two main categories, direct and indirect, and these are further subdivided into five stakeholder types (Table 6).

Table 6: Material flow stakeholders (Enzler 2006)

Category	Stakeholder type	Examples
Direct	Economic stakeholders who directly influence material flows	People or departments in production companies
Indirect	Economic stakeholders whose decisions influence the materials-related decisions made by other stakeholders	Purchasing and marketing departments of commercial companies, banks and insurance agencies
	Economic stakeholders who set the framework conditions for the material flow management of a sector, industry or production chain	Sectoral or industrial associations and cooperative structures
	Stakeholders who set and organize the political framework conditions for the material flow management of economic stakeholders (the previous three types)	Competent government agencies or administrations
	Other stakeholders who influence the material flow management of all other stakeholders	Consumer organizations, environmental protection associations, standardization institutions and other NGOs

Product designers are at the centre of this material flow stakeholder network. They have direct agency on production decisions but also incorporate information from indirect stakeholders (sectoral associations, government agencies, standardization institutions etc.) and provide recommendations to purchasing and marketing departments, for instance.

3.2 Product design and waste: an integrative approach

A traditional product design workflow is composed of 6 stages – design brief, conceptual design, embodiment design, detailed design, manufacture and usage of the product – with varying requirements of material and processes (including transportation). Broader information is required at the early design stages, growing more detailed by the end of the design process. Figure 10 is a simple illustration of the design flow published in 2004 showing the iterative nature of the process. Critical product design decisions have a profound impact on subsequent stages of the product lifecycle, as illustrated by (Rose 2000) in Figure 11.

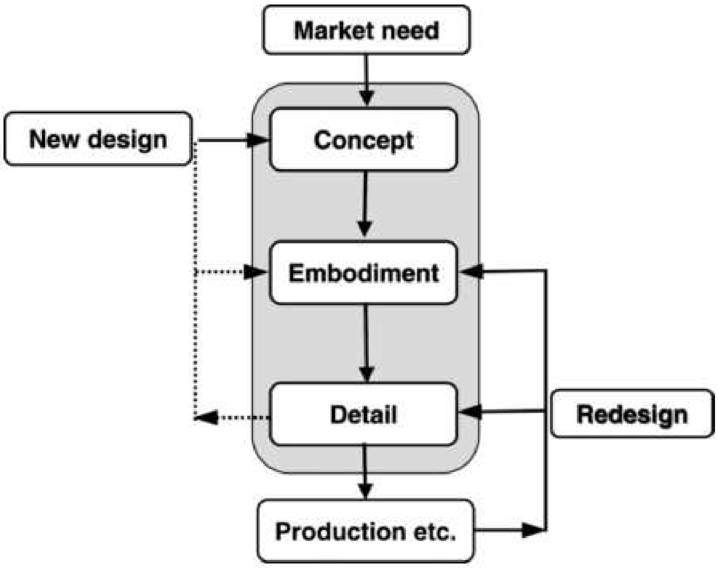


Figure 10: The design flow chart. Materials and processes information is required at every step - breadth at the top, detail at the bottom (Ashby et al. 2004)

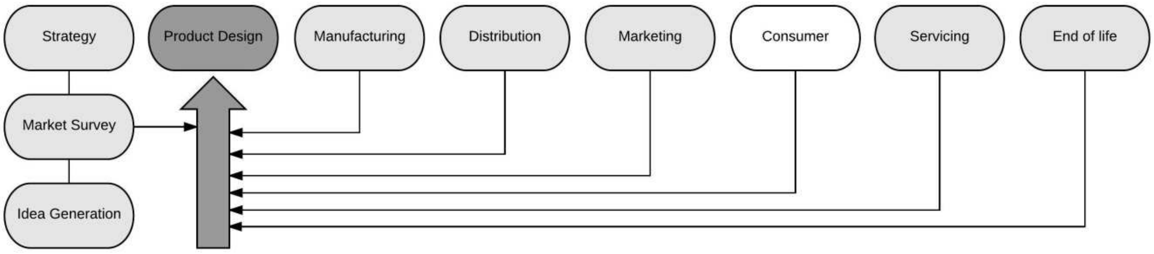


Figure 11: Representation of lifecycle impact decisions made during the design process of a product (Rose 2000)

In the last decades, product design has integrated requirements from all fields affecting industrial companies, in the search for more productivity, efficiency and, more recently, lesser environmental impacts. Several methods already exist to integrate different aspects of the product's lifecycle when designing it. These specific design methods that focus on particular aspects of the product lifecycle are known as Design for X (DfX). (Rose 2000) and (Kuo, Huang, and Zhang 2001) performed a literature review that identified the following applications:

- Design for Assembly
- Design for Manufacture
- Design for Disassembly and Design for Recyclability
- Design for Environment
- Design for Life-cycle
- Design for Quality
- Design for Maintainability

- Design for Reliability
- Design for Serviceability
- Design for Process/Producibility
- Design for Product Retirement
- Design for End-of-Life
- Design for Product Variety
- Design for Supply Chain

Each of these tools is unique and each brings relevant data to the early design stages. Generally speaking, DfX methods usually provide guidelines for product designers "to adapt the product to environmental demands and address the environmental targets to improve" (Zhang 2014).

Lifecycle thinking started to get traction when studying manufacturing activities, as it provides insight into the material and energy needs and their respective impacts in every stage of a product's life, from the extraction of raw materials to the disposal of the waste it generated. This led to the development of methodologies and guidelines to improve the product's design and production process in order to fulfil the same functions with less harmful effects throughout the whole lifecycle. These lifecycle assessment methods usually keep track of the environmental impacts of a product's lifecycle in order to support and steer design decisions. However, the cause and consequence link is hard to establish during product design, as the diversity of expertise involved brings collateral impacts. Ideally, DfX methods should be used in synergies. Their application should be eased by the support of appropriate information systems. In practice, the information systems are heterogeneous (e.g. different syntax and format of data) and are not adequate to rapid information exchanges between product designers and the environmental expertise that assesses the environmental impact of the product being developed. In this sense, (Rio, Reyes, and Roucoules 2014) have proposed a model federation-based information system method (the FESTivE Method). This method aims to improve the flexibility of information exchanges between product designer activities (including material expertise) and environmental experts' information systems.

In a bottom-up perspective of information exchanges, (T. A. O. Wang and Mu 2007) note that the data quality declines when moving from the production and manufacturing phase towards the waste management phase. Their study concerns iron, which is one of the best known and documented material flows, meaning that other material lifecycles find themselves in a similar – if not worse – situation.

The following sections present the different perspectives that have been developed in literature to integrate waste management in the design process.

3.2.1 Value-centered design decisions

Value is the measurable characteristic of an object that is susceptible to be traded, desired or sold (Gaucheron 2000). According to (Delafollie 1992), value analysis[7] is a design method that musters quality optimization and cost minimization in the development of products, thus meeting client expectations while reducing resource consumption. Unlike previous cost reduction methods based on increased yield and productivity, it requires what is called "functional analysis" in order to preserve a product's quality: instead of focusing on improving the manufacture of a product, the design of the product is reassessed in terms of its requirements and functions so as to eliminate useless (and costly) functions. The term value engineering is used if the method is applied to the development of a radically new product.

Value analysis is by definition a multidisciplinary activity that requires the participation of different areas of the company: marketing and sales, purchases, design, manufacture and maintenance. In certain cases, value analysis can guide corporate strategy by establishing long-term goals in terms of the functional improvements that can be achieved by maximizing the value of products (Chevallier 1989). In corporate functional analysis, economic, temporal and human criteria exist to ensure that the result meets the company's objectives.

Value is commonly expressed as the ratio of functions to costs:

$$\mathcal{V} = \frac{functions}{costs}$$

[7] Historically speaking, this method originated as a consequence of material scarcity, during and after World War II, when General Electric's purchasing manager Lawrence D. Miles realized that, by concentrating on the functions required to meet the client's demands before developing the product, he could reduce costs by purchasing cheaper materials (Chevallier 1989).

If the functions are the expression of a specific requirement, then value is the satisfaction of this requirement divided by the costs to fulfil it:

$$\mathcal{V} = \frac{satisfaction}{costs}$$

It can also be regarded as the ratio of quality divided by cost:

$$\mathcal{V} = \frac{quality}{costs}$$

A function that fulfils a given requirement is known as a service function. A product may also have technical functions, i.e. internal functions among its components that were chosen by the designer to provide the service functions. There are three types of service functions: the main function, the secondary functions and the restriction functions. Usually, when performing a full value analysis, one must start with the use value, given by the ratio of use performance divided by market price from the user standpoint; followed by the intended functional value, which is the expected technical performance divided by the intended cost; and lastly the product value, given by the measured technical performance divided by the actual cost (Chevallier 1989).

The value of a given material depends on several factors regarding supply and demand issues. Supply is defined by the raw materials' extraction and production processes. In the case of ceramics and metals, geological occurrence and concentration are key factors that involve geopolitical relations and may be a cause for concern in some cases, especially when few countries possess the bulk of reserves. Mining activities also depend on long-term capital-intensive investments that are usually based on feasibility studies attempting to anticipate profitability and market fluctuations. Some ceramic materials and most metals are the by-products of the extraction of major carrier metals that constitute the ore and have less efficient processing rates. Price increases of these companion materials may encourage the improved recovery of these materials (Graedel and Erdmann 2012). In the case of polymers, the fluctuations of fossil fuel reserves affect supply to the point that investments in plastic recycling and the so-called bio-plastics may be fostered or hindered depending on the rise and fall of oil prices.

Today, value proposition is at the centre of circular business models (Lewandowski 2016). (Ellen Macarthur Foundation 2015a) has developed a framework to translate the principles of circular economy into value-centred guidelines. It is composed of six business actions: REgenerate, Share, Optimise, Loop, Virtualise and Exchange (ReSOLVE). Figure 12 provides examples for each of these actions.

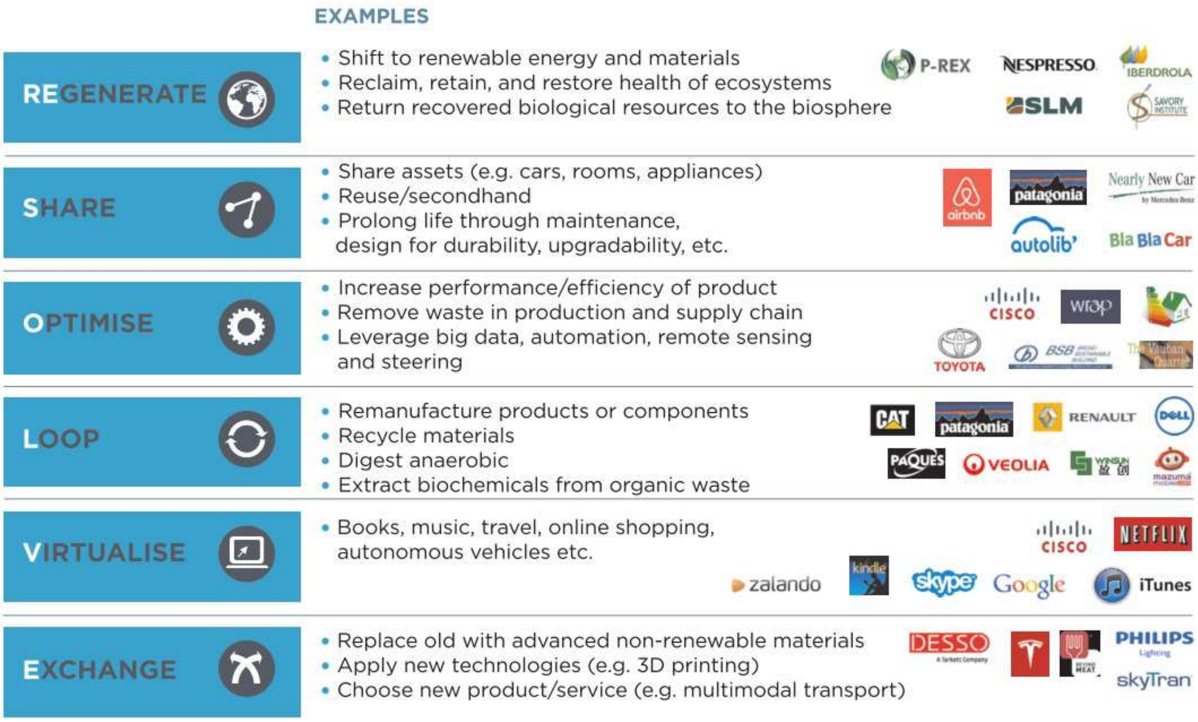


Figure 12: The ReSOLVE framework for circular business actions developed by (Ellen Macarthur Foundation 2015a), with examples for each principle

This framework encompasses a broad range of contexts and industries. It converts concepts for sustainable (or circular) industries such as sustainable supply chain, functionality economy, sharing economy, dematerialization, design for long lasting and other DfX, into guidelines for companies. This initiative has importance for corporate awareness and advocacy at strategic levels but does not provide (yet or in this form) a compilation of tools to implement these value-centred actions.

3.2.2 Environment-centred design decisions

Depending on the scope, environment-centred design practices have different nomenclatures: green design, cleaner production, environmental management system, end-of-pipe control, and eco-design (Figure 13). (De los Rios and Charnley 2017) have produced a taxonomy of eco-design approaches that indicates their respective focus, strategies and design methods (Table 7). (Ashby, Balas, and Coral 2016) indicate that industrial approaches to integrating natural ecosystems vary with the time and spatial scale involved, from the least ambitious pollution control and prevention (P C and P) to sustainable development (Figure 14).

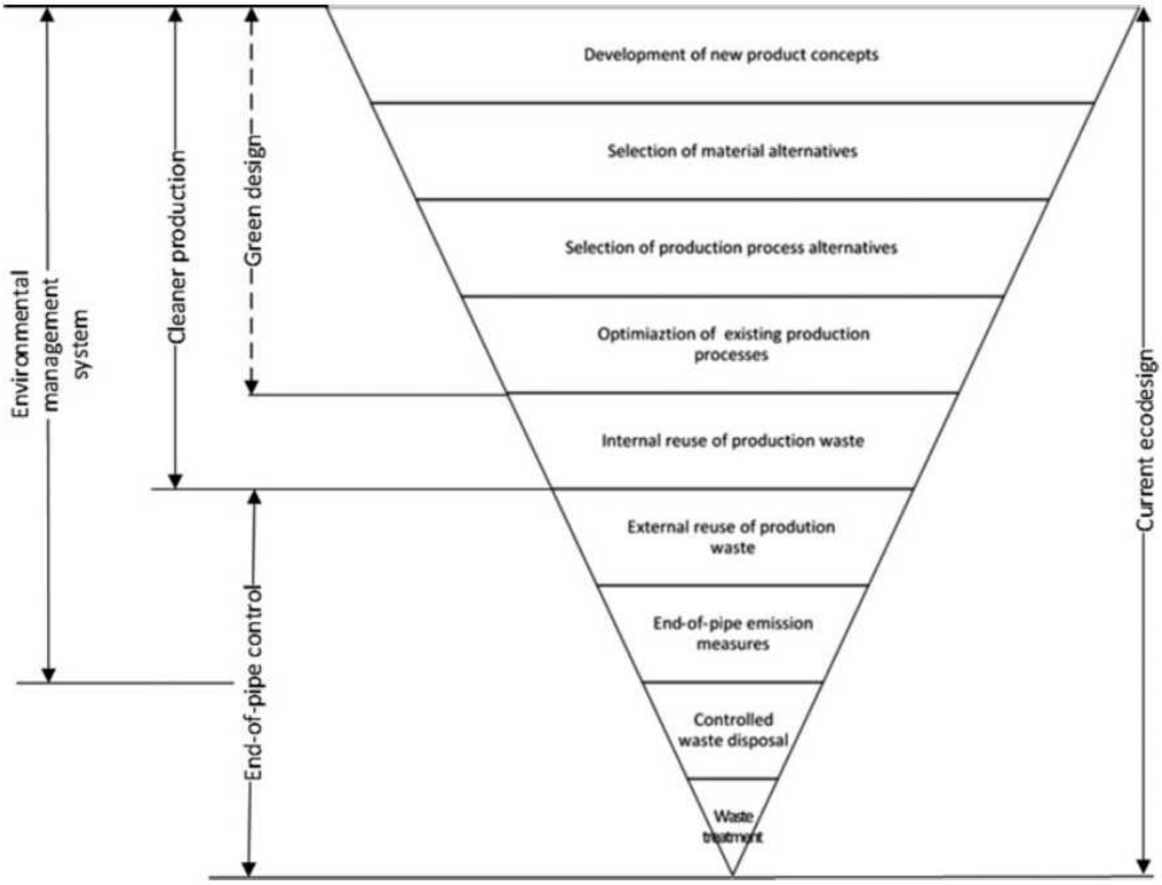


Figure 13: Scopes of green design, cleaner production, environmental management system, end-of-pipe control, and eco-design (Li, Zeng, and Stevels 2014)

Table 7: Taxonomy of design approaches for a sustainable industry (De los Rios and Charnley 2017)

APPROACH	FOCUS	STRATEGY	DFX / METHODS
WHOLE SYSTEMS DESIGN	SUSTAINABLE SYSTEMS	Radical innovation for sustainability	
DESIGN FOR ENVIRONMENT (PREVENTIVE)		Reduced environmental backpacks	Design for Supply Chain
	ENERGY CONSERVATION		Design for Manufacturing and Assembly
		Clean energy consumption	Biomimicry
	MATERIAL CONSERVATION	Material selection for sustainability	
DESIGN FOR LIFE CYCLE	DESIGN FOR EXTENDED LIFE (LONGER LIFECYCLES)	Design for Reliability	Design for Quality
		Design for Maintenance	Design for Repair / Refurbishment
		Design for Reuse	
			Design for Upgrading
	DESIGN FOR END-OF-LIFE (MULTIPLE LIFECYCLES / CRADLE TO CRADLE)	Design for Component Recovery	Design for Remanufacturing
		Design for Material Recovery	Design for Recycling
			Design for Cascaded Use

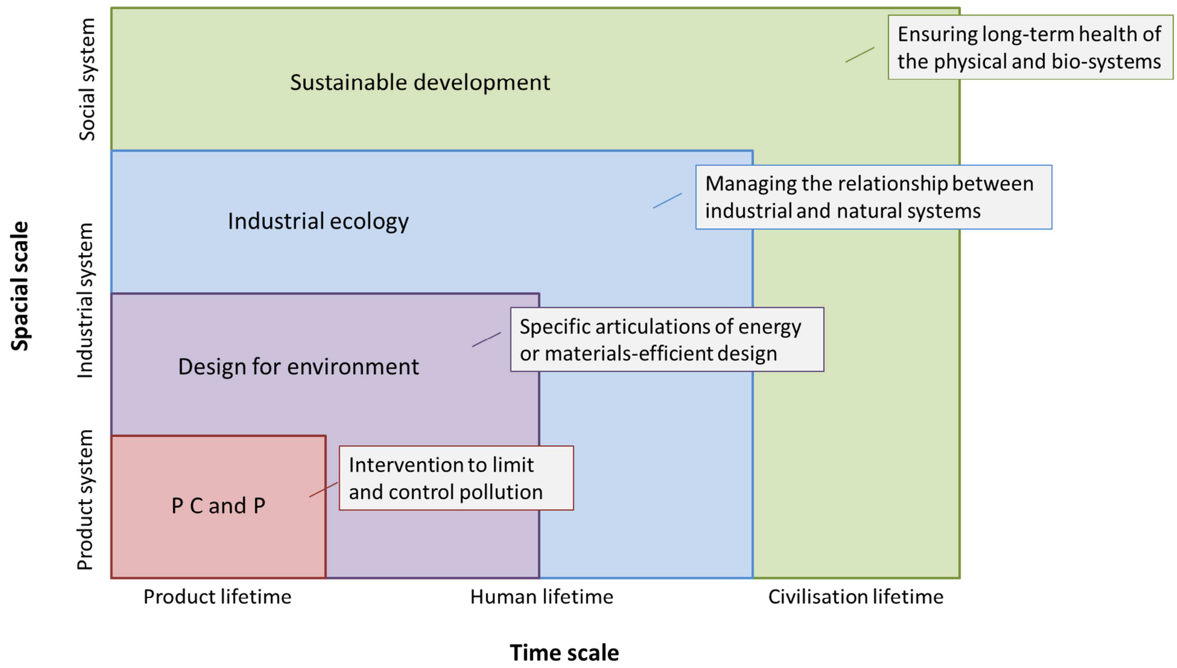


Figure 14: Approaches, differing in spatial and temporal scale of thinking, about the industrialisation and the natural ecosystem (Ashby, Balas, and Coral 2016)

Since its beginnings in the mid-1980s, eco-design (also known as Design for Environment or DfE) theory has evolved from being a concept (1985–1990), to providing methodology and principles (1990–2000), and to strengthening and improvement (2000–). Theoretical eco-design interacts and mutually benefits from applied eco-design, which has also known evolutions. Applied eco-design has varied between industry and academia: whereas in industry, design rules and manuals have evolved from the technical to business integration, and then to ease of recycling via dismantling and deep recovery; in academia, design rules and manuals have covered tools development, life cycle thinking, dismantling for recycling, and disassembling for remanufacturing, as well as design for recovery. The developments in theoretical and applied eco-design are shown in Figure 15.

It is not new that a progressive loss of degrees of freedom occurs as the design process advances, meaning that tools which require more freedom and fewer data are used early in the process, whereas the ones that need more precise information are applied late in the process but have less leeway in terms of adjustments (Figure 16 based on (Rose 2000)).

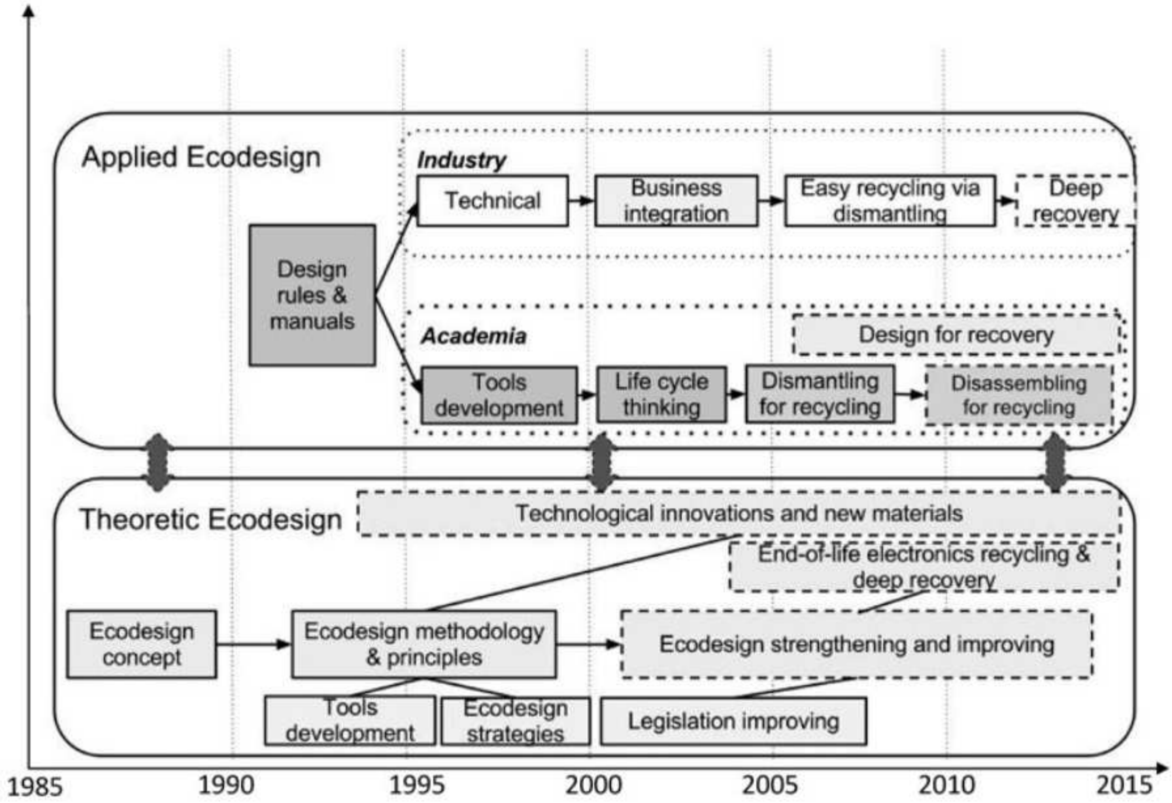


Figure 15: The development of theoretical and applied eco-design since 1985 (Li, Zeng, and Stevels 2014)

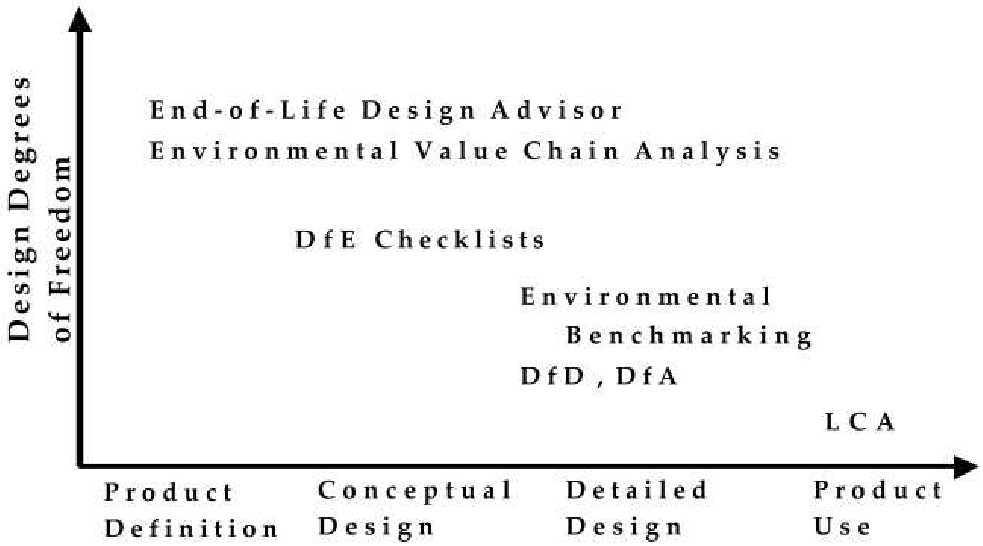


Figure 16: A qualitative illustration of the degrees of freedom in various stages of design, from research conducted 17 years ago by (Rose 2000)

Since then, (Go, Wahab, and Hishamuddin 2015) have collected the DfE guidelines that "lead to the design and development of recoverable products which are technically durable, repeatedly usable, harmlessly recoverable after use, and environmentally compatible in disposal" (Table 8).

Table 8: Design for Environment guidelines (Go, Wahab, and Hishamuddin 2015)

Guideline aspects	Guidelines
Product Structure Guidelines	i. Design a product to be multifunctional or create multifunctional parts ii. Minimize the number of parts iii. Avoid separate springs, pulleys, or harnesses. Instead, embed these functions into parts iv. Make designs as modular as possible, with separation of functions v. Design a reusable platform and reusable modules vi. Locate unrecyclable parts in one subsystem that can be quickly removed vii. Locate parts with the highest value in easily accessible places, with an optimized removal direction viii. Design parts for stability during disassembly ix. Reduce the product's disassembly time x. In plastics parts, avoid embedded metal inserts or reinforcements xi. Access and break points should be made obvious xii. Specify remanufactured parts xiii. Specify reusable containers for shipping or consumables within the product xiv. Design power-down features for different subsystems in a product when they are not in use xv. Implement commonality and upgradability of components
Material Selection Guidelines	i. Avoid regulated and restricted materials ii. Minimize the number of different types of iii. For attached parts, standardize with the same or a compatible iv. Eliminate incompatible materials v. Mark the material on all parts vi. Use materials that can be recycled, typically ones as pure as possible (no additives) vii. Avoid composite materials viii. Use high strength-to-weight materials on moving parts ix. Use low-alloy metals which are more recyclable than high-alloy ones x. Hazardous parts should be clearly marked and easily removed xi. Select suitable materials to ensure reliability and durability of the product
Labelling and Finish Guidelines	i. Ensure compatibility of ink where printing is required on parts ii. Eliminate incompatible paints on parts e use label imprints or even inserts iii. Use unplated metals which are more recyclable than plated iv. Use electronic part documentation
Fastening Guidelines	i. Minimize the number of fasteners ii. Minimize the number of fastener removal tools needed iii. Fasteners should be easy to remove iv. Fastening points should be easy to access v. Snap fits should be obviously located and able to be torn apart using standard tools vi. Try to use fasteners of a material compatible with the connecting parts vii. If two parts cannot be compatible, make them easy to separate viii. Eliminate adhesive unless compatible with both parts ix. Minimize the number and length of interconnecting wires or cables used x. Connections can be designed to break as an alternative to removing fasteners

The main tool used in environment-centred decision-making is Life Cycle Assessment (LCA), whose principles and framework have been standardized (International Organization for Standardization 2006). The result of an LCA is based on a calculation of the different environmental impacts generated throughout the product lifecycle. These calculations require an inventory of the input and output flows of material and energy for each stage and depend on the current scientific models that describe environmental impacts. A substantive amount of data is required even for the simplest LCA, with assumptions being made in the life cycle model and uncertainties in impact assessment.

To address the uncertainties in eco-design methods due to the complexity of information they handle, (Weidema et al. 2013) use a pedigree matrix approach that provides scoring (from 1 to 5) to assess the quality of data sources based on five independent characteristics: reliability, completeness, temporal correlation, geographic correlation, and further technological correlation. Each score on the matrix corresponds to a coefficient that is then used to calculate the standard deviation of the data values in question.

3.2.3 Material-centred design decisions

According to (Ashby, Balas, and Coral 2016), the role of the Materials Engineer in the 21st century involves:

- "Anticipating material supply-chain constraints and their cause and probable duration, particularly where 'critical' materials are involved;
- Precautionary exploration of substitutes for materials important to the enterprise for which they work;
- Adapting to, and complying with environmental and other material-related legislation; and
- Helping the enterprise to adapt to a more circular materials economy, retaining full-life ownership of the materials of their products, maximising reuse and recycling".

Usually, the Lead Product Engineer on a design team is responsible for the technical design, including material choices (Brouwer 2010). An extensive material and process database is therefore fundamental for every stage of the design process (Ashby et al. 2004) and should be composed of numeric and non-numeric attributes, as well as specific and general supporting information, as shown in Figure 17.

Material selection requires four fundamental steps: translating design necessities into requirements for materials and processes; screening candidate materials; ranking remaining materials in terms of how they meet the requirements; and analysing as much supporting information on the top-ranked candidates (Ashby et al. 2004; Jahan et al. 2010). The number of properties considered today by designers and engineers has grown so that numerous screening, comparing and choosing methods have been developed.

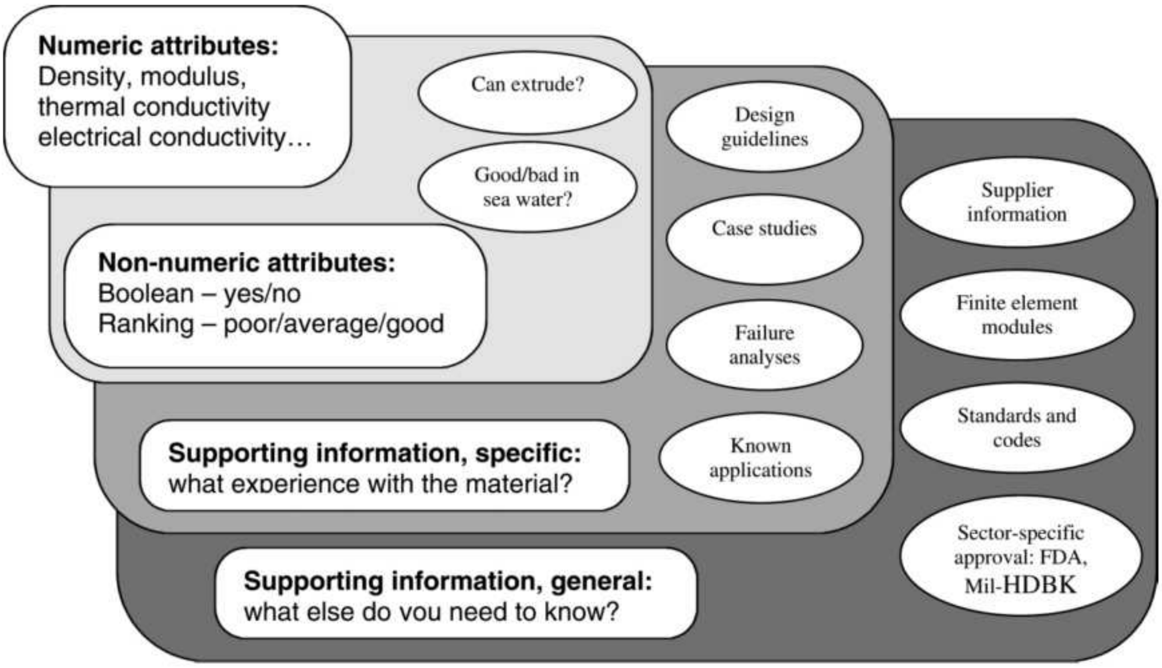


Figure 17: Spectrum of data in a materials and processes database (Ashby et al. 2004)

Table 9 presents the main screening and choosing methods for material selection, each of which has their advantages and limitations (Jahan et al. 2010). The chart method is one of the most common material selection tools, especially because of the Granta CES software that allows visual assessments of materials by comparing up to 4 different properties at a time. Recently, multi-criteria decision-making methods employing fuzzy logic as well as more computational tools have been increasingly researched (Jahan et al. 2010).

Table 9: Main material screening and choosing methods (Jahan et al. 2010)

Screening methods	Cost per unit property method
	Chart method
	Questionnaire method
	Materials in production selection tools
	Artificial intelligence tools
Choosing methods	Multiple attribute decision making
	Fuzzy multi-criteria decision-making methods
	Multiple objective decision making
	Mathematical programming
	Computer simulation
	Genetic algorithms

(Brouwer 2010) provides a comparison of sustainable material selection software used at Philips (Table 10). They all seem focused on the environmental indicators, much more than cycling expertise. Regarding material cycling, the Granta CES database – one of the most important software for material selection – only offers the following information (Brouwer 2010):

- Recycle (yes/no)
- A renewable resource?
- Down cycle (yes/no)
- CO2 footprint, recycle (kg/kg)
- Biodegrade (yes/no)
- Combustion CO2 (kg/kg)
- Landfill (yes/no)
- Embodied energy, recycle (J/kg)
- Recycle as fraction of current supply (%)
- Heat of combustion (net) (J/kg)
- Combust for energy recovery (yes/no)
- Non-recyclable use fraction (%)

Table 10: Overview of important aspects of sustainable material selection software (Brouwer 2010)

	Input	Phase of LCA	Measures	Output
EcoScan	Part, materials, weight, production process and disposal method.	Full Life Cycle Analysis, with eco indicator as output	Life cycle	Eco indicator, CO2 and weight
Granta Eco Audit	Part, materials, weight, production process and disposal method.	Characterisation of energy and CO2	Life cycle	Energy and Co2
Granta CES Selector	Selection criteria	Characterisation or eco indicator for specific material (depends on the property used)	Only material production	All eco data that is available in the database

3.2.4 Cycling-centred design decisions

Despite not being an integral part of material selection methods, adjusting product design to the constraints imposed by the anthropogenic cycles of materials has been attempted in many ways. Several studies have also proposed tools to integrate end-of-life scenario selection to product design, stemming from the DfE methods.

(Bocken et al. 2016) propose that there are basically three design strategies for resource cycling:

- slowing resource loops, by extending product life;
- closing resource loops, by recycling products post use;
- and narrowing resource loops, i.e. making products more resource efficient.

In his integration of recyclability in design, (Gaucheron 2000) makes use of a product model as a descriptive and cognitive tool that uncovers the data and knowledge synergies required in the case of End-of-Life Vehicles (ELV).

(Mathieux 2002) proposes an indicator-based integration of material recovery in product design, since its early stages. These multicriteria recyclability indicators, which became the basis of the ReSICLED tool, stem from design options that are attached to recovery scenarios and provide design improvements in a process that can be repeated iteratively (Mathieux, Froelich, and Moszkowicz 2003). It decomposes recyclability in three criteria: the mass fraction to be recovered; the economic benefit or loss of the operation; and the environmental impacts involved. Its deployment and application have allowed the constitution of a database of recyclability that follows the specifications of the European Commission.

A method which describes the quality losses in metal recycling based on exergy[8] measures was developed in order to address the resource efficiency of product systems and avoid recycling losses (Castro et al. 2007).

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[8] (Reuter and van Schaik 2012) define exergy as the thermodynamically available energy in a particular environment.

(Chan 2008) proposes a multi-criteria decision analysis for selecting appropriate end-of-life scenarios based on the Grey Relational Analysis. Figure 18 presents the basic steps in this tool. It uses an algorithm to select the best end-of-life option (from a list containing remanufacturing, recycling, landfill and incineration) for each component of a product, based on four criteria: damages to human health, damages to ecosystem quality, damages to resources, and end-of-life treatment value.

(Ziout, Azab, and Atwan 2014) base their assessment on an initial analysis of the relevant Political, Economical, Societal, Technological, Environmental and Legal (PESTEL) aspects of the end-of-life recovery options. This analysis provides an importance matrix of major criteria, sub-criteria and factors, with their respective weights, which are then multiplied by the reprocessing costs of each potential end-of-life scenario. In this case, the main vector for decision-making is still the benefit of the cycling scheme, i.e. revenue minus costs.

The Eco-Material tool contained in the G.EN.ESI eco-design software platform supports designers in the choice of the most sustainable material based on indicators such as the embodiment energy needed for primary extraction and production, the exploitation of resources and minerals, the volume of greenhouse gases emitted as well as the possibility of recycling (Dufrene 2015).

(Favi et al. 2017) propose a design for end-of-life approach that favours closed-loop scenarios based on indexes for reuse, remanufacture, recycling and incineration. The indexes are based on revenue and cost balances for each scenario.

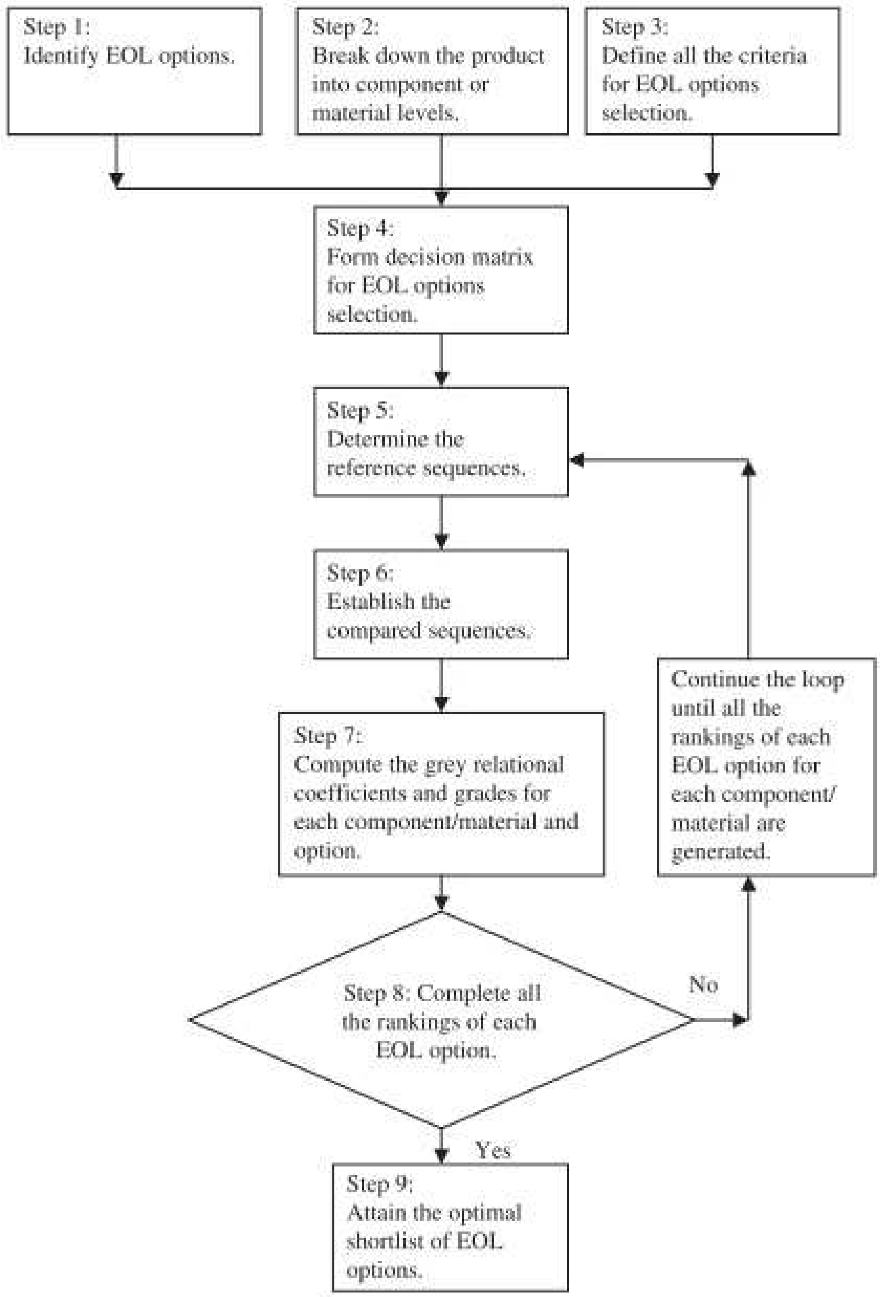

Figure 18: Selection process of end-of-life options using Grey Relational Analysis technique (Chan 2008)

There are also a number of recommendations and guidelines. Van Schaik and Reuter (2014) have proposed a set of ten fundamental Design for Recycling (DfR) rules based on their study of WEEE (van Schaik and Reuter 2014a):

1. “DfR rules are product and recycling system specific; oversimplification of recycling by defining general DfR rules will not produce the intended goal of resource efficiency.
2. DfR needs model and simulation-based quantification.

