METHODOLOGY

An approach to measuring circularity

Published 2015, adapted in 2019

ELLEN MACARTHUR FOUNDATION
GRANTA MATERIAL INTELLIGENCE
Life

The original methodology from which this revision has been adapted was a collaboration between James Goddin, Kim Marshall and Ana Pereira of Granta Design, and Sven Herrmann of the Ellen MacArthur Foundation aided by the Foundation's advisor Chris Tuppen.

This 2019 revision has built upon the original collaboration under the auspices of the Circular Economy 100 (CE100) network co. project led by James Goddin, Circular Economy Lead at ANSYS Granta.

Ellen MacArthur Foundation

The Ellen MacArthur Foundation launched in 2010 with the aim of accelerating the transition to the circular economy. Since its creation, the charity has emerged as a global thought leader, putting the circular economy on the agenda of decision-makers around the world. The charity's work focuses on seven key areas: insight and analysis; business; institutions; governments, and cities; systemic initiatives; circular design; learning; and communications.

ANSYS Granta

ANSYS Granta is the Materials Business unit of ANSYS, one of the largest and most advanced engineering simulation software companies in the world. Granta's focus is on the gathering, curation and management of materials and process information and its application, through engineering and risk management processes, to support better, greener, safer products by providing traceability, assurance and the best possible materials knowledge through each part of the business.

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Executive Summary

A circular economy is a global economic model that aims to decouple economic growth and development from the consumption of finite resources. Increasingly, companies see tremendous opportunity in this model, as it not only allows them to capture additional value from their products and materials, but also to mitigate risks from material price volatility and material supply.

Measuring how effective a company is in making the transition from 'linear' to 'circular' models is still in its infancy. The contribution of the Circularity Indicators Project is to develop indicators that assess how well a product performs in the context of a circular economy. The methodology encompasses material flows and a range of complementary indicators, thereby allowing companies to estimate how advanced they are on their journey from linear to circular in terms of their products and materials. The indices developed consist of a main indicator, the Material Circularity Indicator, measuring how restorative and regenerative the material flows of a product or company are, and complementary indicators that allow additional impacts and risks to be taken into account.

The first version of the Material Circularity Indicator methodology, published in 2015, focussed almost exclusively on technical cycles and materials from non-renewable sources. This update now includes an extension of the methodology to include the treatment of biological materials - a significant advance which allows for inclusion and proper evaluation of all material types.

The indicators can be used as a decision-making tool for designers but might also be used for several other purposes including internal reporting, procurement decisions and the evaluation or rating of companies.

In addition to the methodology, the Circularity Indicators Project has contributed to the development of a web-based measurement system for products, providing businesses with the tools required to track their progress in delivering a circular economy based business model.

The purpose of this methodology paper is to describe the thinking behind this approach, alongside a comprehensive derivation of the equations used to calculate the Material Circularity Indicator.

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1. Introduction

1.1. Context

The current economy can be largely described as **linear**: virgin materials are **taken** from nature, used to **make** products, which are then used and eventually **disposed** of. This model gives rise to chronically high levels of waste and creates dependence between economic development and inputs of new virgin materials. In a world of finite resources, this model cannot work in the long run and there are indications that it is reaching its limits.

In contrast, a **circular economy** is an economic and industrial model that is restorative and regenerative by design. Taking a systemic perspective, it designs out the concept of waste and aims to decouple economic growth from the use of virgin resources.

The model of a circular economy differentiates between two types of cycles:[1]

- **Biological cycles**, in which organic materials and products are **returned to the bioeconomy,** in the process regenerating natural systems.
- **Technical cycles**, in which products, components and materials are **kept in the market** at the highest possible quality and for as long as possible, through repair and maintenance, reuse, refurbishment, remanufacture, and ultimately recycling.

These cycles are illustrated on the circular economy systems diagram in Figure 1.

Underpinned by a transition to renewable energy sources, the circular model builds economic, natural, and social capital. It is based on three principles:

- **Design out waste and pollution.** A circular economy reveals and designs out the negative impacts of economic activity that cause damage to human health and natural systems. This includes the release of greenhouse gases and hazardous substances, the pollution of air, land, and water, as well as structural waste such as traffic congestion and underutilised assets such as cars and buildings
- **Keep products and materials in use.** A circular economy favours activities that preserve value in the form of energy, labour, and materials. This means designing for durability, reuse, remanufacturing, and recycling to keep products, components, and materials circulating in the economy. Circular systems make effective use of biologically-based materials by encouraging many different uses before nutrients are returned to natural systems.
- **Regenerate natural systems.** A circular economy avoids the use of non-renewable resources as far as possible and preserves or enhances renewable ones, for instance by returning valuable nutrients to the soil to support regeneration.

Increasingly, companies see opportunity in following the circular economy model. It allows them to capture additional value from their products and materials instead of them being discarded as waste. Those economic opportunities are substantial, totalling, for example, USD 630 billion of savings for medium-lived complex goods in the EU[2] and USD 700 billion for fast-moving consumer goods globally.[3] Additionally, more circular models allow businesses to mitigate risks from material price volatility and material supply. Economy-wide analysis shows

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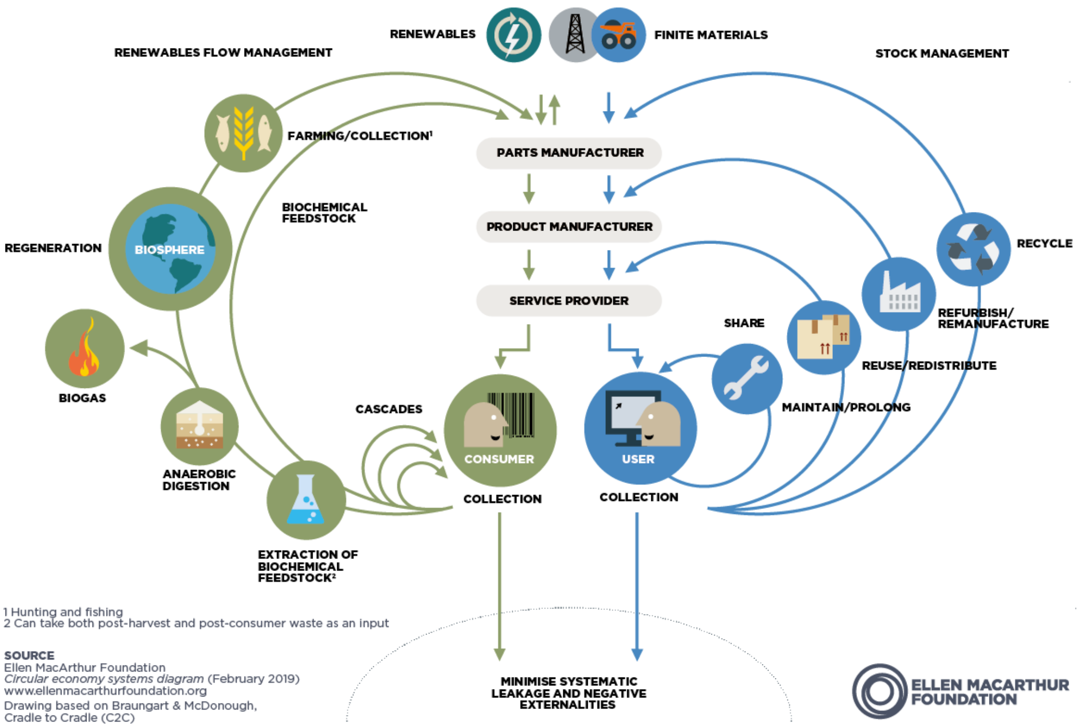
[1] W. McDonough and M. Braungart, Cradle to Cradle: Remaking the Way We Make Things, 2002; The Ellen MacArthur Foundation, Towards the Circular Economy, Volume 1, 2012.

[2] The Ellen MacArthur Foundation, Towards the Circular Economy, Volume 1, 2012.