3. Design data should be accessible and available in a consistent format which is compatible with the detail required to optimise and quantify recycling performance of products for all metals, materials and compounds present.
4. Economically viable technology infrastructure and rigorous tools must be in existence for realizing industrial DfR rules and methodology.
5. CAD, Process and System Design tools must be linked to recycling system process simulation tools to realise technology-based, realistic and economically viable DfR.
6. Identify and minimize the use of materials which will cause losses and contaminations in recycling due to material characteristics and behaviour in sorting.
7. Identify components/clusters in a product, which will cause problems and losses in recycling due to combined and applied materials.
8. Design clusters or sub-units in products that can be easily removed and which match with the final treatment recycling options (i.e. Metal Wheel – see report).
9. Labelling (including carefully considered standardisation) of products/components based on recovery and/or incompatibility so that they can be easily identified from recyclates and waste streams. Thus Design for Waste stream sorting or Design for (Automated) Dismantling/Sorting is important.
10. Be mindful of the liberation of materials in design (Design for Liberation)".

Table 11, Table 12 and Table 13 respectively present the Design for Reuse and Remanufacturing, Design for Recycling, and Design for Disassembly guidelines collected by (Go, Wahab, and Hishamuddin 2015). (Zhang 2014) shows that these exhaustive recommendations are unpractical to implement in companies and require a tactical approach with roadmaps to be adopted. (Gehin, Zwolinski, and Brissaud 2008) and (Alhomsi 2012) also provide tools to integrate and operationalise these guidelines in product design.

Table 11: Design for Reuse and Remanufacturing guidelines (Go, Wahab, and Hishamuddin 2015)

Main criteria	Guidelines
Ease of sorting	i. Reduce the variety of products and parts ii. Provide clear distinctive features that allow for easy recognition iii. Provide readable labels, text, and barcodes that do not wear off during the product's service life
Ease of disassembly	i. Avoid permanent fasteners that require destructive removal ii. If destructive removal is necessary, ensure that damage to the core does not happen iii. Reduce the number of fasteners prone to damage and breakage during removal iv. Increase corrosion resistance of fasteners v. Reduce the total number of fasteners in unit vi. Reduce the number of press-fits vii. Reduce the number of fasteners not in direct line of sight viii. Standardize fasteners by reducing the number of different types of fasteners and the number of different sized fasteners
Ease of cleaning	i. Protect parts and surfaces against corrosion and dirt ii. Avoid product or part features that can be damaged during cleaning processes or make them removable iii. Minimize geometric features that trap contaminants over the service life iv. Reduce the number of cavities that are capable of collecting residue during cleaning operations v. Avoid contamination caused by wear
Ease of inspection	i. Minimize the inspection time ii. Reduce the number of different testing and inspection equipment pieces needed and the level of sophistication required iii. Provide good testing documentation and specifications
Ease of part replacement	i. Minimize the time required to reassemble the product ii. Prevent damage during part insertion iii. Provide good documentation of specifications and clear installation manuals
Ease of reassembly	i. Minimize the time required to reassemble the product ii. Provide good documentation of specifications and clear installation manuals
Reusable Components	i. Design a reusable platform and reusable modules ii. Select materials to ensure reliability and durability of the product iii. Make sure components are robust enough to reuse without replacement iv. Avoid toxic materials
Standardization	i. Standardise and use common parts and materials ii. Standardise and use common fasteners iii. Standardise and use common interfaces iv. Standardise and use common tools

Table 12: Design for Recycling guidelines (Go, Wahab, and Hishamuddin 2015)

Area	Guidelines
Materials	i. Minimise the number of different types of materials ii. Make subassemblies and inseparably connected parts from the same or a compatible material iii. Avoid the mixing of materials in assemblies iv. Mark all plastic and similar parts for ease of identification v. Use materials which can be recycled vi. Use recycled materials vii. Ensure compatibility of ink where printing is required on plastic parts viii. Avoid composite materials ix. Eliminate incompatible labels on plastic parts x. Hazardous parts should be clearly marked and easily removed
Fasteners and connection	i. Minimise the number of fasteners ii. Minimise the number of fastener removal tools needed iii. Fasteners should be easy to remove iv. Fastening points should be easy to access v. Snap-fits should be obviously located and able to be disassembled using standard tools vi. Try to use fasteners of a material compatible with the parts connected. vii. If two parts cannot be compatible make them easy to separate viii. Eliminate adhesives unless compatible with both joined parts ix. Minimise the number and length of interconnecting wires or cables used x. Connections can be designed to break as an alternative to removing fasteners
Product Structure	i. Minimise the number of parts ii. Make designs as modular as possible, with separation of functions iii. Locate unrecyclable parts in one area which can be quickly removed and discarded iv. Locate parts with the highest value in easily accessible places v. Design parts for stability during disassembly vi. Avoid moulded-in metal inserts or reinforcements in plastic parts vii. Access and breakpoints should be made obvious

Table 13: Design for Disassembly guidelines (Go, Wahab, and Hishamuddin 2015)

Main criteria	Guidelines
Less disassembly work	i. Combine elements, create a modular design ii. Use compatible materials iii. Limit material variability iv. Group harmful materials into subassemblies v. Provide easy access to harmful, valuable or reusable parts
Predictable product configuration	i. Lightweight and sturdy, minimize fragile parts ii. Avoid the combination of ageing and corrosive materials iii. Protect subassemblies against soiling and corrosion
Easy disassembly	i. Make joints visible and accessible, avoiding hidden joints ii. Use fasteners rather than adhesives. Use fasteners that are easy to remove or destroy iii. Minimize the number of joints and connections iv. Use the same fasteners for many parts v. Provide easy access to disjoining, fracture or cutting points vi. Avoid multiple directions and complex movements for disassembly vii. Set centre-elements on a base part viii. Avoid metal inserts in plastic parts
Easy handling	i. Leave surface available for grasping ii. Avoid non-rigid parts iii. Enclose poisonous substances in sealed units iv. Design for automated disassembly v. Avoid the need for specialized disassembly procedures vi. Avoid long disassembly procedures
Easy separation	i. Avoid secondary finishing (painting, coating, plating etc.) ii. Provide marking or different colours for easy separation of materials iii. Avoid parts and materials likely to damage machinery (shredder)
Variability reduction	i. Use standard subassemblies and parts ii. Minimize the number of fastener types
Materials	i. Minimise the use of different materials ii. Use recyclable materials iii. Eliminate toxic or hazardous materials

3.3 Towards circular design: closing material loops

(Lewandowski 2016) mentions the following schools of thought that have contributed to the development of the general concept of circular economy: Regenerative Design, Performance Economy, Cradle to Cradle, Industrial Ecology, Biomimicry, Blue Economy, Permaculture, Natural Capitalism, Industrial Metabolism and Industrial Symbiosis. The author points out 5 main principles for it:

"1. Design out waste/Design for reuse;

2. Build resilience through diversity;

3. Rely on energy from renewable sources;
4. Think in systems;
5. Waste is food/Think in cascades/Share values (symbiosis)."

The circular economy is basically an umbrella concept that provides a cognitive unit and a discursive space for previous knowledge on restorative, regenerative and life-extending strategies for products and materials (Blomsma and Brennan 2017). Materials in a circular economy are less seen as disposable commodities and more as valued assets, much as financial capital, which can be invested, recovered as revenue and re-invested (Ashby, Balas, and Coral 2016).

3.3.1 The rise of circular business models

Circular economy initiatives can have different outcomes. According to (J. P. Birat 2016), they can generate economic value, thus self-igniting and self-sustaining (e.g. steel, aluminium, paper etc.); they can destroy economic value while still creating environmental and social value (such as the recycling of electronic waste or tires, in which polluters pay extra taxes); or they can depend on rigorous legal measures (such as with public health concerns with the toxicity of batteries for instance).

There is a fair amount of novelty in the propositions for circular business models, especially in managerial and operational aspects. (Linder and Williander 2017) define circular business models as inherently basing the conceptual logic of value creation on the economic value that is retained after use, when producing a new offer. For these authors, in order to reduce the innovation risk related to the adoption of circular business models, research must be conducted in product design for increased product adaptability to an unknown future. This implies delving deeper into the notion of a circular design that integrates material looping into its decision-making process and strives to limit criticality-related issues. (Linder and Williander 2017) also state that there are inherently more business risks in adopting a circular business model when compared to a corresponding linear business model.

Measuring the success of circular economy business models systematically still presents some challenges. (Laubscher and Marinelli 2014) point out three main areas:

- Measuring the reduced ecological footprint;
- Measuring direct financial value through recovery of materials and assets;

- Measuring top line growth through new business models.

Based on their work at Philips, (Laubscher and Marinelli 2014) identified six key areas for integrating circular economy principles in business processes:

1. sales model (with a shift towards Product-Service Systems);
2. product design/material composition;
3. IT / data management;
4. supply loops;
5. strategic sourcing for own operations;
6. HR / incentives.

3.3.2 Circular design initiatives

Some studies have focused specifically on product design and its relation to circular economy. (De los Rios and Charnley 2017) indicate the design skills that are required to create products for different closed loops:

- "Understand logistics and distribution processes;
- Understand the service experience and how to design services;
- Understand user expectations and the perception of value;
- Understand factors of the user experience;
- Understand product wear by use;
- Assess material physical and chemical properties;
- Understand engineering functions of the product;
- Understand failure mode and maintenance procedures;
- Understand processes for reverse and re-manufacturing;
- Solve aesthetic and structural problems with limited supplied components."

One of the first and most prominent circular design initiatives is the Cradle-to-cradle (C2C) design approach, which is based on the principles of eco-effectiveness, zero waste and intelligent material pooling (Braungart, McDonough, and Bollinger 2007). There are 5 steps to achieve eco-effectiveness via the C2C philosophy that guide product design:

1. Get "free" of known culprits (substances);
2. Follow informed (expert) personal preferences;
3. The passive positive list: criteria to ban materials that are not good;
4. The active positive list: positively technical or biological nutrients;
5. Reinvent: look at function rather than products.

To address the lack of tools for a transition to circular economy, (Ellen Macarthur Foundation 2015b) proposes the Material Circularity Indicator (MCI), aimed at internal use by companies for designing new products, internal reporting and procurement. It associates a measure of restorative flows with complementary impacts and risk indicators. In comparison with Life Cycle Assessment, the MCI methodology considers flows instead of impacts. The MCI (value between 0 and 1) is calculated from the virgin, reused and recycled input of the feedstock as well as the reused input. It considers the usage length and intensity, and finally the end-of-life scenario. The input of the MCI is the product's Bill of Materials.

In classical material screening methods such as the Ashby chart method using the newest version of CES Selector, a material selection tool developed by the company Granta Design, it is possible to filter only recyclable materials. Information is also provided on critical material status by means of five risk metrics (sourcing and geopolitical, environmental country, physical scarcity, price volatility and conflict mineral).

In their analysis of circularity metrics, (Linder, Sarasini, and van Loon 2017) compare product-level circularity metrics Table 14, based on the following desirable qualities of a good circularity metric:

- Focus on the concept of circularity and not on other, ancillary concepts such as environmental performance or competitiveness;
- Be robust against opportunistic behaviour and therefore transparent, i.e. allowing third-party verification, with subjective judgments kept to a minimum, following unambiguous methodological principles;
- Bear a high degree of generality is equally put forward by the authors, meaning that the metric's interpretation should be independent of industry and technology;
- Tend to low dimensionality metrics, i.e. follow aggregation principles to summarize product circularity in a single value, which is useful for correlation studies, customer prioritization and managerial decision making.

Table 14: Summary of reviewed product-level circularity metrics (Linder, Sarasini, and van Loon 2017)

Metric	Construct validity	Reliability	Transparency	Generality	Aggregation principles
Material Circularity Indicator (Ellen Macarthur Foundation 2015b)	**Medium** Measures use of virgin material and resultant waste to landfill or energy recovery. Loop tightness not considered (though mentioned as potential future development).	**Low** Many data inputs required that might be uncertain or depend on several factors, such as ex-ante assumptions regarding the destination of a product after use and the efficiency of recycling processes.	**Low** Required data (includes bill of materials of all components) normally considered confidential. Difficult to verify by a third party.	**High** Indicator can be applied to wide range of products.	**Medium** Circularity represented by a single value ranging between 0 and 1. Acknowledged difficulty weighing different types of cycles. Not applicable to every product, only for reference products that represent a group of similar products.
Eco-efficient Value Ratio (Scheepens, Vogtländer, and Brezet 2016)	**Low** Measures environmental impacts per euro spent, not necessarily focusing on closed material loops, but implicitly taking into account circular economy effects as sharing, reusing, and renewable energy.	**Low** Requires many data inputs for robust outputs. Environmental impacts during usage included, although uncertain: depends on the condition of use.	**Medium** Verifying eco-cost of a product might be difficult because of confidentiality. Content of product may be difficult to trace in upstream supply chain.	**High** Ratio can be applied to wide range of products.	**High** One easily understood value per product for specific use.

Circular economy index (Di Maio and Rem 2015)	**Low** Measures recycling rates, excluding all other circular economy effects and and loops.	**High** Detailed data on all products and components entering the recycling facility are required—information not commonly available. Index is computed per recycler, outputs can differ significantly depending on product assortment of recycler.	**High** If index is based on standards (e.g., material passports).	**Low** Only applicable to recyclers with same assortment.	**N/A**
REPRO – Remanufacturing Product Profiles (Gehin, Zwolinski, and Brissaud 2008)	**Low** Reuse and recycling are excluded.	**Low** Dependent on ex ante assumptions regarding potential future remanufacturing.	**Medium** Requires detailed information about product parts, interfaces and processes.	**Medium** Applicable to many industries, but only remanufacturing loops.	**Low** Does not enable aggregation of different types of (non-reman.) cycles into a single value.
Material reutilization part – Cradle-to-cradle (C2C 2014)	**Medium** Loop tightness not integrated (though energy recovery considered special case).	**Unknown** We have not been able to find enough detail to properly assess this. Includes ex ante assumptions regarding recirculation.	**Low** Required data (include bill of materials of all components) normally considered confidential. Difficult to verify by a third party.	**High** Can be applied to wide range of products.	**Low** Does not allow for a fine-grained value summarizing degree of circularity (five ranks). No theoretical justification for weights for different combinations of cycles and materials.

3.4 Conclusions on the advances towards circular product design

With the advent of increased awareness and regulations regarding products' impacts on the environment, more integrated approaches that encompass at the same time the economic, technical and environmental have appeared, such as Life Cycle Assessment (LCA), Design for Environment guidelines as well as other Life Cycle Engineering tools applied to material selection (Peças et al. 2013), some even based on feedback from recyclers (Mathieux, Froelich, and Moszkowicz 2008).

However, there is both a lack of systematized information on the evolution of recycling chains in these methods and a difficulty in considering the effects of material choices on material lifecycles and end-of-life. (Germani et al. 2013) identify in their review of end-of-life management literature that there are only a few analyses of end-of-life scenarios that provide information to product designers for making decisions on end-of-life management. Apart from general DfX guidelines, there are limited tools to address the impact of design choices on the actual availability and cycling potential of materials. However, these guidelines remain too general and difficult to enforce. Stakeholders – and product designers in particular – probably have difficulty to measure and monitor the evolution of these aspects, which in turn discourages them.

(Reyes Carrillo 2007) proposes a Trojan horse mechanism to introduce collaborative work on an eco-design method in order to propagate knowledge throughout the company. In this sense, the involvement of different stakeholders, both internal and external to the firm, in the discussion of how to integrate new information such as material circularity can have the effect of further establishing the concept and its tools.

There have been many studies indicating that circular economy approaches provide benefits for supply chain management and make sense on an even broader level with industrial ecology projects (Clift and Druckman 2015). Closed-loop supply chains is indeed a mounting topic in the scientific community, with almost 400 papers being published between 2007 and 2013, on the reverse logistics aspects alone (Govindan, Soleimani, and Kannan 2015). From this standpoint, there is a vast field for operational research optimization problems.

However, only a small number of published papers focus on indicators (Ghisellini, Cialani, and Ulgiati 2016). There is some criticism of the fact that circular economy's offset of environmental impacts, via a lowering of the per-product production impacts, might lead firms to also increase production, cancelling the positive effects that could have been obtained in what is called a "circular economy rebound" (Zink and Geyer 2017). So, more than just helping companies be more productive, circularity tools should strive to generate the comprehension of the underlying sustainability notions and "the downstream consequences caused by the chosen end-of-life treatment" (Zink and Geyer 2017).

Finally, circular economy studies are also opening a new field for integrating closed-loop scenarios with product design. Figure 19 collects the technology, strategy and lifestyle based contributions to transition towards a circular economy.

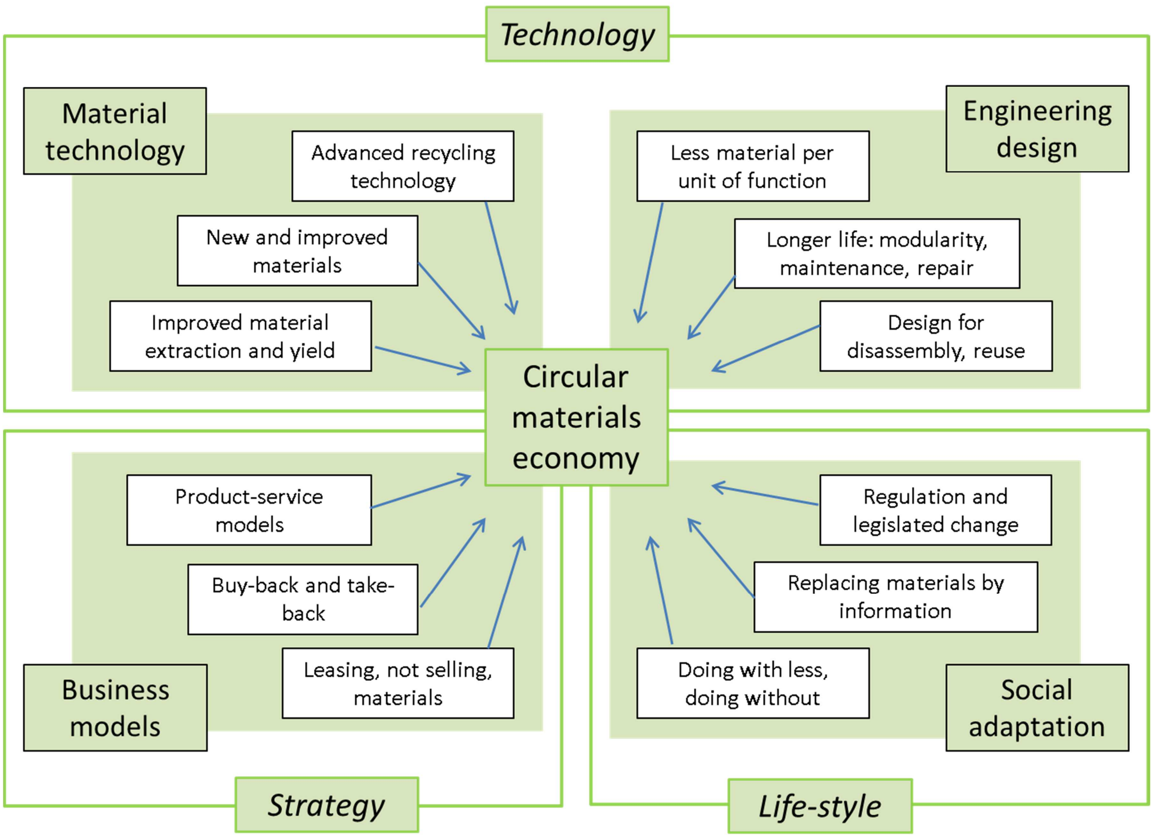

Figure 19: Contributions to creating a circular economy (Ashby, Balas, and Coral 2016)

The challenge of reducing anthropic pressure on the planet's ecosystems is being tackled from a broader perspective than simply reducing environmental impacts via LCA. Frugal approaches of production and consumption, dematerialization and the questioning of the growth paradigm are pointed as the main contributors to a circular economy (Arnsperger and Bourg 2016). But product designers still lack the tools to properly address material scarcity and circularity.

Chapter 4: Thesis statement

The end-of-life of materials involves a vast number of different agents, with very diverse interests and issues, such as policy makers and governing authorities, local citizen groups, environmental associations, waste collectors, waste treatment actors, waste recyclers, as well as raw material producers and traders, but also the companies who manufacture products with these materials and their users. The whole economy is concerned and, in the perspective of closing material loops, it even requires designers themselves to take part in the planning and management of these waste material flows. This, at first sight, seems like a big stretch for the design activity: designers already have a lot to process in terms of constraints, which have increased significantly in recent years. They are expected to constantly provide technological innovations that enhance everyday life, improve production systems, create value and reduce environmental impacts. But, with material scarcity progressively becoming a major issue for supply chains, there is a need to assess it as early in the design stage as possible. The adoption of a circular rationale for resource management should become the norm in the years to come. Thus, in order to close materials loops, it is perhaps necessary to close some information loops beforehand by means of a holistic approach to describe material end-of-life networks to product designers, with a shared perspective from both sides. However, many studies have tackled the issue of circularity only from the company's or the product design standpoint.

In order to promote product and material recycling, designers have compiled Design for Recycling (DfR) guidelines for more than two decades, yet these seem to "lack a combination of concrete instructions, prioritization, and recyclability performance feedback" (Peters et al. 2012). In many cases, designers have little to no contact with the recyclers of their products. How is the loop to be closed if both ends never meet? Recyclers have gathered decades of cycling experiences and there is enough data today to evaluate how – and above all why – recycling chains tend to become necessary and grow, stagnate or disappear depending on the social, economic, political and technological environment of their time. This information is capital to evaluate how designers' decisions affect the shape of material flows and meet the material needs that future technology will require. However, MFA usually presents the material's lifecycle in broad strokes and is not very well-suited to evaluate important issues at a microeconomic level (Reimann et al. 2010). This research wishes to propose a means of integrating the information provided by MFA to the designer's toolkit.

There is thus a need to identify and systematize the relevant information on material cycles that may assist product designers in the material selection stage, all the while considering the evolution of recyclability in different end-of-life scenarios. Conversely, these design choices have an impact on the potential end-of-life networks themselves and the state of these networks should be accounted as well. This was translated into two integration gaps that should be bridged:

Integration Gap 1	To achieve material circularity, design decisions must better encompass information from end-of-life networks and the interconnection between material choices and end-of-life scenarios.
Integration Gap 2	Designers must make use of material cycling data, stemming from real end-of-life expertise, as early as possible in the design stage.

The integration of both these elements in the design process is a step towards material circularity and a circular economy since it fosters information exchanges between the design and end-of-life stages and it favours a holistic vision of material loops. The following research question was therefore formulated, in order to bridge these gaps:

Main Research Question	How can material-related choices that cultivate the circularity of material flows be made during the design process?

In Integrated Design, this sort of problem is usually managed by incorporating indicators or a method to the designer team's toolbox. However, though there are some guidelines and indicators that foster material circularity in product design, none provides insight on the fate of materials beyond the lifecycle for which the material is originally being selected, leaving the matter of what happens after it is discarded almost completely unattended. So, the first hypothesis for answering this question was that a circularity indicator and method that encompasses more than one material lifecycle improves product designers' decisions regarding material circularity.

Moreover, the literature review also showed that material cycling data pertaining to end-of-life expertise is not properly compiled. It is usually the result of an aggregation of material flows for specific regions and timeframes but it is collected with different objectives, methodologies and indicators, with little to no connection to design parameters. Therefore, it is still of little use in the field of design, with few metrics incorporated in databases and tools, and is mostly used in strategic studies at a much broader socioeconomic and geopolitical scale. Consequently, though companies (and product designers in particular) have started to take an interest in sustainable resource management, there are still some difficulties and blind spots where waste is concerned. Thus, a second hypothesis was made and surmised that a robust systematization of cycling schemes expertise is needed to complement any material circularity assessment.

Requirements were established to address each of the hypotheses in the search for a contribution to answering the Research Question and they are listed in the table below:

Hypothesis 1: A circularity indicator and method that encompass more than one material lifecycle improves product designers' decisions regarding material circularity	**Requirements 1:** • Elucidate the interconnections between material choices and cycling networks; • Encompass all potential end-of-life scenarios; • Take into account the uncertainties in the multiple data involved; • Be a stepping stone, i.e. allow evolutions of the method and its results.
Hypothesis 2: A robust systematization of cycling schemes expertise is needed to complement any material circularity assessment	**Requirements 2:** • Take into account all relevant elements that affect the evolution of cycling networks; • Provide knowledge to product designers on anthropogenic cycles; • Applicable to all material classes; • Be robust, covering available information from multiple sources.

Conclusion of Part I

Although it is still distant from most people's thoughts, understanding how material cycles function in the economy and making proper use of this knowledge is primordial for product designers and the industry in general. The basic tenets of the circular economy are going to gradually become the norm in the fight against resource scarcity. To achieve material efficiency, product design is going to have to integrate data on material lifecycles. It is, however, a very complex task and product designers are still ill-equipped to deal with it.

The critical analysis of the state-of-the-art literature on material flows in the economy and the links between product design and end-of-life in the quest for closing material loops have indicated that some gaps exist in the integration of relevant data in the design process. These gaps led to the formulation of a research question focused on bringing together material selection and the circularity of material flows. To answer this question, two hypotheses were outlined and their respective requirements were defined. Figure 20 recapitulates this thesis' statement:

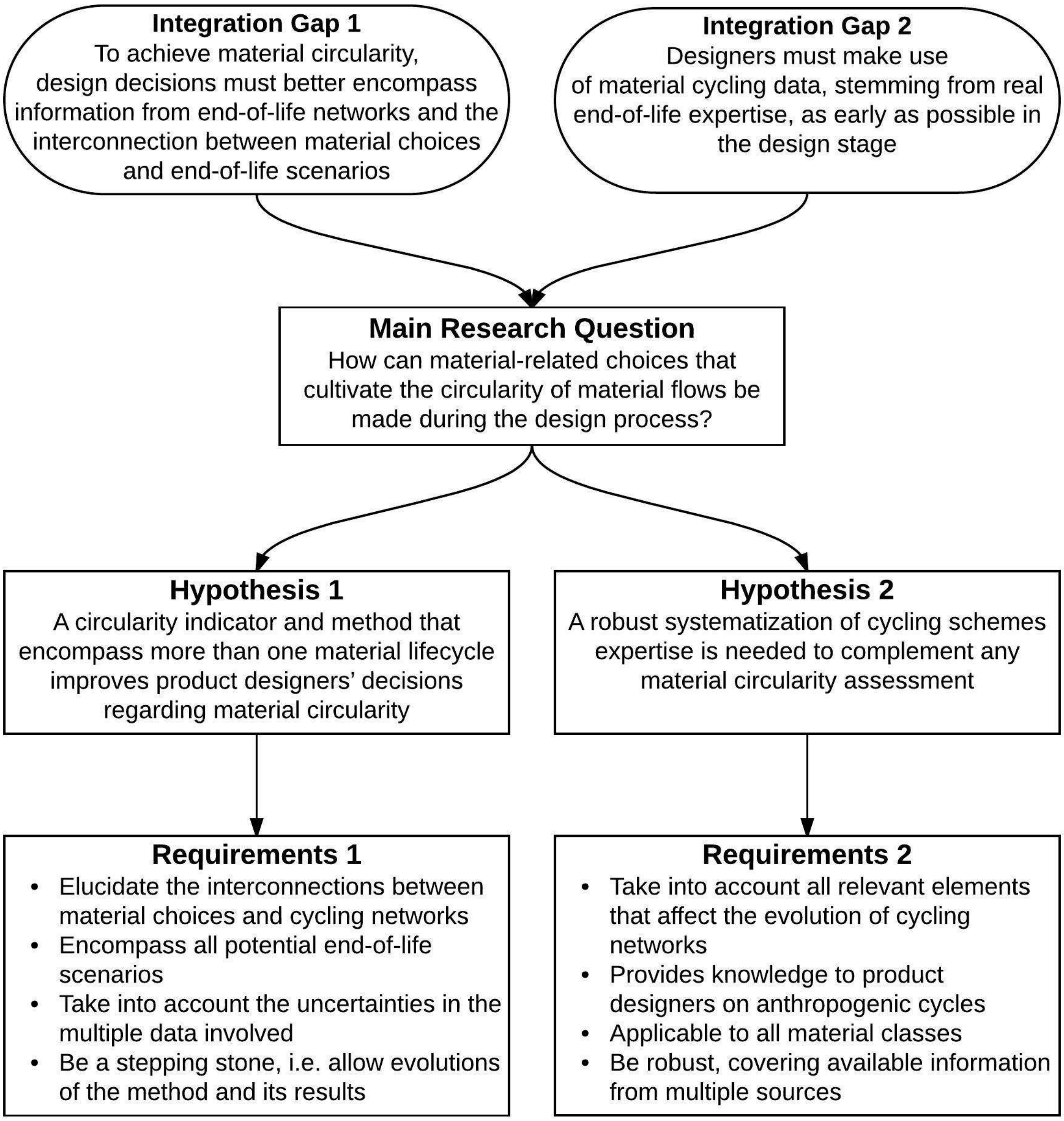

Figure 20: Thesis statement recapitulation

Part II: BRIDGING THE INTEGRATION GAPS

In Part I, the study of the literature on material economic cycles and their connections (or lack thereof) with product design indicated that there are gaps in the integration of end-of-life expertise especially if one is looking to close loops and advance towards a circular economy. This led to the formulation of one main research question and two hypotheses relating to each gap to be bridged, both with their respective requirements.

In Part II, Chapter 5 will focus on the first integration gap and the first hypothesis, with the development of a tool allowing the integration of material circularity in design. This tool is based on the development of a material circularity indicator that encompasses more than one material lifecycle. The indicator has been conceived to address the notion of circular material value and its components include factors related to economic, manufacturing, design and cycling/end-of-life materials issues. It is then inserted in the Design for Material Circularity method in order to be operational for product designers. Chapter 6 will then complete this first contribution with a framework for the characterization of material cycling networks providing cycling expertise in the form of the material CLEARER sheets, responding to the second integration gap and hypothesis. This framework is applied in the analysis of eight material cycling networks to provide their CLEARER sheets. Figure 21 provides an outline of Part II based on the thesis statement.

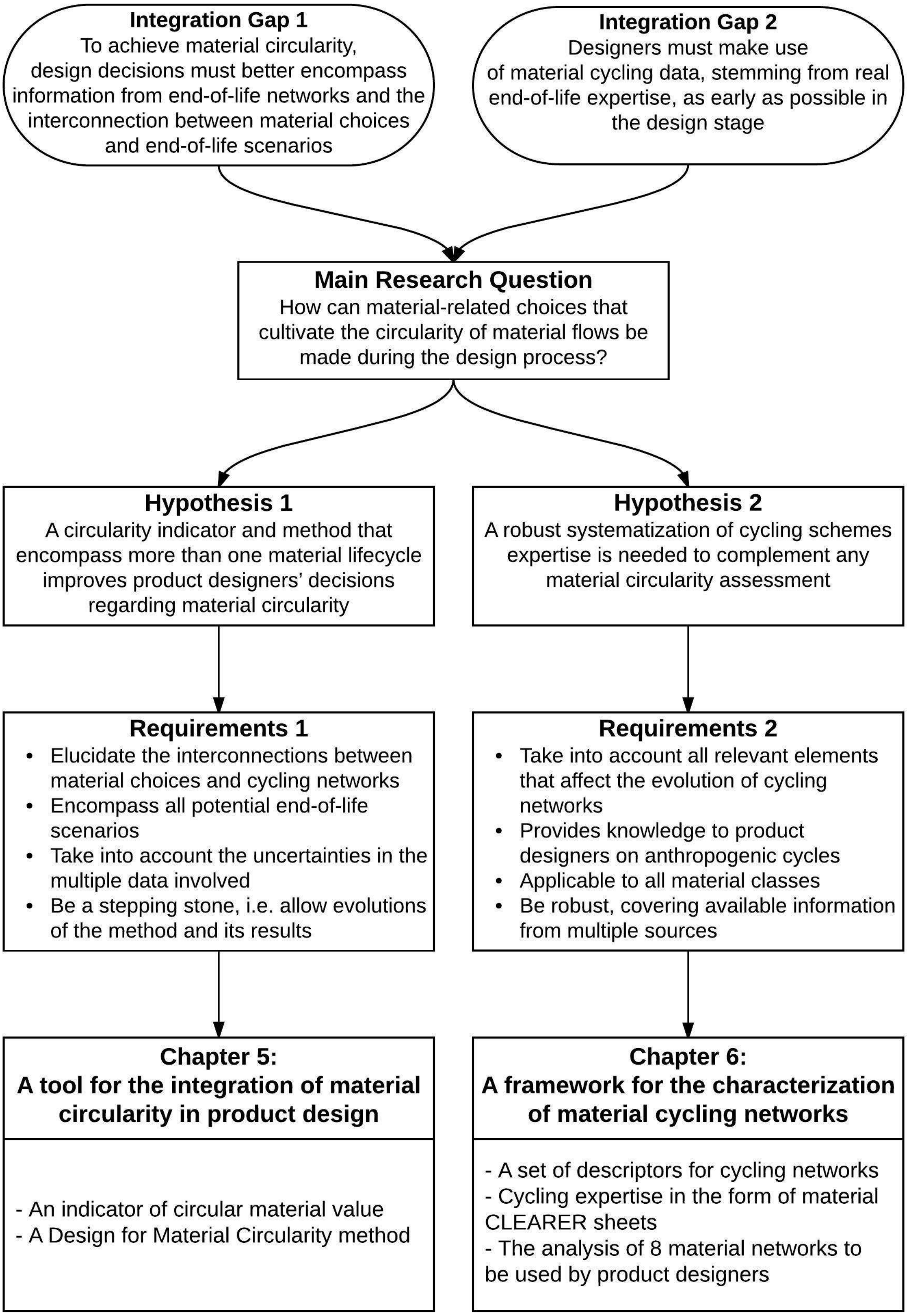

Figure 21: Outline of Part II

Chapter 5: A tool for the integration of material circularity in design

As presented in the previous chapters, while there are tools that integrate the product's lifecycle as a whole into the early design stages and also tools designed to encompass the end-of-life of the product, few of them can assess the fate of materials beyond the first lifecycle. Nor are there many methods that integrate the actual state of a recycling network into their evaluations. Figure 22 shows how the continuous flow of material cycles engages several design and end-of-life stages that are connected yet currently dissociated. Designer teams vary in the course of a sequence of material cycles as material flows circulate in the economy and are potentially incorporated in different applications and industries (e.g. steel cans becoming reinforcing bars or glass bottles being turned into fibreglass). However, the issues of the recyclers between two material cycles, tasked with the regeneration of these materials and usually constrained by the requirements of the industry that will use their secondary resources, must be an integral part of the upstream design process concerns.

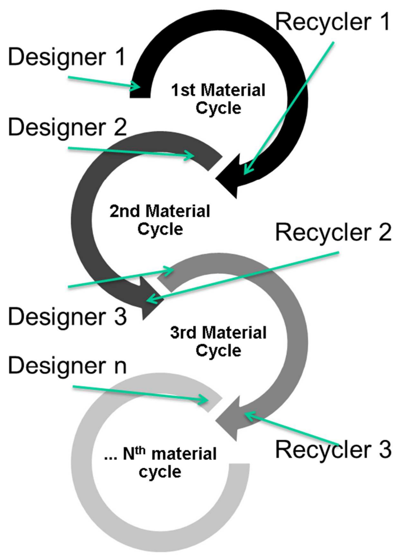

Figure 22: The separation between designer teams and recyclers along multiple material cycles

This is directly related to Hypothesis 1 and the first integration gap that consists in the consideration of the interconnection between material choices and end-of-life scenarios so as to prepare for subsequent lifecycles and improve material circularity. In order to perform this evaluation, product designers require an indicator during the design process, to follow the evolution of a material's properties and how they are affected during the first product lifecycle, across the first cycling (or end-of-life) stage and into a new lifecycle.

The tool presented in this section aims at satisfying the requirements specified in Chapter 4 to answer the main Research Question of "how can material-related choices that cultivate the circularity of material flows be made during the design process". The hypothesis of this research is that a method based on a circularity indicator encompassing more than one material lifecycle would improve product designer's decisions regarding material circularity. This method has to:

- Elucidate the interconnections between material choices and cycling networks;
- Encompass all potential end-of-life scenarios;
- Take into account the uncertainties in the multiple data involved;
- Be a stepping stone, i.e. allow evolutions of the method and its results.

The tool specifications are summarised in Table 15.

Table 15: Functions and sub-functions of the proposed tool

Specifications of design functions for the general proposition	**Sub-functions**
F1. Elucidate the interconnections between material choices and cycling networks	**SF1.1** Formalize links between design parameters and cycling network variables through formulas (explicit variable relationships) **SF1.2** Choose variables that: a. continue over multiple lifecycles b. are coherent with industrial experiences c. rely on easily obtainable data
F2. Encompass all potential end-of-life scenarios	**SF2.1** Incorporate end-of-life variables: a. that are compatible with different types of end-of-life scenarios b. whose corresponding data is readily available **SF2.2** Allow improvements according to the evolution of circular economy and cycling network models
F3. Take into account the uncertainties in the multiple data involved	**SF3.1** Opt for variables that allow assessing the uncertainty of variables' action-reaction on each other (i.e. their "degree" of relative dependency) **SF3.2** Opt for variables that allow assessing the uncertainty of one variable over the global result (i.e. the global influence of one variable on the total result)
F4. Be a stepping stone, i.e. allow evolutions of the method and its results	**SF4.1** Have a format that enables the addition of other pertinent variables **SF4.2** Be adaptable to the type of results searched by the user of the method

The concept of value is thus used as a metric to serve as the proxy that provides visibility into the second lifecycle. This helps product designer's go beyond their initial scope of action. Value analysis is a well-trodden design tool that speaks not only to product designers but also to the other areas of an industrial company and managing decision-makers in particular. In Chapter 3, it was found that value relates to the satisfaction of a need. If a given need is satisfied by a certain material, the value of this material is, therefore, in part or entirely, connected to the material's properties. Since material properties may be preserved over the course of multiple lifecycles, then so should material value. This is the reasoning that allows overcoming the issue of waste still having a negative representation in the eye of production companies and also of the general public, in financial, social, and even emotional terms. It is chosen as it may also foster material regeneration and therefore contribute to the dissemination of a circular production paradigm.

This chapter presents the first proposition of this research work. First, the circular material value notion and indicator are presented. Then, the Design for Material Circularity (DfMC) method is detailed so that product designers can easily put circular material value into use in the design process. Both the indicator and the DfMC method constitute a tool for the integration of material circularity in design, illustrated in the case studies of Part III.

5.1 Components of circular material value

The value chain of a material comprises a multitude of value-adding operations along the phases of merely one lifecycle. For the sake of simplicity, in this study, these operations will be considered as a whole for each phase. In Figure 23, as materials flow out of the extraction phase, they are considered to have an initial value. After fabrication and manufacturing operations, they are turned into a product and the value associated to each of them is at its highest point. It then enters the use phase, during which the materials may suffer some degradation. After the product is discarded, it reaches the end-of-life stage, in which, if little to no degradation took place, it can be reused or remanufactured by closing the loop directly to the use phase or manufacturing phase, respectively. If these options are not available, perhaps some of its value can be recovered and it can be employed in a second lifecycle.

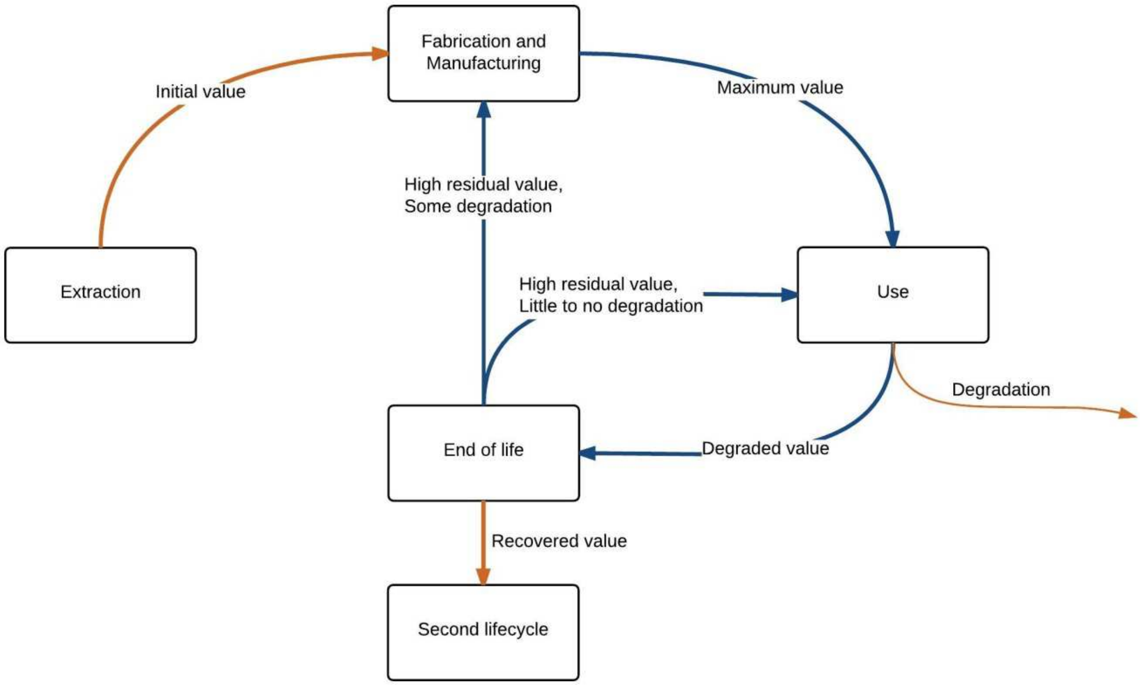

Figure 23: The evolution of value from one lifecycle to the next (material flows are in yellow, product flows are in blue)

The notion of a circular material value, i.e. that the value of a material can be recovered after the product is abandoned and considered waste, is not difficult to grasp. It is what makes recycling operations possible and viable in most cases. The circular material value does not only account for the financial "added value" of the operation, since materials are sometimes recovered and recycled at a loss, and should incorporate interdisciplinary elements to its analysis.

Also, in accordance with the observations made in Chapters 2 and 3, the lifecycle of a material involves multiple disciplines and areas of expertise, thus requiring the components of the circular material value indicator to originate from different fields such as economics, industrial and process engineering and, of course, product design. Each selected factor represents a crucial element of the material lifecycle. Economic and market dynamics, which can broadly encompass supply and demand, as well as material availability, are expressed using material prices and the market risk coefficient. Product design issues are translated by both the functional mass and the design yield. Global supply chain concerns and material criticality are conveyed by means of a criticality factor. Finally, cycling-related effects are represented by three coefficients that equate material degradation after use, the yield of transformation processes necessary for a second lifecycle of the material, and the property degradation provoked by these processes. These components of circular material value are presented in Table 16 and detailed in the next section.