[3] The Ellen MacArthur Foundation, Towards the Circular Economy, Volume 2, 2013.

that applying circular economy principles in the EU could unlock value to business and society worth EUR 1.8 trillion a year in 2030 - EUR 900 billion greater than in a business as usual scenario. This conception of value includes positive impacts on human health and the environment such as cleaner air, lower congestion, and healthier food. It therefore contributes to addressing some major global challenges. For instance, global greenhouse gas emissions in five key areas (steel, cement, plastics, aluminium, and food) were found to fall by 9.3 billion tonnes a year in 2050 in a circular economy pathway versus business as usual - equivalent to cutting all current transport emissions to zero.

Figure 1: Circular economy systems diagram



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

SOURCE
Ellen MacArthur Foundation
Circular economy systems diagram (February 2019)
www.ellenmacarthurfoundation.org
Drawing based on Braungart & McDonough,
Cradle to Cradle (C2C)

1.2 The Need for Circular Economy Metrics

Methods of measurement are necessary in a large number of applications, such as product design, material selection, progress tracking (e.g. Key Performance Indicators (KPIs)), supporting internal decision making on e.g. investment choices. These different uses will require different types of metrics, based on different sets of data.

This paper describes a methodology to assess the circularity of companies' flows of products and materials. This will allow companies to understand how far they are on transitioning their products from linear to circular.

Circularity of product and material flows does not necessarily lead, due to regulatory environments and other factors, to more viable business models, lower business risks, or improved social equity. This methodology doesn't directly incorporate any of these other metrics, but instead seeks to provide the user with a frame of reference for discussing how circular a product is, and to discuss how circularity impacts these other objectives.

A set of suggested 'complementary indicators' is provided in Section 2.3 of this methodology and represents a non-exhaustive list of the types of metrics among which circularity is likely to be considered. It should be noted that some of the methodologies for calculating these complementary indicators may also require adjustment to appropriately represent circular systems as many have been established on the basis of measuring linear models. When comparing different product systems, value judgements will still need to be made on which metrics are the most important to consider. Therefore, care needs to be exercised when comparing circularity with other indicators to ensure that the metrics are indeed being calculated on an appropriate basis.

1.3. Objectives and Scope

At the product level, the methodology is aimed in particular at the following possible use cases:

- The indicators can be used in the design of new products to take circularity into account as a criterion and input for design decisions. The indicators allow for comparing different versions ('what if' scenarios) of a product regarding its circularity at the design level. They could also be used to set minimum circularity criteria for designers. This can apply to new products as well as the further development of products with the aim to make them more circular. Aspects of product design that can influence the Circulytics range from material choices to new business models for the product.
- The indicators can be used for **internal reporting** purposes. Companies are able to compare different products regarding their circularity. This also allows stakeholders from different departments to learn from each other regarding circular product design.
- Companies can also make the indicators of their products available to the public or selected organisations. This would allow these organisations to use the indicator as part of their **procurement decisions**, for example, by defining a minimum threshold for the products they buy.

The company-level methodology builds on the indicators developed on the product level and aims in particular for the following use cases:

- The indicators can be used **internally** to compare the circularity of different product ranges and departments. They can also allow tracking of progress on a product range, department or at whole company level.
- The indicators can be used **externally** by third-party stakeholders to compare the circularity of different companies that make their scores available to them.

More details on how this methodology can be used in practice can be found in the document 'Circularity Indicators – Non-Technical Use Cases', which can be downloaded from the Circularity Indicator Project website.[4]

The first version of this methodology, published in 2015, focussed almost exclusively on technical cycles and materials from non-renewable sources. At the time, the circularity strategies and associated business benefits of technical materials were thought to be better understood than bio-based alternatives. There are, however, some very significant benefits that may be gained through the use of biological materials when shifting from a linear to a circular economy. It is therefore important to be able to evaluate the circularity of both technical and biological materials using a consistent methodology.

This update now includes an extension of the methodology to include the treatment of biological materials alongside technical materials - a significant advance which allows for inclusion and proper evaluation of all material types.