Table 16: Circular material value variables, their definition and the potential source providing information related to this data in the company

Variable	**Definition**	**Potential data source**
Price ($\mathcal{P}$)	Current material price Usually expressed in \$/kg	Purchasing
Functional mass (m_f)	Actual material mass (m) multiplied by the functional unit coefficient ($\frac{U}{U_{av}}$) and divided by the mass required to fulfil the functional unit(m_{fu})	Design and marketing
Design yield (φ)	Main function's costs (C_F) divided by the total costs (i.e. main function's costs and design costs, C_D) Ranging from 0 to 1	Design and manufacture
Material criticality factor (κ)	Multi-criteria factor based on an assessment of material availability, supply chain vulnerability, societal addiction and substitutability Discrete values 1 (low), 2 (medium) or 3 (high)	*Availability and supply chain vulnerability* from purchasing; *Societal addiction* from marketing; *Substitutability* from R&D or design/material expert
Market risk coefficient (π)	Standard deviation ($\sigma_{\mathcal{P}}$) of the material's price function ($\mathcal{P}$) divided by its average ($\mu_{\mathcal{P}}$)	Purchasing
Material degradation after use coefficient (δ_m)	Material mass and property loss after one use cycle, ranging from 0 (complete degradation) to 1 (no degradation) It is determined by studying the state of the product after the use phase	Design and end-of-life experts (internal to the design team or external, e.g. eco-organizations and recycling federations)
Transformation process yield coefficient (η)	Efficiency of the end-of-life process, ranging from 0 to 1 It depends on technological, economic and organizational variables (see Chapter 5)	End-of-life experts (internal to the design team or external, e.g. eco-organizations and recycling federations)
End-of-life scenario functional degradation coefficient ($\delta_{\mathfrak{f}}$)	Material degradation caused by the operations required by the selected end-of-life scenario, ranging from 0 to 1 It is based on the maximum number of cycles ($\mathcal{N}_{scenario}$) of that scenario before property degradation is such that a new scenario is required	Design and end-of-life experts (internal to the design team or external, e.g. eco-organizations and recycling federations)

5.1.1 Material prices

First and foremost, based on Fama's Nobel Prize-winning Efficient Market Hypothesis, material prices ($\mathcal{P}$) should be the perfect rendition of value in a market supposed to be open and efficient, thus encompassing all the variables and information on the state of offer and demand[9]. This hypothesis is however difficult to generalize and to prove, especially in the case of resources being traded as commodities (even though (Kristoufek and Vosvrda 2013) found metal commodities to be quite efficient). Once materials are engineered into products, and even more so after they have become waste and have been recycled, their markets tend to become more inefficient and other issues require scrutiny when defining value. This hypothesis is therefore inadequate for a design method because it flattens every aspect of the product in a single indicator. Price can therefore only be considered an approximation of value, which is proportional to it. In this sense, precious metals probably hold more value after their lifecycle than pig iron or glass, for example. They would thus, at a first glance, be more interesting to recover for a second lifecycle. Material prices are often expressed in US$/kg.

Value being an ultimately non-quantifiable concept, it is best then to use value units to represent the different factors that affect circular material value in the form of coefficients that modulate price and approximate the product's value.

5.1.2 Functional mass

In the multiple lifecycles that the material may endure, mass (m) is the first characteristic that can provide information on the efficiency of the product and its use. Since mass is not lost (merely dissipated depending on the uses) over the course of a lifecycle, it is possible to gain insight also on the efficiency of the passage to the second lifecycle by analysing the evolution of the material mass flows in a product beyond the end-of-life stage. Yet it is the use of this mass (the function it is serving or the need it is satisfying), whose efficiency is being measured. What must be followed is not simply the amount of material that constitutes the product, but the amount of material required to realize the function served by the product ($\mathrm{m_{fu}}$). In order to take into account the transformations in the

[9] The Efficient Market Hypothesis is studied and criticized extensively across financial literature. For an analysis of the debate between predictability and efficiency, see (Malkiel 2003).

transition to a new lifecycle, mass and functional unit are thus considered simultaneously, as part of the same variable, the functional mass (m_f).

The relative utility of the application of the material (u) must, therefore, be assessed. The product in which the material will be used fulfils a specific function that represents the satisfaction of a given need with a certain quality for an allotted time period. These specifications describe a functional unit (in the sense developed by (Schrijvers, Loubet, and Sonnemann 2016)). When evaluating the material efficiency of products, it is necessary to compare the number of functional units they provide (U) divided by the number of functional units provided by an average industrial product, a reference product (U_{av}). This corresponds to a functional unit coefficient.

Here, the function and functional unit of a material will be approximated by the function and functional unit of the product in which it is used. Because materials may serve different functions in consecutive lifecycles depending on the product in which they are used (e.g. a glass window, whose function is being insulating and transparent, can be turned into glass wool and become a light, thermal and acoustic insulator), an iso-satisfaction hypothesis is made concerning these different functions and needs. This hypothesis is necessary and was formulated so as to avoid comparing the utility of products that have different functional units, due to an application change after the first lifecycle. Therefore, according to the iso-satisfaction hypothesis, regardless of which need is being met, the user's satisfaction is always deemed complete.

The functional mass is therefore proposed as a factor equal to the mass divided by the mass required to fulfil the functional unit, multiplied by the functional unit coefficient:

$$m_f[\text{adim.}] = \frac{m[kg]}{m_{fu}[kg]} \times \frac{U[adim.]}{U_{av}[adim.]}$$

The first ratio of the expression allows the interpretation of the mass quantity being used compared to the mass required to accomplish the functional unit. In the first lifecycle, this ratio is always 1, since the mass of reference being used is the same as the one required for one functional unit. When considering posterior lifecycles after some dissipation has taken place, this ratio acquires more significance as there might be a difference between m and m_{fu}, thus decreasing the functional mass. The lower the ratio, the further the material is from realizing the functional unit and the less the iso-satisfaction hypothesis can be held. On the other hand, the functional unit coefficient multiplying this ratio also translates the durability or the dematerialization (specific functional efficiency) of the product compared to other similar products. As it increases, so does the ability to satisfy the functional unit of that given material mass. Thus, the circular material value is proportional to $\mathrm{m_f}$.

Later, for the operationalization of the circular material value, $\mathrm{m_f}$ will be set to 1 on the first lifecycle, creating a reference mass flow of material that will serve as a baseline for the evaluation of the second lifecycle. If there is less material (lower m) to fulfil the functional unit on later lifecycles, mass drops and the recoverable value as well. Likewise, if less functional units are accomplished (lower U), less value will be associated to the material. However, the functional mass can exceed 1 in cases where the number of functional units is greater than the average product. The functional mass is, therefore, a factor that comprises the notion of functions being delivered by the product (which is essential in value analysis) and the concept of functional unit (which has been well developed especially in eco-design (International Organization for Standardization 2006; Schrijvers, Loubet, and Sonnemann 2016)). It sets the physical amount of material being used and also indicates the degree of dematerialization of the function being served analogously to the "utility" factor in (Ellen Macarthur Foundation 2015b), in which a product's efficiency in fulfilling its function (i.e. how long and intensively it is used) is compared to industry average products of the same type.

5.1.3 Design yield

The operations that add value in the manufacturing process have a cost and it should be considered in the value analysis. (Chevallier 1989; Delafollie 1992; Petitdemange 1995) propose an expression that represents the relative cost of providing the product's main functions. It is a yield between the cost involved in obtaining these functions ($\mathrm{C_F}$) and the total costs, which in this case can be considered as the costs of the functions and the extra design costs ($\mathrm{C_F + C_D}$). Generally, if it is below 60%, it means that the product is not cost effective and should be redesigned. The design yield (φ) formula is thus:

$$\varphi[adim.] = \frac{C_F[\$]}{C_F[\$] + C_D[\$]}$$

The more costs are associated with the main function, the more important the yield is, and the more efficient the design is. It is also proportional to circular material value since more value can be attributed to a more cost-effective design.

5.1.4 Criticality factor

Because of the uncertainties involved in the supply of certain materials and the need to preserve finite and scarce resources, it seems important to add a criticality factor (κ) to the value analysis in order to represent its strategic scope regarding supply chain stability. Material criticality is essential in assessing the importance of circular flows for a resource and must, therefore, be inserted in the estimations of the circular material value.

As a synthesis of different studies (Graedel and Nuss 2014; European Commission 2010; Binnemans et al. 2013; Bustamante, Gaustad, and Goe 2014; Erdmann and Graedel 2011; Graedel et al. 2012; Graedel et al. 2015), four criteria should be taken into account: the material's availability; the vulnerability of the supply chain in terms of geographic concentration and geopolitical situation of its extraction zones; the addiction that society has to that material; and its substitutability. Based on ISO 26262 (Kafka 2012), which provides a methodology for hazard analysis and risk assessment, a method was devised to determine the criticality factor using a risk tree. This method is based on the four criteria mentioned above, which are given grades from 1 to 4 (so as to prevent a tendency for middle answers), in which 1 is Satisfactory, 2 is Acceptable, 3 is Mediocre and 4, Insufficient. Table 17 describes each grade of the criticality criteria used to calculate the criticality factor. In Table 18, the grades for each criterion are multiplied and the results are divided into three balanced frequency subsets. Each subset corresponds to a criticality factor level ranging from 1 to 3, in order of growing criticality: scores between 1 and 12 were attributed to level 1; 16 to 36 to level 2; and 48 to 256 to level 3. Thus, the circular material value is proportional to the criticality factor, as it can be assumed that there is more interest in recovering materials that are critical since their scarcity will be high and so will its value.

Table 17: Description of the grades for analysing the criticality criteria

Criticality criterion	Grade 1 (Satisfactory)	Grade 2 (Acceptable)	Grade 3 (Mediocre)	Grade 4 (Insufficient)
Availability	Abundant resource in the earth's crust, little to no signs of depletion (depletion time is not an issue)	Relatively abundant resource in the earth's crust, but consumption rates are such that shortages may occur at some point	Lower concentration in the earth's crust, resource supplies are compromised due to intense extraction, depletion time of a couple of decades	Rare deposits, low concentration in ores, depletion time of a few years
Vulnerability of supply chain	Material occurrence is relatively widespread and no conflicts are involved in its supply	Low geographic concentration and low geopolitical risks in the regions where it is produced	Medium geographic concentration and/or medium geopolitical risks in the regions where it is produced	High geographic concentration and/or high geopolitical risks in the regions where it is produced
Societal addiction	No addiction, products concerned are not essential to current or future needs of industries and society in general	Low addiction, products concerned are of some commercial or social interest in the present but are not strategic for industries and society in the near future	Medium addiction, products concerned are important to current or future needs of industries and society in general	High addiction, products concerned are indispensable to current or future needs of industries and society in general
Substitutability	High substitutability, there are known substitutes and their use does not require costly investments	High substitutability, known substitutes exist or have been identified but their use requires some investments, whose costs can easily be absorbed by the clients	Medium substitutability, substitutes are not promptly available and require research and investments whose costs cannot be entirely absorbed by the clients	Low substitutability, there are no known substitutes

Table 18: Combination of material criticality criteria forming the different values of the criticality factor (green equals 1 [values 1-12], is low; yellow equals 2 [values 16-36], is medium; and red equals 3 [values 48-256], is high)

		Addiction															
		1				2				3				4			
		Substitutability															
Availability	Vulnerability	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	1	1	2	3	4	2	4	6	8	3	6	9	12	4	8	12	16
	2	2	4	6	8	4	8	12	16	6	12	18	24	8	16	24	32
	3	3	6	9	12	6	12	18	24	9	18	27	36	12	24	36	48
	4	4	8	12	16	8	16	24	32	12	24	36	48	16	32	48	64
2	1	2	4	6	8	4	8	12	16	6	12	18	24	8	16	24	32
	2	4	8	12	16	8	16	24	32	12	24	36	48	16	32	48	64
	3	6	12	18	24	12	24	36	48	18	36	54	72	24	48	72	96
	4	8	16	24	32	16	32	48	64	24	48	72	96	32	64	96	128
3	1	3	6	9	12	6	12	18	24	9	18	27	36	12	24	36	48
	2	6	12	18	24	12	24	36	48	18	36	54	72	24	48	72	96
	3	9	18	27	36	18	36	54	72	27	54	81	108	36	72	108	144
	4	12	24	36	48	24	48	72	96	36	72	108	144	48	96	144	192
4	1	4	8	12	16	8	16	24	32	12	24	36	48	16	32	48	64
	2	8	16	24	32	16	32	48	64	24	48	72	96	32	64	96	128
	3	12	24	36	48	24	48	72	96	36	72	108	144	48	96	144	192
	4	16	32	48	64	32	64	96	128	48	96	144	192	64	128	192	256

Examples: Satisfactory Availability (1) X Acceptable Vulnerability (2) X Satisfactory Addiction (1) X Insufficient Substitutability (4) = (8 or Green), which corresponds to a Low Criticality Level, $\kappa = 1$;

Mediocre Availability (3) X Acceptable Vulnerability (2) X Mediocre Addiction (3) X Satisfactory Substitutability (1) = (18 or Yellow), which corresponds to a Medium Criticality Level, $\kappa = 2$;

Acceptable Availability (2) X Mediocre Vulnerability (3) X Insufficient Addiction (4) X Acceptable Substitutability (2) = (48 or Red), which corresponds to a High Criticality Level, $\kappa = 3$.

5.1.5 Market risk coefficient

Many economists dealing with the sourcing of commodities are interested in the evaluation of the risks involved in their future prices. Commodity markets are known to be extremely volatile and this is especially the case when dealing with recyclable materials whose price volatility is in some cases five times greater than that of virgin materials (OECD 2007). The market risk represented by the volatility of prices can be assessed and compared between different time series by means of the coefficient of variation, π, which is given by the standard deviation of the product's price ($\sigma_{\mathcal{P}}$) divided by its average ($\mu_{\mathcal{P}}$).

$$\pi[adim.] = \frac{\sigma_{\mathcal{P}}[adim.]}{\mu_{\mathcal{P}}[adim.]}$$

This ratio allows the comparison of standard deviations between materials that have large differences in prices, by normalizing them with their averages. A material with a high volatility must be considered as less valuable than a material with a low one, thus the market risk is inversely proportional to circular material value.

5.1.6 Cycling coefficients

After the first use of the product, when it has been discarded and its materials must be recovered and perhaps reinserted into new lifecycles, the material flow is affected and the circular material value is altered. This transition depends on the cycling scenarios that can be followed and the subsequent application of the material. Cycling coefficients are required in order to take into account the effects that the cycling operations have on the circular material value, as the product is discarded by the user and its materials are incorporated into a second lifecycle.

5.1.6.1 Material degradation after use coefficient

Material degradation is caused by the wear, tear, corrosion or other forms of dissipation to the environment of the product materials, during the use phase. These losses induce a decrease in the general value of the product and its materials. They are sometimes the result of a deliberate design choice as with selenium and manganese in fertilizers, aluminium, magnesium, copper and barium in pyrotechnics, and zinc in sacrificial anodes (Ciacci et al. 2015).

Usually, product designers have some idea of use patterns of their products and the user behaviour of their clients and they can assess the state of the product's materials after the use phase. They can, therefore, evaluate the mass and property losses after one use cycle and quantify that into a material degradation coefficient (δ_m), ranging from 0 (complete degradation) to 1 (no degradation).

5.1.6.2 Transformation process yield coefficient

Based on the affirmation by (Washida 1998) that recycling activities inevitably cause material dispersion, on top of the dissipation and properties' degradation that occurs in the use phase, there are also quality and mass losses in transforming waste materials back into the raw material input of production processes. Thus, the recycling processes' yields are taken into account when evaluating the new circular material value. This can be achieved by introducing a transformation process yield coefficient, η, going from 0 to 1, as a representation of the losses entailed by that specific material cycling operation. This coefficient therefore provides the actual (or expected) efficiency of the cycling operation in a given context and scenario, based on the knowledge of the process, market and waste management system conditions. These elements will be further described in Chapter 6.

Each cycling scenario corresponds to a type of transformation, which can be characterized by its own yield. In the case of reuse, this transformation is relatively lossless but in other scenarios, especially recycling, process yields can vary greatly, from the high-collection and high-efficiency of steel products to the mediocre collection rates and efficiency polymer recycling in general.

5.1.6.3 End-of-life scenario functional degradation coefficient

The passage of the material through the end-of-life scenario may entail some consequences on it, due to the very act of recovering the material, which can be thermodynamically or industrially problematic. The operations required in the selected end-of-life scenario may, therefore, cause some type of property or functional degradation to the material, such as when recycling polymers via mechanical recycling when the polymer chains are progressively shortened, with each lifecycle, ultimately leading to the complete loss of the initial mechanical properties of the material. The end-of-life functional degradation coefficient (δ_f) translates this gradual property loss that happens in the recovery process. It is based on the maximum number of cycles ($\mathcal{N}_{\text{scenario,max}}$) from that scenario before property degradation is such that a new scenario is required and it is given by the expression:

$$\delta_f = 1 - \frac{1}{1 + \mathcal{N}_{scenario,max}}$$

The expression contains a $(1 + \mathcal{N}_{\text{scenario,max}})$ on the denominator since it must encompass the current lifecycle contribution to the value in the subsequent one and prevent that the value drops to zero for scenarios that can only be applied one time.

5.1.7 Circular material value indicator

Circular material value ($\mathcal{V}$) is defined as a representation of the functions or utilities provided by a material in a product (assimilated to those of the product itself) modulated by the costs involved in its production and the social and economic risks stemming from its consumption and the operations required for its return to the economy in a new lifecycle. It measures the potential value that the material holds for future cycles that could be tapped into after the product is discarded and that could, in the near future, be recovered in financial terms. It therefore indicates the extent to which using that material has strong ramifications in the material's flows in the economy. It also serves as an approximation of the material's scarcity.

The circular material value indicator is composed of variables that can be defined by (or that relate to) the product designers and of variables that come from the network of stakeholders involved in all of the material's cycle (Table 19). It conveys the impacts of design choices in material flows but also incorporates material flow information in the estimation of material value, as well as a risk and criticality assessment, all the while encompassing multiple end-of-life scenarios and different recovery options. If this indicator is implemented in a design method, supply chain specificities and scarcity issues would then be added to the understanding of the product. Also, instead of having to perform a multi-criteria choice using the pertinent variables separately, it aggregates them in a comprehensive way, as stipulated in the proposition's sub-functions (Table 15).

Table 19: Design and network variables in the circular material value equation

Design variables	**Network variables**
Design yield (φ)	Price ($\mathcal{P}$)
Functional unit (U)	Market risk (π)
Mass (m)	Material criticality (κ)
Material degradation after use (δ_{m})	Transformation process yield coefficient (η)
	End-of-life scenario functional degradation coefficient ($\delta_{\mathfrak{f}}$)

These factors have been assembled in the simplest formula to account for their respective effects on the circular material value. The objective here is to obtain a first means of evaluating it, showing its use and significance. As mentioned earlier, the indicator was built by adding coefficients to modulate material prices and therefore represent the material circularity issues.

Depending on where the circular material value is estimated, some of its components are not included in its estimation. Before the end-of-life stage, it is a function only of its price, mass, functional unit, the cost-efficiency of its design, its criticality and market risk, since the cycling coefficients do not apply:

$$\mathcal{V}_1 = f(\mathcal{P}, m, \mathrm{U}, \varphi, \kappa, \pi)$$

If resource efficiency and preservation are aimed, this initial value $\mathcal{V}_1$ is attributed to materials in products that are more expensive, more useful and long-lasting, all the while avoiding volatile, critical, expensive and densely applied materials.

$$\mathcal{V}_1 = \mathcal{P}_1 \times m_{f_1} \times \frac{\varphi_1 \times \kappa_1}{\pi_1}$$

After the end-of-life, when considering possible second lifecycles, the end-of-life coefficients are added:

$$\mathcal{V}_2 = f(\mathcal{P}, m, \mathrm{U}, \varphi, \kappa, \pi, \eta, \delta_m, \delta_{f})$$

As it enters the new lifecycle, depending on the time that has passed since the first lifecycle or the application in which they are used, the materials may have new prices, functional masses, design yields, criticality factors and market risks. $\mathcal{V}_2$ is the new value for the second lifecycle after a new manufacturing process. It encompasses both the end-of-life coefficients for the transition from the first lifecycle and a new manufacturing process (represented by the new design yield):

$$\mathcal{V}_2 = \mathcal{P}_2 \times m_{f_2} \times \frac{\varphi_2 \times \kappa_2}{\pi_2} \times \eta \times \delta_m \times \delta_{f}$$

Circular material value is thus expressed in price units divided by mass units, as only material prices have a unit since every other factor involved is dimensionless.

5.2 Design for Material Circularity method

Evaluating material circularity or seeking circular flows in the inputs and outputs of a product can become an important part of the product designers' and the company's strategy in the future, as circular thinking is inserted in the technical specifications of materials and products. From an integrated product lifecycle design perspective, the sooner material circularity is addressed in the design process, the less costly and time consuming the eventual redesigns will be. Thus, in a four-step product design process (specification, conceptual design, embodiment design, detailed design), the evaluation of material circularity should be performed as early as the conceptual design phase in order to provide insight on how to improve material sourcing and destination, but also for designers to have some flexibility regarding the full lifecycle status of their products. If performed during the embodiment design phase, the circularity evaluation is useful to gather information on specific aspects of embodiment choices and their repercussions on the product's end-of-life, which can help in achieving recovery goals and comply with the applicable legislation. After the embodiment design, during the detailed design phase, since little to no redesign is possible, a circularity evaluation can serve as a means of identifying materials that are potential circularity hotspots and proposing specific cycling guidelines regarding them. The proposed method supports product designers in anticipating material sourcing and end-of-life treatment contexts, taking multiple variables and criteria into account. Such support can be used to formulate future ISO guidelines for product lifecycle integration, for instance.

The Design for Material Circularity method is based on an assessment and comparison of circular material value ($\mathcal{V}$) over two lifecycles. This analysis requires the evaluation of $\mathcal{V}$ as the product enters its first use cycle ($\mathcal{V}_1$), i.e. a baseline value, defined as the product leaves the manufacturing phase and enters the use phase of the lifecycle. Potential values for the second lifecycle ($\mathcal{V}_2$) of each cycling scenario that is deemed feasible and available for the product's materials must also be calculated. Depending on whether a closed loop (reuse, remanufacturing or closed loop recycling) or open loop scenario is planned, the information required to calculate $\mathcal{V}_2$ may come from the company itself or stem from the knowledge of the end-of-life networks (*cf.* Table 16). Once all baseline values and second lifecycle estimations are set, they can be compared using relevant heuristics in order to select the most suitable material for that application and the corresponding end-of-life scenario. This in turn can generate some recommendations to simultaneously improve the design and the end-of-life treatment.

Though it might be assigned to a materials expert in the design team, who would carry the responsibility of completing it, the application of this method invites all the departments of the company to exchange information that is pertinent to the product's lifecycle. Also, due to multi-expertise requirements and the interdisciplinary nature of the task, assigning a team with complementary knowledge of the company's work is advisable in order to facilitate the application of the method.

The method is divided into three phases divided into nine steps (Table 20). As in most design methods, these phases and steps may be accomplished in iterations, creating evaluation and design loops that deepen the product design team's knowledge of the end-of-life implications of their material choices and foster the circularity of materials.

Table 20: Phases and steps of the Design for Material Circularity method

Phase 1: Initialization	a. Goal definition; b. Data gathering and hypotheses
Phase 2: Operationalization	c. Establishment of a baseline; d. Evaluation of material degradation after use; e. Identification of potential cycling scenarios; f. Estimation of second lifecycle values
Phase 3: Interpretation	g. Selection of an evaluation strategy; h. Results analysis; i. Recommendations

In order to find an optimal combination of material and end-of-life scenario, it is necessary to know if there are any constraints in their choice. If the end-of-life scenario is imposed (by present infrastructure, industrial configuration, corporate strategy and culture, or legislation) and the choice of different materials is possible, the method becomes a material selection tool. It is complementary to other material selection tools (e.g. the Granta Suite), focusing specifically on the circularity of material flows. In this case, the circular values are calculated for each material and then compared between them. If the material is pre-defined and cannot be changed but the end-of-life scenario is flexible, applying this method will foster the choice of a preferential end-of-life treatment, based on the criteria that were set in the course of the analysis. In this case, the baseline values defined for the material are compared to the values at the end of each scenario in order to choose the most suitable treatment. If both materials and end-of-life scenarios can be modified, the method can assist in finding an optimal solution from a global perspective, evaluating their possible pairings.

If the recommendations generate new product designs, concepts or solutions, these could also be the object of an evaluation. By comparing the incremental or disruptive innovations brought by the application of the method, circular design loops can be created. One can also imagine that, if the method is applied consecutively and generates recommendations along the chain of material cycles shown in Figure 22, then overall optimal choices can be made and circularity increased along multiple material cycles. Also, this could be of notable interest in the case of relatively closed recycling loops or remanufacturing loops, because it would inform the design team of the potential number of cycles before degradation takes its toll and renders the material unusable. This way, product design could be adjusted to a specific number of cycles or simply improved for long lasting by focusing on the materials or parts that degrade faster.

5.2.1 Scope delimitation

The general model of an industrial lifecycle considers four main phases: extraction, manufacture, use, and end of life. This has been applied to both product flows (through LCA (International Organization for Standardization 2006)[10]) and material flows (in MFA). However, the boundary between material and product flows in the lifecycle is not as clearly definable. Some mono-material products can be confounded with the material with which they are made, such as firewood or a nickel coin, while certain products have their own specific end-of-life industrial sectors and treatments so that they can almost be treated as a single "material" flow, as with tires and glass.

At the beginning of the cycle, what comes out of the extraction phase is considered as a material flow. After being transformed during the manufacturing stage, the materials are converted into a product flow. They follow their course in the economy during their use phase until they are discarded and officially enter their end-of-life stage. In European countries that adopt the Extended Producer Responsibility legislation, for instance, waste products are grouped into specific flows according to how they should be handled after being discarded and in order to structure and optimize the whole

[10] Contrarily to LCA, this research does not focus on calculating on calculating the environmental impacts generated by products or services.

waste management network. However, at some point in their journey, the products will be dismantled, shredded and sorted so as to recreate material flows, as purely as possible. While this assessment may be used to address end-of-life product flows such as reuse and remanufacturing, it focuses primarily on the comparison of material value between the manufacturing stage and the material end-of-life flows. Figure 24 shows the different end-of-life scenario possibilities in a product's lifecycle that are considered in this research.

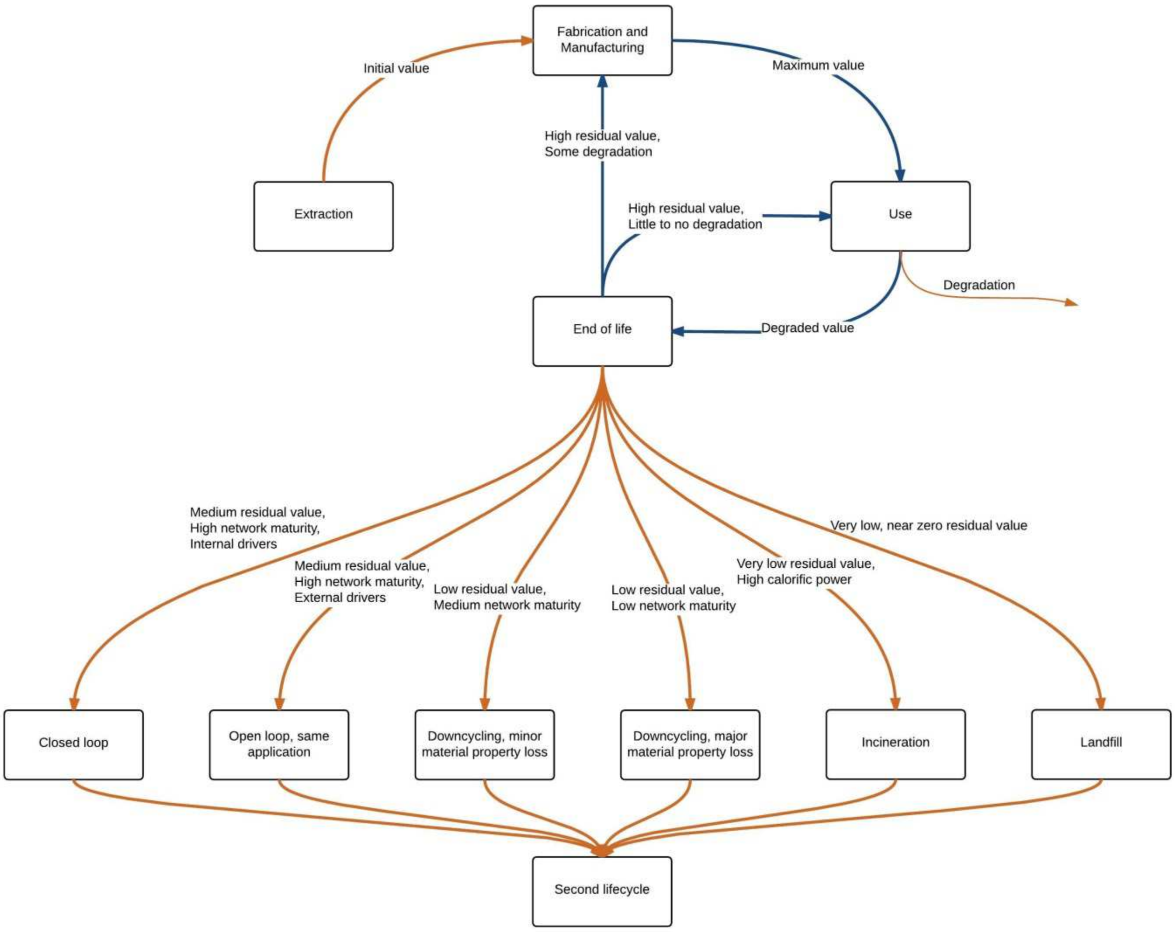

Figure 24: Product lifecycle and material end-of-life scenarios (product flows are in blue and material flows are in orange)

This method focuses mainly on the value optimization and maximization from the perspective of the direct stakeholders, i.e. production companies, or focal companies as addressed by supply chain management literature (Seuring and Müller 2008). The method is intended to cover the impacts of all the stakeholders mentioned previously by (Enzler 2006) but it focuses on their implications on the last form of material flow management, namely the cooperation between manufacturers, disposal companies and recyclers.

The lifetime of products has a significant impact on the estimation of the second lifecycle, which becomes less precise the longer the span of the first lifecycle is. If long lifecycles such as the ones for built environments and infrastructure are being evaluated, accurate projections of the variables in the circular material value indicator will be hard to obtain. In this sense, the method is better suited for short and mid-term lifecycles such as consumer goods and less applicable to longer lifecycles.

Making material and end-of-life choices based on a perception of their value is especially interesting for products containing strategic materials that companies use in great volume, that possess high intrinsic value, or whose supply presents some risks. Products with critical materials as defined by any of the multiple studies on the subject (Graedel et al. 2015; Erdmann and Graedel 2011; Fromer, Eggert, and Lifton 2011; European Commission 2010; Coulomb et al. 2015; Peck, Kandachar, and Tempelman 2015; Bush et al. 2014; Moss, Tzimas, and Willis 2013) are also good candidates for a circularity assessment.

Because the method is aimed at addressing potential scenarios for subsequent material lifecycles, it extends to situations and decisions over which the designer (or the company as a whole) has no power and may potentially have no information either, as they might concern other companies, other processes and perhaps even different products and functions. For this reason, the more the designer can gather information on the several end-of-life possibilities, the more pertinent his evaluation will be. This will be the case for well-documented and consolidated industrial sectors with well-established and active industrial federations or eco-organisations that have compiled the data from all the material cycling scenarios.

5.2.2 Data and expertise requirements

Regardless of the objective and the step in the design process in which the method will be applied, there are two types of information required to assess material flows in order to connect design and end-of-life activities. Both elements correspond to what is expected in Integrated Design approaches as defined by (Tichkiewitch and Brissaud 2004) by encompassing the viewpoints of all relevant stakeholders and experts.

The first requirement consists in accessing two databases that will be used and can be progressively completed by the experts involved in the application of the method, one regarding materials' properties and production processes, another gathering information on the state and evolution of end-of-life networks. Materials databases should readily provide material prices ($\mathcal{P}$), market risk (π), criticality (κ) and perhaps even material degradation after use (δ_m), while the cycling networks' database should inform on the transformation process yield coefficient (η) and the end-of-life scenario functional degradation coefficient (δ_f).

While these databases can be filled and hosted by the company, truly extensive inventories could and, in practical terms, should be provided by external, independent and research-oriented consultants as well as sectoral associations and industrial federations. As was shown in previous chapters, these repositories may already exist in some form but are not always complete or available in a form that can be readily employed by material experts and product designers. The provision of this data should be performed by experts in each related field and constitutes the second requirement: the analysis of the circular value of materials requires expertise and knowledge of every lifecycle phase as well as projections and insight over the next potential lifecycles. This involves virtually all of the company's departments: material prices, market variations and supply chain information from purchasing; manufacturing costs from the manufacturing experts; use behaviours and consumer expectations (in terms of product lifetime, functions and market segmentation) from the sales and marketing department; as well as the product's bill of materials from the design team. End-of-life data on the potential second cycles can be scattered throughout the different areas and is usually treated by the professionals responsible for sustainability issues, who can be within the company or externalized. In order to gather the information needed to evaluate the circular material value, the product designer must interact with the experts from each field and some knowledge management tools should be implemented to foster these interactions[11]. Applying the method will in itself be a means of increasing the knowledge of the product and can leverage the expertise across the organization, as represented in Figure 25. Table 21 summarizes the variables that compose the material circularity potential, their formulas as well as the source for their data inside the company.

[11] These are however beyond the scope of this work. (Baouch 2016) provides three appropriate tools that could be adapted to the application of the method, to help gathering information from different company departments' expertise.

Table 21: Recapitulation of circular material value variables, their definition, data source in the company and formula

Variable	Definition	Data source	Formula
Price ($\mathcal{P}$)	Current material price Usually expressed in $/kg	Purchasing	--
Market risk coefficient (π)	Standard deviation ($\sigma_{\mathcal{P}}$) of the material's price function ($\mathcal{P}$) divided by its average ($\mu_{\mathcal{P}}$)	Purchasing	$\pi = \frac{\sigma_{\mathcal{P}}}{\mu_{\mathcal{P}}}$
Design yield (φ)	Main function's costs (C_F) divided by the total costs (i.e. main function's costs and design costs, C_D) Ranging from 0 to 1	Design and manufacture	$\varphi = \frac{C_F}{C_F + C_D}$
Functional mass (m_f)	Actual material mass (m) multiplied by the functional unit coefficient ($\frac{U}{U_{av}}$) and divided by the mass required to fulfil the functional unit(m_{fu})	Design and marketing	$m_f = \frac{m}{m_{fu}} \times \frac{U}{U_{av}}$
Material criticality factor (κ)	Multi-criteria factor based on an assessment of material availability, supply chain vulnerability, societal addiction and substitutability Discrete values 1 (low), 2 (medium) or 3 (high)	Availability and supply chain vulnerability, from purchasing; Societal addiction, from marketing; Substitutability, from R&D or design/material expert	See criticality matrix in section 5.1.4.
Material degradation after use coefficient (δ_m)	Material mass and property loss after one use cycle, ranging from 0 (complete degradation) to 1 (no degradation) It is determined by studying the state of the product after the use phase	Design and end-of-life	--
Transformation process yield coefficient (η)	Efficiency of the end-of-life process, ranging from 0 to 1 It depends on technological, economic and organizational variables (see Chapter 5)	End-of-life	--
End-of-life scenario functional degradation coefficient ($\delta_{\mathcal{f}}$)	Material degradation caused by the operations required by the selected end-of-life scenario, ranging from 0 to 1 It is based on the maximum number of cycles ($\mathcal{N}_{scenario}$) from that scenario before property degradation is such that a new scenario is required	Design and end-of-life	$1 - \frac{1}{1 + \mathcal{N}_{scenario,max}}$

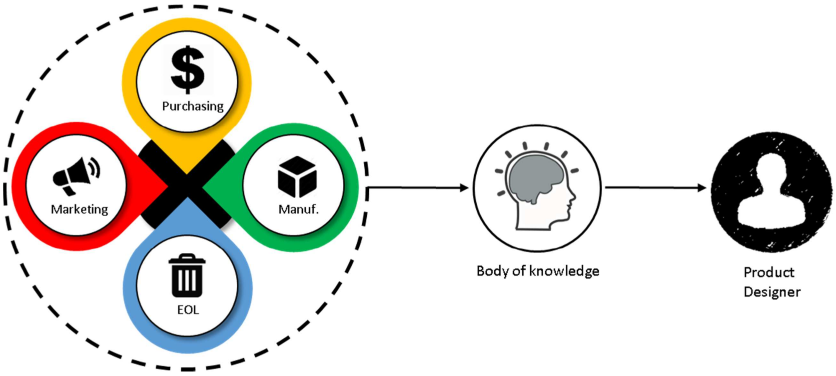

Figure 25: The product designer's role of knowledge integration via the Design for Material Circularity method

Deploying this method thus creates a flow of data that enriches the available material and end-of-life databases. The product designer becomes the integrator of all of the incoming data but also of the knowledge that has been amassed by purchasing, manufacturing, marketing and end-of-life experts (Figure 26). The refinement of the product's design can be achieved via multiple design loops, as constraints go back and forth between the experts, especially when resolving trade-offs.

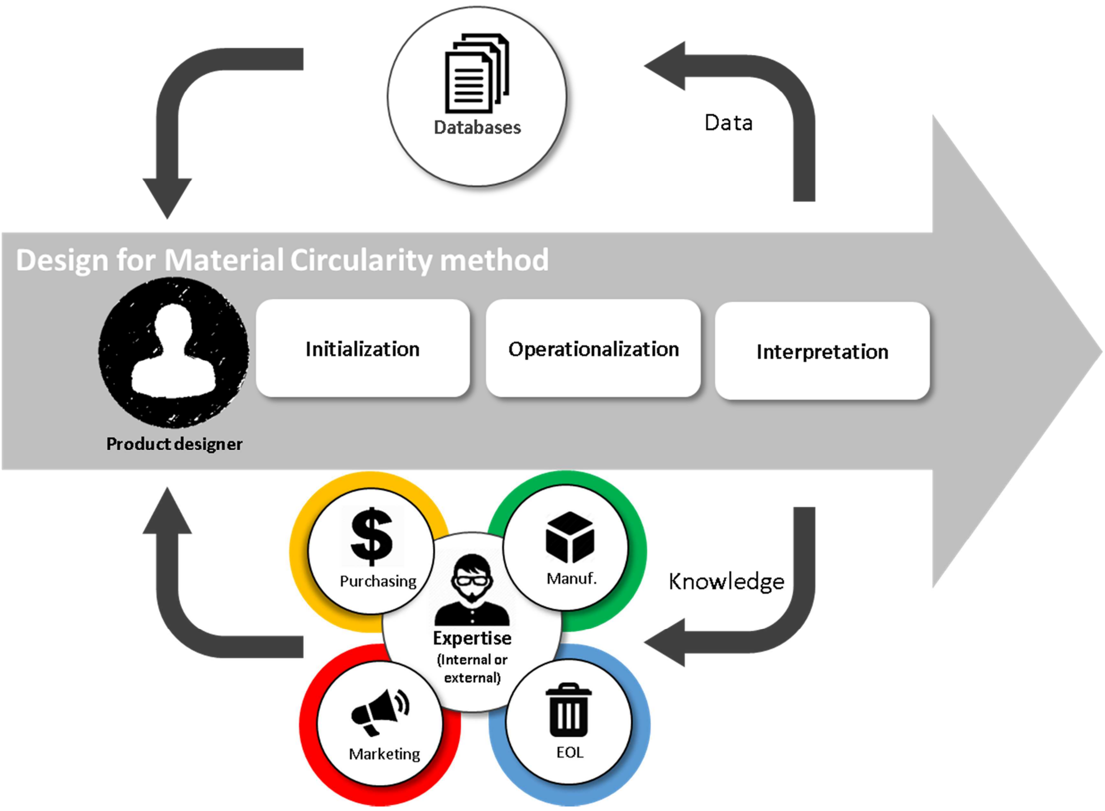

Figure 26: General diagram of the Design for Material Circularity method showing the data and knowledge flows during product design development in the industry

After the first iteration of the method, new and more systematized data can be added to the existing databases and more knowledge can be added to the pool of corporate expertise. This knowledge will ideally be shared among the multiple departments involved and integrated by the product design team.

5.2.3 Phase 1: Initialization

a. Goal definition

Whether the method is applied to all the material candidates of each product component or only to some of them is contingent on the objectives that were set as well as the available information, time and resources. If there are no material and time limitations, a thorough analysis will provide insight into the most important components in terms of availability and risk. It may, however, be more practical to select the most strategic elements in the product, which are usually already identified by the company. Multiple goals can be defined by the product design team regarding material circularity, simultaneous or independently. These goals usually concern a specific department in the company, as shown in Table 22:

Table 22: Goals of the method and their respective company department

Company department	Goal	Sub-objectives related to the provided variables
Product design	Include circularity as a factor in material selection screening methods Adapt product specifications to increase material circularity	Report and justify material selection based on design yield (φ), functional mass (m_f) – by conducting functional analysis of the product's parts – and end-of-life scenario functional degradation coefficient (δ_{f})
Purchasing	Avoid vulnerable supply chain routes Increase circularity in purchasing practices	Monitor material criticality factor (κ) based on the assessment of material availability, supply chain vulnerability, societal addiction and substitutability of the targeted material flow
Marketing	Contribute to the circular economy initiative Capitalize on circularity gains Promote circular value as a concept	Monitor the transformation process yield coefficient (η) by encouraging technological development, economic efficiency and organizational improvements
End-of-life	Prevent or decrease material scarcity	Target an adapted functional degradation coefficient (δ_{f}) by monitoring an optimal number of cycles ($\mathcal{N}_{scenario.max}$) for a material flow in a given context

b. Data gathering and hypotheses

As in the methodologies presented in (Ellen Macarthur Foundation 2015b; Ardente et al. 2011), the evaluation of material circularity in a product should use the product's Bill of Materials as its main source of information for the analysis of the product's design. This provides the material candidates for each component as well as their respective mass. If the method is applied at a later design stage, additional information on the product's architecture (its parts, sub-parts and connections) is desirable as well.

If there is a lack of information on any variable, the designer or respective expert must provide the best possible estimation and formulate a hypothesis. Estimates should always be made so that they are more disadvantageous in terms of the material value, in order to deliberately underestimate it and obtain an approximate minimal value. Each hypothesis must be duly noted and, if possible, confirmed afterwards or, at least, tested in a sensitivity analysis. The quality of the data should be assessed, if possible, using the pedigree matrix approach developed by (Weidema et al. 2013) for instance.