While a circular economy is about systems thinking, the combination of design and business models and the effective flows and feedback loops, the creation of an analytical methodology and tool requires a more narrowly defined scope. The **Material Circularity Indicator (MCI)** developed in this paper therefore focuses on the restoration of material flows at product and company levels and is based on the following six principles:

i) Sourcing biological materials from sustained sources[5]
ii) Using feedstock from reused or recycled sources
iii) Keeping products in use longer (e.g., by reuse/redistribution/increase durability)
iv) Reusing components or recycling materials after the use of the product
v) Making more intensive use of products (e.g. via service, sharing or performance models)
vi) Ensuring biological materials remain uncontaminated and biologically accessible

Given this scope, it is evident that improving the MCI of a product or a company will not necessarily translate as an improvement of the circularity of the whole system. Nonetheless, a widespread use of this methodology could form part of such a system's improvement.

Evidence indicates that more economic value can often be captured in the end-of-use strategies corresponding to the inner, shorter, technical cycles.[6] Indeed, reusing components of a product preserves more of its integrity, embedded energy, and complexity than recycling it, which consists in only recovering its basic materials. Purely from the perspective of materials savings, this principle is reflected in the Material Circularity Indicator thanks to the inclusion of a factor representing the efficiency of the recycling process, while reuse is assumed to have an efficiency of 100%.

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[4] http://www.ellenmacarthurfoundation.org/circularity-indicators/

[5] Terms used are defined in Chapter 1.8.

[6] The Ellen MacArthur Foundation, Towards the Circular Economy, Volume 1, 2012.

The question arises whether principles iv) and v) should form part of circularity: Is a product more circular because it is used longer, even if it is landfilled after its use? Circular economy is all about the initiatives that can create an important impact in materials use, and case studies have shown that an increased serviceable life or a higher usage intensity leads to substantial materials savings (see, for example, the analysis of reusable bottles[7]). Longer serviceable lives also enable the creation of repair, reuse and/or resale (e.g. refillable products or second-hand shops) and are therefore well suited to the idea of increased circularity and correspond to inner, short cycles.

In the development of the MCI the proportion of the product being restored (through component reuse and recycling, i.e. principles ii) and iii)) and coming from reused or recycled sources is described as the **restorative part of the flow**, while the **linear part of the flow** is the proportion coming from virgin materials and ending up as landfill (or energy recovery). Principles iv) and v) are treated as improvements on the **utility** of a product, an additional component in the derivation of the MCI that depends on the linear part of the flow. As per the arguments above, this is a slight simplification, but one that helps towards understanding the structure of the equations.

The addition of biological materials to this methodology has required the introduction of two additional principles. Principle i) seeks to ensure that the extraction of renewable materials from a biological source doesn't exceed the capacity for the renewal of those materials by that source, and aspires to go beyond this to regenerate natural systems. Principle vi) likewise seeks to ensure that, at the end-of-use of a biological material, the nutrients contained within it are usefully returned to the natural environment in a manner that is biologically accessible and which doesn't compromise the future capacity of that source to create new materials. If Principles i) and vi) are met then biological materials are considered to comprise an effective component of the biological cycle and, as such, are considered circular.

While the MCI provides an indication of how much a product's materials circulate, it neither takes into account what these materials are, nor does it provide information on other impacts of the product. As additional support to decision making, this methodology therefore recommends an approach to prioritise product improvements by using the MCI in combination with complementary indicators to identify relevant risks and impacts. These are of two types:

- **Complementary risk indicators,** giving an indication on the urgency of implementing circular practices. These are related to the drivers for change from the current linear model. These include, for example, measures of material **scarcity** (which has a substantial impact on the value of recovering the materials) and a measure of **toxicity** (which impacts the risks and costs of manufacture, reverse logistics and public safety liabilities).
- **Complementary impact indicators,** giving an indication of some of the benefits of circular models. They include a measure of the **energy, water, and greenhouse gas** impacts of a given setup and may also include measures of loss of **biodiversity** or **soil loss** for example for biological materials.

As the circular economy is also about creating and retaining value from products and materials, this methodology also provides guidance on assessing the **profitability impact** of moving to more circular business models.

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[7] The Ellen MacArthur Foundation, Towards the Circular Economy, Volume 2, 2013.

The MCI presents the following differences and commonalities with Life-Cycle Assessment (LCA) methodologies:

- An LCA focuses on deriving the environmental impacts throughout the life cycle of a product for different scenarios, whereas the MCI concentrates on the flow of materials throughout the use of a product. It specifically encourages the use of recycled or reused material and recycling or reusing it at the end of use, while recognising increased utility of a product (i.e. durability and usage intensity). The MCI further focuses on the maintenance of biological systems as a source of consistently renewed material flows.
- Many of the input data required for an LCA are the same as for the MCI and the complementary impact indicators may indeed be derived from an LCA approach (e.g. relevant standards[8] to assess the Carbon footprint of a product). Additionally, in the future, the MCI could be one of the parameters considered as an output from an LCA or eco-design approach alongside those already typically used.

These complementary indicators have been selected on the product level, though they can all be used at the company level provided there is a suitable way of combining them for a product range. Additionally, it may be appropriate to use relevant complementary indicators that have already been established at company level.

Finally, this document provides a first step in developing a measurement of circularity and how extensions and refinements could be addressed in future developments, as explained in Section 1.4.

1.4. Systems Thinking

Following the release of the original methodology in 2015, early comparisons between LCA and MCI highlighted a common issue when comparing these approaches which is worthy of reflection.

LCAs are traditionally defined using system boundaries that typically extend from the creation of the product to its disposal and are often bound by region specific assumptions (for example energy mix). MCI similarly considers a product from the source of its materials to the destination of those materials through the use of the product and also requires region specific assumptions (for example recycling infrastructure). If we stop here, the two approaches would, at first, seem to be ideally comparable.

However, the circular economy doesn’t commonly stop with a single product lifecycle and we are instead encouraged to think beyond the initial product to the reuse of components, their remanufacture and recycling. For biological materials, we are similarly encouraged to consider where these originate, how to maintain them as uncontaminated materials and to return them to the biological cycle as accessible nutrients. As products designed for the circular economy will contain components with different durability, and as the life and use of each cycle will differ depending upon the nature of the user, it is clear that the circularity of the first lifecycle of a product will most likely be different to the second, third, etc.

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[8] For example, PAS 2050:2011, Specification for the assessment of the life cycle greenhouse gas emissions of goods and services (www.bsigroup.com/PAS2050), ISO14067:2018, Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification, Greenhouse Gas Protocol Product Life Cycle Accounting and Reporting Standard.

Likewise, if we wish to retain products and materials in circulation for longer (and achieve a high MCI score) we are likely to find ourselves selecting materials that are more durable and these, quite commonly, have higher embodied impacts. The economic and environmental benefits from using such materials do not commonly rest with the initial product but instead accrue through the successive use of the product or material over the multiple life cycles that they enable. We therefore need to consider the embodied impact of the material in this context if the result is to reflect the overall benefits gained by a circular system.

When we start thinking about multiple life cycles, it also quickly becomes apparent that the additional transportation, for reverse logistics for example, starts to contribute more significantly in some cases to the overall economic and environmental assessment of the product. Such impacts would commonly be missed by the typical system boundaries of a more traditional linear LCA focussed on a single life cycle of a product.

To overcome this, it is necessary to extend the boundaries of the traditional LCA and calculate the intended impacts for each successive life-cycle of the product, taking into account the likely failure rates of components, product damage and losses, the ability to reuse and remanufacture components multiple times, recycling or disposal, losses to and contamination of the environment, and all transportation and interventions such as maintenance or disassembly in a form of **Circular LCA.** It is also necessary to consider MCI in the same context and recognise that the circularity of a product is likely to change from one life cycle to the next. In both cases, it is the overall benefits from the system we are directed towards. Given the complexity of such assumptions it would be advisable to perform a sensitivity analysis and to not seek a precise answer but a more probabilistic result for both complementary indicators and MCI and to reflect upon the reliability of the results as a function of the accuracy and relevance of the input data used.

When we subsequently compare the average or overall impacts of the circular product to the repeated impacts of single lifecycle alternatives, taking into account uncertainties in each case, we then gain a better understanding of two key points:

1. The like-for-like comparison of our circular system compared to a linear alternative taking into account the impacts per product life cycle.
2. An indication of any break-even point for a circular system, where any additional up-front costs or impacts have been offset against the linear alternative and after which we start to realise a net benefit.