5.2.4 Phase 2: Operationalization

When focusing on circularity from a product design perspective, the estimation of circular material value is performed in two particular moments: to establish the baseline, as the product leaves the manufacturing process and heads to the use phase (when value is considered to be maximal for that lifecycle as shown in Figure 23), and as it goes through the end-of-life and into a new lifecycle. The first circular material value serves as a reference, while the second represents the value that is expected to enter the second lifecycle after passing through an end-of-life scenario.

c. Establishment of a baseline

Once the first conceptual design has been proposed, the product can be evaluated in terms of the multicycle material circularity of its components. The baseline of the material M_i given by the value analysis performed earlier is proposed as an approximation of the initial material circularity potential. It does not include the end-of-life coefficients at this point:

$$\mathcal{V}_{1,M_i} = \mathcal{P}_1 \times m_{f1} \times \frac{\varphi_1 \times \kappa_1}{\pi_1}$$

Considering all the materials in a product part:

$$\mathcal{V}_{part} = \frac{\sum \mathcal{V}_i \times x_i}{\sum x_i}$$

in which $\mathcal{V}_{\mathrm{i}}$ is the circular material value of material M_i and $\mathrm{x_i}$ is its mass fraction. Similarly, in order to obtain the product circularity appraisal based on the materials contained in its parts:

$$\mathcal{V}_{product} = \frac{\sum \mathcal{V}_{part_i} \times x_{part_i}}{\sum x_{part_i}}$$

The baseline is a specific case of the circular material value, in which there is no influence of the end-of-life coefficient. It refers to a given functional unit that is set by the product designer for the product's first lifecycle. This will serve as a reference for the evolution of circularity in subsequent lifecycles even if the function may change. It is important however that the functional mass be defined for a given mass and functional unit in order to have a reference flow and allow the comparison of lifecycles.

d. Evaluation of material degradation after use

The material residual value is the value the material retains after going through the use phase and suffering the related degradation. This degraded value is determinant to whether the waste product will be kept as a product to be reused or whose parts may be remanufactured, or if it will follow its course so as to be dismantled and decomposed into material flows. The more value is kept after a lifecycle, the more efficient the waste management solution will be. If the material degradation coefficient is too low, some scenarios may become impractical. In the worst case scenario, if the product contains materials that are toxic, storage in a properly contained environment is necessary. If liberation is too difficult and contamination is such that no material recovery is possible, the best solution is to recover at least the energetic potential of the material after incineration. On the other hand, if no value loss and degradation occurred during the use phase, the product may potentially be reused. If little degradation occurred and the residual value is still high, perhaps some components may be salvaged through remanufacturing. Finally, when the materials retain only a fraction of their initial value and must go through a proper recycling process, the issue of the state of the industrial recycling network has to be addressed. This has already been represented in Figure 24.

e. Identification of potential cycling scenarios

Expertise on the product's end-of-life and its material cycling networks provides the practicable cycling schemes from which the second lifecycle material values can be calculated. If the actual waste treatment scenario is known, it can serve as a reference for the cycling scenarios in the subsequent comparisons.

The assessment of the material cycling network requires previous knowledge of the state of the corresponding industries. These exceed the scope of the designer's activity and rely on expertise that must be collected in the company by a specific expert or group of experts. This knowledge can be acquired internally, via an in-house expert in the company's material flows and its end-of-life possibilities and requirements, or it can be provided by resorting to external consultants. In every case, the expertise gained by delving into the issues of the lifecycle of the product's materials should be capitalized and duly stored after each evaluation.

The knowledge of the cycling networks that apply to the product can be translated into a decision tree that describes the different scenario choices. This decision tree is composed of questions regarding the Extended Producer Responsibility scheme adopted to manage the waste stream, the desired application of the material in the new lifecycle, whether the functions and properties of the material are preserved in the new lifecycle, the degradation level after the first use phase, as well as technical, economic, regulatory and organizational information on the cycling process. A thorough knowledge of the product's end-of-life requirements and possibilities is fundamental in order to correctly assess the available scenarios. This can be performed by analysing the material cycling networks' variables that have been previously described. When gathering data for the recycling rates, one must consider the current dismantling techniques employed in the product at its end-of-life, since it can seriously impact the recovery of materials. Moreover, closed loop or open loop scenarios may concern different methods and therefore have significant disparities between process and network yields. The main elements that are addressed for the identification of the end-of-life scenarios are shown Table 23. Figure 27 presents a generic example of an end-of-life scenario tree. Chapter 6 further delves into the issue of gathering systematized data from material cycling schemes and provides a framework for the characterization of material cycling networks, as well as analyses of the open-loop recycling schemes of eight important industrial materials from distinct material classes.

Table 23: Elements composing the end-of-life scenario tree

End-of-life decisions	Potential outcomes	Description
What type of Extended Producer Responsibility?	Individual management	The waste flow is handled by the company directly responsible for it
	Eco-organism	The waste flow is handled by a network of waste management stakeholders
Will the application be preserved?	Yes	The material will be used in the same type of product in the subsequent lifecycle, in an open or closed loop. Value data regarding costs, utility and mass are approximately the same
	No	The material will be used in a different type of product in the subsequent lifecycle. Value data regarding costs, utility and mass may vary significantly
Will its functions/properties be preserved?	Yes	The useful/functional material properties are the same in both lifecycles
	No	The useful/functional material properties differ from one lifecycle to the next
What is the level of material degradation after use?	No sensible degradation	There is virtually no material degradation or dissipation in the use phase; material could be reused in its current state
	Low degradation	There is a low level of material degradation or dissipation; the initial material performance could be easily recovered
	Medium degradation	There is a medium level of material degradation or dissipation; material cycling operations are necessary to recover the material's properties
	High degradation	There is a high level of material degradation or dissipation; material properties have been completely lost
Is the process technically feasible?	Yes	Assessment based on the process variables: process technical optimization, efficiency of cycling process, recycled material properties
	No	
Is the process economically viable?	Yes	Assessment based on the market variables: global material supply, global material demand, material accumulation in use, dissipative uses, price of raw materials (virgin and recycled), waste deposit (size and quality), transportation costs, labour costs, downstream recycled material applications.
	No	
Are there any regulatory, organizational or social drivers for its recycling?	Yes	Assessment based on the environment conditions: collection mechanisms, waste management development level, environmental regulations, raw material policies, manufacturer and consumer attitude
	No	
Does the material have a high calorific value?	Yes	The combustion of the material provides enough heat for it to fuel industrial processes
	No	The combustion of the material does not provide enough heat for it to fuel industrial processes
Does the material contain any known pollutants or toxic elements that are banned from incinerators or kilns?	Yes	The combustion of the material may liberate harmful gases or cause damage to the incinerators or kilns in which it is performed
	No	The combustion of the material does not liberate harmful gases or cause damage to the incinerators or kilns in which it is performed

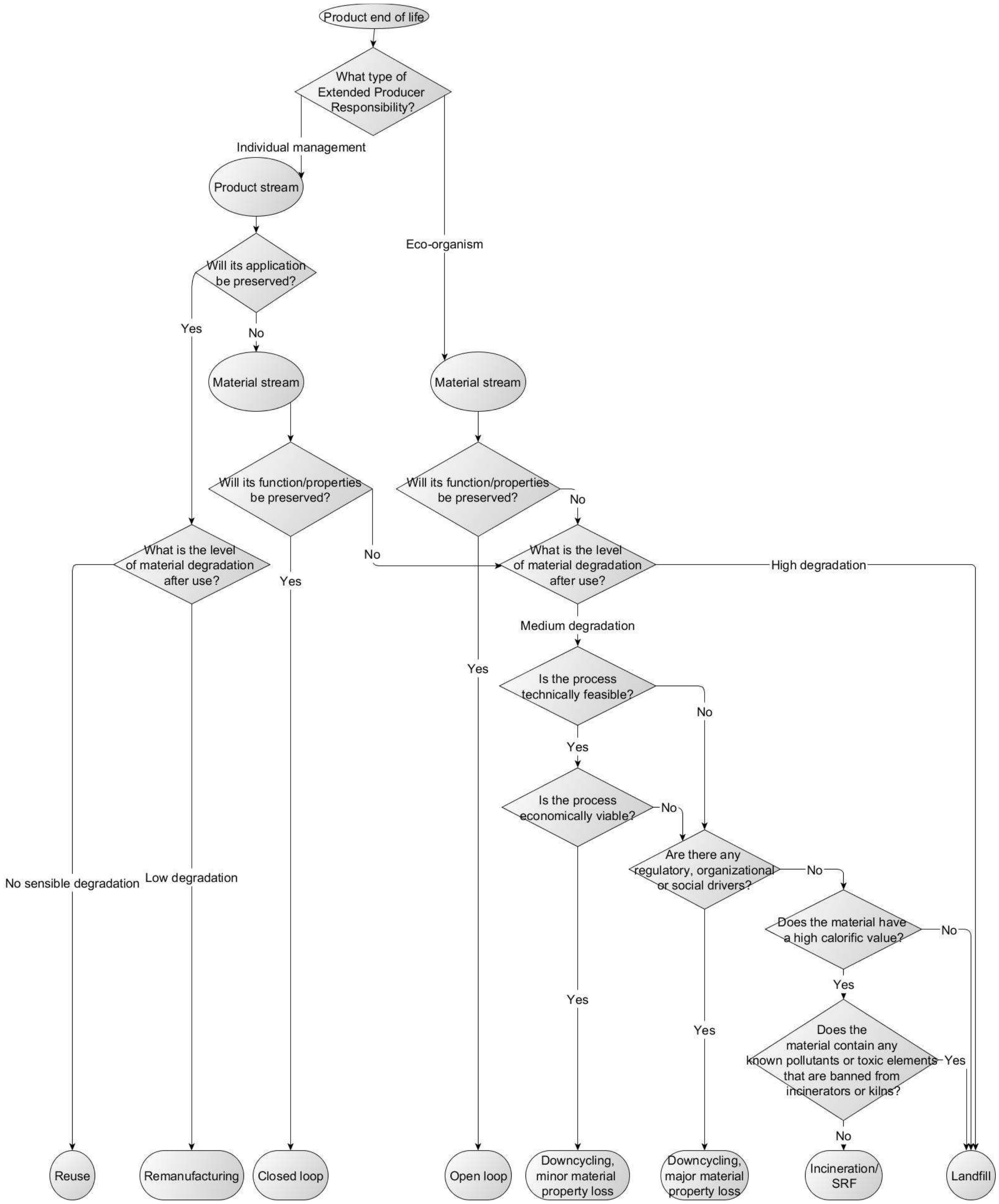

Figure 27: Generic example of an end-of-life scenario tree

f. Estimation of second lifecycle values

For each potential scenario, a new initial material value is estimated for the second lifecycle, as shown in Figure 24. It now includes the end-of-life coefficients and the other variables are projected in the subsequent lifecycle:

$$\mathcal{V}_{2,M_i} = \mathcal{P}_2 \times m_{f2} \times \frac{\varphi_2 \times \kappa_2}{\pi_2} \times \delta_m \times \eta \times \delta_f$$

In end-of-life scenarios that preserve the same application, (i.e. reuse, remanufacturing, closed and open recycling loops), the company can assess or estimate all the variables based on the same expertise that was gathered in the first lifecycle. Data from the cycling processes is required and is incumbent to the (internal or external) end-of-life expert, who must be well-versed on the state of the respective networks. Auditing the networks can provide the necessary information and should be the preferential resort in this step, and will be shown in Chapter 6. As mentioned earlier, the new lifecycle may concern a new designer group or product and the material may not even be used in the same application. In this case, the functional mass and design yield is then investigated or approximated.

Most of the variables considered in this method are also time-dependent: as recycling technologies evolve, so does the industrial aptitude to regenerate the materials. Applying this method provides a snapshot that relates to the perceived state of the material lifecycle possibilities in a given moment and its projected future. The second lifecycle estimation is in a sense an update of the baseline. Table 24 presents all the variables required for estimating the second lifecycle circular material value for each main potential end-of-life scenario.

In reuse scenarios, mass is considered to be the same as in the first lifecycle. Price estimation must take into account the potential fluctuation in the span of the first lifecycle. $\mathcal{P}_2$ is the future price after one lifetime. If future prices are difficult to estimate, then current prices could be used. The functional unit is the same as in the first lifecycle and the mass should barely have changed (as this is one of the main conditions for a reuse scenario). Because there is no new manufacturing process, the design yield should be close to 1. The criticality factor is also a future projection for the material, as is the market risk. The transformation process yield is set at 1, as there should be no losses in this scenario. A similar case can be made with remanufacturing scenarios, in which the value after use is sufficiently high that the component can be reinserted in a new product. However, there are processing costs involved and a new design yield must be estimated. Likewise, closed and open loop recycling and downcycling scenarios also are projections of the values in the new lifecycle that require the assessment of all variables in the new design scenario, as well as the end-of-life coefficients. If many different recycling and downcycling scenarios exist (depending on the applications on the new lifecycle), each case has its own specificity and should be studied as a separate scenario. In incineration and landfilling scenarios, there is no actual circular flow. Value can be deemed as negative and is given by the costs associated to each option multiplied by the residual mass ($m_1 \times \delta_m$).

By applying the method consecutively, it is possible to assess material circularity even further, over multiple lifecycles. This type of evaluation is mandatory to resolve the matter of material ownership and responsibility that can extend beyond the second lifecycle: for scenarios in which the company maintains possession and responsibility over the material – such as reuse, remanufacturing and closed-loop recycling – all the subsequent lifecycles must be considered until another scenario is reached and responsibility is transferred.

Table 24: Variables required for calculating the circular material value in the second lifecycle

	Price	Functional mass	Design yield	Material criticality	Market risk	Transformation process yield	Material degradation after use coefficient	End-of-life functional degradation coefficient	Secondary circular material value
Reuse			1^{****}			1		$1-\frac{1}{1+\mathcal{N}_{reuse}}$	
Remanufacturing						$\eta_{\text{remanufacturing}}$		$1-\frac{1}{1+\mathcal{N}_{reman}}$	
Recycling closed loop						η_{cloop}		$1-\frac{1}{1+\mathcal{N}_{cloop}}$	
Recycling open loop	$\mathcal{P}_2{}^{*}$	$\frac{U_2{}^{*}}{U_{av,2}{}^{*}}\times\frac{m_1}{m_{fu,2}}$	$\varphi_2{}^{*}$	$\kappa_2{}^{*}$	$\pi_2{}^{***}$	η_{oloop}		$1-\frac{1}{1+\mathcal{N}_{oloop}}$	$\mathcal{V}_{2,M_i}{}^{*}$
Downcycling, minor property loss						η_{dcminor}	δ_m	$1-\frac{1}{1+\mathcal{N}_{dcminor}}$	
Downcycling, major property loss						η_{dcmajor}		$1-\frac{1}{1+\mathcal{N}_{dcmajor}}$	
Incineration	$\mathcal{P}_2{}^{**}$	m_1	NA	NA	NA	NA		NA	$\mathcal{V}_{2,M_i}{}^{**}$
Landfilling									

* Projected after one lifetime.

** In this case, the value is negative and is estimated by the costs associated with incineration or landfilling.

*** Price averages and standard deviation must be calculated based on future projections of the price function. However, this data is not always available or reliable and therefore the market risk could be estimated as worth the same as π1 in the case of materials whose prices have followed stable trends and for which there seems to be no future shortage or risk to the supply (see also the criticality factor). In the case of less stable price functions, especially for materials that have distinct prices for virgin and recycled sources, one should consider $\pi_2$ranging from π_1 to $5\times\pi_1$ based on (OECD 2007).

**** There is no manufacturing process.

5.2.5 Phase 3: Interpretation

g. Selection of an evaluation strategy

Analogously to (Ashby et al. 2004), the selection of an evaluation strategy acts as a transfer function that converts lifecycle expertise into a pairing of selected material and end-of-life scenarios. These combinations have to be defined according to the objectives that were originally set at the initialization phase. Depending on the goals, different evaluation strategies can be used to analyse the results. These strategies are translated in heuristics that represent the conditions that were established for the decision process. Table 25 presents the possible heuristics that can be selected and combined so as to compose an evaluation strategy.

Table 25: Heuristics descriptions for evaluation strategies

Heuristics	Description
Initial value minimization	The goal is to minimize value in the first lifecycle ($\mathcal{V}_1$) This fosters the choice of sufficient materials for the application and prevents any excess quality Suitable for consumer goods when material investments are to be kept to a minimum
Initial value maximization	The goal is to maximize value in the first lifecycle ($\mathcal{V}_1$) This fosters the choice of value-intensive materials for the application Suitable for high added value products
Second lifecycle value maximization	The goal is to maximize value recovery after the first lifecycle ($\mathcal{V}_2$) This favours end-of-life scenarios with high value efficiencies Suitable when searching for the material-scenario combination with the best potential for value recovery
Value preservation over two lifecycles	The goal is to preserve value over two lifecycles This favours material-scenario combinations with minimal value loss (or in some cases, maximal value gain) Suitable when looking to minimize value loss

h. Results analysis

In this step, the results are presented and analysed by highlighting hotspots for each circular material value that was calculated. Then, based on the evaluation strategy selected, the material candidates and/or the potential end-of-life scenarios are compared and an optimal choice must be made. Usually, in order to take the uncertainties of the data into consideration, a sensitivity analysis should be performed, to confirm that the adopted solution is reliable or needs to be questioned. When the quality of the data has been previously assessed (using the pedigree matrix (Weidema et al. 2013) for instance), this information should be considered as well for optimal decision-making.

If a heuristics $\mathcal{H}$ is employed as an evaluation strategy, the analysis of the results and the decision-making process must be performed by comparing the combinations of first lifecycle material candidates and second lifecycle scenarios, as shown in Table 26.

Table 26: Combination of potential materials and end-of-life scenarios

	$\boldsymbol{\mathcal{V}_{2,M_i,scenarioA}}$	$\boldsymbol{\mathcal{V}_{2,M_i,scenario\ B}}$	**…**	$\boldsymbol{\mathcal{V}_{2,M_i,scenario\ Z}}$
$\boldsymbol{\mathcal{V}_{1,M_i,candidate\ A}}$	$\mathcal{H}_{AA}$	$\mathcal{H}_{BA}$	…	$\mathcal{H}_{ZA}$
$\boldsymbol{\mathcal{V}_{1,M_i,candidate\ B}}$	$\mathcal{H}_{AB}$	$\mathcal{H}_{BB}$	…	$\mathcal{H}_{ZB}$
…	…	…	…	…
$\boldsymbol{\mathcal{V}_{1,M_i,candidateZ}}$	$\mathcal{H}_{AZ}$	$\mathcal{H}_{BZ}$	…	$\mathcal{H}_{ZZ}$

Depending on the constraints and goals defined in the initialization phase, finding the optimal result may correspond to different examinations of Table 26: when identifying the best scenario to a given material candidate, there should be only one line; if several material options exist but the scenario is fixed, it would consist of one column; and if the optimal couple of material-scenario is the objective, then the solution is a specific intersection. In the case of conflicting results, a trade-off analysis is required, in which the multiple criteria of circular material value can be studied and prioritized.

i. Recommendations

Once the results are analysed, instructions regarding material and end-of-life choices are devised, in consonance with the goals that were established at the onset of the method. These recommendations are aimed primarily to the design and end-of-life experts, but their consequences can be relayed to all the other departments in the company, especially to the purchasing and marketing teams. Table 27 collects the typical "generic" recommendations that can come out of the Design for Material Circularity method and how they are related to the previously defined goals.

Table 27: Recommendation types and their respective goals for each company department involved in the Design for Material Circularity method

Company department	Circularity goal	Type of recommendation
Product design	Include circularity as a factor in material selection screening methods Adapt product specifications to increase material circularity	Material selection Product specifications
Purchasing	Avoid vulnerable supply chain routes Increase circularity in purchasing practices	Monitoring of critical materials in the supply chain
Marketing	Contribute to the circular economy initiative Capitalize on circularity gains Promote circular value as a concept	Adapt business model to the end-of-life choice Inform clients of value retention at end-of-life
End-of-life	Prevent or decrease material scarcity	Select the best-suited end-of-life scenario

Virtually every company department can thus be engaged in the improvement of material circularity, depending on the goals that are envisioned. In terms of decision-making, product design teams obtain information that can influence both material selection and product specifications, purchasing teams gain insight on the critical materials of their supply chain, marketing teams enhance the suitability of their business models to end-of-life requirements and bring awareness of this to their clients, and end-of-life (or sustainability) experts have a more compelling argument for their cycling choices.

A second, more precise level of recommendations is established by the designers using the method, targeting specific actors intervening in the scope of the company. These product design recommendations relate to the product, part and material properties optimisation, either in the case of the initial design or an actual redesign of the product and its components. In both cases, product designers should monitor certain variables and follow the corresponding design guidelines. These recommendations, variables and guidelines are shown in Table 28.

Table 28: Product design recommendations with the respective variables to monitor and guidelines

Product design recommendations	Variables to monitor	Guidelines
Product optimisation	$\mathcal{V}_{product} = \frac{\sum \mathcal{V}_{part_i} \times x_{part_i}}{\sum x_{part_i}}$	Identify which part creates the biggest hot spot – reverse design logic to optimise each part locally and the product globally Consider part's assembly for optimising their separation for appropriate end-of-life treatments
Parts optimisation: - functional analysis - material concentration in component	$\frac{U_2}{U_{av,2}} \times \frac{m_1}{m_{fu,2}}$	Investigate components satisfying the same functions with a lower $\mathcal{V}_{part_i}$ based on an optimised functional mass Consider material mixes and material concentration in components
- design yield	$\varphi = \frac{C_F}{C_F + C_D}$	Optimise the main function's costs (C_F) regarding the total costs (i.e. main function's costs and design costs, C_D)
Material property optimisation	Material degradation after use coefficient (δ_m)	Conduct mechanical design analysis for in-use material fatigue (optimise density over young modulus ratio for different materials, for instance)

5.3 Conclusion

In this chapter, to bridge the first integration gap that had been identified, a circularity indicator and method that encompass more than one material lifecycle was developed. This proposition considers the interconnection between material choices and end-of-life scenarios and improves product designers' decisions regarding material circularity. This new indicator for the circular material value and the method conceived to deploy it, the Design for Material Circularity method, constitute a tool for the integration of material circularity during product design. It allows to simultaneously address material design and end-of-life scenario choices and highlights the contact points that exist between lifecycles among the respective designers and material recyclers. It is centred on a novel approach that tracks the value of a product's materials over two lifecycles and enables designers to make material and end-of-life choices based on the industrial aptitude for material regeneration. It supports decisions that foster the preservation of materials in terms of their value and that contribute to closing material loops as insights and knowledge on the existing cycling scenarios are increased.

The method relies on a quantitative indicator that serves as a metric for the circular value of materials in a swift and simple manner, suitable to product designers to make decisions during the design process. It fills a gap in the designers' toolkit by uniting lifecycle and end-of-life thinking in order to consider multiple material and product lifecycles and address the real state and evolution of recycling networks. This rapid information gain is fundamental when proposing a new methodological tool for experts (Choulier 2008). The two case studies in Chapters 7 and 8 will illustrate the use of this tool and serve as a validation of the coherence of the circular material value equation with real-case scenarios. In each case, different aspects of the application of the indicator and Design for Material Circularity method will be examined. Table 29 provides a summary of the functions accomplished by the proposed tool and its further expected developments.

Table 29: Summary of accomplishments and future developments for each function of the proposed tool

Functions	Accomplishments	Expected future developments
F1 Elucidate the interconnections between material choices and cycling networks		
SF1.1 Formalize links between design parameters and cycling network variables through formulas (explicit variable relationships)	An indicator, which employs variables that encompass the whole lifecycle of a material.	Further studies can support the refinement of the formulas and adapt them to different cases.
SF1.2.a Choose variables that continue over multiple lifecycles	Circular material value in itself was chosen as an indicator because it represents an aspect of the material that evolves and persists over multiple lifecycles. It is composed of elements that also carry through to subsequent lifecycles such as material price, mass, criticality and market risk; other variables that remain representative and relevant beyond the first lifecycle such as the design yield and material degradation after use; and variables that characterize the cycling operations taking the material from one cycle to the next.	This study focuses on applying the Design for Material Circularity method to two consecutive lifecycles. It is assumed that it can be applied to subsequent lifecycles ($\mathcal{V}_3, \mathcal{V}_4 \dots \mathcal{V}_n$) but this requires a deeper scrutiny of product lifecycles and it would be imprudent to generalize it at this moment. Specific studies should be conducted in this sense.
SF1.2.b Choose variables that are coherent with industrial experiences	Material prices, design yield and market risk are common industrial variables. Functional mass, the criticality factor and cycling coefficients are introduced because of the growing concern with scarcity and circularity. They are grounded on issues that are clear to industrial routine and corporate knowledge databases and are used in the formula according to the general principle of maximizing productivity while minimizing risks and harmful impacts. The industrial coherence of results obtained with the method will be further illustrated in the two case studies.	Applications of the indicator calculation and method will allow the verification of its coherence with industrial contexts. A database of cases should be constituted to make the tool more robust and adapt it to the evolution of circularity knowledge. In this sense, regular assessments of what constitutes circular material value should be performed. Testing the method within "real-life" design processes in the industry will provide further understanding of how coherent with industrial experiences the variables are.

SF1.2.c Choose variables that rely on easily obtainable data	Most variables are quite straightforward (though the criticality factor relies on a qualitative analysis grid and is based on a research field that is quite *à la mode* yet still maturing) and data should already be well-known by the respective departments. However, for second lifecycle analyses, in which the company is projecting values for other applications or industries, access to this data might require some research.	The compilation of material and product databases for the circular material value variables will ease the acquisition of data for material lifecycles. Also, deploying the tool in a product design team to evaluate how easy or practical the procurement of required data really seems necessary, through observatory research and interviews.
F2 Encompass all potential end-of-life scenarios		
SF2.1.a Incorporate end-of-life variables that are compatible with different types of end-of-life scenarios	The transformation process yield coefficient and the end-of-life scenario functional degradation coefficient can both be estimated for any end-of-life scenario.	Further studies should be conducted to identify actual closed-loop scenarios in the industry and characterize them. Such requirement is further developed in Chapter 6.
SF2.1.b Incorporate end-of-life variables whose corresponding data is readily available	Open-loop scenarios are frequently the norm and therefore more data is available for them. However, data for closed-loop scenarios such as reuse, repurposing and remanufacturing might not be currently available.	Data collection and systematization for both open and closed-loop scenarios should be the focus of further research. As closed-loop scenarios progress, more studies such as this one should be performed on them and shared among industrialists. Such recommendation is further specified in Chapter 6.
SF2.2 Allow improvements according to the evolution of circular economy and cycling network models	If circular economy and cycling network models evolve, the proposed circularity indicator allows cycling coefficients to be modified or added.	Monitor the evolution of circularity models and update the tool accordingly.
F3. Take into account the uncertainties in the multiple data involved		
SF3.1 Opt for variables that allow assessing the uncertainty of variables' action-reaction on each other (i.e. their "degree" of relative dependency)	The variables were selected to be as independent as possible, to avoid compounding effects that are hard to track. However, with broad macroeconomic and geopolitical criteria such as material prices and the criticality factor, there are probably overlaps whose influence is difficult to pinpoint and isolate.	With the support from specialists from other fields, further research could be conducted to refine the circular material value indicator.

SF3.2 Opt for variables that allow assessing the uncertainty of one variable over the global result (i.e. the global influence of one variable on the total result)	Having an indicator based on the simple multiplication and division of factors among themselves allows for straightforward sensitivity analyses. However, these assessments require the collection and use of a great volume of data, due to the number of variables, which is not always accessible (especially regarding subsequent lifecycles).	A database containing information about each variable (e.g. on secondary material use) should be constituted empirically.
F4. Be a stepping stone, i.e. allow evolutions of the method and its results		
SF4.1 Have a format that enables the addition of other pertinent variables	As seen in section 5.1.7, the proposed formula for the circular material value was simply constructed in terms of proportional and inversely proportional factors.	Further research can provide additional pertinent variables, which can be easily added to the indicator. Weighting factors may also be added to accentuate certain variables if required. However, transparency should be maintained.
SF4.2 Be adaptable to the type of results searched by the user of the method	This can be observed in the multiple goals and recommendations that the tool encompasses (5.2.5 §i)	As the method is applied to more cases, more recommendations and guidelines can be added to each case.

The use of this tool depends on an understanding of material cycling networks that requires information which is not always available and adequate for product designers, as exposed in Part I. The deployment of the Design for Material Circularity, and particularly the formulation of proper recommendations stemming from it, requires a comprehension and quick assessment of the dynamics that define these networks by product designers. In the next chapter, the results of a research conducted to define the elements that influence the state and evolution of cycling networks are presented. It provides a framework to characterize these networks, which allows for different agents, from product designers to recyclers, to identify the potential drivers and bottlenecks occurring throughout these networks, and ultimately make decisions regarding material end-of-life. It complements the tool presented here by allowing a systematization of material schemes' expertise.

Chapter 6: A framework for the characterization of material cycling networks

A method addressing material circularity in design has been proposed in the previous chapter to bridge the first integration gap by connecting material selection to end-of-life scenarios. However, it was observed that when the time comes to provide recommendations concerning material circularity to the various company departments, more in-depth knowledge and understanding of the material cycling networks and schemes are necessary. This relates to the second hypothesis that was defined in Part I and the need for material cycle information that could be used by product designers. This proposition must comply with the following requirements:

- Take into account all relevant elements that affect the evolution of cycling networks;
- Provide knowledge to product designers;
- Applicable to all material classes;
- Be robust, covering available information from multiple sources

These requirements are further detailed in Table 30.

Table 30: Functions and sub-functions of the proposed framework

Specifications of design functions for the proposition	Subfunctions
F1 Take into account all relevant elements that affect the evolution of cycling networks	**SF1.1** Integrate factors from multiple fields of knowledge **SF1.2** Be based on real-life expertise
F2. Provide knowledge to product designers on anthropogenic cycles	**SF2.1** Allow the rapid understanding of the state and issues of a cycling network and scheme **SF2.2** Indicate the cycling parameters that are pertinent to product designers
F3. Applicable to all material classes	**SF3.1** Stem from the study of metals, polymers and ceramic materials **SF3.2** Contribute to the analysis of the specificities of metal, polymer and ceramic anthropogenic cycles
F4. Be robust, covering available information from multiple sources	**SF4.1** Collate knowledge from academic research and the industry **SF4.2** Allow improvements with the aggregation of more data

Ideally, this solution should be applicable to all the cycling scenarios that were evoked in the previous chapter. However, not all scenarios are pertinent to be studied at this time. Closed-loop scenarios such as reuse, remanufacturing and closed-loop recycling are still either underdeveloped or lack documentation. On the other side of the spectrum, the termination scenarios such as waste incineration and storage present little interest in terms of material circularity. Open-loop recycling is the most widespread scenario and therefore benefits from extensive coverage by the literature, it was then chosen as the basis for this study of network and schemes characteristics.

In this chapter, a framework for the characterization of material cycling networks and schemes will be proposed applied to the open-loop recycling case. First, the research methodology that was used to build the framework will be exposed; then, the descriptors that were selected to compose the framework and characterize the cycling networks will be detailed; and finally, an analysis of the main material cycling networks will be shown to illustrate the use of the framework.

6.1 Research methodology

For practical reasons, material flows were addressed in groups of similar physical and industrial conjuncture. While an investigation of each individual material flow would have contributed to more accurate results, it seemed impractical due to the lack of systematized data on the cycles of each element of the periodic table or specific substance. Concerning metals, the United Nations Environmental Program (UNEP) recently divided them into categories (UNEP 2010) and aggregated data on ferrous, non-ferrous, precious and specialty metals. Rare earth elements, though part of the specialty metals group of the UNEP, were added as a group of their own due to their strategic importance for the development of recent technologies (Moss, Tzimas, and Willis 2013).

Table 31 presents the metals in each category. Thermoplastic materials were considered as a single industrial network (which is how they are commonly assessed in sectorial reports) due to the shortage of consistent data for individual polymer networks. Glass was also studied in order to have a sample material from each major class (metals, polymers and ceramics) and because it is one of the oldest recycled materials (Dyer 2014).

Table 31: Metal groups (UNEP 2010)

Ferrous metals	Iron, Manganese, Vanadium, Niobium, Chromium, Nickel, Molybdenum, Silicon, Bismuth
Non-ferrous metals	Aluminium, Cobalt, Copper, Lead, Magnesium, Tin, Titanium, Zinc
Precious metals	Silver, Gold, Platinum, Palladium, Rhodium, Osmium, Iridium, Ruthenium
Specialty metals	Antimony, Arsenic, Barium, Beryllium, Boron, Cadmium, Cesium, Gallium, Germanium, Hafnium, Indium, Lithium, Mercury, Rhenium, Selenium, Strontium, Tantalum, Tellurium, Thallium, Tungsten, Zirconium
Rare earth metals	Lanthanum, Cerium, Praseodymium, Neodymium, Samarium, Europium, Gadolinium, Terbium, Dysprosium, Holmium, Erbium, Thulium, Ytterbium, Yttrium, Scandium, Lutetium

The characterization of material cycling activities was based on empiric and historical data from the industry, as well as a review of the scientific literature on the subject. Four types of references were studied: scientific research on recycling processes, industrial expert reports, MFA and sectorial waste recycling reviews. The analysis of scientific research and reports from industry specialists provided insight on the issues related to material cycles from both an academic and a field perspective. Both described the steps necessary to improve recycling activities, but the former focused mainly on the technical aspects, while the latter usually put forth a wide-ranging set of concerns. In terms of scope, material flow analyses encompassed every stage of the materials' lifecycle, from ore extraction to end-of-life and the feedback loops. They spanned periods of one year to a full century and focused on a region, country or the whole planet. MFA, therefore, linked waste management and recycling operations to the concentrations and stocks in previous stages of the lifecycle. They were also used to identify potential bottlenecks and anticipate the evolution of offer and demand. While there were MFA for a few plastics and other substances, they were mostly available on metals. Sectorial reviews frequently were compilations of data from a group of recycling activities that shared some common properties, objectives or issues. It served for comparing similar material cycles. They focalized in the industrial activities but were broader in scope than the industrial expert reports.

The study began with the identification and definition of the factors mentioned in the assessment of recycling activities. The critical literature review focused on the elements that were used to describe these activities which were put forth as modifiers of the use of scrap material in new product cycles. In short, a list was made of the descriptors employed to indicate the evolutionary state of a material cycling network and their relation to the development of the networks' operation. These factors were then grouped into five main categories: technical, economic, regulatory, organizational, and social, inspired by the holistic PESTEL approach (meaning Political, Economic, Societal, Technical, Environmental and Legal) as used in (Ziout, Azab, and Atwan 2014). This provided a first network description map. In order to collate the results of this classification with the reality of the field, industrialists were interviewed to validate the relative importance of the parameters found for each network and verify whether the concerns of academic research were compatible with those from the industry. Finally, the validated descriptors coalesced into a smaller number of factors for the sake of simplicity and practicality in terms of use. Figure 28 sums up the approach that was used for identifying the network descriptors.

Figure 28: Approach used for the identification of the recycling networks descriptors

Despite the difference in terms of the accounting of environmental impacts on the lifecycle of materials and products, this study does not distinguish between pre-consumer (post-manufacture prompt scrap) and post-consumer recycling. Also, in order to obtain a list of factors that includes all possible development issues encountered in recycling activities, specificities from different regions or countries were not considered either[12]. While they do have an influence in trade balances and economic material flows mainly in terms of commercial energy transfers (since when materials are exported or imported, their embedded extraction and production energy is being transferred), this study of material cycles focused on the global recycling of a material, regardless of where it takes place.

6.2 Cycling network characterization

6.2.1 Initial descriptor list based on the literature review

Generally speaking, recycling networks are socio-technical in nature, i.e. they are the result of complex interactions between technological infrastructures and social behaviour. A report on the

[12] For a theoretical and case study approach to the workings and potential impacts of scrap trade, see (van Beukering 2001).

recycling potential of certain rare metals issued by the French environmental agency ADEME, which studied the recycling of 35 rare metals, identified four main categories of factors affecting the sector: technical, economic, organizational and regulatory (Monier et al. 2010a). After the initial literature review performed in this study, five major categories of parameters characterizing the performance of recycling networks were employed to aggregate the descriptors that were found: technical feasibility, economic viability, regulatory framework, organizational configuration and social involvement. The initial list of cycling networks parameters (descriptors) that were adopted is presented in Table 32.

Table 32: Initial descriptor list

CATEGORIES	DESCRIPTORS
Technical feasibility	Product design Technical optimization of the separation process Technical optimization of the recycling process Efficiency of recycling process Recycled material properties
Economic viability (Macroeconomic)	Global material offer Material demand prediction Material accumulation in use Dissipative uses Size of waste deposit Quality of waste deposit Price of virgin raw materials
Economic viability (Microeconomic)	Transportation costs Labour costs Price of recycled raw materials Downstream recycled material applications
Regulatory framework	Environmental regulations Economic incentive mechanisms State policies
Organizational configuration	Collection mechanisms Waste management development
Social involvement	Consumer attitude Manufacturer attitude

6.2.1.1 Technical parameters

The first group of factors relates to the technical feasibility of recycling operations. It can be a major obstacle for the development of recycling networks, at any point in their evolution, sometimes even impeding its cost-effectiveness. The first factor to influence the technical feasibility of recycling activities is product design, which contains material mixes, component sizes and material concentration in each component. These are variables that can substantially influence a product’s recyclability. When designing a product, the number of materials used adds complexity to end-of-life operations and usually increases the number of contaminants that may decrease the efficiency of the process or impede it altogether. It is the case of tramp elements in steel (Björkman and Samuelsson 2014) or additives and other charges in plastic masterbatches (M. K. Patel et al. 1998; Shen and Worrell 2014).

The technical feasibility of recycling operations is also dependent on specific characteristics of the recycling activities themselves, i.e. the technical optimization of the separation (sorting) process, the technical optimization of the regeneration (recycling) process, the efficiency of the recycling process and the properties (quality) of the recycled material.

Specific materials can have their own particular technical issues that should be added to the regular list of factors. This is the case of composite materials, whose cycles are especially influenced by the properties of their matrix: recycling fibre-reinforced thermoset matrix polymers is usually much more difficult to achieve and yields poorer results if compared to thermoplastic matrix composites[13].

The literature review for technical feasibility descriptors is provided in Table 33.

[13] This study does not deal with the recycling of composite materials. For an overview of the state of composite recycling see (Yang et al. 2012; Pimenta and Pinho 2014).

Table 33: References for technical feasibility descriptors

Category	Descriptor	Materials
Technical feasibility	Product design	- Aluminium (Kang and Schoenung 2005), Copper (Samuelsson and Björkman 2014; Glöser, Soulier, and Espinoza 2013; Ichiro Daigo et al. 2007; Graedel et al. 2002), PGM (Hagelüken 2012), Precious metals (Peiro, Villalba, and Ayres 2013), Rare Earth Elements (Chancerel et al. 2013; Habib and Wenzel 2014; Peiro, Villalba, and Ayres 2013; Rademaker, Kleijn, and Yang 2013), Tantalum (Sibley 2004), Specialty metals (Reck and Graedel 2012; Chancerel et al. 2013; Peiro, Villalba, and Ayres 2013), Steel (Björkman and Samuelsson 2014) - PET (Welle 2011), Plastics (M. Patel et al. 2000; Shen and Worrell 2014) - Glass (Dyer 2014)
	Technical optimization of the separation process	- Aluminium (Gaustad, Olivetti, and Kirchain 2012; Velasco and Nino 2011; Thomas and Wirtz 1994), Copper (Glöser, Soulier, and Espinoza 2013; Samuelsson and Björkman 2014), PGM (Hagelüken 2012), Precious metals (Reck and Graedel 2012; Rombach and Friedrich 2014) Rare Earth Elements (Rademaker, Kleijn, and Yang 2013; Binnemans et al. 2013), Specialty metals (Reck and Graedel 2012), Steel (ADEME 2012; Björkman and Samuelsson 2014) - Bioplastics (Soroudi and Jakubowicz 2013), PET (Welle 2011), Plastics (M. Patel et al. 2000), - Glass (Dyer 2014; ADEME 2012) - Cardboard and paper (ADEME 2012)
	Technical optimization of the recycling process	- Aluminium (Reck and Graedel 2012), Copper (Samuelsson and Björkman 2014; Reck and Graedel 2012), Magnesium (Reck and Graedel 2012), Precious metals (Reck and Graedel 2012), Specialty metals (Reck and Graedel 2012; Kang and Schoenung 2005) - Bioplastics (Soroudi and Jakubowicz 2013), PET (Welle 2011), Plastics (M. Patel et al. 2000; Shen and Worrell 2014)
	Efficiency of recycling process	- Aluminium (Thomas and Wirtz 1994), Copper (Samuelsson and Björkman 2014), PGM (Hagelüken 2012), Rare Earth Elements (Rademaker, Kleijn, and Yang 2013), Steel (Björkman and Samuelsson 2014) - Plastics (Hamad, Kaseem, and Deri 2013)
	Recycled material properties	- Steel (ADEME 2012) - Bioplastics (Soroudi and Jakubowicz 2013), PET (Howell 1992; ADEME 2012), Plastics (M. Patel et al. 2000; Shen and Worrell 2014; Hamad, Kaseem, and Deri 2013) - Glass (Dyer 2014)

6.2.1.2 Economic parameters

The economic whys and wherefores of material cycles can be divided into macroeconomic and microeconomic factors in terms of their effect on recycling networks. Most studies concentrate on macroeconomic criteria related to material flows such as global material offer, material demand prediction, material accumulation in use, dissipative uses, size and quality of waste deposits, and the price of virgin raw materials. These are the parameters that affect recycling activities but upon which recyclers have little to no agency. Microeconomic factors, on the other hand, have a straightforward impact on recyclers' finances and are variables that they can manage directly where their activity is concerned.

The first four macroeconomic factors (global material offer, material demand prediction, material accumulation in use and dissipative uses) are generally related to the material's (primary) availability. Assessing material offer and demand is a common resort at both the policy and organizational levels that can be used to formulate national resource conservation strategies (Monier et al. 2010a) and to evaluate the risks of corporate supply chains. In general, low material availability is considered as a condition that fosters R&D and investments for the promotion of recycling activities (Monier et al. 2010a). Recently, it has been a driver for an initiative to set-up a recycling network for rare earth elements (Rademaker, Kleijn, and Yang 2013; Binnemans et al. 2013). With high availability, however, there is less economic pressure to find other sourcing alternatives and recycling industries seem to develop at a slower pace. Nevertheless, abundant materials that see a growing accumulation of in-use stock due to extended product lifetime can also trigger alerts regarding potential future shortages (Du and Graedel 2011c; Bastian, Fougerolle, and Martinon 2013; Binnemans et al. 2013; Habib and Wenzel 2014). This also hinders recycling activities because of a lack of available scrap until the end of the longer use cycle (Rauch 2009; Chen and Graedel 2012a). Likewise, the bigger the share of dissipative uses in the material's applications, the less material is available for recycling. The size (referring to the tonnage of scrap or waste containing the desired material) and quality (meaning the concentration and sometimes the ease to recover said material) of waste deposits also affect (secondary) material availability and can either prevent or provoke the development of a recycling network. Finally, the price of virgin raw materials is another important driver: when virgin raw material prices are high or rise, economic viability and the impetus to recycle grow; however, when prices go down, recycling often becomes less cost-efficient and takes a hit as well. This is clearly the case with plastic materials for instance.

Though they are less mentioned in scientific articles, microeconomic parameters such as labour and transportation costs, as well as the characteristics of the recycled material market (i.e. price of recycled materials and downstream recycled material applications), were deemed extremely important in the interviews with field experts.

The literature review for the macroeconomic descriptors is listed in Table 34 and for the microeconomic descriptors in Table 35.

Table 34: References for economic viability descriptors (macroeconomic)

Category	Descriptor	Materials
Economic viability (Macroeconomic)	Global material offer	- Cobalt (Sibley 2004), Precious metals (Monier et al. 2010b), Rare Earth Elements (Monier et al. 2010b; Binnemans et al. 2013), Specialty metals (Monier et al. 2010b)
	Material demand prediction	- Gold (Sibley 2004), Platinum (Sibley 2004), Precious metals (Monier et al. 2010b), Rare Earth Elements (Monier et al. 2010b; Rademaker, Kleijn, and Yang 2013; Binnemans et al. 2013), Specialty metals (Monier et al. 2010b), Steel (Björkman and Samuelsson 2014)
	Material accumulation in use	- Aluminium (Chen and Graedel 2012b), Copper (Glöser, Soulier, and Espinoza 2013), Iron (T. Wang et al. 2008; Rauch 2009), PGM (Saurat and Bringezu 2009), Rare Earth Elements (Du and Graedel 2011a; Bastian, Fougerolle, and Martinon 2013; Binnemans et al. 2013; Habib and Wenzel 2014)
	Dissipative uses	- Copper (Glöser, Soulier, and Espinoza 2013; Graedel et al. 2002), Precious metals (Peiro, Villalba, and Ayres 2013), Rare Earth Elements (Peiro, Villalba, and Ayres 2013), Silver (Johnson et al. 2005), Specialty metals (Peiro, Villalba, and Ayres 2013)
	Size of waste deposit	- Aluminium (Chen and Graedel 2012b; Thomas and Wirtz 1994; Reck and Graedel 2012), Cobalt (Sibley 2004), Copper (Reck and Graedel 2012), Lead (Reck and Graedel 2012), Nickel (Reck and Graedel 2012), Precious metals (Monier et al. 2010b; Rombach and Friedrich 2014), Rare Earth Elements (Monier et al. 2010b; Rademaker, Kleijn, and Yang 2013; Binnemans et al. 2013; Reck and Graedel 2012), Selenium (Kavlak and Graedel 2013), Specialty metals (Monier et al. 2010b), Steel (Reck and Graedel 2012), Tantalum (Sibley 2004), Zinc (Reck and Graedel 2012) - Bioplastics (Soroudi and Jakubowicz 2013), PET (Welle 2011), Plastics (M. Patel et al. 2000)
	Quality of waste deposit	- Cobalt (Sibley 2004), Copper (Samuelsson and Björkman 2014), Precious metals (Rombach and Friedrich 2014; Monier et al. 2010b), Rare Earth Elements (Monier et al. 2010b; Du and Graedel 2011b; Binnemans et al. 2013), Specialty metals (Monier et al. 2010b), Steel (Björkman and Samuelsson 2014) - Plastics (Shen and Worrell 2014)
	Price of virgin raw materials	- Aluminium (Chen and Graedel 2012b; Reck and Graedel 2012), Cobalt (Sibley 2004), Copper (Reck and Graedel 2012; Tanimoto et al. 2010; Glöser, Soulier, and Espinoza 2013; Samuelsson and Björkman 2014), Gold (Sibley 2004), Lead (Reck and Graedel 2012), Nickel (Reck and Graedel 2012), Precious metals (Reck and Graedel 2012), Rare Earth Elements (Rademaker, Kleijn, and Yang 2013; Binnemans et al. 2013; Reck and Graedel 2012), Silver (Johnson et al. 2005), Steel (Reck and Graedel 2012; Björkman and Samuelsson 2014), Tantalum (Sibley 2004), Zinc (Reck and Graedel 2012) - Plastics (M. Patel et al. 2000; ADEME 2012)

Table 35: References for economic viability descriptors (microeconomic)

Category	Factors	Materials
Economic viability (Microeconomic)	Transportation costs	- Plastics (M. Patel et al. 2000)
	Labour costs	- PGM (Sibley 2004)
	Price of recycled raw materials	- Aluminium (Thomas and Wirtz 1994), Copper (Tanimoto et al. 2010), Steel (ADEME 2012) - Cardboard and paper (ADEME 2012)
	Downstream recycled material applications	- Copper (Samuelsson and Björkman 2014) - PET (Welle 2011) - Glass (Dyer 2014)

6.2.1.3 Regulatory parameters

Regulations are often the major source of external pressure for the development of material recycling and are frequently one of its main drivers, sometimes the first reason for their setup. If technical feasibility is achieved and economic viability is uncertain or requires costly investments, regulatory measures become the major driver for the advancement of recycling activities. The first type of regulation that appears in the literature pertains to environmental protection. Today, environmental regulations mostly define recycling rate objectives for a specific Extended Product Responsibility network. These objectives can either relate to mass percentages to be recovered or a specific process quality and material property that must be achieved. Hazardous substance laws have also had an effect on the evolution of end-of-life networks due to the close attention that they have brought to the dismantling and discarding of specific components, which improved the recyclability of products and parts containing such substances (Rombach and Friedrich 2014). Economic incentive mechanisms are another major type of government action that can greatly improve the recycling of a given material. They can take the form of tax exemptions or facilitated access funds and loans. Finally, countries may sometimes implement public policies regarding materials that can have a positive effect on recycling networks. Having well-defined distinctions between what constitutes waste and what can be called a resource (Hagelüken 2012), controlling waste exports (Hagelüken 2012; Saurat and Bringezu 2009) or having a general resource conservation policy (Tanimoto et al. 2010) are some examples of effective state policies.

6.2.1.4 Organizational parameters

The organization of a given network or scheme plays a significant role in their state. There are two aspects to the organizational configuration of recycling activities: collection mechanisms and the waste management system's development level. The first relates to the physical components of waste management logistics such as the existence of specific collection points and waste transportation infrastructure. The second concerns the managerial aspects of the system's logistics: when the organizational development level is low, there are usually no waste sorting and treatment facilities; conversely, when a high-level waste management system exists, there are specific networks for recycling, such as the Extended Producer Responsibility schemes.

6.2.1.5 Social parameters

The social aspects of recycling activities relate to the effect that societal agents can have on the networks. In this case, the stakeholders that were mentioned were consumers in general and product manufacturers. Consumers can have positive effects on recycling activities by enacting pressure on government and industry, by choosing to buy recycled products or by adopting sustainable measures such as sorting out their trash. Consumers may also produce a negative impact if they refuse or reject secondary materials as less valuable or of lesser quality. Product manufacturers may sometimes foster recycling by carrying out awareness campaigns, investing in recycling activities and organizing themselves locally in industrial ecology systems for instance.

The literature review for the regulatory, organizational and social descriptors is collected in Table 36.

Table 36: References for the regulatory framework, organizational configuration and social involvement descriptors

Category	Factors	Materials
Regulatory framework	Environmental regulations	- Cobalt (Sibley 2004), Copper (Tanimoto et al. 2010), Lead (Reck and Graedel 2012), PGM (Hagelüken 2012), Precious metals (Reck and Graedel 2012; Hagelüken 2012), Rare Earth Elements (Binnemans et al. 2013; Reck and Graedel 2012), Rhenium (Reck and Graedel 2012), Specialty metals (Reck and Graedel 2012) - Plastics (ADEME 2012) - Glass (Dyer 2014)
	Economic incentive mechanisms	- Copper (Tanimoto et al. 2010; Samuelsson and Björkman 2014)
	State policies	- Copper (Tanimoto et al. 2010), PGM (Saurat and Bringezu 2009; Hagelüken 2012)
Organizational configuration	Collection mechanisms	- Aluminium (Thomas and Wirtz 1994), Cadmium (Reck and Graedel 2012), Copper (Samuelsson and Björkman 2014; Spatari et al. 2005), Gold (Sibley 2004), Lead (Reck and Graedel 2012), PGM (Hagelüken 2012), Precious metals (Reck and Graedel 2012), Rare Earth Elements (Rademaker, Kleijn, and Yang 2013) - Bioplastics (Soroudi and Jakubowicz 2013), PET (Welle 2011), Plastics (Shen and Worrell 2014; Al-Salem, Lettieri, and Baeyens 2010) - Glass (Dyer 2014; ADEME 2012)
	Waste management development	- Aluminium (Chen and Graedel 2012b; Lu, Qi, and Liu 2014), Copper (Spatari et al. 2005), Gold (Sibley 2004), PGM (Sibley 2004), Precious metals (Monier et al. 2010b; Hagelüken 2012; Lu, Qi, and Liu 2014), Rare Earth Elements (Monier et al. 2010b; Binnemans et al. 2013; Lu, Qi, and Liu 2014), Specialty metals (Monier et al. 2010b) - Plastics (Haeusler and Pellan 2012) - Glass (Dyer 2014)
Social involvement	Consumer attitude	- Copper (Tanimoto et al. 2010) - PET (Welle 2011)
	Manufacturer attitude	- Critical materials (Fromer, Eggert, and Lifton 2011), PGM (Hagelüken 2012) - PET (Welle 2011) - Glass (Dyer 2014)

6.2.2 Final descriptor list

From this first review of the literature, the list of descriptors was translated into network description maps that were used during the interview process to address the specificities of each material. Experts were asked to validate the usefulness of each parameter regarding the specific material on which they have experience. Figure 29 shows the representation that was used for the descriptors validation with the industry experts.

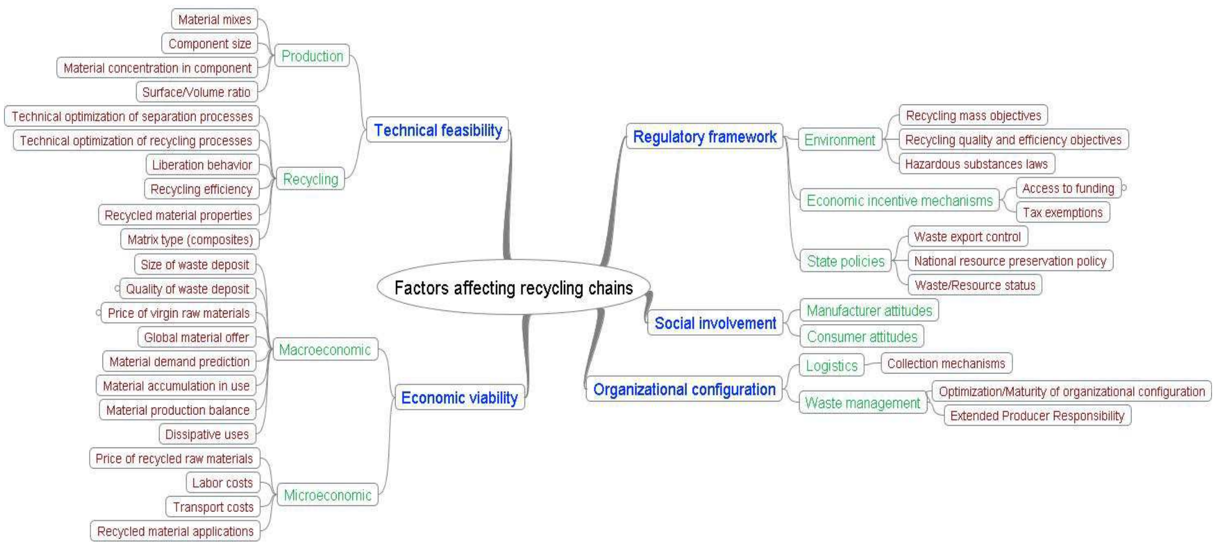

Figure 29: Representation of all the initial descriptors used in the validation process with industrialists

The interviews were conducted with specialists, each possessing knowledge of different material cycling networks. They covered ferrous metals, non-ferrous metals (copper and aluminium in particular), precious and specialty metals, polymers, but also the materials stemming from the Extended Producer Responsibility networks dealing with end-of-life vehicles, waste of electric and electronic equipment and furniture waste. Table 37 provides a list of the interviewed experts. An interview script was followed to collect the information from these experts as shown in Table 38. The interviews focused on obtaining information on the specific network that the expert worked on and then inquire about what constitutes the development of recycling activities in a more general manner. This permitted the comparison of different material networks. Lastly, the expert was asked to comment on the descriptor cartography that had been conceived based on the literature review.

Table 37: Interview list

Role/Position	Materials
Sustainability Manager at Constellium (Aluminium products manufacturer)	Non-ferrous metals
Polymer recycling expert, former General Manager of VMA recycling group (WEEE and furniture waste)	Polymers
Professor at ENSAM Chambéry, Head of the Process and Recycling laboratories	Ferrous and non-ferrous metals; Polymers
Engineer at the French Environment and Energy Management Agency (ADEME), working at the Products and Material Efficiency service	Ferrous and non-ferrous metals; Polymers; Precious metals
Sustainable Development Technical Manager at Nexans (Cable manufacturer)	Non-ferrous metals
Senior Manager of Government Affairs at Umicore (Material technology and recycling group)	Precious metals; Specialty metals; Rare-Earth Metals
General Manager of the Plastics Recycling Division at Suez Environnement	Polymers
Former Head of Sustainability research at Arcelor Mittal	Ferrous metals

The validation of the descriptors was obtained via the experts' interviews, by analysing their answers regarding the functioning of their networks and also their review of the network description map. Their opinion in conjunction with the volume of literature references produced the expected validation of the different parameters that had been listed. Some differences were identified in some cases between the focus of the scientific community and that of the industry. With this information, the initial descriptor list and categorization was revised in order to propose a final list for the framework.

After reviewing with the sector specialists which descriptors had an impact on their network and collating these results with the literature review, the factors were reorganized and a new systematization was achieved. In this new framework, three major categories were proposed: the process variables, the market variables, and the waste management conditions.

Table 38: Interview script

Presentation questions	– Who are you? What is your background? What is your current activity? – What are the missions of the organization for which you work? – What is your role in the accomplishment of these missions?
Specific model	*Material tracking, second cycles and downstream applications* – What is the proportion of secondary raw materials in the production process? – In your industry, who are the buyers of secondary raw materials? – What are the different products and applications that stem from recycling? *Parameters connected to specific networks, based on a historical example* – When and how was your network set up? – What developments has it known? – To what events do you attribute these developments? – What factors bear an influence on the evolution of the network? – What must be implemented to improve recyclability? – What are the obstacles and pitfalls? – What future do you imagine for your network?
General model (not applicable if the interviewee is a specialist of a single specific network)	*Network set-up, development, decline, stagnation and maturity* – What factors bear an influence on the evolution of the network? – Can we speak of the success of a network? If yes, what are the main parameters connected to the success of a recycling network? – Can we speak of the decline of a network? If yes, what are the main parameters connected to the decline of a recycling network? – Why would a network stagnate? – How could the maturity of a recycling network be measured or identified?
Open discussion about the network description map	Please feel free to provide all your critical observations on the cartography

The technical feasibility descriptors were reinserted in a broader category relating to the process variables. In this category, the elements of the process that could be subjected to technical optimization (separation and recycling, with the addition of the recycled material's properties) were distinguished from the product design variables. The design variables were brought together and singled out so that each became an actual descriptor. With this, the variables relating directly to the design activity and those concerning the cycling phase were properly separated.

The economic viability category was renamed since almost every descriptor has an influence in the cost-efficiency of the network. Economic factors actually refer to what could be called "market variables". The distinction between macroeconomic and microeconomic was maintained and the descriptors were practically unaltered, with only the price of recycled raw materials moving to the macroeconomic subcategory.

The regulatory, organizational and social aspects were all coalesced into a category pertaining to the waste management system's environment and conditions, with each aspect being turned into a specific sub-category. Raw material state policies and economic incentives were brought together to form a single descriptor, but the other factors remained unmodified.

Table 39 shows the final list of descriptors composing the framework, their definition and perceived effects.

Table 39: Final list of descriptors, their definition and perceived effects

CATEGORIES	SUBCATEGORIES	DESCRIPTORS OF OPEN LOOP RECYCLING	DEFINITION	PERCEIVED EFFECTS
Process variables	**Technical optimization**	Separation	First stage of the recycling process, composed of sorting and separation operations (including dismantling and shredding)	As separation methods improve, recycling quality increases and processing prices drop
		Recycling	Conversion of discarded components and products into secondary raw materials	As recycling operations improve, recycling quality increases and processing prices drop
		Recycled material properties	Overall quality of secondary raw materials based on expected properties	When current processes do not provide satisfactory properties, the perceived value of recycled materials decreases, which in turn affects the network's viability
	Product design	Material mixes	Presence of multiple materials in a part or product	Material mixes lead to the contamination of waste streams over multiple cycles and the decrease of recycling efficiency and cost-effectiveness
		Material concentration in component	Relative quantity of the material in a part or product	Components with higher concentration are more prone to recycling whereas components with lower concentration are more frequently disregarded by recyclers
		Density	Material or component mass divided by its volume	Low-density waste is ineffective in terms of transportation and must be compressed
		Liberation behaviour	Ability to liberate materials during dismantling or shredding	Appropriate liberation behaviour greatly improves the efficiency of recycling operations

Market variables	**Macro**	Global materials supply	Supply of material, comprising both primary and secondary sources	Small supplies usually increase the will to recycle whereas large supplies tend to placate it
		Global material demand (prediction)	Prediction of future material demand (different estimation scenarios may apply)	Depending on the predictions of future demand and its comparison with supplies, there can be a perception of a relative shortage of material that can increase prices and induce recycling
		Material accumulation in use	Lifetimes of in-use stock	Long material applications keep the material in use and remove it from waste streams, transpose it to a future time. This must be accounted when material availability and the size of waste streams
		Dissipative uses	Importance of applications in which the material is irrecoverable, whether by design (e.g. sacrificial anodes for corrosion protection) or because of current dispositions and limitations (e.g. deep steel foundations for buildings and infrastructure)	The relative importance of dissipative uses in the full set of material applications indicates how much material is lost and will never enter waste deposits
		Price of virgin raw materials	Observed trade price of primary raw materials (this may include the price of energy resources necessary for primary production, such as oil)	Low virgin materials prices have a tendency to block the development of recycling activities, whereas high prices, foster them
		Price of recycled raw materials	Observed trade price of secondary raw materials	If the network is not cost-effective, high prices for recycled raw materials will reduce their competitive edge
		Size of waste deposit	Volume of discarded material available and the stability of the waste flows	Big and stable waste deposits are a pre-requisite for establishing a recycling activity and allow economies of scale
		Quality of waste deposit	Concentration of the material in the deposit, its degree of contamination and dispersion	Highly concentrated and pure waste deposit greatly increase recycling cost-effectiveness and avoid dilution with virgin materials to meet property requirements

	Micro	Transportation costs	Logistic costs of transporting waste from collection site to recycling facility	High transportation costs (due to low-density waste or distances) decreases recycling cost-effectiveness
		Labour costs	Cost of labour involved in the recycling operations	If recycling operations require too many time-consuming tasks, then they may promote automatization or relocation to countries with lower wages (when possible and/or legal)
		Downstream recycled material applications	Existing applications for secondary raw materials	The more high-value downstream applications exist, the more incentive there is to recycling
Waste management conditions	**Network configuration**	Collection mechanisms	Implemented system for collecting waste: capillarity, coverage, modes of transport, fleet size, collection points	Thorough collection mechanisms can improve all aspects of material recycling
		Waste management development	State of the waste management system: number of treatment facilities, depth of pre-processing operations, integration level of waste treatment network, existence of a macro-scheme such as an Extended Producer Responsibility network	The maturity level of the waste management system defines in large part how well it will perform both technically and economically. The more they are developed, the more efficient the network will be
	Regulatory framework	Environmental regulations	Hazardous substances laws, recycling rate objective laws (of mass, process quality and material efficiency)	These regulations define the rules of a network and sometimes impose and foster its development, whether directly or indirectly
		Raw material policies and economic incentives	Legislation that regulates and protects certain material networks, prevents waste export, and provides access to funds, tax credits and other subsidies	They allow overcoming economic obstacles: when there are no regulations, only self-sustaining material recycling activities endure. If they exist, networks can get established even without being profitable
	Social involvement	Consumer	Consumer awareness and engagement level	Consumers can have positive effects on recycling networks by correctly pre-sorting their waste and exerting pressure on businesses
		Manufacturer	Material and product manufacturers awareness and engagement level	Manufacturers can foster recycling and circular economy practices as part of company strategy and raise awareness levels among stakeholders

This framework for characterizing open-loop recycling networks can be adapted to other schemes such as reuse, repurposing, remanufacturing and closed-loop recycling for instance. In these cases, the categories (process variables, market variables and waste management conditions) and their respective subcategories would remain unchanged. Then, a similar work as the one performed in this study (literature review followed by expert interviews) has to be carried out in order to identify robust corresponding descriptors. However, the main structure of the framework (Table 40) can be applied to other cycling schemes. Moreover, even within a particular scheme, some descriptors may be added to adhere to the specificity of a material (such as matrix type for composites, for instance).

Table 40: General framework for characterizing material cycling networks

CATEGORIES	SUBCATEGORIES	GENERAL DESCRIPTION
Process variables	**Technical optimization**	Describe the elements of the process that can be optimized
	Product design	Describe the product designers' actions that can improve material cycling
Market variables	**Macro**	Describe the dynamics of material scarcity in markets, whose factors affect recyclers but on which they have little to no impact/action
	Micro	Describe the economic factors directly dealt by recyclers
Waste management conditions	**Network configuration**	Describe the general logistics and organization aspects of the network/scheme
	Regulatory framework	Describe the legal context and its ramifications on the network/scheme
	Social involvement	Describe the social actors that have agency on the development of the network/scheme

6.2.3 Cycling expertise for product designers – the material CLEARER sheets

The proposed characterization framework is a tool to audit recycling activities. It can be used by government agencies and recycling industrialists as a means of compiling knowledge on material cycling. The implemented framework can also be translated into easy-to-use information for product designers or any other stakeholder, in the form of a material cycling network characterization expertise sheet (CLEARER sheet), as shown in Table 41. By referring themselves to these sheets, product designers have a quick understanding of the important parameters for the anthropogenic cycle of a given material and evaluate the congruence between their academic and industrial standpoints, as well as the focus of scientific research and the issues of recyclers. By performing successive audits and following the changes between them, but also collecting data sets for different locations, a database of cycling expertise can be constituted.

The application of this framework and the analysis it supports regard the Design for Material Circularity method presented in Chapter 5. At any given phase of the method, but in the recommendations step in particular, the use of this data systematization elucidating the hotspots for material cycling (and in this case, open-loop recycling) provides the quick insights required when proposing improvements based on the selected cycling scenarios. The data collected within this framework allows product designers, other members of the design team, as well as corporate and external stakeholders, to have a shared vision of the issues regarding material cycling networks.

In this study, a first step in the compilation of data about material cycling was performed with the analysis of the main material networks, which is shown in the next section. It serves as a complement to the assessment of material circularity but also as a record in itself, an example of how material cycling expertise could and should be systematised.

Table 41: Example of a material cycling network characterization expertise sheet or CLEARER sheet. Yellow descriptors have been mentioned only in scientific references; blue descriptors have been mentioned only by industrial experts; and green descriptors have been mentioned by both.

			Ferrous metals
PROCESS VARIABLES	**Technical optimization**	Separation	(green)
		Recycling	(yellow)
		Recycled material properties	(blue)
	Product design	Material mixes	(green)
		Material concentration in component	
		Density	
		Liberation behaviour	(blue)
MARKET VARIABLES	**Macro**	Global materials supply	
		Global material demand (prediction)	(green)
		Material accumulation in use	(green)
		Dissipative uses	(blue)
		Price of virgin raw materials	(yellow)
		Price of recycled raw materials	
		Size of waste deposit	(green)
		Quality of waste deposit	(green)
	Micro	Transportation costs	(blue)
		Labour costs	(blue)
		Downstream recycled material applications	
WASTE MANAGEMENT CONDITIONS	**Network configuration**	Collection mechanisms	(blue)
		Waste management development	
	Regulatory framework	Environmental regulations	
		Raw material policies and economic incentives	
	Social involvement	Consumer	(blue)
		Manufacturer	(blue)

6.3 Analysis of main material networks

The main material networks' characteristics are gathered below and analysed regarding their current state, with some inferences regarding their potential evolution. This constitutes a first compendium of cycling data, specifically of the open-loop recycling scheme of the main material types, which can be used by designers, recycling agents and other end-of-life experts. In each CLEARER sheet, the descriptors mentioned in scientific studies are highlighted in yellow, those evoked by industrialists in blue, and when both concurred they are green. The idea is not to present an exhaustive breakdown of the issues regarding each network but rather to show how the framework for their characterization can be applied and how it facilitates the understanding of the major points to be considered, in a systematized manner. It is a starting point to communicating on the material's cycling network among the designer team, inside the company or between product designers and recyclers.

6.3.1 Steel

The steel cycling network also encompasses the ferrous metals contained in the alloys or that are compatible with its applications. Historically, it is perhaps one of the most ancient recycling activities and, due to steel's important role in modern society, it is also a clear example of a mature material cycling network, with high process efficiency and a 55% share in steel production for Western Europe (Björkman and Samuelsson 2014).

The information gathered in the literature shows that scientific research is focusing on the optimization of the separation techniques and the recycling techniques, though the latter is not an industrial issue. This is due to industrial recycling processes – based almost entirely on electric arc furnace processes (Björkman and Samuelsson 2014) – being quite well developed. The properties of recycled materials are mentioned by industrialists because of the ever-more stringent requirements in steel composition that they must tend to in industrial use, but this is not a scientific issue. In some cases, the ferritic and austenitic content of the alloy can come into play, requiring more refined separation of the waste stream to maintain higher grades (AJI-Europe 2012; Björkman and Samuelsson 2014). However, the presence of tramp elements (intentionally added to the alloy or not) is the main focus to obtain superior mechanical properties and this is achieved thanks to the aforementioned sorting processes but also the avoidance of material mixes in product design. Also, the property requirements often lead to lower efficiencies in recycling due to the addition of virgin material in the feed to correct compositions (Björkman and Samuelsson 2014). Copper is a known contaminant that tends to concentrate as the number of cycles progress, especially in the automobile industry (AJI-Europe 2012).

Where the steel recycling market is concerned, every macroeconomic descriptor is involved in defining the evolution of the network and its economic viability. Material availability governs the proportion of scrap that is used by the industry and it is affected by the dynamics of supply and demand, the fluctuations of ore and scrap prices, the uses of steel (which can usually last a few decades and involve irrecoverable losses in foundation works for instance) and the size and quality of available scrap deposits (in which tramp elements can lead to overall steel dilution in recycling processes (Björkman and Samuelsson 2014)). In poorer countries, steel tends to accumulate for longer periods, modulating the waste stream even more (Müller et al. 2006; Rauch 2009). As an example of a mature network in regards to its history and the development of its processes, reaching almost optimal technical efficiency rates, overall scrap use and proportion in stock are still small, i.e. primary steel is still the major source of the material. It should be noted that, while the literature focuses on the price of virgin raw materials, recyclers are more concerned with the price of scrap, showing how viewpoints can differ based on where the agents' interests are: (Reck and Graedel 2012) indicate that steel is more recycled because of the great value that can be obtained out of this straightforward activity, whereas the industrialists explained that the industry turns to scrap when economic crises arise and re-melting scrap becomes more attractive. There was no mention of the microeconomic parameters of steel recycling in the literature reviewed, even though recyclers are affected by transportation and labour costs in their quest for cost-efficiency.

The academic community also seemed to not consider the general conditions of the management of steel waste, perhaps due to its already "mature" status, since it may not pose any scientific problems to be solved. However, collection mechanisms and the mentality and involvement of both manufacturers and consumers are pointed as drivers by industrial recycling specialists.

The characterization sheet for the steel cycling network is given in Table 42.

Table 42: Steel CLEARER sheet

			Steel
Process variables	**Technical optimization**	Separation	
		Recycling	
		Recycled material properties	
	Product design	Material mixes	
		Material concentration in component	
		Density	
		Liberation behavior	
Market variables	**Macro**	Global materials supply	
		Global material demand (prediction)	
		Material accumulation in use	
		Dissipative uses	
		Price of virgin raw materials	
		Price of recycled raw materials	
		Size of waste deposit	
		Quality of waste deposit	
	Micro	Transportation costs	
		Labour costs	
		Downstream recycled material applications	
Waste management conditions	**Network configuration**	Collection mechanisms	
		Environmental regulations	
		Waste management development	
	Regulatory framework	Raw material policies and economic incentives	
	Social involvement	Manufacturer	
		Consumer	

6.3.2 Copper

Copper recycling used to be very straightforward and widespread but has become a more complex activity in recent years with the fast changes in material (and therefore scrap) composition (Samuelsson and Björkman 2014). The maturity level of the network and its overall efficiency vary significantly from one country to the other, however, there is a general consensus that there is value to be recovered in scrap and the different type of copper-rich waste.

The copper network analysis showed that scientific and industrial expert data converge significantly. Processing issues seem to arise from a difficulty of separating and achieving high-quality in recycled products, due to material mixes and diffusion (especially in cables for the former and printed wire boards from WEEE for the latter). The less copper is concentrated and pure, the more difficult the smelting and purification process becomes, leading to a loss in cost-efficiency that may render its recycling less attractive.

In terms of market variables and economic viability, there were shortage concerns with the constantly growing use of copper, whose properties can hardly be matched in certain applications. While demand was perceived as a cause for this issue by industrialists, scientific research is focused on dissipative uses (Graedel et al. 2002; Glöser, Soulier, and Espinoza 2013). Copper recycling does not seem to be affected by the network costs involved in the activity as cost-efficiency is relatively high provided that a proper ensemble of process, downstream material applications and collection mechanism is found.

The state of the waste management network also has a significant impact on the overall performance of copper recycling. The logistics aspects are key, with proper collection mechanisms and the advent of specific Extended Producer Responsibility schemes greatly improving the separation of high-grade scrap for instance, as well as user/consumer involvement. Given that copper availability is sometimes considered to be menaced due to its large industrial use, governmental economic incentives are seen as an effective driver to increase recycling rates.

The characterization sheet for the copper cycling network is given in Table 43.

Table 43: Copper CLEARER sheet

			Copper
Process variables	**Technical optimization**	Separation	
		Recycling	
		Recycled material properties	
	Product design	Material mixes	
		Material concentration in component	
		Density	
		Liberation behavior	
Market variables	**Macro**	Global materials supply	
		Global material demand (prediction)	
		Material accumulation in use	
		Dissipative uses	
		Price of virgin raw materials	
		Price of recycled raw materials	
		Size of waste deposit	
		Quality of waste deposit	
	Micro	Transportation costs	
		Labour costs	
		Downstream recycled material applications	
Waste management conditions	**Network configuration**	Collection mechanisms	
		Environmental regulations	
		Waste management development	
	Regulatory framework	Raw material policies and economic incentives	
	Social involvement	Manufacturer	
		Consumer	

6.3.3 Aluminium

Aluminium recycling is an activity that makes a lot of economic and environmental sense, since producing primary aluminium from ore is extremely costly and energy-intensive. Beverage cans have the highest recycling rates, with Brazil attaining almost 100% in 2011 (van Schaik and Reuter 2014b). However, other applications and alloys still do not reach these soaring results.

There is still progress to be made on the technical optimization of recycling processes, on which both academia and the industry seem to be working. Recycling experts have mentioned several issues that hinder the network’s efficiency: the diversity of technical alloys that are not correctly sorted and end up being recycled into lower-grade parts; the inclusion of other materials that are difficult to separate from the aluminium; as well as low volume and low density parts that are more oxidized on the surface, resulting in more losses upon re-melting.

Scientific research focuses on the fluctuations of primary and secondary raw materials along with the size and quality of waste deposits as the major economic drivers for the evolution of aluminium recycling. Economic crises and the rise of energy costs have been known to promote the recourse to recycling (Chen and Graedel 2012b; Reck and Graedel 2012). There is a large potential for future aluminium recycling in hibernating stock and landfills (Thomas and Wirtz 1994; Chen and Graedel 2012b; Reck and Graedel 2012). On the other hand, recyclers are also affected by the shifts in global supplies and the long-term applications of aluminium, which can reduce its availability and can promote recycling activities. Labour costs and suitable downstream applications for recycled materials are also a concern for the development of the sector, in the expert’s opinion.

All of the waste management’s environment conditions were mentioned. For scientific researchers, the development of waste management systems (such as the packaging EPR scheme) and economic incentives for recycling have been the most effectual drivers for the network. Recyclers evoked better collection mechanisms (allowing better alloy separation and avoiding downgrading after recycling), strict environmental regulations and both consumer and manufacturers’ attitudes towards the sector as well. Also, recycling operations can be fostered with the integration of producers and recyclers, such as when Alcoa acquired part of Electronics Recyclers International (Lu, Qi, and Liu 2014). Regarding the involvement of manufacturers, there are even some actions being undertaken to constitute a lobby group to support the interests of aluminium recyclers.

The characterization sheet for the aluminium cycling network is given in Table 44.

Table 44: Aluminium CLEARER sheet

			Aluminium
Process variables	Technical optimization	Separation	
		Recycling	
		Recycled material properties	
	Product design	Material mixes	
		Material concentration in component	
		Density	
		Liberation behavior	
Market variables	Macro	Global materials supply	
		Global material demand (prediction)	
		Material accumulation in use	
		Dissipative uses	
		Price of virgin raw materials	
		Price of recycled raw materials	
		Size of waste deposit	
		Quality of waste deposit	
	Micro	Transportation costs	
		Labour costs	
		Downstream recycled material applications	
Waste management conditions	Network configuration	Collection mechanisms	
		Environmental regulations	
		Waste management development	
	Regulatory framework	Raw material policies and economic incentives	
	Social involvement	Manufacturer	
		Consumer	

6.3.4 Precious metals

Precious metal recycling networks are driven by the high prices of the recovered materials, which keep both scientific and industrial interest flowing. Some recycling activities are well-established and possess high efficiency such as pre-consumer, photography, special catalysts and coin/jewellery scraps. However, post-consumer recovery is usually crippled by dissipative uses, especially in electronics applications (Rombach and Friedrich 2014).

Because of its precious nature, separation and recycling optimization are absolutely crucial and much of the effort is focused on them (whereas material properties are not an issue). Pre-processing operations are necessary and, when not available, can hamper recycling efficiency (Hagelüken 2012). Product design can also play a role by avoiding material mixes, easing liberation and increasing concentration in components, thus facilitating the recycling process and increasing yields (Hagelüken 2012; Peiro, Villalba, and Ayres 2013).

All market variables also come into play with dissipative uses being a major concern. Because recycled precious metals present sensibly no difference from their virgin counterparts, only the virgin raw material prices matter. If these prices rise, more materials enter the recycling stream (Sibley 2004; Monier et al. 2010c). The quality and size of waste deposits are once again important drivers for the development of recycling activities and authors have noted that reaching an economy of scale is an issue for precious metals, as is the dispersion and reliability of waste streams (Monier et al. 2010a; Rombach and Friedrich 2014). Scientific literature has shown signs of discomfort with the potential accumulation of silver and the platinum-group metals in use, especially in WEEE (Monier et al. 2010a), which is one of the only issues not shared by recyclers. These are quite attentive to the variations in supply and demand but also to the microeconomic variables (transportation and labour costs as well as the existence of suitable downstream applications). The labour intensity of the recovery of catalytic converters containing platinum is mentioned as a problem, for instance (Sibley 2004).

For superior efficiency in the network, scientists and recyclers agree that collection mechanisms, the development of waste management systems, and environmental regulations all play a role, especially where electronic waste is concerned. Specifically, the European end-of-life vehicle directive of 2000 has had a positive impact on the recycling of catalytic converters by imposing their removal in the minimum technical requirements (Saurat and Bringezu 2009). In open loop cycles, the correct handling and traceability of waste plays a major role in ensuring network efficiency for precious metals (Reuter et al. 2012). In regulation terms, raw material policies (and not economic incentives, for obvious reasons) that foster the recovery of these strategic materials should be implemented. These policies have to aim at impeding secondhand and end-of-life exports of waste, to avoid the loss of recycling potential, especially if precious metals are sent to locations that do not have access to the proper (and rare) recycling process (Saurat and Bringezu 2009; Hagelüken 2012).

The characterization sheet for the precious metals cycling network is given in Table 45.

Table 45: Precious metals CLEARER sheet

			Precious metals
Process variables	Technical optimization	Separation	
		Recycling	
		Recycled material properties	
	Product design	Material mixes	
		Material concentration in component	
		Density	
		Liberation behavior	
Market variables	Macro	Global materials supply	
		Global material demand (prediction)	
		Material accumulation in use	
		Dissipative uses	
		Price of virgin raw materials	
		Price of recycled raw materials	
		Size of waste deposit	
		Quality of waste deposit	
	Micro	Transportation costs	
		Labour costs	
		Downstream recycled material applications	
Waste management conditions	Network configuration	Collection mechanisms	
		Environmental regulations	
		Waste management development	
	Regulatory framework	Raw material policies and economic incentives	
	Social involvement	Manufacturer	
		Consumer	

6.3.5 Specialty metals

The recycling of specialty metals (along with rare earth elements) are usually based on the process routes of mass metals such as copper, lead, zinc and aluminium. Being dispersed and diluted in their applications, they are usually not treated in a specific process and their geogenic and anthropogenic chains sometimes overlap (Rombach and Friedrich 2014). Their recycling rates are also notably low in most cases (UNEP 2011).

Industrial recycling is still in its infancy, with process optimization still in the realm of scientific research. In this case, product design can play a significant role in mitigating material losses and promoting a higher recovery of concentrated waste by avoiding material mixes and increasing material concentration in components and their density. Liberation behaviour could also have a positive impact, by focusing on the accessibility of parts with high specialty metal grades (Chancerel et al. 2013), as in the case of tantalum used in superalloys for jet engines or other applications (Sibley 2004).

Material scarcity and availability are potential drivers for promoting recycling but research only mentions dissipation and obtaining a sizable waste deposit (Kavlak and Graedel 2013; Peiro, Villalba, and Ayres 2013), whereas recyclers are also interested in supply and demand variations, raw material prices and the quality of said deposits. Microeconomic variables are still untapped in this case.

In terms of the conditions of the waste management system, scientific literature highlights the importance of better collection mechanisms (Reck and Graedel 2012; Peiro, Villalba, and Ayres 2013) and a proper recovery in existing (or new) EPRs (Monier et al. 2010a). Hazardous substance laws, that have imposed specific collection mechanisms for metals such as cadmium, have shown a positive impact on recycling efficiency (Reck and Graedel 2012). Environmental regulations that foster decarbonized energy production and clean technologies can also have a rebound effect on specialty metals networks, by increasing their use all the while including a recovery route, but also enforcing recycling objectives in terms of process quality and material efficiency (for high technology applications) due to the strategic importance of these metals (Reck and Graedel 2012).

The characterization sheet for the specialty metals cycling network is given in Table 46.

Table 46: Specialty metals CLEARER sheet

			Specialty metals
Process variables	**Technical optimization**	Separation	
		Recycling	
		Recycled material properties	
	Product design	Material mixes	
		Material concentration in component	
		Density	
		Liberation behavior	
Market variables	**Macro**	Global materials supply	
		Global material demand (prediction)	
		Material accumulation in use	
		Dissipative uses	
		Price of virgin raw materials	
		Price of recycled raw materials	
		Size of waste deposit	
		Quality of waste deposit	
	Micro	Transportation costs	
		Labour costs	
		Downstream recycled material applications	
Waste management conditions	**Network configuration**	Collection mechanisms	
		Environmental regulations	
		Waste management development	
	Regulatory framework	Raw material policies and economic incentives	
	Social involvement	Manufacturer	
		Consumer	

6.3.6 Rare earths

Rare earth metals recycling is still quite limited, with an average of less than 1% end-of-life recycling rates (UNEP 2011) and quite dissipative uses. It has become an issue recently, with the distress that arose from its rapid increase in consumption and the shortage risks that ensued, mostly due to geopolitical issues (Bandara et al. 2015). This is definitely the most incipient network covered by this study. The industry is still relatively under-developed as volumes still are neither sizable nor constant enough to justify investments in this activity. The intensification of research activity identified by

(Binnemans et al. 2013) indicates that recycling rates will rise in the near future even though there are uncertainties regarding the growth rates of applications with different lifetimes, changes in material compositions and recycling schemes. In 2020, global collection rates may vary between 30% to 60% for magnets, 40% to 70% for nickel-metallic-hydride batteries as well as lamp phosphors. Recycling process efficiencies will reach 55% (magnets), 50% (batteries) and 80% (lamps), resulting in end-of-life recycling rates of 16,5%-33%, 20%-35% and 32%-56% respectively (Binnemans et al. 2013).

Process variables are only addressed by scientific research since no mature, industrial-grade processes have been implemented at a large scale. Recycling processes are not the issue, it seems, since the chemical processes involved are well-trodden, but separating the relatively-low concentrated rare-earths parts from other metallic waste. Also, design-related issues have been identified such as the concentration and mass of parts containing these elements (Chancerel et al. 2013) and the liberation behaviour of components, which is particularly important in the case of neodymium magnets in consumer goods, less in wind turbines and electric vehicles (Rademaker, Kleijn, and Yang 2013).

The matter of cost-efficiency is still principally defined by the market variables. These, along with proper collection mechanisms, are the drivers that can effectively jumpstart the whole network. Right now, industrialists are alert to macroeconomic parameters and the dynamics that rule material availability: global supply and demand, material accumulation in use and the size and quality of waste deposits. Once the anthropogenic stocks reach critical mass, recycling activities will receive the economic boost they require. On the other hand, scientists are angled as well at how to prevent dissipative uses and the impact that virgin material prices have on recycling activities (Ciacci et al. 2015). Furthermore, because rare earth elements are mined together, there are balance problems when supply and demand are not equal between them, creating shortages or excesses of some elements, thus driving forward recycling activities to even this out (Binnemans et al. 2013).