It is also important to differentiate between the **design intent** of a circular system and the **actual performance** of the system. It is possible to design beautifully circular systems, however the actual circularity will be impacted by the users and stakeholders in the actual product. Products that are designed to be returned but are damaged or lost will make the system less circular than intended. Products that are designed to be durable, but which contain substances that are subsequently banned by legislations such as REACH may not re-enter supply and may have to be landfilled. Chemicals in the material may leach into the environment where they may harm people, marine life and other species. Products that are lost to the environment may end up in a different form (e.g. micro or nano particulates) where they may have a disproportionate effect. Products that are designed to be recycled may not have the infrastructure available due to market changes or insufficiencies and may, instead, be landfilled or incinerated.

It is therefore clear that to make full use of MCI in a multiple-life-cycle approach, the user must first design for the multiple life-cycles of the intended system and then monitor the performance of the actual system they implement, taking corrective measures if appropriate to deliver the intended benefits. Figure 2 illustrates how the implementation of a circular product system may differ from the conceptual design and may require corrective actions or adjustments to realise the intended benefits.

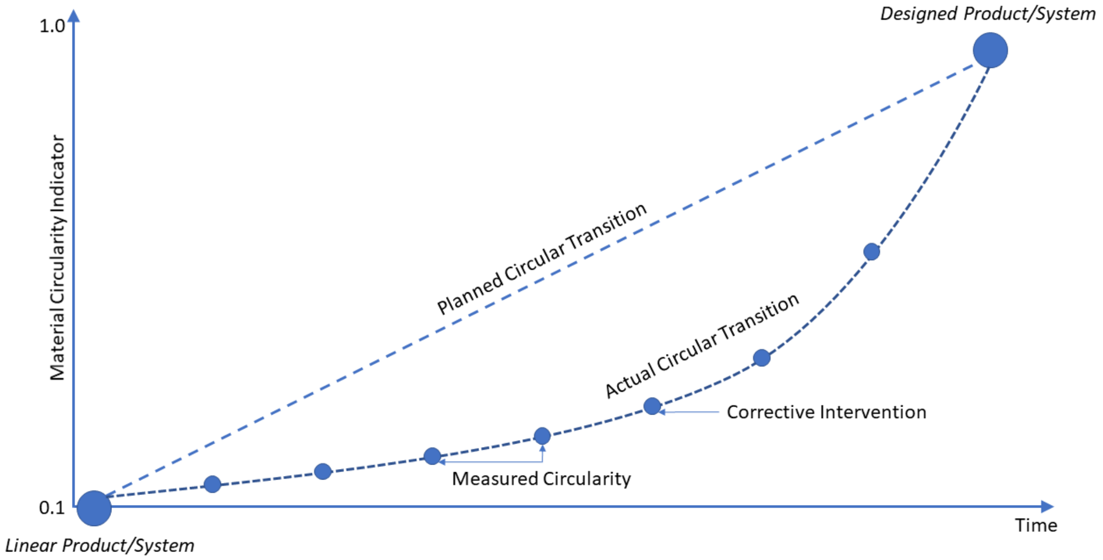

Figure 2: Illustration of the application of MCI to the design of a circular product system and real-world monitoring of the product system performance with the need for corrective action to realise benefits.

It would also be acceptable for a user to conduct sensitivity analyses on possible end of use scenarios and use these data to present a range of MCIs. Users should be careful to accurately communicate the assumptions in these calculations and how realistic each scenario is. This approach would be useful for stakeholders who are far upstream in the value chain with limited visibility into the end of use phase of their materials.

1.5. Development of the Methodology

This paper describes an updated methodology for calculating a Material Circularity Indicator for manufactured products and companies comprising technical and/or biological materials. The paper describes the thinking behind the methodology, alongside a derivation of the equations that lead to the calculation of the Material Circularity Indicator.

The original 2015 version of the methodology covered primarily technical materials and was published by the Ellen MacArthur Foundation and Granta Design following a two-year LIFE+ project co-funded by the European Commission and supported by a wide range of stakeholders from about 30 organisations including investors, regulators, consultancies and universities.