Regarding the waste management system’s conditions, the lamp EPR scheme has been touted as an important factor in potential increases of REE recycling from fluorescent lamps, as was the environmental restriction of mercury content in lamps. Finally, manufacturers may also have a role to play according to industrialists, by collaborating with governmental agencies and recyclers in order to promote recycling projects.

The characterization sheet for the rare earth cycling network is given in Table 47.

Table 47: Rare earth CLEARER sheet

			Rare earth
Process variables	**Technical optimization**	Separation	
		Recycling	
		Recycled material properties	
	Product design	Material mixes	
		Material concentration in component	
		Density	
		Liberation behavior	
Market variables	**Macro**	Global materials supply	
		Global material demand (prediction)	
		Material accumulation in use	
		Dissipative uses	
		Price of virgin raw materials	
		Price of recycled raw materials	
		Size of waste deposit	
		Quality of waste deposit	
	Micro	Transportation costs	
		Labour costs	
		Downstream recycled material applications	
Waste management conditions	**Network configuration**	Collection mechanisms	
		Environmental regulations	
		Waste management development	
	Regulatory framework	Raw material policies and economic incentives	
	Social involvement	Manufacturer	
		Consumer	

6.3.7 Plastics

Polymers have become ubiquitous from the 1950s onwards and their consumption has steadily increased in the last decades. However, the recovery and recycling of plastic waste are generally low when compared to other materials such as paper, glass or metals (Shen and Worrell 2014). Though efforts have been made in recent years, the development and maturity of these networks are typically much lower than other networks. Thus, almost every descriptor seems to affect plastic recycling and there are several drivers to raise its recyclability.

All process variables, bar liberation behaviour, were mentioned, which suggests that liberating plastic parts may not be a problem due to its lower fusion temperature and mechanical properties. New technology is still needed to attain high-purity plastic from the recovered material, with both literature and experts agreeing that there is much work to be done on the optimization of separation and recycling processes to achieve better properties for secondary plastics. The decontamination process of plastic waste is a critical part in this as is the choice of the type of recycling being performed (mechanical, feedstock or chemical), both having an impact on whether downcycling can be avoided. As the number of cycles increase, material properties tend to be lost, with contamination from other materials, observed in PET and PVC for instance (AJI-Europe 2012; Sadat-Shojai and Bakhshandeh 2011) or polypropylene in the automotive industry (Howell 1992; Maudet-Charbuillet 2009). In some cases, contaminants may impede food safety approval and lead to downcycling into fibre for example (Welle 2011). Moreover, the recent increase in bioplastics production has further complicated the requirement for better sorting since these new polymers are not always compatible with other waste streams (Soroudi and Jakubowicz 2013). Avoiding material mixes in product design plays a significant role for this and, while (Welle 2011) focuses on the importance of having a low concentration of impurities in PET recyclates (such as bottle caps made from other materials and chemicals that are stored in the bottles and not washed away), industrial recycling experts are more interested in the density of plastic parts, which contributes both to transportation cost-efficiency and to the general purity of the recycled raw material. In this sense, the lightweighting of bottles, though effective on the environmental level, reduces cap to bottle ratios and thus hinders recycling. (M. Patel et al. 2000; Shen and Worrell 2014; Hamad, Kaseem, and Deri 2013) mention the variety of additive and charges that are present in polymer masterbatch formulas and compounds as a source of complexification in waste streams.

Regarding the macroeconomic market variables, polymer recycling is inherently dependent on the fluctuations of oil prices, which predominantly determines the competitiveness of recycled raw materials. Even though the scarcity of oil resources is always the subject of much debate, the supply of plastics is hardly going to become an issue in the long run. Nevertheless, if materials accumulate in use and demand increases abruptly, there may be momentary supply shortages that encourage the recycling industry, but this is not addressed by literature. Once again, for the adequate development of this network, having a constant, sizable and quality deposit of plastic waste is indispensable. The increase in waste deposits and cumulative recycled plastics indicate a significant (possibly 50%)

reduction in processing costs (M. Patel et al. 2000). In terms of the microeconomic variables, transportation costs can really hinder cost-efficiency because of the low density of most plastic waste, which is why there is a lot of effort in pre-treating and baling it. Labour costs are an issue for recyclers who must deal with low benefit margins and are constantly looking for automated solutions to treat a large volume of waste, especially in sorting operations. Finally, finding suitable downstream applications is key both from a scientific and an industrial viewpoint, especially due to the property losses incurred in the recycling process that ultimately lead to downcycling.

All of the waste management system's conditions have an impact on recyclers' activity. Scientific studies address the improvement of collection mechanisms and the involvement of both consumers and manufacturers. Dedicated systems, with refunds, for example, are considered to improve recycling efficiency in the case of PET bottles and high-quality recycled materials such as PVC windows (Welle 2011; Al-Salem, Lettieri, and Baeyens 2010; Shen and Worrell 2014). This regards the effect that better municipal solid waste collection can have on recycling rates as a whole, with more participation from individuals in pre-sorting and more actions from manufacturers to foster the sustainability of plastics. Having a more integrated waste management system, with more concentrated facilities and a higher percentage of plastics in their activities is also deemed to have positive effects on recycling (Haeusler and Pellan 2012). The specialists have also seen progress stemming from the establishment of the ELV and the WEEE EPRs and other environmental legislation.

The characterization sheet for the plastics cycling network is given in Table 48.

Table 48: Plastics CLEARER sheet

			Plastics
Process variables	**Technical optimization**	Separation	
		Recycling	
		Recycled material properties	
	Product design	Material mixes	
		Material concentration in component	
		Density	
		Liberation behavior	
Market variables	**Macro**	Global materials supply	
		Global material demand (prediction)	
		Material accumulation in use	
		Dissipative uses	
		Price of virgin raw materials	
		Price of recycled raw materials	
		Size of waste deposit	
		Quality of waste deposit	
	Micro	Transportation costs	
		Labour costs	
		Downstream recycled material applications	
Waste management conditions	**Network configuration**	Collection mechanisms	
		Environmental regulations	
		Waste management development	
	Regulatory framework	Raw material policies and economic incentives	
	Social involvement	Manufacturer	
		Consumer	

6.3.8 Glass

Glass networks are quite well established and few parameters were found regarding their evolution. It is a very ancient activity that consists in re-melting the material and, much like the process for metals, it can be performed indefinitely without major property losses. Industrial large-scale recycling dates back to the 1970s and was fostered by legislation aimed at diverting waste from landfills (Dyer 2014). No specific industrialist was interviewed regarding this material and the only expertise from the field came from a sectoral report.

Avoiding contaminants and separating by colour or type are key elements to obtain high-quality recycled materials. Other process variables were not mentioned in literature or by industrial experts probably due to the fact that glass products and components are generally simple and recycling processes are very similar to those of primary glass production. Where the industry is concerned, improving separation is the essential element.

Market variables do not seem to affect this industry, except for the price of glass cullets and the downstream applications for secondary glass. Depending on the region and the organization of the network, these can vary significantly and thoroughly change the economic viability of recycling.

Industrial and scientific experts agree that collection mechanisms are fundamental to obtaining quality input for the networks, with container-deposit legislation being the norm in countries where the highest recycling rates are achieved (Dyer 2014). Where specific collection is not organized and glass finds itself mixed in the waste stream, interest in recycling it drops significantly due to its low value. The scientific literature on the subject points out that these collection mechanisms were set up after environmental legislation and the Extended Producer Responsibility scheme were instituted. Environmental benefits are reaped not only from reducing pollution but also from the large energy savings when using secondary glass. In some cases, contaminated scrap can be subject to closed-loop recycling, with increases in efficiency rates.

The characterization sheet for the glass cycling network is given in Table 49.

Table 49: Glass CLEARER sheet

			Glass
Process variables	**Technical optimization**	Separation	
		Recycling	
		Recycled material properties	
	Product design	Material mixes	
		Material concentration in component	
		Density	
		Liberation behavior	
Market variables	**Macro**	Global materials supply	
		Global material demand (prediction)	
		Material accumulation in use	
		Dissipative uses	
		Price of virgin raw materials	
		Price of recycled raw materials	
		Size of waste deposit	
		Quality of waste deposit	
	Micro	Transportation costs	
		Labour costs	
		Downstream recycled material applications	
Waste management conditions	**Network configuration**	Collection mechanisms	
		Environmental regulations	
		Waste management development	
	Regulatory framework	Raw material policies and economic incentives	
	Social involvement	Manufacturer	
		Consumer	

6.4 Conclusion

The importance of cycling expertise in product design has been addressed in previous chapters. It is a fundamental part of the Design for Material Circularity method. In this chapter, the second contribution to the research question has provided two main results: a general framework for the characterization of material cycling networks and the application of this framework to analyse eight specific material cycles. This is the basis for a shared understanding among product designers and recyclers of the issues with material cycling, but also the first step for the systematization of recycling network data.

While one could argue that recycling hinges essentially on cost-effectiveness, the results show that there are some nuances to this statement depending on the material. Each material network is at a different stage of maturity, which corresponds to a specific set of bottlenecks for its evolution. The current framework allows an initial correlation to be made between the perceived maturity and the positioning of both the academic community and industrial experts. Three levels of network maturity are thus described in Table 50, with the respective characteristics and materials. In this case, incipient, developing and peak maturity levels were derived from the recycling rates collected in (UNEP 2013), with only glass and steel being distinguished as having reached peak maturity.

Table 50: Network maturity levels based on the analysis of their characteristics

Network maturity	Characteristics	Materials
Incipient	Market dominates industrial concerns, most other variables are only tackled by scientific research	Rare earth and specialty metals
Developing	All parameters arise, with a tendency to a consensus between scientific research and industrial issues as maturity increases.	Copper, aluminium, precious metals and plastics
Peak	Few parameters are listed as drivers, attention shifts to increments in the collection-separation-properties dynamics.	Steel and glass

The framework presented in this chapter, applied to the case of open-loop recycling, was successful to provide a quick characterization of material cycling in accordance with the requirements set in Chapter 4. Table 51 summarizes the functions and sub-functions that were accomplished in the development of the framework proposed in this chapter, as well as the expected future developments.

Table 51: Summary of accomplishments and future developments for each function of the proposed framework

Functions	Accomplishments	Expected future developments
F1 Take into account all relevant elements that affect the evolution of cycling networks		
SF1.1 Integrate factors from multiple fields of knowledge	The descriptors that constitute the framework comprise technical, economic, regulatory, organizational and social parameters.	With the support from specialists from other fields, further research could be conducted to refine the framework and its descriptors.
SF1.2. Be based on real-life expertise	Sectoral reviews were consulted and industrial experts interviewed in the identification and validation of the descriptors.	Primary data from cycling industries should be collected and collated to the findings of this study.
F2 Provide knowledge to product designers on anthropogenic cycles		
SF2.1 Allow the rapid understanding of the state and issues of a cycling network and scheme	The aggregation and coalescence of descriptors into three categories and seven subcategories, forming the general framework, provide a straightforward synthesis of the parameters that govern material cycling. The CLEARER sheets are also a format that allows both simplified recordkeeping and quick visual assessments.	The use of the framework by product design teams in the field will provide feedback on the practicality of the method.
SF2.2 Indicate the cycling parameters that are pertinent to product designers	Design variables have been specifically highlighted to draw attention to their implication in material cycling.	Other, more specific design variables relating to product disassembly efficiency could be added with further studies.
F3. Applicable to all material classes		
SF3.1 Stem from the study of metals, polymers and ceramic materials	The descriptors were obtained from the study of glass, plastics in general and ferrous, non-ferrous, specialty, precious and rare-earth metals.	Composite materials deserve to be researched in particular.
SF3.2 Contribute to the analysis of the specificities of metal, polymer and ceramic anthropogenic cycles	The analysis of eight material cycling networks from the three major material classes has provided some insight into the specificities of their cycles.	Studies and audits should be conducted on as many material networks as possible, focusing on strategic materials, in order to identify their specificities and resemblances.

F4. Be robust, covering available information from multiple sources		
SF4.1 Collate knowledge from academic research and the industry	The research methodology employed in the elaboration of the framework consisted exactly in the coverage of both scientific and industrial sources.	Regular updates can be performed with regards to the literature review and expert interviews.
SF4.2 Allow improvements with the aggregation of more data	The general framework was composed in such a way that the addition of categories, subcategories and descriptors is possible, not only for the open-loop recycling study case presented here but also if adapting to other scenarios or schemes.	As more audits of cycling networks are performed, with different schemes and scenarios, the framework will be refined and extended.

Conclusion of Part II

In this Part, two propositions were made to answer the general research question. First, in Chapter 5, a tool for the integration of material circularity in design was developed, comprising a circular material value indicator and a method for using it, the Design for Material Circularity method. The Design for Material Circularity method consists in comparing the circular material value of the product's components materials – i.e. the potential value that the materials hold for future cycles – over two lifecycles, according to the available end-of-life scenarios. It provides insights on circularity hotspots and the best material-cycling scenario combinations.

Then, in Chapter 6, in order to constitute the necessary end-of-life expertise and provide an assessment of anthropogenic cycles to product designers, a framework for the characterization of material cycling networks was presented. The descriptors were identified after a deep review of literature followed by a validation by industrial experts. This framework was used as the basis for material cycling expertise capitalization in the form of material CLEARER sheets. Eight material cycling networks were studied using the framework, with the respective CLEARER sheets being provided: steel, copper, aluminium, precious metals, specialty metals, rare earth elements, plastics and glass. This is the first step in the construction of a shared and systematic compilation of cycling data that is pertinent to both designers and recyclers. Moreover, it may also serve as a tool to assess and audit the current state of recycling industries while looking to promote their activities through policies.

Both contributions are interdisciplinary views on material cycles translated in formats that are relatable to product designers and aimed at bridging both integrational gaps identified in Chapter 4. They confirm the need for an end-of-life expert to gather data about recycling processes and evaluate potential end-of-life scenarios.

In Part III, the Design for Circularity method will be implemented and exemplified in two study cases, in order to verify its applicability and illustrate its use. The network analyses will also serve in their ability to complement the circular value assessments and recommendations.

Part III: CASE STUDIES

In previous chapters, we established the need for an assessment of material circularity and an evaluation of product lifecycle beyond the first lifecycle for which the product was designed. Then, we identified the main descriptors of material cycling networks and devised a formula to analyse circular material value. These were incorporated in a Design for Material Circularity (DfMC) method aimed at the material experts of the product design process, in order to firstly support design decisions in accordance with the reality of end-of-life networks and related experts advice, as well as taking the interconnections between material choices and end-of-life scenarios in consideration. Secondly, a framework to support the characterization of material cycling networks was proposed in Chapter 6 allowing a systematization of cycling schemes expertise through a set of specific cycling networks descriptors. Eight material cycling networks have thus been established and characterized.

In this Part, these contributions are employed in two case studies conducted to illustrate the application of the method and assess its use. The material cycling network characteristics' ability to assist and deepen the circularity analysis is also observed. The assessment of the method and framework is based on the functions that have served to specify them, established in Part 1.

The first case is a simple monomaterial product for which a simultaneous study of several material candidates and end-of-life scenarios was performed. The second study focuses on a more complex product architecture, with multiple materials, and tests the limits of the method in locating circularity hotspots and ideal end-of-life scenarios.

In both cases, the evaluation was conducted from the standpoint of a material expert on a product design team looking to improve the circularity of the material flows of his product. They are presented as they would be from the perspective of these engineers, with additional annotations highlighted throughout the studies, commenting and critically reviewing the contributions in the process.

Chapter 7: Optimal choice of material and end-of-life scenario for a 1,5-litre bottle container

7.1 Introduction to the case study objectives: the DfMC in use

The Design for Material Circularity method is applied to a 1,5-litre bottle container, a simple monomaterial product, in order to validate the method's properties and functions, putting it to use and verifying that the results given by the circular material value equations are coherent with a real case situation. Bottle containers are a common product with widespread use and big production and consumption volumes. They also have short use cycles and relatively mature end-of-life treatment networks. For the sake of simplicity, only the container is considered even though bottle caps are known contaminants in most recycling facilities. Table 20 summarizes the application of the method for the case study.

Table 52: Design for Material Circularity (DfMC) method applied to the 1,5-litre bottle container without cap

Phase 1 – Initialization: **Scope delimitation based on available data and required assumptions for the study of glass, PET and aluminium circularity**	a. **Goal definition:** material and end of life selection in early design stage for improving the container's material circularity over two cycles b. **Data gathering and hypotheses:** investigating glass, PET and aluminium material cycling networks around the world (and in particular for 1,5-litre containers); material prices, functional masses, design yield and criticality factors on availability, vulnerability, addiction and substitutability of the 3 considered materials
Phase 2 – Operationalization: **Container circularity assessment using the circular material value indicator for PET, glass, and aluminium on closed and open loop end-of-life scenarios**	c. **Establishment of a baseline** with the circular material value equation d. **Qualitative evaluation of material degradation after use** referring to design predictions and cycling network information e. **Identification of potential cycling scenarios**: scenario tree for the end-of-life of a 1,5-litre bottle containe**r** f. **Estimation of second lifecycle values**: assessment of second lifecycle variables
Phase 3 – Interpretation: **Results analysis of PET, glass and aluminium to provide recommendations for experts**	g. **Selection of an evaluation strategy:** maximizing material value over two lifecycles, with a minimum value for the first lifecycle; identifying a material and end of life combination with maximum value conservation over two lifecycles h. **Results analysis** for glass, PET and Aluminium reuse, closed and open loops, and PET downcycling scenario, focusing on the chosen decision-making strategy i. **Recommendations** made to encompass product designers' constraints and cycling network expertise to the optimal choices

7.2 DfMC, Phase 1 – Initialization: Scope delimitation based on available data and required assumptions for the study of glass, PET and aluminium circularity

a. Goal definition: material and end of life selection in early design stage for improving the container's material circularity over two cycles

The evaluation is performed in the first specification phase of the design process. In this case, no particular impediment or obligation related to the material or end-of-life scenario (i.e. no previous specification) is considered, so the DfMC method is used to find the optimal combination among all the available options. The purpose is to select the most favourable material and end-of-life scenario combination for material circularity.

b. Data gathering and hypotheses: investigating glass, PET and aluminium material cycling networks around the world (and in particular for 1,5-litre containers); material prices, functional masses, design yield and criticality factors on availability, vulnerability, addiction and substitutability of the 3 considered materials

For this desktop simulation, only three material candidates are evaluated, based on typical commercial products: PET, glass and aluminium. The information gathered to apply the method was either collected from specialized material consultants or, when they were not readily available, estimated based on prior knowledge of the product and its materials. When assumptions had to be made, the most disadvantageous values for circularity were kept as a general rule of thumb, in order to prevent the overestimation of circular material value.

Mass is given by the design of standard 1,5l containers sold on the market. The current price and price history for the last 12 months are taken from an online plastics price overview[14] corresponding to PET regrind or flakes, from Eurostat price histories of glass waste in Europe[15], and from the online

[14] www.plasticker.de, accessed in April 2016. Prices for the last 12 months.
[15] http://ec.europa.eu/eurostat/statistics-explained/index.php/, accessed in April 2016. Price history for glass waste for 12 months between November 2012 and November 2013.

commodity price list for aluminium with 99.5% minimum purity[16]. Thus, all three candidate materials present some part of secondary sourcing. The functional mass is set at 1 for the baseline since the bottles are considered to supply one functional unit (i.e. contain 1.5 litres of liquid), for a hypothetical lifetime of 6 months. The design yield is established at 0,6, which is the minimum value for a design to be economically sound (Petitdemange 1995). Table 53 presents the criteria and values set for the criticality factors. The use scenario is considered ideal, with no property degradation over the 6 months lifetime.

Table 53: Criticality factors for 1,5-litre bottle container material candidates based on the criticality matrix

	Availability	Vulnerability	Addiction	Substitutability	K
PET	Mediocre (3)	Insufficient (4)	Acceptable (2)	Acceptable (2)	**3**
Glass	Satisfactory (1)	Satisfactory (1)	Mediocre (3)	Acceptable (2)	**1**
Aluminium	Acceptable (2)	Satisfactory (1)	Mediocre (3)	Acceptable (2)	**1**

NOTES ON PHASE 1: INITIALIZATION

Since the method is being used at an early stage of the product design process, the scope of the case study allowed the evaluation of both materials and cycling scenarios simultaneously, thus testing the first requirement of the method, "F1: Elucidate the interconnections between material choices and cycling networks". The candidate materials for the container represent the three major material classes (metals, polymers and ceramics) and therefore correspond to the third requirement of the framework, "F3: Be valid for all material classes".

Gathering data and formulating clear and well-grounded hypotheses are the fundamental steps for the correct application of the method. Data sources must be documented and users of the method must strive for consistency with time periods and locations, whenever possible.

In the case of the criticality factor and the values used for its criteria, these are established based on the literature review on critical materials, following the definition of each constituent in Chapter 5. This evaluation is ultimately quantitative and should always be carried out by the design team's

[16] www.indexmundi.com, accessed in April 2016. Price history for Aluminium, 99.5% minimum purity, LME spot price, CIF UK ports, US Dollars per Metric Ton between March 2015 and March 2016. Converted from US dollars into Euros using a 1,145 conversion rate from xe.com (April 30 2016).

material expert. It affects the circular material value as a constant coefficient but does not vary in the second lifecycle because of the short lifespan of the product.

Keeping the design yield at a 0,6 standard for all materials (due to a lack of real manufacturing data) cancels this variable's effect on the results, precluding the evaluation of its pertinence to the method. The same can be said about the material degradation after use coefficient that was kept at 1 (meaning no degradation after use in the cases studied) for all calculations. Further studies should be conducted with real data of the products' manufacturing and use phase to analyse the effects of these variables.

7.3 DfMC, Phase 2 – Operationalization: Container circularity assessment using the circular material value indicator for PET, glass, and aluminium on closed and open loop end-of-life scenarios

c. Establishment of a baseline ($\mathcal{V}_1$) with the circular material value equation

The baseline values ($\mathcal{V}_1$) for each material candidate are established using the circular material value equation:

$$\mathcal{V}_1 = \mathcal{P}_1 \times m_{f_1} \times \frac{\varphi_1 \times \kappa_1}{\pi_1}$$

They are presented in Phase 3.

d. Qualitative evaluation of material degradation after use referring to design predictions and cycling network information

With the baseline established, the remaining variables required to calculate the circular material values of the second lifecycles ($\boldsymbol{\mathcal{V}_2}$) are sought. An ideal use case is considered, in which the containers do not lose mass or drop in performance after being used and thus material degradation after use is insignificant. A more accurate evaluation would require actual knowledge of the state of the product after use and/or the proportion of broken and useless containers. The material degradation after use coefficient (δ_m) is thus equal to 1 in all second lifecycle estimations.

e. Identification of potential cycling scenarios: scenario tree for the end-of-life of a 1,5-litre bottle container

With no material degradation after use, closed-loop scenarios can be applied. The end-of-life scenarios examined are reuse, closed loop recycling, open loop recycling (for all material candidates) and downcycling (for PET only). These are identified as being the main options for the product. While other downcycling options exist for aluminium and glass, no precise data was found on the specific processes and products that could apply and thus only PET downcycling into polyester fibres is studied. Figure 30 shows the end-of-life scenario selection tree.

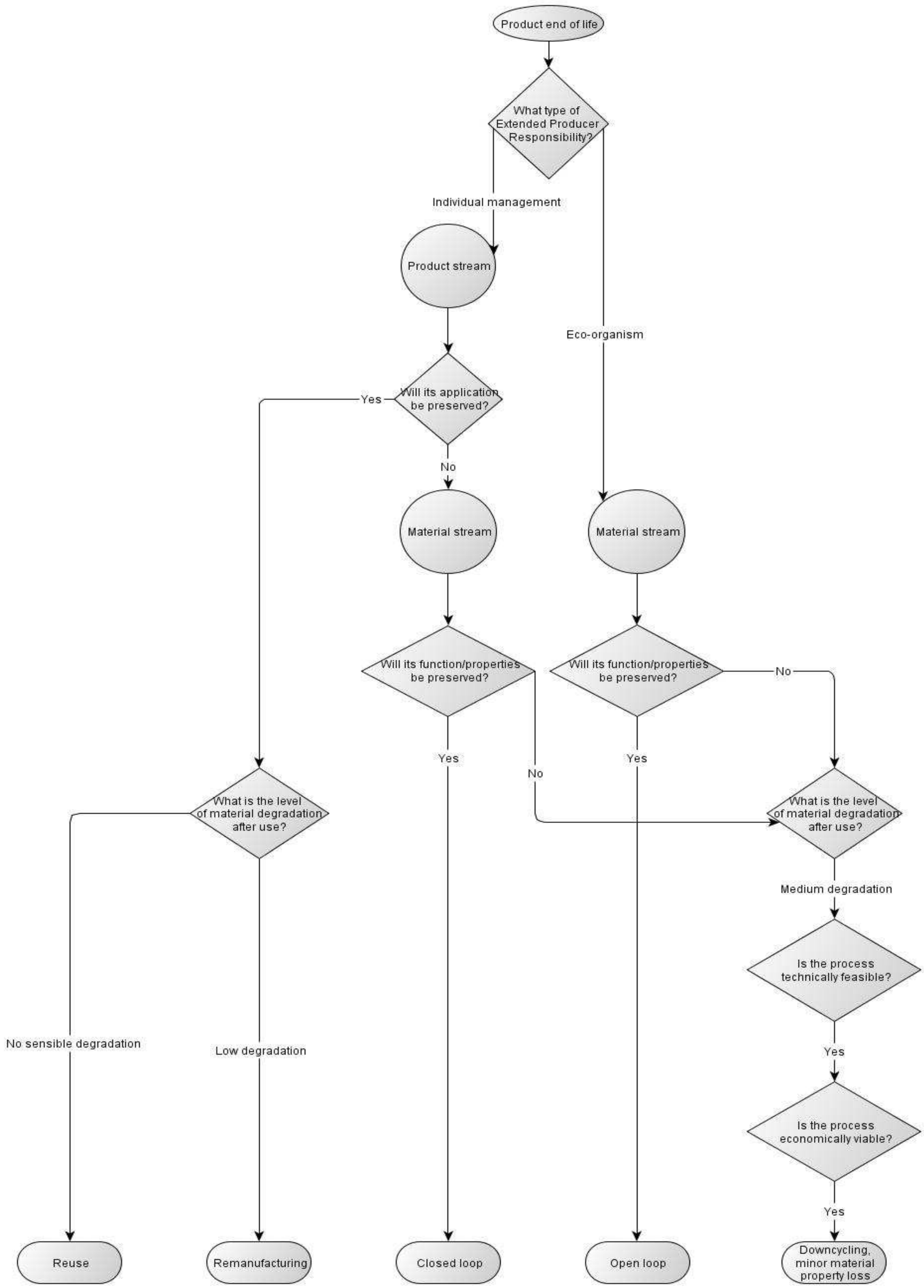

Figure 30: Scenario tree for the end-of-life of a 1,5l bottle container

f. Estimation of second lifecycle values: assessment of second lifecycle variables

The estimation of the second lifecycle values ($\mathcal{V}_2$) for each material candidate are established using the circular material value equation:

$$\mathcal{V}_2 = \mathcal{P}_2 \times m_{f_2} \times \frac{\varphi_2 \times \kappa_2}{\pi_2} \times \eta \times \delta_m \times \delta_f$$

In the reuse scenario, as there should be no losses, the transformation process yield coefficient η is set at 1. The secondary price is estimated as equal to the first lifecycle price (based on the short 6-months product lifetime) as well as the market risk, functional mass and criticality factor. In the absence of any manufacturing process, the design yield is set at 1. For the functional degradation, the number of reuse operations before having to change the scenario is estimated at 5 for the PET bottle (based on potential degradation of the polymer due to UV rays for instance) and 100 for both the glass and aluminium bottles (representing a seemingly inexhaustible loop).

In the closed-loop scenario, the transformation process yield is estimated at 90% for PET to account for processing losses in the regeneration of the polymer (whether via mechanical or chemical treatment) and 100% for glass and aluminium. Prices and market risk remain the same, as the material only circulates through the company's own supply chain, and functional mass, design yield and criticality factor are not altered from the baseline. In this scenario, PET could last 10 operations and glass and aluminium, 100.

In the open loop scenario, the transformation process yields are taken from the recycling network actual recycling efficiencies for each material candidate: PET values of collection for recycling in the EU in 2012 come from (Shen and Worrell 2014); glass collection for recycling values in the EU in 2012 are taken from the European Glass Container Federation 2013 report[17]; and the world average for aluminium recycling from (van Schaik and Reuter 2014b). While glass and aluminium prices remain unchanged (as most of these materials already include waste in their processing), recycled PET prices are used[18]. Likewise, market risks for recycled PET are approximated as amounting to 5 times those of virgin PET based on (OECD 2007), while those of glass and aluminium are still the same. Again, no

[17] Available at www.feve.org
[18] PET bale prices from www.plasticker.de, accessed in April 2016.

difference in design yield, criticality and functional mass. And only 5 recycling operations are deemed necessary before having to change scenarios for PET.

The only downcycling scenario assessed is that of PET being turned into fibres for clothing (in this case, an adult T-shirt). The transformation yield is considered to be the same as in the open loop scenario since PET flake to fibre conversion is a relatively lossless process (Shen, Worrell, and Patel 2010). The functional mass is divided by 5 as an adult T-shirt weighs approximately 160 grams. The number of downcycling operations is lower than for the open loop scenario, at 3. Every other variable is the same as for the open loop scenario.

NOTES ON PHASE 2: OPERATIONALIZATION

Product designers should seek data that allows them to be as precise as possible in their circular material value assessments, which means considering they must consider region and timeframe of the study. All estimations should rely on proper expertise and be duly specified.

The baseline variables are usually already available inside the company, whereas second lifecycles require some investigation to be performed, either in the same hypothetical manner as in this study, or by conducting a downstream assessment of the use of recycled materials with recyclers themselves and other industries that use the materials in question. For multinational companies, data comparison between different countries can also provide insights.

This case study allowed the consideration of a wide array of cycling scenarios, from closed to open loop situations, which fulfils "F2: Encompass all potential end-of-life scenarios". The downcycling scenario is helpful to evaluate the effects of downcycling in circular material value, but more examples could have been shown as this is a quite diverse type of cycle. However, the more scenarios are added, the bigger the amount of data to be collected and assessed, so scenarios should be chosen wisely for pertinence and reduced quantity. In this case, the Downcycling scenario serves to show the impact of variations in the functional mass, as the results will demonstrate in the next section.

As with criticality, the definition of potential cycling scenarios depends on knowledge of material end-of-life networks. This end-of-life expertise can be pre-existent in the company or stem from a previous characterization of the networks using the framework proposed in Chapter 6. In this case, the CLEARER sheet is used only in the Interpretation Phase, to provide further details to the recommendations.

The transformation process yield is usually available for open loop scenarios yet, for closed loops, there is less information. If no contradictory information is given, then reuse scenarios should be awarded $\eta = 1$ and, in closed-loop recycling, only processing losses should be considered (since general network losses linked to waste management have no incidence). The assumption of variable stability over short lifecycles (in this case, six months) should be taken with caution and duly justified.

The maximum number of cycles for each scenario and material was established in a more qualitative manner, to consider both the difference between recyclability of glass and metal when compared to polymer (here resulting in ten times more cycles on average) and the care that would go into the prevention of material degradation when the company retains possession of the product (such as the closed-loop recycling scenario. These values were based on knowledge of material and recycling processes properties and the general understanding that glass and metals are almost endlessly recyclable, especially when compared to polymers.

7.4 DfMC, Phase 3 – Interpretation: Results analysis of glass, PET and aluminium to provide recommendations for experts

g. Selection of an evaluation strategy: maximizing material value over two lifecycles, with a minimum value for the first lifecycle; identifying a material and end of life combination with maximum value conservation over two lifecycles

Two heuristics are used to evaluate the results of the value analysis with the aim of addressing simultaneously the different material candidates and the potential end-of-life scenarios: a comparison of the values obtained among material candidates and an assessment of value depreciation among end-of-life scenarios. In order to prevent excess quality in the manufacture of the containers while fostering the recovery of value after one product lifecycle, the first heuristic consists in looking for the maximum value for the second lifecycle with a minimum value for the first lifecycle. This translates into the following conditions:

$$\boldsymbol{\mathcal{C}_1}: \begin{cases} max\mathcal{V}_2 \\ min\mathcal{V}_1 \end{cases}$$

The second heuristic is based on an appraisal of the relative variation of value for each scenario and the identification of the combination of material and end-of-life scenario with maximum value conservation over two lifecycles. This corresponds to the condition:

$$\mathcal{C}_2 : max\left[\frac{(\mathcal{V}_2 - \mathcal{V}_1)}{\mathcal{V}_1}\right]$$

Thus, in order to find the optimal solution, the evaluation strategy adopted is the union of both conditions, as expressed below:

$$\mathcal{C} : \begin{cases} \mathcal{C}_1 \\ \mathcal{C}_2 \end{cases}$$

h. Results analysis for glass, PET and Aluminium reuse, closed and open loops, and PET downcycling scenario, focusing on the chosen decision-making strategy

The baseline values are collected in Table 54. The results show that PET possesses 28 times the circular value of glass. Aluminium is found to be 23 times more valuable than glass. The circular value of glass is quite low due to it having the lowest price and low criticality. Aluminium has the highest price (more than 55 times that of glass) but also the highest market risk (more than two times that of glass). PET, with its intermediary price and market risk but triple criticality (due to it being partly sourced from oil) is the material with the highest baseline value.

Table 54: Baseline values for the 1,5L container case study

	$\mathcal{P}_1$ (€/kg)	π_1	$m_{fu,1}$	φ_1	κ_1	$\mathcal{V}_1$
PET	0,400	0,075	1	0,6	3	9,6
Glass	0,024	0,042	1	0,6	1	0,34
Aluminium	1,340	0,100	1	0,6	1	8,0

The results for the circular material values of the second lifecycles are gathered in Table 55. Overall, the second lifecycle value is higher than the baseline for the reuse scenario. This is mainly due to the fact that, without manufacturing operations, the design yield is set at 1 for this scenario (whereas it was worth 0,6 in the first lifecycle), since almost every baseline parameter stays the same and the process yield and degradation coefficient are equal or near 1.

For the closed loop scenarios, the circular material value practically remains unchanged from the baseline with a mere 1% drop for glass and aluminium. In the case of PET, there are losses due to the transformation process yield coefficient (0,9) and the functional degradation coefficient (0,8).

The open loop scenario has a drop in $\mathcal{V}_2$ for all materials: less important for glass (one quarter lost), quite substantial for aluminium (three quarters lost), and extremely high for PET (only 4% remained). These losses are mainly due to the recycling networks' yields that, in an open loop situation, can be quite low. Concerning PET, this negative effect is compounded by the lower price of secondary material (half of the one used in the other scenarios). Also, the hypothesis of a market risk for secondary PET five times greater than that of the first lifecycle and the 17% functional degradation decrease for each recycling operation further reduce its value. In this case, PET containers have almost the same circular value as glass.

As for the downcycling of the PET containers into another product (a polyester-fibre T-shirt), it provides an even smaller value than for the open loop since the functional mass decreases (due to more mass being required to fulfil the new function) and less downcycling operations are possible.

Table 55: Second lifecycle circular material values for each potential end-of-life scenario

	Second lifecycle								
	$\mathcal{P}_2$ (€/kg)	π_2	$m_{fu,2}$	φ_2	κ_2	η	δ_m	$\delta_{\not{f}}$	$\mathcal{V}_2$
					Reuse				
PET	0,400	0,075	1	1	3	1	1	0,83	**13**
Glass	0,024	0,042	1	1	1	1	1	0,99	**0,56**
Aluminium	1,340	0,100	1	1	1	1	1	0,99	**13**
					Closed loop				
PET	0,400	0,075	1	0,6	3	0,9	1	0,91	**7,8**
Glass	0,024	0,042	1	0,6	1	1	1	0,99	**0,34**
Aluminium	1,340	0,100	1	0,6	1	1	1	0,99	**7,9**
					Open loop				
PET	0,180	0,376	1	0,6	3	0,520	1	0,83	**0,37**
Glass	0,024	0,042	1	0,6	1	0,730	1	0,99	**0,25**
Aluminium	1,340	0,100	1	0,6	1	0,270	1	0,99	**2,1**
					Downcycling				
PET	0,180	0,376	0,2	0,6	3	0,520	1	0,75	**0,07**

The comparison between the material candidates' values over two lifecycles with the condition system $\mathcal{C}_1$ produces two conflicting results: the maximum value for $\mathcal{V}_2$ is obtained for PET and aluminium (which have much higher scores in general) but the minimum value for the first lifecycle is achieved with glass. Thus, a trade-off is required: while PET or aluminium hold more value to be recovered at the second lifecycle, they also require a bigger initial investment in terms of production, whereas glass accomplishes the functions required using the least value. Considering this financial argument, minimization of value on the first lifecycle is favoured instead of maximum value recovery and thus glass seems likely to be the best suited material to accomplish a compromise on $\mathcal{C}_1$. For $\mathcal{C}_2$, the preservation of value over two lifecycles, reuse presents the best results, especially for glass and aluminium.

The matter of material ownership and responsibility still has to be addressed. After an open loop recycling scenario, the company loses possession and therefore responsibility for the material. On the other hand, in a reuse scenario, the company maintains possession and responsibility for the material and should then consider all the subsequent lifecycles until another scenario is reached and responsibility is transferred. Since reuse could be performed a substantial number of times (especially for glass) and it results in an increase of value, there seems to be no problem for circularity until another scenario is required. The best combination of material and end-of-life scenario is, therefore, to make containers out of glass and reuse them. This, however, may or may not be feasible for companies depending on their business models.

Another, more practical (and perhaps realistic) option is to recycle the materials in an open loop. In the case of glass, almost three-quarters of the value are still preserved. Thus, glass containers recycled in an open loop are also an acceptable solution. Table 56 provides the results of the relative evolution in value from the first to the second lifecycle.

Table 56: Relative evolution of value over two lifecycles for each end-of-life scenario

	Relative evolution (%)			
	Reuse	**Closed loop**	**Open loop**	**Downcycling**
PET	39	-18	-96	-99
Glass	65	-1	-28	--
Aluminium	65	-1	-73	--

Some light should be shed nonetheless on the uncertainties related to the assumptions and hypotheses that are made due to the lack of actual data via a sensitivity analysis (though the procedure is also beneficial in cases with actual empirical data). The major hypotheses were made for the design yields (which were guessed as equal for all material candidates and set at a minimal value), the criticality factors (which were based on expertise acquired while completing the criticality matrix but not on actual studies of the material candidates) and the functional degradation coefficients (whose maximum number of end-of-life operations before changing scenarios were assumed without exact knowledge of the actual state of the corresponding networks in that case). Although sensitivity analyses are the usual means of evaluating if the results of the study are affected by changes in the assumptions, in this case, seeing how the baseline values for glass are at least 23 times smaller than those of the two other material candidates, it would still be the most suited material based on $\mathcal{C}_1$. As for $\mathcal{C}_2$, the ranking of the end-of-life scenarios would not be modified by alterations on the values of these variables.

i. Recommendations made to encompass product designers' constraints and cycling network expertise to the optimal choices

Once the potential choices of material and end-of-life scenarios are made, the corresponding recommendations in terms of design constraints are defined. As shown on the scenario tree, reuse is possible when little to no degradation occurs after use. This is a condition associated with the maintenance of chemical and mechanical properties of the product during the use phase and should be added to the specifications in subsequent design phases. Another potential focus should be user behaviour, in order to prevent container degradation and also promote reuse practices. This could be achieved via communication efforts but also by adapting the business model so as to implement post-consumer recovery loops. These recommendations should be shared and studied with all the concerned experts inside and outside the company.

In the open loop recycling scenario, value loss is due almost entirely to η. To improve the transformation process yield, the product designer must look at the material cycling factors, and in this case, specifically to those of glass, presented in the CLEARER sheets (Table 57). The glass CLEARER sheet shows that glass cycling is particularly sensitive to contamination in the waste stream and that material mixes should be avoided. Also, as waste management conditions evolve and new downstream recycled material applications develop, so should glass cycling networks mature and process yields improve. Monitoring this evolution should, therefore, be added to the care of the end-of-life expert, who should then provide feedback to the user of the DfMC method.

Table 57: CLEARER sheets for the material candidates

			PET	Glass	Aluminium
Process variables	Technical optimization	Separation	Decontamination process is critical to avoid downcycling; Complex masterbatch formulas add complexity to waste streams	Colour and type separation are critical for quality	Diversity of technical alloys hinders sorting processes
		Recycling	High-purity is still difficult to achieve		
		Recycled material properties	Successive recycling quickly degrades properties; Low quality is detrimental to the network		
	Product design	Material mixes	Contaminants impede food safety approval; Bioplastics add complexity to sorting operations	Avoiding material mixes enhances separation	Contamination in recycling facilities is difficult to prevent
		Material concentration in component	Higher concentration improves purity of recycled material		
		Density	Higher density improves transportation cost-efficiency and purity of recycled material		Oxidation losses in low-density parts
		Liberation behaviour			
Market variables	Macro	Global materials supply			Long-term applications increase recycling
		Global material demand (prediction)	Abrupt increase may cause momentary shortage and foster recycling		
		Material accumulation in use			Large potential for future deposits
		Dissipative uses			
		Price of virgin raw materials	Fluctuations of oil prices are determinant		Rise of energy costs favours recycling

		Price of recycled raw materials	Competitiveness depends on oil prices	The main factor for competitiveness, varies with region and development of the network	Fluctuations drive recourse to recycling
		Size of waste deposit	Stable stream is fundamental; Increase in size will reduce processing costs		Fluctuations drive recourse to recycling
		Quality of waste deposit	Stable quality is fundamental		Fluctuations drive recourse to recycling
	Micro	Transportation costs	Pre-treatment and baling are required to reduce costs		
		Labour costs	Automation is usually desired		Hinder recycling
		Downstream recycled material applications	Property losses require creative solutions for applications to avoid downcycling	A downstream industry for recycled glass is required for the cost-effectiveness of the network and varies with region	Foster recycling
Waste management conditions	**Network configuration**	Collection mechanisms	Dedicated, refund-based systems improve efficiency	A refund collection scheme has a very positive effect on the cost-efficiency of glass packaging	Increase cost-effectiveness of the network
		Environmental regulations	ELV and WEEE EPR has improved the network		Packaging EPR has greatly improved the network
		Waste management development	Concentrated facilities and integrated system improves output		
	Regulatory framework	Raw material policies and economic incentives			Effective driver
	Social involvement	Manufacturer			Recent positive effect
		Consumer	Pre-sorting is fundamental		Recent positive effect

The analysis of the CLEARER sheets for the other material candidates also provides interesting information for the assessment. Regarding the objective of value preservation, there is a lot to be done on polymer cycling networks before they generate adequate yields. However, aluminium networks could see some progress, particularly if the packaging container yield can be ensured for the product (resulting in very high collection and recycling rates).

NOTES ON PHASE 3: INTERPRETATION

The heuristics presented in the selection strategy are relatively simple since the product is monomaterial and there are only three material candidates and four cycling scenarios. In more complex studies, with multiple material candidates, multi-material components and several cycling scenarios, translating the heuristics in mathematical conditions is a necessary step for applying optimization algorithms. However, the DfMC method provides more information than merely an optimal material selection: in the process of deploying it, product design teams gain visibility on the different variables that compose material value and should capitalize that knowledge. It is the comprehension of the underlying reasons for the evolution of circular material value that is the biggest result, and not the values themselves.

The results provided by the DfMC, i.e. using glass in a reuse or open-loop recycling scenario, make sense in terms of what is currently done in many European countries. This being a circularity analysis, it does not include mechanical, environmental or commercial considerations and should, therefore, serve as an initial ground for integrating material circularity to other requirements of the product's design. Adding these requirements to the assessment could be performed with more variables or subsequent analyses, which validates the method's "F4: Be a stepping stone, i.e. allow evolutions of the method and its results". Having circular values for reuse cases higher than the baselines is an interesting result that is coherent with circular economy objectives. The results obtained with the DfMC should be followed by a sensitivity analysis, in order to verify the potential imprecisions and the most impactful variables on the results, which should be monitored to see if the decisions are altered.

The CLEARER sheets provide a broad overview of the concerned networks, which is more than what is required for the decision-making and recommendations in this case. Regular audits of the networks allow the assessment of the evolution of their maturity and can signal whether the results of the DfMC are still valid or have changed. In the case of redesigns, they can also provide information on material substitution and how the cycling scheme would have to be adapted. This case study thus verified the framework's requirements "F1: Take into account all the relevant elements that affect the evolution of cycling networks" and "F2: Provides knowledge to product designers".

7.5 Conclusions on the usage of the DfMC method for product designers assessing the material circularity of a 1,5L bottle container over two lifecycles

Applying the Design for Material Circularity method to the study of a 1,5l bottle container has shown that the underlying equations provide results that are coherent with real-case scenarios, even though this was a desktop simulation and many assumptions of the actual variables were made. To deploy this method, the user must gather information regarding all the activities related to the manufacture of the product and thus gain insight on the first designed lifecycle as a whole and especially on the end-of-life scenarios and subsequent lifecycles, even though these are sometimes beyond the reach of the product designer. By looking simultaneously at the material candidates and respective cycling options of the containers, an optimal combination was found that was coherent with the best practices found in the industry, in terms of cost-efficiency for production companies and end-of-life networks.

Focusing on a simple monomaterial product could be compared to the analysis of a single material part in a complex multi-material product. In this sense, the Design for Material Circularity method adequately fulfilled the requirement of enabling product designers to consider the interconnection between material choices and end-of-life scenarios in design, consequently allowing them to make material-related choices that improve the circularity of material flows. It also made use of information and data from the affected cycling networks that supported the decisions and recommendations of the product designers. The DfMC method presents clear steps, with clearly defined variables. This case study illustrates its application at the early design stage of the product design process. The product's material flows are still undetermined and subject to investigations with the product lifecycle potential stakeholders. A plausible perspective of a second loop of the material flows can be established at this stage.

The two integration gaps were apparently bridged in this simple case. As for the specified functions of the method, it has allowed the assessment of the product's materials beyond the first lifecycle, encompassed all of the product's potential end-of-life scenarios and provided insights on the interconnections between material choices and cycling networks. The uncertainties in the data involved were addressed and the results given by the method were sufficiently robust (and realistic). Actual design data and constraints from the industry could obviously provide a finer assessment of the product, as would the inclusion of the bottle cap in the scope of the study. Also, combinations of end-of-life scenarios were not assessed for closed-loop scenarios (the question being irrelevant for open loop scenarios as property and responsibility are passed on after the first lifecycle), which could provide an even more precise end-of-life strategy if this type of scenario was chosen.

Chapter 8: Identification of material circularity hotspots and ideal end-of-life scenarios for a vehicular lithium-ion battery pack[19]

8.1 Introduction to the case study objectives: evaluation of material circularity in a complex product containing critical materials

This case study presents an application of the Design for Material Circularity method more akin to what would actually take place in the industry. The product is a vehicular lithium-ion battery pack, which is considered the main battery chemistry for the foreseeable future (Moss, Tzimas, and Willis 2013). Assessing the circularity of its materials is pertinent since, as product volumes increase, so will the concerns about the fate of its materials after they are discarded, in terms of toxicity but also regarding resource scarcity. Lithium is a relatively abundant element in the Earth's crust and no shortages have been predicted (Kushnir and Sandén 2012) even though authors mention limited opportunities for recycling before 2050 due to long lifetimes (Bastian, Fougerolle, and Martinon 2013). It has nonetheless been included in three out of six of the major material criticality studies (Erdmann and Graedel 2011). Cobalt, present in the battery packs, is also listed as a critical material mainly due to demand growth (Buchert, Schüler, and Bleher 2009). Copper, though it is not considered critical principally because of its low supply risk due to its abundance, is prone to some vulnerability to supply disruption as well (Erdmann and Graedel 2011). Moreover, since battery recycling is still low and incipient for lithium-ion technology, a study of its potential end-of-life treatments is quite opportune. Table 58 summarizes the application of the method for the case study.

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[19] A special acknowledgment must be made to Daniel Belchi Lorente and Tom Bauer, researchers at the G-SCOP laboratory of the Grenoble Institute of Technology and lithium-ion battery specialists, for their expert contribution to this case study on the lifecycle assumptions of batteries.

Table 58: Design for Material Circularity (DfMC) method applied to vehicular lithium-ion battery pack

Phase 1 – Initialization: **Scope delimitation based on available data and required assumptions for the study of a vehicular lithium-ion battery**	a. **Goal definition:** assessing the circularity hotspots (recoverable value) for a lithium-ion battery pack during the embodiment design stage b. **Data gathering and hypotheses** made on the battery pack inventory
Phase 2 – Operationalization: **Lithium-ion battery circularity assessment using the circular material value indicator for main parts and components on closed and open loop end-of-life scenarios**	c. **Establishment of a baseline** with the circular material value equation d. **Qualitative evaluation of material degradation after use** referring to design predictions and cycling network information e. **Identification of potential cycling scenarios**: scenario tree for the vehicular lithium-ion battery pack f. **Estimation of second lifecycle values**: assessment of second lifecycle variables
Phase 3 – Interpretation: **Results analysis of main parts and components to provide recommendations for experts**	g. **Selection of an evaluation strategy:** identification of material circularity hotspots and selection of an ideal cycling scenario h. **Results analysis** of major parts and components for remanufacturing, closed-loop and open-loop recycling, focusing on the chosen decision-making strategy i. **Recommendations** made to encompass product designers' constraints and cycling network expertise in the management of the product's end-of-life and potential redesign

8.2 DfMC, Phase 1 – Initialization: Scope delimitation based on available data and required assumptions for the study of a vehicular lithium-ion battery

a. Goal definition: assessing the circularity hotspots (recoverable value) for a lithium-ion battery pack during the embodiment design stage

In this case study, the material circularity evaluation is performed as if the design process is at the embodiment stage, with materials and parts already defined, in order to assess the circularity hotspots in terms of recoverable value, rather than looking for material alternatives. Also, the best end-of-life scenario is sought so that adjustments could be made to optimize the product design and business model and therefore foster the circularity of the components. Once again, the material expert of the multidisciplinary design team is the conductor of the evaluation process, integrating all the data and expertise from the different departments in the company.

b. Data gathering and hypotheses made on the battery pack inventory

First, a model of the product was established based on the lifecycle assessment of a 253 kg Nickel-Cobalt-Manganese (NCM) lithium-ion battery vehicle pack from a Bill of Materials provided by Miljøbil Grenland, a Norwegian battery producer (Ellingsen et al. 2014). The general flowchart of the battery is shown in Figure 31. The mass composition of the battery is given in Figure 32.

The inventory list of the battery contains 49 elements (Ellingsen et al. 2014). It can be reduced to 11 elements that comprise over 83% of the battery's mass (see Table 59). The components are selected for their relative mass, simple composition and structural importance. Due to a lack of information on the composition of the printed wiring boards, the Battery Management System (including fixings and electric inputs and outputs), is not considered at all, even though it could contain precious metals with high added-value. The $LiPF_6$ electrolyte is also left out because of missing information, even though it is quite important in terms of mass. For the purpose of this case study, this simplification is deemed non-detrimental (especially considering the above-mentioned abundance of lithium resources).

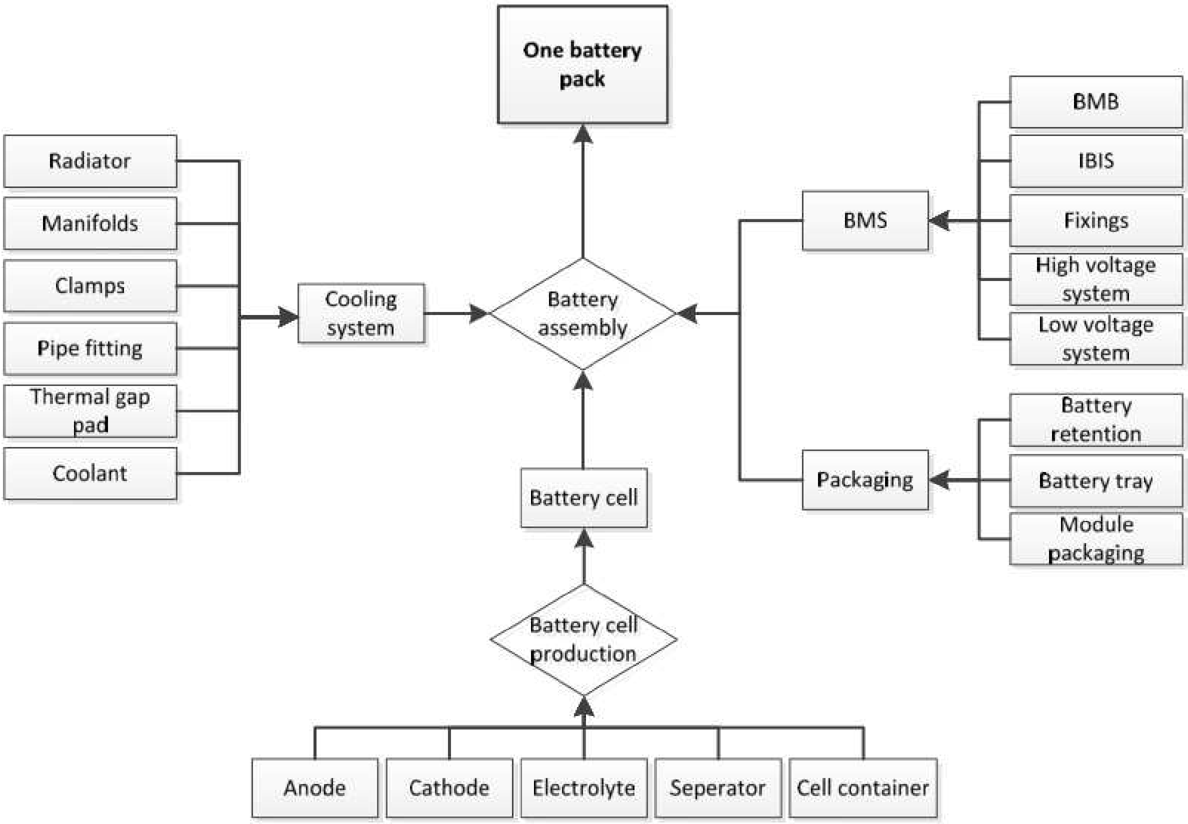

Figure 31: General flowchart of Miljøbil Grenland lithium-ion battery pack (Ellingsen et al. 2014)

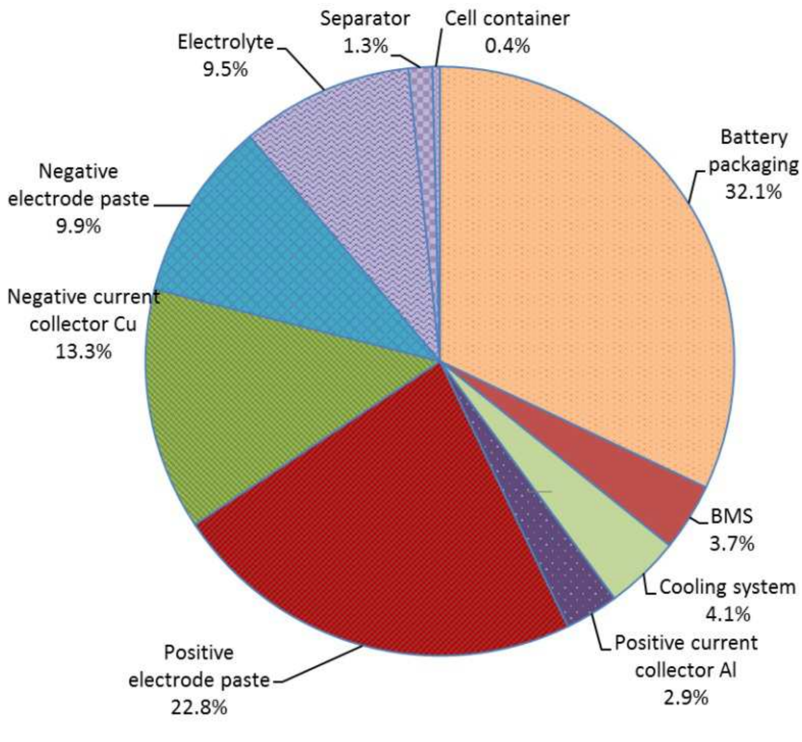

Figure 32: Mass composition of Miljobil Grenland lithium-ion battery, by component (Ellingsen et al. 2014)

Table 59: Components of the case study

Parts	Sub-parts	Components	Material	Mass (kg)	Mass (%)
Battery packaging	Battery retention	Lower retention + Propagation plate	Steel	7,2	2,9
	Battery tray	Tray with fasteners	Steel	19	7,5
		Tray lid	PP	5	2,0
	Module packaging	Module fasteners	Steel	2,3	0,9
		Frame	Aluminium	42	16,7
		Module lid	ABS	1,3	0,5
Cooling system		Radiator	Aluminium	9,1	3,6
Battery cell	Cathode	Positive current collector	Aluminium	7,5	3,0
		Positive electrode paste	NCM	58	23,0
	Anode	Negative current collector	Copper	34	13,5
		Negative electrode paste	Graphite	25	9,9

The timeframes for the pricing[20] histories are not the same for all materials. Due to the longer product lifecycle than in the previous case study (10 years vs. 6 months), data sources were sought in order to have the longest and most detailed information possible. In some cases, they are taken monthly for the last year (regular data, short interval data, short period), whereas in other cases they are yearly values spanning the course of a few decades (regular, long interval data, long period). This is mainly due to the diversity of available free data sources to collect the information on such a range of materials (ceramics, metals and polymers) and their ease of access.

Polymer pricing data for polypropylene (PP) and acrylonitrile butadiene styrene (ABS) is taken from an online plastics review for PP and ABS regrinds and flakes[21]. Historical prices for graphite are taken from the USGS Mineral Yearbook[22] representative year-end prices for crystalline large, 94% to 97% carbon +80 mesh average prices, yearly from 2002 until 2013 and current prices from (Simandl, Paradis, and Akam 2015). Virgin grade is set for crystalline large, 94% to 97% carbon +80 mesh FCL, CIF European port, while recycled grade is set for 94 to 97% C, -100 mesh, FCL, CIF European port (Simandl, Paradis, and Akam 2015). Aluminium prices are taken from the London Metal Exchange database, on a quarterly basis from March 1980 until June 2016, for aluminium, 99.5% minimum purity, LME spot price, CIF UK ports. Copper prices and price history are gathered from the French

[20] Prices were converted into euros per kilogram using the dollar to euro conversion rate of 0,902329US$/€ taken from xe.com on July 6th 2016, when required.
[21] www.plasticker.de, accessed in July 2016. Prices for the last 12 months.
[22] http://minerals.usgs.gov/minerals/pubs/commodity/graphite/index.html#myb, accessed in July 2016.

INSEE database[23] for imported Grade A Copper settlement prices on the London Metal Exchange, with monthly values from January 1990 until May 2016. Steel prices and price history are taken from the World Bank Global Economic Monitor for Commodities, for hot-rolled coil sheets of steel, with monthly values from January 1979 until June 2012. As for the Nickel-Cobalt-Manganese Lithium Oxide cathode paste material (NCM), the only reliable price for the powder from which it is made was found in (Gaines 2014) review of lithium battery recycling processes and was given for the constituents after smelting recovered modules. The price history for the constituents was however impossible to find, this being a relatively recent technology and because cobalt and manganese are not compiled as commodities. The monthly price history for nickel from the World Bank Global Economic Monitor for Commodities from January 1960 until June 2016 is used instead as an approximation.

The functional unit is defined as follows: "deliver the required energy for an electric vehicle for 10 years (33699,44 KWh of energy, for approximately 193120km)". The functional mass is set at 1 for all components. Materials are chosen for a hypothetical lifetime of 10 years since no particular information is available to place the battery of the study above or below industrial average. Due to a lack of design and manufacturing data on the components' costs, the design yield is set at 0,6 (the minimum cost-effective value according to (Petitdemange 1995)), except for the remanufacturing scenario in which it is considered that the cost-effectiveness would be superior and thus a 0,8 factor is attributed. Table 60 presents the criteria and values set for the criticality factors. The use scenario is considered ideal, with no mechanical degradation after use to all components.

[23] http://www.insee.fr/fr/bases-de-donnees/bsweb/serie.asp?idbank=000484333, accessed in July 2016.

Table 60: Criticality factors for Li-ion battery pack materials based on the criticality matrix

	Availability	Vulnerability	Addiction	Substitutability	κ
PP	Mediocre (3)	Insufficient (4)	Acceptable (2)	Acceptable (2)	3
ABS	Mediocre (3)	Insufficient (4)	Acceptable (2)	Acceptable (2)	3
Graphite	Mediocre (3)	Insufficient (4)	Mediocre (3)	Mediocre (3)	3
Aluminium	Acceptable (2)	Satisfactory (1)	Mediocre (3)	Acceptable (2)	1
Copper	Acceptable (2)	Acceptable (2)	Insufficient (4)	Mediocre (3)	3
Steel	Acceptable (2)	Satisfactory (1)	Mediocre (3)	Acceptable (2)	1
NCM	Mediocre (3)	Mediocre (3)	Acceptable (2)	Acceptable (2)	2

NOTES ON PHASE 1: INITIALIZATION

This case study was selected in order to apply the DfMC method on a complex product containing relevant materials in the discussion about criticality and that plays a strategic role in the future of the energy sector and the automobile industry. While the first case study, with its simple product, allowed the deployment of the method without any constraints, early in the design process, the analysis of the lithium-ion battery is conducted in the late stages of the design process, to show how circularity assessments can provide powerful insights even on products with little to no possibilities of changes in their design.

The simplification of the scope of the analysis based on an evaluation of the product's Bill of Materials is an example of an engineering strategy aimed at concentrating efforts in the most effective elements of the problem at hand. Whether or not this is possible or desirable depends on the resources available. If time is of the essence, then this step has a major role in the assessment of complex products. However, it should always be accompanied by reasonable arguments that justify the simplification such as critical materials or components, mass, legislation etc.

In this case, material prices and their history came from a variety of sources whereas in most companies a supplier list with price records would be easily available. Since there is no information on other industrial batteries, the functional mass is defined as a constant and therefore has no incidence in the circular material value here. This applies to the material degradation after use coefficient as well, that can only be precisely defined with feedback from users or recyclers.

8.3 DfMC, Phase 2 – Operationalization: Lithium-ion battery circularity assessment using the circular material value indicator for main parts and components on closed and open loop end-of-life scenarios

c. Establishment of a baseline with the circular material value equation

The baseline values are established for each monomaterial component using the circular material value equation:

$$\mathcal{V}_1 = \mathcal{P}_1 \times m_{f_1} \times \frac{\varphi_1 \times \kappa_1}{\pi_1}$$

The values are then aggregated to obtain the corresponding circular material value of each major part (i.e. the battery packaging, the cooling system and the battery cell) by using a weighted average of each component's value as in the formula below:

$$\mathcal{V}_{part} = \frac{\sum \mathcal{V}_i \times x_i}{\sum x_i}$$

in which $\mathcal{V}_{\mathrm{i}}$ is the circular material value of component i and $\mathrm{x_i}$ its mass fraction. They are presented in Phase 3.

d. Qualitative evaluation of material degradation after use referring to design predictions and cycling network information

According to the battery recycling experts that contributed to this study, there is no homogeneity in the state of the battery cells after use since it can be very dependent on how the discharge cycles were handled, thus battery end-of-life capacity can vary from 80% of the initial capacity to as low as 25%. An ideal use scenario was considered with no degradation after use even though some concerns on the state of the battery cell are addressed depending on the end-of-life scenario in the next sections.

e. Identification of potential cycling scenarios: scenario tree for the vehicular lithium-ion battery pack

According to the existing literature, besides being disposed, battery packs can be recycled (Amarakoon, Smith, and Segal 2013; Zeng, Li, and Singh 2014; Ellingsen et al. 2014; Dunn et al. 2015).

Two types of recycling scenarios are therefore addressed: a closed loop scenario in which the production company is in charge of the treatment of the end-of-life treatment, and an open loop scenario in which the recycling is undertaken by a recycling network outside the company.

Since there may be little degradation after use, closed-loop product streams may also be conceived. Currently, lithium-ion vehicular battery packs can be remanufactured after their first lifecycle in order to be used as stationary battery packs (for remote lighting systems for instance). In this case, the use is different between lifecycles, which would not qualify exactly as a remanufacturing scenario but neither could it be considered reuse (since the batteries must be opened, the cells assessed and sometimes replaced, and the battery management system is changed). Some authors have called this scenario repurposing (Dunn et al. 2015). For this to take place more efficiently, it was hypothesised that the recovery operations would be handled by the company that initially produced the batteries, in a circular and individual business model. The corresponding scenario tree is shown in Figure 33.

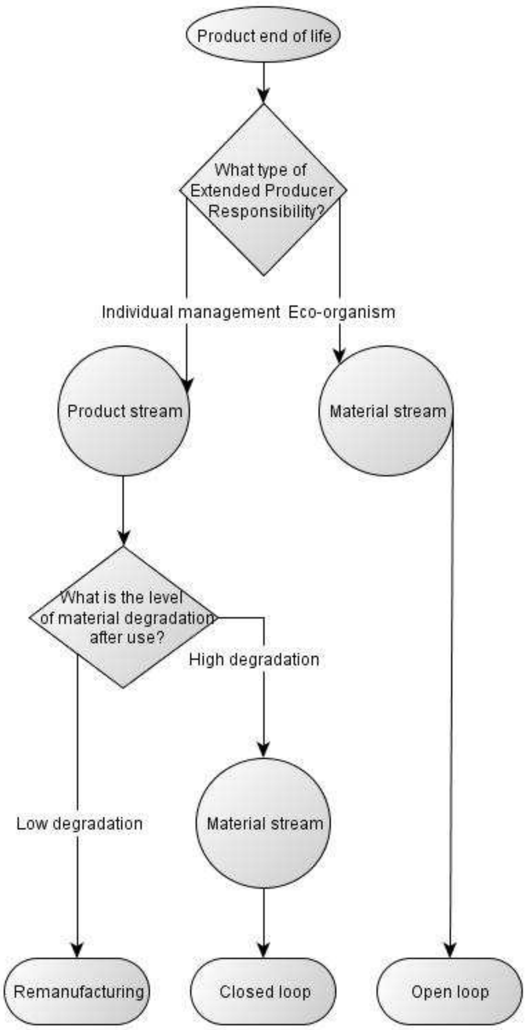

Figure 33: Scenario tree for the end-of-life of vehicular lithium-ion battery packs

f. Estimation of second lifecycle values: assessment of second lifecycle variables

The estimation of the second lifecycle values ($\mathcal{V}_2$) for each material candidate are established using the circular material value equation:

$$\mathcal{V}_2 = \mathcal{P}_2 \times m_{f_2} \times \frac{\varphi_2 \times \kappa_2}{\pi_2} \times \eta \times \delta_m \times \delta_f$$

with values being projected after one lifetime (i.e. 10 years). They are presented in Phase 3. Overall, no variations are established in the period for prices, market risk, functional mass and criticality.

In the remanufacturing scenario, all components are considered to be fully preserved after the cycling process ($\eta = 1$), except the battery cell components, for which a degradation is allocated to account for the potential property loss after the first use cycle ($\eta = 0{,}8$). Since these properties can be recovered with the metallurgical processes of the recycling scenarios, the loss is allocated only on the remanufacturing scenario. As mentioned previously, the design yield is deemed higher (0,8) for this scenario, assuming that there is a better cost-effectiveness in reusing used parts and 80% of the costs would be attributed to the main function. Only one such operation is considered possible so the functional degradation coefficient is equal to 0,5.

For the closed-loop recycling scenario, no losses are attributed to the steel and aluminium recycling processes ($\eta = 1$). The recycling rates of the copper anodes are taken from Zhu et al. (2011); of NCM from the values of Wang et al. (2009); and the recycling rates of the graphite anode is based on Zhou et al. (2011), all of which were reviewed in (Zeng, Li, and Singh 2014). The yield of both PP and ABS is set at 90% efficiency to account for processing losses in the regeneration of the polymer (whether via mechanical or chemical treatment). The number of potential successive closed-loop scenarios is estimated at 100 for metals and graphite and 10 for PP and ABS.

In the open loop scenario, the PP recycling rate is taken from the French recycling industry in 2005, given by (Maudet-Charbuillet 2009). The same rate is considered for ABS because of a lack of specific data for this specific material stream. Since no data for graphite anodes recycling rates was found, the minimum regulatory rate given by the European 2006/66/CE Directive is used, i.e. 50%. For copper, the end-of-life recycling efficiency rate for end-of-life vehicles from a global analysis in 2010 by (Glöser, Soulier, and Espinoza 2013) is used; for steel, the end-of-life recycling rate from a global stainless steel cycle analysis from 2005 by (Reck et al. 2010); and for aluminium, the world average rate from (van Schaik and Reuter 2014b). The recycling rate of NCM in an open loop scenario is considered as the lowest value provided in (Amarakoon, Smith, and Segal 2013), i.e. 60%. While the number of potential successive open loop scenarios remains the same for all metals and graphite, PP and ABS' drops to 5.

NOTES ON PHASE 2: OPERATIONALIZATION

The criticality factors are again static values for both lifecycles as it seemed very risky and would have been cavalier to emit any consideration on the evolution of material criticality after ten years. On the other hand, while no real information on the manufacturing costs is available and all components are considered in the same way, the design yield increase for the remanufacturing scenario seems coherent. The 0,8 coefficient was an educated guess from researcher Tom Bauer.

Having only one remanufacturing or repurposing operation makes sense in terms of the scenario but generates a steep loss of value with the functional degradation coefficient even though it should be considered a positive circular scenario. This shows the importance of correctly interpreting the results in the final phase and not only seeking quantitative values. In this sense, the DfMC method is a rationale in which the knowledge that is capitalized during its deployment is more important than the result itself.

The interest that is being shown for this type of battery has generated a few helpful studies on its end-of-life scenarios that contribute to having reliable data on closed-loop recycling values. There are however more inconsistencies in terms of regions and more hypotheses being made for open-loop recycling values. However, being able to rely on minimal values defined by regulatory documents is a good alternative in this case.

8.4 DfMC, Phase 3 – Interpretation: Results analysis of main parts and components to provide recommendations for experts

g. Selection of an evaluation strategy: identification of material circularity hotspots and selection of an ideal cycling scenario

In this study, two goals are sought: to identify circularity hotspots and to select an ideal end-of-life scenario. The hotspots can be found by looking at the circular material values of each component of the product's architecture, in the first and second lifecycle. The best end-of-life scenario is selected by means of an appraisal of the relative variation of value for each scenario in order to find the scenario with the maximum value conservation over two lifecycles. This corresponded to the condition:

$$\mathcal{C}: max\left[\frac{(\mathcal{V}_2 - \mathcal{V}_1)}{\mathcal{V}_1}\right]$$

h. Results analysis of major parts and components for remanufacturing, closed-loop and open-loop recycling, focusing on the chosen decision-making strategy

The baseline values are collected in Table 61. The analysis of the circular material values shows that the most valuable material in the battery is the NCM cathode paste. Its value was around 68 times steel's value, the lowest ranking material, as shown in Table 62. The cathode paste is more valuable due to its price, relatively low risk and medium criticality. It is followed in terms of value by the two polymers, PP (19) and ABS (21), which have an extremely low risk (probably due to the short timeframe of the price history that was used) and a high criticality. Copper (12), with its high value and criticality, also has a significant score. When aggregated based on their weights in the different major parts of the battery, the value of the battery cell is 12 times higher than the packaging or the cooling system values (Table 67).

Table 61: Baseline values for individual components of a lithium-ion vehicular battery pack

	$\mathcal{P}_1$	π_1	$m_{fu,}$	φ_1	κ_1	$\mathcal{V}_1$
Battery retention (steel)	0,72	0,43	1	0,6	1	**1,0**
Tray with fasteners (steel)	0,72	0,43	1	0,6	1	**1,0**
Tray lid (PP)	0,57	0,05	1	0,6	3	**19**
Module fasteners (steel)	0,72	0,43	1	0,6	1	**1,0**
Frame (aluminium)	1,40	0,29	1	0,6	1	**2,9**
Module lid (ABS)	0,67	0,06	1	0,6	3	**21**
Radiator (aluminium)	1,40	0,29	1	0,6	1	**2,9**
Positive current collector (aluminium)	1,40	0,29	1	0,6	1	**2,9**
Positive electrode paste (NCM)	9,69	0,17	1	0,6	2	**68**
Negative current collector (copper)	4,24	0,62	1	0,6	3	**12**
Negative electrode paste (graphite)	1,13	0,53	1	0,6	3	**3,9**

Table 62: Components and materials ranked by ascending circular material value

	$\mathcal{V}_1$
Battery retention (steel)	1
Tray with fasteners (steel)	1
Module fasteners (steel)	1
Frame (aluminium)	2,9
Radiator (aluminium)	2,9
Positive current collector (aluminium)	2,9
Negative electrode paste (graphite)	3,9
Negative current collector (copper)	12
Tray lid (PP)	19
Module lid (ABS)	21
Positive electrode paste (NCM)	68

The results for the remanufacturing scenario are collected in Table 63. While there are gains in value due to the more effective design yield and little losses in the transformation process (occurring only on the battery cell components), the fact that there can only be one operation of this kind entailed a 50% value reduction. Although the number of remanufacturing operations differs from material to material being taken separately, in this scenario one must consider that it is a whole product unit that is repurposed and therefore the maximum number of remanufacturing operations is given by the component that has the lowest number, i.e. the NCM cathode that can only be reused once. There are nonetheless no significant differences in the component value ranking from the baseline.

Table 63: Second lifecycle circular material value for the remanufacturing scenario

	$\mathcal{P}_2$	π_2	$m_{fu,2}$	φ_2	κ_2	η	δ_m	δ_f	$\mathcal{V}_2$
Battery retention (steel)	0,72	0,43	1	0,8	1	1	1	0,5	**0,67**
Tray with fasteners (steel)	0,72	0,43	1	0,8	1	1	1	0,5	**0,67**
Tray lid (PP)	0,57	0,05	1	0,8	3	1	1	0,5	**13**
Module fasteners (steel)	0,72	0,43	1	0,8	1	1	1	0,5	**0,67**
Frame (aluminium)	1,40	0,29	1	0,8	1	1	1	0,5	**2,0**
Module lid (ABS)	0,67	0,06	1	0,8	3	1	1	0,5	**14**
Radiator (aluminium)	1,40	0,29	1	0,8	1	1	1	0,5	**2,0**
Positive current collector (aluminium)	1,40	0,29	1	0,8	1	0,8	1	0,5	**1,6**
Positive electrode paste (NCM)	9,69	0,17	1	0,8	2	0,8	1	0,5	**37**
Negative current collector (copper)	4,24	0,62	1	0,8	3	0,8	1	0,5	**6,6**
Negative electrode paste (graphite)	1,13	0,53	1	0,8	3	0,8	1	0,5	**2,1**

The closed-loop scenario values are shown in Table 64. There are not many losses in value from the baseline since the theoretical recycling process yields and the functional degradation coefficients are all quite high. The biggest value reductions are observed for the graphite electrode due to the assumption that the recycled material would be of lower quality than the virgin material, thus causing a steep price decrease in the second lifecycle. This is followed by the two plastic materials and copper (due to processing and functional losses).

Table 64: Second lifecycle circular material values for the closed loop recycling scenario

	$\mathcal{P}_2$	π_2	$m_{fu,2}$	φ_2	κ_2	η	δ_m	δ_f	$\mathcal{V}_2$
Battery retention (steel)	0,72	0,43	1	0,6	1	1,00	1	0,99	**1,0**
Tray with fasteners (steel)	0,72	0,43	1	0,6	1	1,00	1	0,99	**1,0**
Tray lid (PP)	0,57	0,05	1	0,6	3	0,90	1	0,91	**15**
Module fasteners (steel)	0,72	0,43	1	0,6	1	1,00	1	0,99	**1,0**
Frame (aluminium)	1,40	0,29	1	0,6	1	1,00	1	0,99	**2,9**
Module lid (ABS)	0,67	0,06	1	0,6	3	0,90	1	0,91	**17**
Radiator (aluminium)	1,40	0,29	1	0,6	1	1,00	1	0,99	**2,9**
Positive current collector (aluminium)	1,40	0,29	1	0,6	1	1,00	1	0,99	**2,9**
Positive electrode paste (NCM)	9,69	0,17	1	0,6	2	0,96	1	0,99	**65**
Negative current collector (copper)	4,24	0,62	1	0,6	3	0,89	1	0,99	**11**
Negative electrode paste (graphite)	0,83	0,53	1	0,6	3	0,97	1	0,99	**2,7**

The open loop scenario has greater value reductions due to the overall worse transformation process yields for all recycling networks, with the lowest values for aluminium and both polymers. This brings aluminium to the same level as steel and makes copper surpass PP and ABS in value, as shown in Table 65.

Table 65: Second lifecycle circular material value for the open loop recycling scenario

	$\mathcal{P}_2$	π_2	$m_{fu,2}$	φ_2	κ_2	η	δ_m	δ_f	$\mathcal{V}_2$
Battery retention (steel)	0,72	0,43	1	0,6	1	0,70	1	0,99	**0,70**
Tray with fasteners (steel)	0,72	0,43	1	0,6	1	0,70	1	0,99	**0,70**
Tray lid (PP)	0,57	0,05	1	0,6	3	0,17	1	0,83	**2,7**
Module fasteners (steel)	0,72	0,43	1	0,6	1	0,70	1	0,99	**0,70**
Frame (aluminium)	1,40	0,29	1	0,6	1	0,27	1	0,99	**0,78**
Module lid (ABS)	0,67	0,06	1	0,6	3	0,17	1	0,83	**3,0**
Radiator (aluminium)	1,40	0,29	1	0,6	1	0,27	1	0,99	**0,78**
Positive current collector (aluminium)	1,40	0,29	1	0,6	1	0,27	1	0,99	**0,78**
Positive electrode paste (NCM)	9,69	0,17	1	0,6	2	0,60	1	0,99	**41**
Negative current collector (copper)	4,24	0,62	1	0,6	3	0,49	1	0,99	**6**
Negative electrode paste (graphite)	0,83	0,53	1	0,6	3	0,50	1	0,99	**1,4**

Table 66 collects all values and indexes for the baseline and the three end-of-life scenarios. The circularity hotspots, i.e. the components that present the highest circular value and thus restore the most value if properly cycled, are the NCM cathodic paste, the polymer lids and the copper current collector. The steel and aluminium components (as well as the graphite electrode), though somewhat easy to recycle, have less value to recover.

Table 66: Circular material values for the components of a lithium-ion vehicular battery pack

	Baseline	Remanufacturing	Closed loop	Open loop
	$\mathcal{V}_1$	$\mathcal{V}_2$	$\mathcal{V}_2$	$\mathcal{V}_2$
Battery retention (steel)	1,0	0,67	1,0	0,70
Tray with fasteners (steel)	1,0	0,67	1,0	0,70
Tray lid (PP)	19	13	15	2,7
Module fasteners (steel)	1,0	0,67	1,0	0,70
Frame (aluminium)	2,9	2,0	2,9	0,78
Module lid (ABS)	21	14	17	3,0
Radiator (aluminium)	2,9	2,0	2,9	0,78
Positive current collector (aluminium)	2,9	1,6	2,9	0,78
Positive electrode paste (NCM)	68	37	65	41
Negative current collector (copper)	12	6,6	11	6,0
Negative electrode paste (graphite)	3,9	2,1	2,7	1,4

The weighted aggregation of the components into the three main parts that constitute the battery (Table 67) indicates that the battery cell holds the most value in the battery pack, especially in the open loop scenario, when it achieves 27 times the value of the packaging and the cooling system.

Table 67: Aggregated circular material values for the main parts of a lithium-ion vehicular battery pack

	Baseline	Remanufacturing	Closed loop	Open loop
	v_1	v_2	v_2	v_2
Battery packaging	3,6	2,4	3,3	0,91
Cooling system	2,9	2,0	2,9	0,78
Battery cell	36	19	34	21

The comparison between end-of-life scenarios over two lifecycles (Table 68) shows that open loop is the worst scenario for practically all components. The remanufacturing scenario suffers as it could only be performed once and therefore has a significant value reduction from the functional degradation coefficient, as expected. However, this scenario does not preclude the other two and, because responsibility over the product at end-of-life remains to the producer in the second lifecycle, it could take place before a recycling operation, especially since it is a one-shot scenario. The best solution is by far the closed loop scenario, which presents low losses for almost all the components and the hotspots in particular. Even though the responsibility remains with the company, the closed loop recycling scenario can be performed a number of times and will always be a better alternative than the open loop scenario. When comparing the three major parts of the battery, the closed loop scenario is also the best solution for the product (Table 69).

Table 68: Relative evolution of the circular material value over two lifecycles (components)

	Relative evolution (%)		
	Remanufacturing	**Closed loop**	**Open loop**
Battery retention	-33	-1	-31
Tray with fasteners	-33	-1	-31
Tray lid	-33	-18	-86
Module fasteners	-33	-1	-31
Frame	-33	-1	-73
Module lid	-33	-18	-86
Radiator	-33	-1	-73
Positive current collector	-47	-1	-73
Positive electrode paste	-47	-5	-41
Negative current collector	-47	-12	-51
Negative electrode paste	-47	-29	-63

Table 69: Relative evolution of the circular material value over two lifecycles (major parts)

	Relative evolution (%)		
	Remanufacturing	Closed loop	Open loop
Battery packaging	-33	-9	-74
Cooling system	-33	-1	-73
Battery cell	-47	-6	-42

However, in terms of the quality of the results, some aspects deserve to be noted. Price history timescales should be better adjusted, i.e. follow a regular frequency and span the same period for all materials, in order to avoid potential discrepancies in the market risk factor. The more granularity and longer timeframes, the more accurate the representation of the market risk.

i. Recommendations made to encompass product designers' constraints and cycling network expertise in the management of the product's end-of-life and potential redesign

From the results, a first suggestion can be made that the remanufacturing of vehicular battery packs into stationary batteries should be viewed as an extension of the first lifecycle and perhaps become a mandatory second life. However, for this to be effective, the battery packs must be designed to sustain the two lifecycles and appropriate use behaviours should be promoted in that sense.

Once the batteries arrive at their end-of-life, after one ten-year lifecycle or a longer period for the two lifecycles mentioned above, a closed loop recycling scenario has to be implemented as it provides much better results than the current open loop networks allow. Thus, unless these open networks progress significantly, especially for the hotspots that were identified (NCM paste, copper, PP and ABS), a closed-loop business model should be set up. This requires that the experimental yields observed in the scientific studies be achieved in industrial processes that would be performed either by the company itself or by a recycling partner and reported by the corresponding expert.

Furthermore, the analysis of the cycling factors of specialty metals (that we can assimilate to the NCM paste), copper and plastics can help all company experts in gathering insights to influence the evolution of existing open loop networks, so as to protect existing material supplies or, eventually, migrate to an open loop recycling scenario. In this case, based on Table 70, separation and recycling processes of the NCM are still undergoing research, can perhaps improve in the near future and their evolution should be monitored. Better collection mechanisms can also promote recycling and manufacturers should push for this. Product designers must be particularly attentive to avoid material mixes and increase material concentration in their components. The density of the NCM electrodes and plastic parts should also be high and the cathodes liberation facilitated. Purchasing experts have to monitor the evolution of the prices of all materials and their demand, as well as the supply of the NCM components. Marketing experts, besides focusing on fostering user behaviour for the closed loop recycling scenario, should also be aware of internal (the company's) and external (consumer's) social involvement and consciousness regarding the recycling of these materials. This information exchange requires the setup of communication channels or surveys. Material and/or end-of-life experts have a long list of factors to monitor and should, therefore, tighten their relation with recyclers and public authorities, in order to follow the development of the cycling networks, improve the internal and external databases for these materials and evaluate whether a reassessment of the material circularity results is required.