As part of the development, the original 2015 methodology was tested by a group of pilot companies using real product data. Testing was an iterative process running through five test phases and included in-person and virtual workshops. The 2015 pilot companies are listed in Appendix D.1. The stakeholders participating in the development of the original methodology and in this revision are listed in Appendix D.2. The 2015 methodology has also been through two detailed peer review phases by expert panels of reviewers as listed in Appendix D.3.

The current 2019 revision of the methodology has been led by James Goddin at ANSYS Granta with input from a range of circular economy leaders from the Ellen MacArthur Foundation's CE100 network who are leading the transition to a circular economy, as well as other carefully selected participants with specific knowledge and expertise.

The project team is grateful to the pilot companies, stakeholders and reviewers, whose generous input and feedback led to substantial improvements in this methodology.

1.6. Potential Future Developments

The limitation of the original 2015 methodological focus on technical materials was recognised at the time of publication and has now, we believe, been addressed by this revision, including the often-contentious issue of energy recovery.

Since 2015 there have been a range of published reviews of the Material Circularity Indicator methodology in the scientific literature and a number of well-established tools have integrated the calculations to enable commercial application at a product level.

The question of integrating the methodology into a standard remains open and the authors believe that this is almost inevitable given the ongoing momentum in the area. This would be particularly valuable for the application of the product-level indicators in procurement, and for the external application of the company-level indicators. Further refinements, including specialisations for specific industries, could also be used for the certification of products or companies.

The formula developed for the Material Circularity Indicator could also be further refined, for example by:

- including additional guidance or validation methodologies to demonstrate that a biological material has been extracted from a Sustained Resource
- developing a more comprehensive approach on downcycling, taking into account the level of material quality loss in the recycling process
- introducing more granular levels of recovery beyond recycling and reuse, such as remanufacturing or refurbishment

While the methodology makes allowance to consider the influence of leasing or hiring business models via improvements to the product's utility, the product-level methodology could further be extended to cover a wide range of business models, for example, performance models and reselling via secondary markets. This would also allow an extension of the company-level methodology to include and allow comparisons between all kinds of companies.

Further developments could also extend the technique to consider Material Circularity Indicators for major projects, such as building a railway line, as well as for geographic regions, like a city or country.

Lastly, this methodology assumes access to a fair amount of internal company data. It could inform the development of an outside-in method, based on publicly available data. This could be used by investors and other interested third parties to assess the circularity of products and companies that do not provide information directly.

1.7. Outline of the Paper

After this introduction, the paper divides into two parts: Chapter 2 develops the product-level methodology, whilst Chapter 3 builds on this to derive a methodology at the company level. An appendix includes further information, in particular case studies applying the methodology to examples.

For the product level, Section 2.1 describes the methodology to compute the Material Circularity Indicator. It begins with a whole product calculation (Section 2.1.2) and then describes a more comprehensive approach (Section 2.1.3) that allows for the incorporation of subassemblies, components and materials. Section 2.2 covers practical guidance on the use of the product level methodology.

Section 2.3 describes a range of suggested complementary indicators that are classified into complementary risk and impact indicators. In Section 2.4, guidance on how to assess the profitability of the introduction of circular products and business models is given.

Section 3.1 develops the Material Circularity Indicator of a company from the product-level Material Circularity Indicator. Section 3.2 gives guidance on the use of the indicator, whereas Section 3.3 describes suggested complementary indicators on a company level.

A series of case studies that explain the use of the methodology are available separately at the following link: http://www.ellenmacarthurfoundation.org/circularity-indicators/

A description of how to include production waste can be found in Appendix A, some details on the derivations of the Linear Flow Index and the utility factor (Appendices B and C) and a list of project stakeholders (Appendix D).