Table 70: Main CLEARER sheets for the vehicular lithium-ion battery pack

			Steel	PP	Copper	ABS	NCM	Aluminium
Process variables	**Technical optimization**	Separation		Decontamination process is critical to avoid downcycling; Complex formulas add complexity to waste streams	Difficulty in separation prevents high-quality recycled material	Decontamination process is critical to avoid downcycling; Complex formulas add complexity to waste streams	Research stage	Diversity of technical alloys hinders sorting processes
		Recycling	Electric arc furnace processes are well-developed	High-purity is still difficult to achieve		High-purity is still difficult to achieve	Research stage	
		Recycled material properties	For high property requirements, virgin material must be added to correct composition	Successive recycling quickly degrades properties; Low quality is detrimental to the network		Successive recycling quickly degrades properties; Low quality is detrimental to the network		
	Product design	Material mixes	Copper is known contaminant to be avoided, especially in the automobile industry	Contaminants impede food safety approval; Bioplastics add complexity to sorting operations	Seriously hinders cost effectiveness	Contaminants impede food safety approval; Bioplastics add complexity to sorting operations	Improves recovery	Contamination in recycling facilities is difficult to prevent
		Material concentration in component		Higher concentration improves purity of recycled material	High concentration facilitates smelting and purification	Higher concentration improves purity of recycled material	Improves recovery	Oxidation losses in low volume parts
		Density		Higher density improves transportation cost-efficiency and purity of recycled material		Higher density improves transportation cost-efficiency and purity of recycled material	Improves recovery	Oxidation losses in low-density parts

		Liberation behavior					Accessibility of high-grade components has a positive impact	
		Global materials supply						Long-term applications increase recycling
		Global material demand (prediction)		Abrupt increase may cause momentary shortage and foster recycling	Shortage concerns	Abrupt increase may cause momentary shortage and foster recycling		
		Material accumulation in use	Long lifetimes lead to decreased availability					Large potential for future deposits
		Dissipative uses			Shortage concerns			
Market variables	**Macro**	Price of virgin raw materials	Economic crises lead to more recycling	Fluctuations of oil prices are determinant		Fluctuations of oil prices are determinant		Rise of energy costs favours recycling
		Price of recycled raw materials		Competitiveness depends on oil prices		Competitiveness depends on oil prices		Fluctuations drive recourse to recycling
		Size of waste deposit		Stable stream is fundamental; Increase in size will reduce processing costs		Stable stream is fundamental; Increase in size will reduce processing costs	Critical mass is not yet reached	Fluctuations drive recourse to recycling
		Quality of waste deposit	Tramp elements lead to increased dilution of scrap in recycling processes	Stable quality is fundamental		Stable quality is fundamental		Fluctuations drive recourse to recycling
	Micro	Transportation costs	Affects cost efficiency	Pre-treatment and baling are required to reduce costs		Pre-treatment and baling are required to reduce costs		

		Labour costs	Affects cost efficiency	Automation is usually desired		Automation is usually desired		Hinder recycling
		Downstream recycled material applications		Property losses require creative solutions for applications to avoid downcycling	Quality of recycled material defines downstream applications	Property losses require creative solutions for applications to avoid downcycling		Foster recycling
Waste management conditions	**Network configuration**	Collection mechanisms	Driver for recycling	Dedicated, refund-based systems improve efficiency	Collection mechanisms improve separation	Dedicated, refund-based systems improve efficiency	Better systems are necessary	Increase cost-effectiveness of the network
		Environmental regulations		ELV and WEEE EPR has improved the network		ELV and WEEE EPR has improved the network	Hazardous substances have been effectively recovered; Clean technology incentives can have a rebound effect	Packaging EPR has greatly improved the network
		Waste management development		Concentrated facilities and integrated system improves output	EPRs have greatly improved recovery	Concentrated facilities and integrated system improves output	Specific recovery in existing or new EPRs is desired	
	Regulatory framework	Raw material policies and economic incentives			Governmental economic incentives can drive recycling activities			Effective driver
	Social involvement	Manufacturer	Driver for recycling					Recent positive effect
		Consumer	Driver for recycling	Pre-sorting is fundamental	Improves separation	Pre-sorting is fundamental		Recent positive effect

NOTES ON PHASE 3: INTERPRETATION

The issues dealt with in this case are vastly different than in the previous one because of the complexity of the product, the fact that it is being assessed with no flexibility in terms of material choice (unless a redesign is considered), the longer lifespan and the materials involved. Identifying the circularity hotspots ends up being an analysis of the product's architecture in terms of its baseline circular material values. Though there was no simultaneous choice of materials, the same strategy was used to identify the best end-of-life scenario.

Using a short timeframe in price history can reduce price volatility and affect circular material value results, highlighting once again the importance of having data with as much consistency in terms of time period and geographic range. Also, as in the previous case study, design yield, criticality and functional degradation hypotheses and assumptions were made, which could hold some repercussions on the results. For this reason, in the case of a real application of the method in the industry, a sensitivity analysis should be performed on these parameters to verify the validity range of the results and the decisions that stem from them, thus avoiding any sort of bias.

The weighted average for studying the relative importance of components and parts in terms of their mass is crucial for the analysis of complex products. It modulates the circular material value depending on how much material can be recovered, giving an idea of the "return on investment" when focusing on the concerned components and parts. A similar modulation with weighting coefficients based on disassembly times could provide even more accurate information on the costs of the recovery of these materials.

The closed-loop recycling scenario being put forward in this case has interesting ramifications regarding the company and the contributions of this thesis. A manufacturer that decides on a closed-loop recycling scheme ultimately never loses track of his materials, as they remain his property. Thus, he has to be in constant contact with the recyclers of his materials (whether they are internal or external) and can monitor the results of the DfMC and the evolution of the process, market and waste management variables of the product's materials.

The application of the method was also coherent with the current state of the analysis of vehicular batteries remanufacturing, indicating that it is actually a repurposing intended to prolong the lifespan of the initial product in a second product lifecycle. The corresponding recommendation of designing the battery for repurposing is coherent with recent research (Bauer, Brissaud, and Zwolinski 2017).

The method and the framework complement each other and also provide insights for how and when to redesign the battery pack. For instance, by monitoring the evolution of the cycling networks, designing for open-loops could eventually become less detrimental to the circularity of materials and increase the degrees of freedom for product designers. All the information gained with the application of the DfMC method should be capitalized regarding supply chains, market histories, legislation, user behaviour and recyclers, and used in future design projects.

Once again, all functions of the contributions' requirements were verified in this case study. Product designers who apply the DfMC method gain visibility on all aspects of their product's material circularity. The CLEARER sheets can be seen as a support for cycling analysis that goes well beyond the product designer's needs and provide a complete overview of the issues affecting the product's recycling. This clarity in what affects circularity spreads to all stakeholders and allows everyone to have the same grounds for communication and action.

8.5 Conclusions on the use of the DfMC method for product designers assessing the material circularity of a vehicular lithium-ion battery pack

The results obtained from the Design for Material Circularity method are coherent with industrial practices or "intended" practices. In this case, the simplification of the Bill of Materials proved to be an important step for reducing the volume of data and hypotheses, thus rendering the evaluation less time-consuming. It should systematically be considered by product designers so as to increase the practicality of the method when operating on a tight schedule. However, while this study removed the lithium electrolyte from the evaluation due to a lack of information, battery designers probably should include it in their application of the method.

By identifying material circularity hotspots in the product and proposing suitable recommendations to implement the best available end-of-life scenario, this case study showed that even if the method was applied later in the design process, once material selection had already taken place, the two integration gaps were bridged. As for testing the tool's functions, some uncertainties were encountered due to the lack of harmonized data sources (for prices and recycling rates) in terms of geography and timeframes that would prove difficult to reduce in the current state of the databases. They could be dealt with via sensitivity analyses or by resorting to the data qualification established by the aforementioned pedigree matrix.

Conclusion of Part III

In this Part, the use of the contributions conceived in Part II to answer the research question and bridge the gaps defined in Part I was illustrated in two case studies. The first one, involving the evaluation of a simple monomaterial product – a 1,5-litre bottle container – at an early stage of the design process, showed that the Design for Material Circularity method is useful in selecting optimal couples of materials and end-of-life scenario in order to maximize value (and material) preservation of multiple lifecycles. In the second case study, a multi-material product comprising critical materials and important in carbon-lean energy technologies for future industrial use – a vehicular lithium-ion battery pack – was examined and potential circularity hotspots, as well as the best end-of-life scenario for value conservation after the first lifecycle, were found. All functions that had been set as requirements for the tool were verified in the case studies.

The studies highlighted different aspects and difficulties encountered in the application of the method and may serve to guide product designers in using it. As it is based on an important volume of data from diverse data sources and experts, documentation of this type of study is key in the establishment and implementation of the Design for Material Circularity as a routine evaluation in design processes, but also to ensure that the uncertainties and assumptions inherent in this interdisciplinary task are properly dealt with, to avoid biased results.

GENERAL CONCLUSIONS AND PERSPECTIVES

"The time will come when diligent research over long periods will bring to light things which now lie hidden. A single lifetime, even though entirely devoted to the sky, would not be enough for the investigation of so vast a subject... And so this knowledge will be unfolded only through long successive ages. There will come a time when our descendants will be amazed that we did not know things that are so plain to them... Many discoveries are reserved for ages still to come, when memory of us will have been effaced."
— Seneca, Natural Questions

The study of society's metabolism and material cycles is relatively recent and has arisen in the last decades with the sudden growth of the world's population and its concentration in cities, whose resource consumption has surpassed the regenerative capabilities of natural cycles. This has been followed by an intensification of research to tackle the management of shortage risks and the mitigation of environmental impacts associated to this over-exploitation, from two sides: a "big picture" point of view, mostly geopolitical and economic in nature, generally led by government agencies and policymakers, that focuses on accounting appraisals of stocks and flows; and a "business level" standpoint, aimed at companies and their ability to integrate social and environmental aspects in their operations, most effectively in product design, in order to generate practical positive results in the entire product cycle, even encompassing the recovery of raw materials from waste – what is known as circular thinking. Both perspectives have produced a vast body of knowledge, trying to convey the complex and interdisciplinary intricacies of how billions of people make use of a growing number of increasingly sophisticated materials, in a globalized market.

Many tools have been developed in this attempt to understand and manage the anthropogenic cycles of materials, with different approaches. Each handles the material flows in society in different ways and each possesses its respective databases that fuel their uses. Yet product designers still lack the means of considering all the agents and variables involved in the cycles of materials. Moreover, there seems to be no common ground of communication between design activities and cycling activities, which hinders the information exchanges required for a proper management of discarded products (and their materials).

At the product designer's level, the ability to grasp the dynamics of material cycles and make decisions that foster the circularity of material flows is still in development. This study has provided contributions in this sense, to connect the macro-level analysis of anthropogenic cycles to product design activities, by providing a basis for structured reasoning and data collection that embraces the fact that materials are in constant transformation, between being dormant in deposits and used in products.

This final part of the thesis presents, in Chapter 9, a synthesis of what was developed in this study and the limits to what was accomplished. This is then complemented in Chapter 10 with the perspectives that have been opened and that await further research.

Chapter 9: Contributions

9.1 Synthesis

There is a shortage of systematized information on industrial recycling activities, especially in terms of recycled material use, despite a recent interest in industrial ecology research. This further emphasizes the role of environmental agencies and national industrial and recycling organizations that have collected and compiled data for secondary material flows such as the USGS (Sibley and Butterman 1995; Sibley 2004), the French ADEME or the Stock and Flows initiative led by Professor Graedel at Yale. But these initiatives are often scattered and cover very heterogeneous timeframes and locations, creating an incomplete patchwork of references.

Companies have nonetheless advanced in their environmental practices, gradually encompassing different dimensions of their activities in their strategic development, beyond simple economic productivity goals. From the triple bottom-line of sustainability to corporate social responsibility, environmental, social and cultural issues have changed the way business is conducted and production processes are managed. Designing a product is not a question of only satisfying technical requirements anymore, but the result of the integration of different specifications, which include the whole product lifecycle, from material extraction to waste management. It entails a holistic approach that makes use of multiple criteria in the decision-making process.

In this context, circular design seems to be the way forward for product designers. It is the epitome of Integrated Design in regards to material efficiency. It is, however, a very complex task to perform and designers are still ill-equipped to deal with it, despite recent initiatives such as Cradle-to-cradle design and the Material Circularity Indicator from the Ellen Macarthur Foundation. The analysis of the state-of-the-art literature on the matter produced one research question to bridge two integration gaps in order to promote circular thinking in product design (Figure 34).

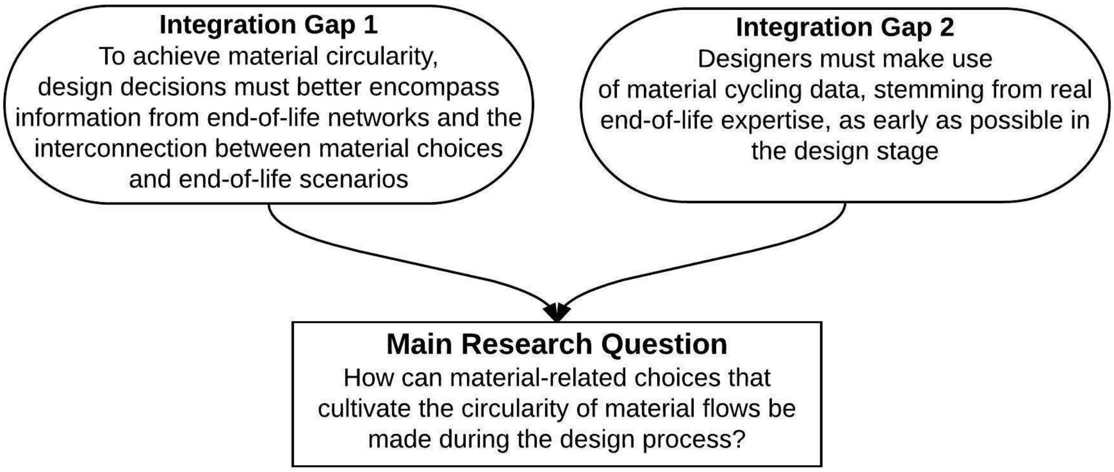

Figure 34: Integration gaps and research question stemming from the review of state-of-the-art literature that were answered in this thesis

This question gave rise to two hypotheses (each with its own requirements):

- **Hypothesis 1:** A circularity indicator and method that encompass more than one material lifecycle improves product designers' decisions regarding material circularity
- **Hypothesis 2:** A robust systematization of cycling schemes expertise is needed to complement any material circularity assessment

To address each hypothesis, this thesis provides an original contribution to material-centric circularity assessments in design with two elements: a tool for the integration of material circularity in design and a framework to characterize material cycling networks. The first hypothesis is tackled by a tool combining qualitative and quantitative approaches, composed of an indicator for circular material value and a method for applying it, the Design for Material Circularity method. This method consists in comparing the circular material value of the product's component materials over two lifecycles, depending on the available end-of-life scenarios, and making recommendations to the company's departments that preserve material value globally, ultimately fostering material circularity. It is unique in its ability to address multiple material cycles in product design and allows the identification of material circularity hotspots in a product by considering the multiple criteria that compose circular material value.

This assessment differentiates itself from previous attempts at circular design methods because it incorporates data from product design, manufacture, material sourcing, marketing and end-of-life. It has been built based on the notion of circular material value, stemming from value analysis, which is a well-known procedure for industrial engineers, in order to render explicit the importance of following materials beyond the first lifecycle. The circular material value indicator is proposed as a combination of material prices, the functional mass being used, the design yield, a criticality factor, a market risk coefficient and cycling coefficients (material degradation after use, transformation process yield and functional degradation due to the cycling scenario). It expresses a concept that is at the threshold of material recyclability, criticality and availability, and allows other relevant factors to be added to its formula, enabling it to evolve with the requirements of product designers, circular economy models, the affected stakeholders and context. The Design for Material Circularity method then operationalizes this indicator and adapts its use according to the respective goals and heuristics that were chosen for the analysis. Having a unified indicator such as the circular material value can be somewhat controversial. However, in its construction, product designers perform a multicycle audit of their products in terms of material circularity and its variables, which also provides a means of analysing a wide array of information and making decisions quickly, with relative ease.

The Design for Material Circularity method has been conceived with the material expert of a design team in mind (or the professional responsible for the material choices). It is to be used as a support for decision-making uniting many fields of expertise. It provides multiple instructions for the company's departments. First and foremost, it supports decision-making simultaneously in material selection and end-of-life scenario choices. Also, in the process of applying the method, the company's supply chain and purchasing practices are reviewed, and prospective and strategic studies can be conducted. The company can even use the method to project itself in the future and analyse the state of their materials' cycles by asking: what if material X, Y or Z turned critical? This would allow it to become less vulnerable to material supply disruptions.

However, it becomes clear that not all companies would be interested in deploying such a method, nor would any given product be worth the effort. It makes sense to use the DfMC method in the case of high-added value products that contain rare and/or critical materials. In this case, applying all the effort and mobilizing the company's departments to identify the circular economy hotspots is a key issue and the method delivers insights into securing the circularity of the concerned materials.

The second hypothesis was then worked on to address the strategic need for expertise on material cycling networks, in order to properly execute these material circularity assessments. This led to the development of a framework for the characterization of material cycling networks: a set of variables, adeptly organized in categories and sub-categories, that provides a detailed understanding of the inner workings of material cycling schemes. The process variable category includes process technical optimization and product design, highlighting the elements that are linked to design decisions. The market variables are divided in macroeconomic and microeconomic descriptors allowing cycling network businesses to specify the economic factors on which they have a direct influence. Finally, the waste management conditions encompass aspects relating to the network's configuration, its regulatory framework and social involvement, providing the relevant information on the context and conjuncture of waste management evolution.

This framework is the result of a thorough investigation of the literature on secondary material recovery and uses, enhanced by interviews with industry experts. It structures the way cycling networks are viewed so as to provide both an overview of key aspects to designers, but also a foundation for recyclers to collect and present their data. In this study, the framework was instantiated only for open loop recycling, the most frequent waste management scenario today. The categories and sub-categories were populated with descriptors that correspond to these networks in particular, for the sake of recyclers themselves, to enhance the exchange of information and the communication with product designers and to improve end-of-life management in general. The research methodology employed to identify these descriptors can nonetheless be used for other cycling schemes in an analogue manner.

Though it has a specific use as a complement to the Design for Material Circularity method, the framework for the characterization of material cycling networks has applications beyond that. It is a step toward the systematization of secondary material information and the exchange of information between designers and recyclers, among other stakeholders. If employed as a means of compiling and systematizing material cycle data, this characterization framework can be used as a tool to audit recycling activities and be implemented by government agencies and recycling industrialists, for instance. It has been applied here to characterize eight material networks: steel (representing ferrous metals), copper and aluminium (non-ferrous metals), precious metals, specialty metals, rare earth metals, plastics and glass.

Two products were then studied as cases that illustrate the application of the method and confirm that its results are coherent with current industrial practices. The first case study centred on a 1,5-litre bottle container, a simple monomaterial product, whose assessment was proposed at the early stages of the design process. The method allowed the selection of optimal couples of materials and cycling scenarios for the product with the objective of maximizing value and material preservation over multiple lifecycles. This simpler case that cast aside most aspects of product complexity could be compared to the analysis of a single material part in a more complex product.

The second case study focused on a vehicular lithium-ion battery pack, a multi-material and multicomponent product containing critical materials, which is also an important prospect for carbon-lean energy technologies required for future industrial uses. In this case, material selection was not the issue since the analysis was meant to take place at a later stage of the design process. The application of the method permitted the examination of the product's Bill of Materials and the identification of potential circularity hotspots. This led to the formulation of the best cycling scenarios for each part of the battery, in order to preserve material value after the first lifecycle. Adaptations of the method were required to address the complexity of the product and keep the tool practical for product designers, all the while maintaining the depth in the analysis. In this sense, a simplification of the Bill of Materials seems like an important first step in the case of complex products.

These studies illustrate that the Design for Circularity method is indeed appropriate to identify improvements and make design decisions that ultimately enhance the circularity of materials, bridging both integration gaps each time. The interconnection between material cycles and end-of-life scenarios was made clear, making use of the cycling networks' data that was presented in Chapter 6. However, a large amount of information must be utilized each time, which requires not only good internal communication between company departments and the constitution of an interdepartmental design team but also access to data from subsequent product cycles that is not always readily available. The two hypotheses have thus been confirmed, though with some limits that will be detailed below. Figure 35 presents the contributions that were proposed in this thesis.

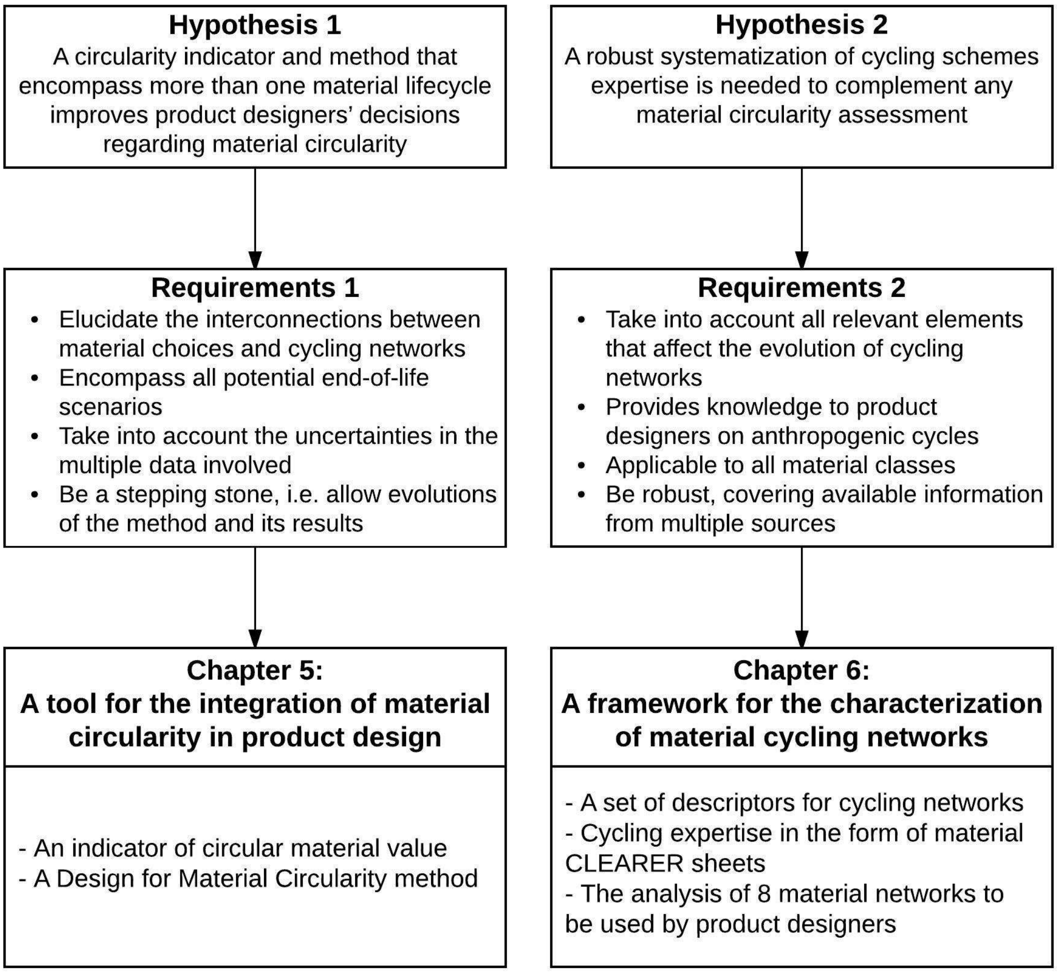

Figure 35: Contributions of this thesis

9.2 Limits

This research work does not pretend to be the definitive answer to the issue of integrating material circularity in product design. It is a step towards a better assessment of circular economy issues by design teams and lays the foundations for future work, but it has shortcomings, which have already been mentioned in the previous chapters and will be developed here.

The study of circular economy, a relatively new field with a burgeoning scientific community, presents inherent difficulties and limitations, mostly due to the lack of systematized data on secondary raw materials (which was one of the drivers of this thesis). The interdisciplinary aspect of the subject matter adds an element of complexity to the endeavour, which is difficult to fully address. The research was conducted in an industrial engineering context by an eco-design team, already accustomed to handling multiple fields of expertise. However, some phenomena and concepts have been simplified in the modelling process, especially concerning economic variables both in the indicator and in the material network characterization framework. It would have been very valuable to the contributions in this study if specialists on commodity markets had been consulted to verify the considerations that were made regarding supply and offer dynamics.

The interconnections of parameters, such as the effects of material criticality in the market variables of cycling networks, for instance, have been knowingly avoided because a quantitative estimation would have been difficult. Likewise, the degree of dependency between factors in the circular material value indicator should be tested to verify and improve the underlying equation, with sensitivity analyses.

Also, though it provides insight on several aspects that are still under-explored in the field of eco-design, such as the consideration of multiple material lifecycles in product design for instance, the tool for integrating material circularity in design lacks integration with other methods in the product design toolkit.

Regarding the functions and sub-functions for the integration tool, three of its requirements have not been completely met (Table 71). All three relate to the variables that were chosen for the indicator and method and have to do with the designer team’s ability to gather all the necessary data with an appropriate level of reliability. The amount of information required to apply the method was kept to a practical size but there are some factors that should prove hard to evaluate for all cycling scenarios because of the lack of data on closed-loop schemes and on the fate of materials in other industrial applications as they move on to the next lifecycles. In time, this limitation should be lifted but right now simplifications and hypotheses must be made in order to apply the tool to complex products, as was shown in the lithium-ion battery study case. Regarding the uncertainty levels of the indicator's variables, either in terms of their internal independence or in terms of the evaluation of their reliability, no sensitivity analyses were made due to the sheer volume of data to be gathered and treated, without having a proper design team's resources. Having based a lot of the data gathering on hypotheses, testing the sensitivity of circular material value results to the most uncertain variables could have been beneficial to the method and would have allowed a fine tuning of the indicator. However, the sensitivity analyses would also have been limited by the information available. Another solution would have been to rate the variables using a pedigree matrix similar to the one in (Weidema et al. 2013).

Table 71: Partially accomplished functions and sub-functions of the material circularity integration tool

F1 Elucidate the interconnections between material choices and cycling networks	
SF1.2.c Choose variables that rely on easily obtainable data	*PARTIALLY ACCOMPLISHED*
F2 Encompass all potential end-of-life scenarios	
SF2.1 Incorporate end-of-life variables that are compatible with different types of end-of-life scenarios, whose corresponding data is readily available	*PARTIALLY ACCOMPLISHED*
F3. Take into account the uncertainties in the multiple data involved	
SF3.1 Opt for variables that allow assessing the uncertainty of variables' action-reaction on each other (i.e. their "degree" of relative dependency)	*PARTIALLY ACCOMPLISHED*
SF3.2 Opt for variables that allow assessing the uncertainty of one variable over the global result (i.e. the global influence of one variable on the total result)	*PARTIALLY ACCOMPLISHED*

In terms of validation, most functions and sub-functions of the framework's requirements were accomplished, as seen in the conclusion of Chapter 6. The partially accomplished requirements of the framework are shown in Table 72. In the case of the network analyses, much as in the case studies, the flows should have been elemental (not in groups, particularly plastic and specialty metals) even though similar behaviours can be observed within the material groups that were used. This approach was limited by the fact that in the available reports and articles, materials are usually considered in macro classes instead of their elemental form. Although they seem to correspond to a general behaviour of the material groups, detailing the results by specific monomaterial flows could have provided more precision in the evaluations. The approach and framework that were presented here can serve as a foundation for more material-specific data collection for the characterization of the cycles of independent materials (especially polymers) and perhaps even substances.

Table 72: Partially accomplished functions and sub-functions of the cycling network characterisation framework

F3. Applicable to all material classes	
SF3.2 Contribute to the analysis of the specificities of metal, polymer and ceramic anthropogenic cycles	*PARTIALLY ACCOMPLISHED*
F4. Be robust, covering available information from multiple sources	
SF4.1 Collate knowledge from academic research and the industry	*PARTIALLY ACCOMPLISHED*

There was also heterogeneity in the availability of data, some descriptors being much more cited than others and the volume of references ascertaining their importance is clearly not balanced: metals are generally better covered than polymers and ceramics; and economic factors, in large part, and technical descriptors in close second, dominate the attention of researchers when compared to regulatory, organizational or social issues. The question of rating the importance of the factors to the development of the network was therefore left out of the results and only briefly alluded to in the maturity evaluation mentioned in Chapter 6. Studying the effects of each variable on the network in general, with the critical values that serve as a reference point to the maturity of the scheme, would have required a titanic effort that was unattainable in the scope of this thesis. This first step, mainly based on a literature review and expert interviews is then the foundation for building such knowledge in future studies.

The expert interviews were performed with the specialists that replied to the invitation to participate in the study. Though they are indeed very qualified consultants to this research, there were not enough experts to fully consider that the framework review process was exhaustive. The robustness of the chosen variables is assured by the convergence of the data from literature and the experts, but with further analyses being performed using this model, the framework's reliability will increase. That is why elaborating it with the potential to evolve with new case studies and interviews was so important. Also, the interview script should have been reviewed and reformatted in order to ease the process of processing the collected information, perhaps by devising an electronic survey that could be swiftly sent and answered by a large number of recycling agents. While qualitative studies of this nature are non-absolute, the validation rationale of this research was consultative, with experts verifying answers, rather than providing them. This afforded the proposition of new answers based on empirical and theoretical data while ensuring the correct interpretation of secondary data based on the industrialists' experiences.

Regarding the case studies, they were all desktop simulations, i.e. they were not based on an application of the method in real-life conditions. Because of a lack of industrial or business partnerships for this project, a high number of suppositions were made to circumvent the deficiency of design and end-of-life information in the completion of the case studies. A proper test on the field, with a real industrial case and data, in partnership with a design team, would allow to fully grasp the applicability of the contributions of the thesis for product designers and businesses in general.

In the second case study, the simplification of the Bill of Materials, though needed for practical reasons, resulted in the removal of the lithium electrolyte from the evaluation, which – were this a true industrial case – would not have been appropriate. Also, a choice was made to consider the NCM cathode regeneration into the same alloy but, in real cases, it could very well be recycled into three distinct metallic by-products of pure nickel, cobalt and manganese. In this case, an adaptation of the method would be required so as to calculate each individual material flow and reassemble them using a weighted average. This, in turn, would pose a problem for the initial hypothesis of isometric satisfaction in the circular material value formula: what function would each material fulfil and to what extent? Further studies should, therefore, be performed on how to refine the formula to address the evolving applications in the subsequent material and product cycles for complex material compositions with multiple recycled by-products., which would require an adaptation of the method to equate them.

The evaluations performed with the Design for Material Circularity method are static, an instantaneous assessment of the product's materials aimed at guiding the designer's decisions. There is not, at this point, any effective way of subsequently measuring the positive impacts the implemented actions have on material circularity. The method intrinsically looks to the future to address the present so, other than applying the method multiple times over the course of a few product lifetimes, there would be no means of monitoring its effects over time.

Finally, though developed within the boundaries of eco-design, this thesis does not directly address environmental aspects or impacts related to the lifecycles of materials. It focuses on resource scarcity and depletion issues, which are only part of the common set of environmental indicators used in lifecycle assessments, and could be in contradiction with other environmental impact assessments.

Chapter 10: Perspectives

The limits presented earlier should be viewed as opportunities for further research. In this final chapter, the possibilities of expanding on this work are shown.

This thesis is a contribution to material lifecycle studies that could be used at the product design level. It provides a tool and a framework that complement other existing assessments by implementing a multi-criteria analysis of circular design decisions and presenting cycling networks' issues in a format that can be understood by both product manufacturers and recyclers, clearly identifying their stakes. In doing so, it opens two fields of perspectives: the deepening and further development of multiple lifecycle assessments, and the integration of these proposals with the current product designer toolkit.

Both contributions have been developed so that future studies can easily update and improve them, adding or removing variables according to the information available and advances to material lifecycle models. In this sense, more studies should be conducted to expand the understanding of material cycles and perhaps refine both method and formula. Weighting coefficients based on a PESTEL importance matrix of major criteria such as the one employed by (Ziout, Azab, and Atwan 2014) could be tested and included in the indicator. Also, the interconnection between parameters has yet to be rigorously and quantitatively evaluated, beyond the assumption of relative independence that was used in this work, adjusting the formula if required.

To help in this deeper analysis, critical values for each parameter should be collected. This was one of the preliminary objectives of this study that could not be accomplished due to a lack of comprehensive data in the literature and the need for a longer-term research with industrialists. The complexity involved in assessing and comparing the qualitative and quantitative thresholds for each descriptor is significant. As much as the present framework has tried to identify independent factors, there are intricacies and interconnections between them that could be spotted with this type of analysis. Also, the qualification of maturity levels requires the consideration of the maximum theoretical (i.e. thermodynamic and process-related) recyclability to define the peak of a network's efficiency and comparisons between materials can only be performed with this in mind.

The evolution of these networks could be assessed by performing successive audits and following the changes between them. Also, by collecting and systematizing data sets for different locations, a cycling database could be constituted in future studies. As the use of the tool and framework increases in research and the industry, databases of common products and cycling networks can be created, in order to serve as references for further evaluations and assessments. Performing more field tests in manufacturing companies is, therefore, a necessity in order to gain first-hand insights on the issues affecting material cycles, improve the thesis' contributions, and enrich the material cycle database. This knowledge should be shared under open licences as much as possible.

Successive audits using the framework should be performed in order to create a database of material networks characteristics. Ideally, these audits could be commissioned by public authorities and become an asset for all the stakeholders involved in circular economy initiatives. But they could also be made at a smaller scale by companies who wish to have an understanding and monitor the evolution of strategic material networks in their own supply chains.

Also, if the material networks' analyses presented here are updated at regular intervals, their evolution could be observed. Perhaps the issues that interest academics and industrialists may change, converging or diverging, showing how this focus is affected and affects the development of recycling activities. If recycling rates (and maturity levels) are also watched, this could bring further insights and precision on the evolution stages of each material cycling network. This maturation process may take different forms and the reasons for the networks' stagnation, ascension and decline could thusly be inferred.

The CLEARER sheets (proposed in Chapter 6) for the related materials must be examined as well in order to assess the eventual levers for action on the company's behalf and those that must be considered and monitored regarding the cycling networks. They can be used to assess the maturity of the networks and its projected evolution, identify the cycle variables that must be checked by the end-of-life expert and, if it is relevant, the values that these variables must attain so that new courses of action are undertaken. Though the material data sheets are an example of a practical format for the characterization information collected using the framework, if a temporal dimension is added to the analyses, with data sheets for multiple dates, they could quickly become less intelligible. When collecting and making an inventory of material cycling data, the results of successive audits could then take the form of a dashboard for material cycling factors (Figure 36), in which each descriptor is attributed a value based on the afore-mentioned maturity evaluation and cycling hotspots. With this, the trends in the networks' evolution could be made clear and monitored more conveniently.

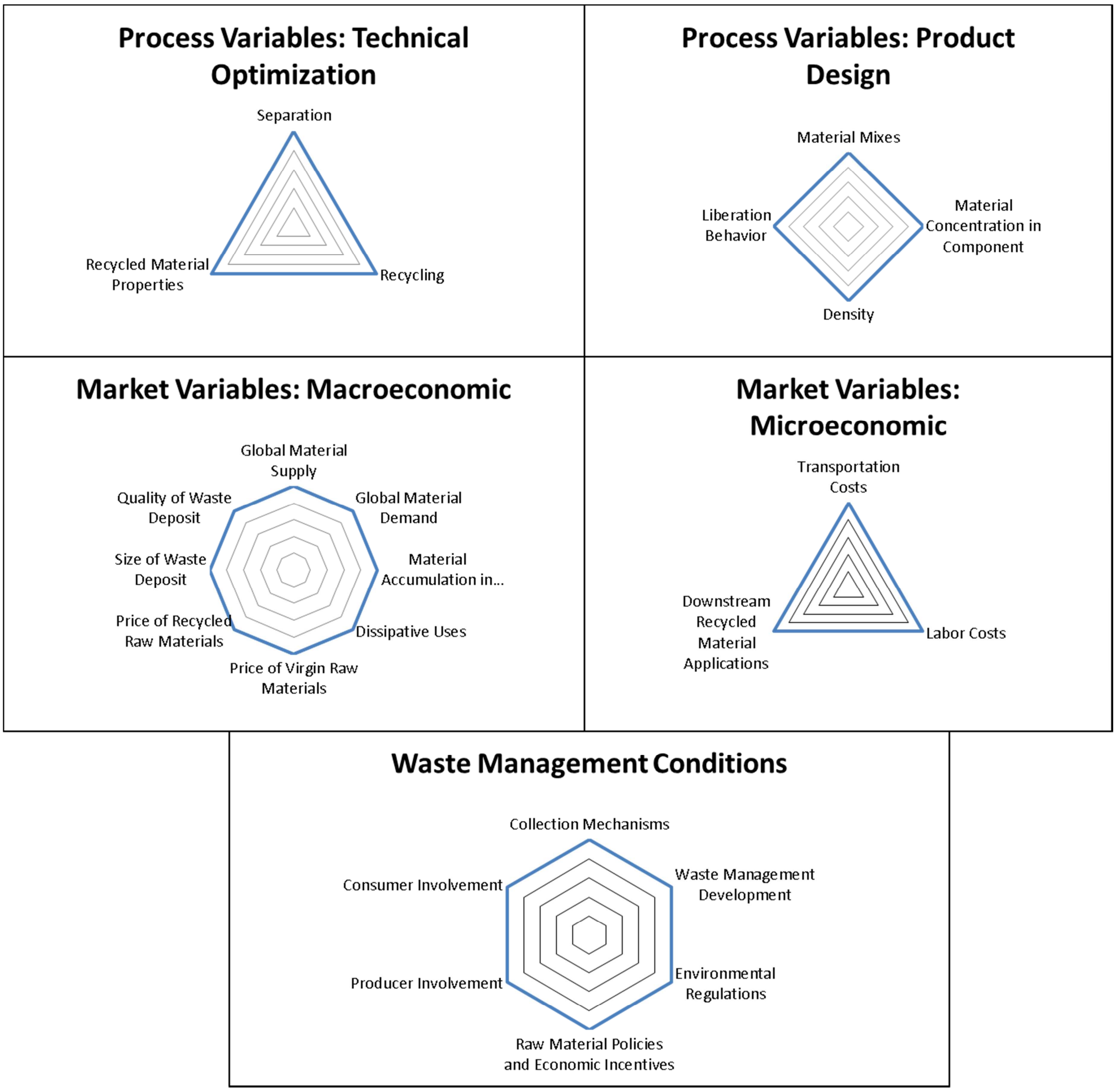

Figure 36: Example of a dashboard for evaluating material cycling networks

The overall environmental coherence of the recommendations obtained using the circular material value indicator, Design for Material Circularity method and the framework to characterize material cycling networks has yet to be tested. While the economic and environmental impacts of the choices proposed by the DfMC method have not been contemplated in the decision-making process, they could comfortably be encompassed by using complementary indicators methodology proposed by (Ellen Macarthur Foundation 2015b). In this case, the available solutions are compared by plotting their circular material values against other selected indicators, as shown in Figure 37. This representation then allows the potential trade-offs between indicators to be made.

Example:	Indicator X	Indicator Y	etc...
Product risk:	XX	YY	
Materials breakdown:			
Material A	XX	YY	
Material B	XX	YY	
Material C	XX	YY	
etc...			

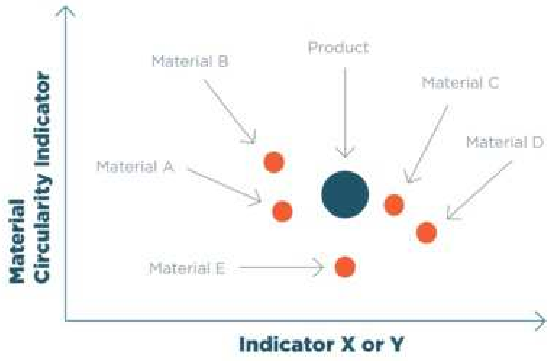

Figure 37: Complementary indicator methodology (Ellen Macarthur Foundation 2015b)

The next step would be to integrate the thesis' contributions with other tools for product designers. On the environmental front, Life Cycle Assessments should be used to complement the circularity analysis, by looking for potential environmental impact transfers from resource scarcity avoidance. It would be interesting to connect the circularity assessments proposed here to a product design method focused on end-of-life optimization such as the Design for Disassembly oriented works of (Haoues 2006). Also, adding disassembly times such as the ones quantified in (Movilla 2016) to the circularity assessments can deepen the analysis and bring even more practical elements to the decision-making process. Moreover, the material selection tools published by Granta could integrate part or all of the framework's variables to extend their recyclability parameters.

By following the same methodology employed to identify the descriptors of open-loop recycling networks, future research can provide descriptors for other schemes such as repurposing, reuse, remanufacturing or closed-loop recycling. These will undoubtedly be adaptations of the present set of descriptors. Eventually, if material characteristics are gathered for different types of cycling schemes, they could be compared and positioned on a circularity scale, from a downcycling open loop to a fully closed loop, and provide quantitative data on the choices for waste treatment.

Further work can also be performed in the sense of more circumstantiated networks and schemes characterization. A deeper analysis taking into account, for instance, the relation between geogenic and anthropogenic processes, based on the carrier and hitchhiker metals dynamics (UNEP 2011; Talens Peiro, Villalba Mendez, and Ayres 2011) could provide further details on the qualification of network maturity, in the shape of an analogue of the "metal wheel" (UNEP 2013) applied to material recycling.

Finally, Extended Producer Responsibility seems even more extended after having performed these analyses, since producers are led to project themselves well beyond the first product end-of-life, especially in closed loop scenarios. If this becomes the norm, companies may have to plan several years and product cycles into the future, thus requiring an assessment of the supply chain and the waste generated in terms of material flows at terms significantly longer than those that are studied nowadays. In this sense, an analysis of material circularity will acquire a strategic level of importance for businesses and could be performed by product designers in critical stages of the product's development or by managers who wish to evaluate the resilience of their material sourcing.

In addition, the two contributions to the consideration of material circularity in product design presented in this thesis can be used to provide engineering students a holistic view of the issues concerning materials and the emerging circular economy. This approach should be included in engineering courses as an application of the principles of circularity in a product design environment and the questions that arise from the deployment of the method and the framework can be discussed among teachers and students.

***

Some would say that trash is a state of mind, that refuse is just a resource at the wrong place and the wrong time. Indeed, there is much to be gained by relearning to see the value in the materials and products around us, even after their use has been completed. The materials that are engineered into products today are the result of a myriad of human efforts and impacts on the environment. This should inspire respect and admiration and not be taken lightly. Companies and consumers alike can benefit from following the intrinsic value that is embedded in each product.

In Japan, old Shinto beliefs have considered objects to have souls and the Buddhist have the word *mottainai*, which conveys a sense of regret concerning waste. It seems that by encompassing more aspects of reality in the complex task of designing products that meet the needs of our complicated world, a reconnection is being made with ancient spiritual wisdom. Japan has always had to deal with living besieged by resource and land restrictions. Perhaps it is finally time for the rest of the world to understand that planet Earth is a finite source of materials and energy and that every element taken from the ground is one day going to return to it.

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