1.8. Definitions of Principal Terms and Variables

Term	Definition
Bill of materials	A bill of materials (BoM) is a list of the parts or components that are required to build a product. For each of the components the precise type and amount of material is listed.
Biological cycles	In circular economy, bio-based materials are used, consumed, and cycled in ways that regenerate natural systems and can be transformed using treatment types that generate cascades of value.
Biosphere	The biosphere denotes the global sum of all ecosystems on the planet, including all life forms and their environment. This corresponds to a thin layer of the earth and its atmosphere – extending to about 20 km.
Circular economy	A circular economy is a global economic model that decouples economic growth and development from the consumption of finite resources. It relies on three principles: designing out waste and pollution; keeping products and materials in use; and regenerating natural systems.
Closed loop	In a closed loop, used products come back to the manufacturer and components or materials are used again to produce new products of the same type.
Complementary impact indicators	The complementary impact indicators described in this methodology are designed to give an indication of some of the benefits of circular models. For example, they include measure of the energy and water impacts of a given setup.
Complementary risk indicators	The complementary risk indicators described in this methodology give an indication on the urgency of implementing circular practices. These are related to the drivers for a change from the current linear model and include measurements for material scarcity or toxicity.
Component	In general, a component is part or element of a larger whole, for example, a product, especially a part of a machine or vehicle.
Composting	For Biological Cycles, the act of converting the material into biologically accessible and otherwise uncontaminated nutrients.
De minimis rule	The de minimis rule allows disregarding products in the computation of a department or company-level MCI whose contribution is below a certain threshold.
Downcycling	Downcycling is a process converting materials into new materials of lesser quality and reduced functionality.
Energy Recovery	The act of recovering the energy content of materials through means such as incineration or gasification. This term specifically excludes energy conversion where the energy content is not usefully recovered.
Feedstock	Feedstock is anything used to produce a new product. This in particular includes raw materials (from either virgin, bio-based, or recycled sources) but can also include components from old products reused in a new product.

Functional unit	A functional unit is a measure of the product's use. For example, it could be one kilometre driven for a car, or one wash cycle for a washing machine.
Fully linear product	A product is called fully linear if it is made purely from virgin material and it completely goes into landfill or energy recovery after its use, that is, $\mathrm{LFI} = 1$.
Life cycle assessment (LCA)	LCA is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service. It is derived by compiling an inventory of relevant energy and material inputs and environmental releases and evaluating the potential environmental impacts associated with identified inputs and releases.
Lifetime	The lifetime is the total amount of time a product is in use, including potential reuse of the whole product. The lifetime can be increased by repair or maintenance.
Linear economy	A linear economy consists of 'take, make, dispose' industrial processes and associated lifestyles resulting in a depletion of finite reserves. Virgin materials are used to create products that end up in landfills or incinerators.
Linear flow	The linear part of the material flow of a product is the part that comes from virgin materials and ends up as landfill (or energy recovery).
Material Circularity Indicator	The main indicator developed in this methodology. It assigns a score between 0 and 1 to a product (or company) assessing how linear or restorative the flow of the materials for the product (or the company's products) and how long and intensely the product (or the company's products) is used compared to similar industry-average products.
Natural capital	Natural Capital is defined as the earth's stocks of natural assets, which include geology, soil, air, water and all living things.
Reference product	For a range of products with similar material composition, recycled and reused content, recycling and reuse at end-of-use, and utility, one of these products is selected to represent the whole product range in the aggregation on a department or company level.
Recycling	Recycling is the process of recovering materials to feed back into the process as crude feedstock. Recycling excludes energy recovery.
Refurbishment	Refurbishment is the process of returning a product to good working condition by replacing or repairing major components that are faulty or close to failure and making cosmetic changes to update the appearance of a product, such as changing fabric or painting.
Remanufacture	Remanufacture denotes the process of disassembly and recovery at the sub-assembly or component level. Functioning, reusable parts are taken out of a used product and rebuilt into a new one. This process includes quality assurance and potential enhancements or changes to the components.
Restorative flow	The restorative part of the material flow of a product is the proportion that comes from reused or recycled sources and is restored through reuse or recycling.

Reuse	Reuse is the reintroduction of the same product for the same purpose and in its original form, following minimal maintenance and cosmetic cleaning. Within this methodology, this is considered via an increase of the product's utility (lifetime or functional units). If a product cannot be reused as a whole, individual components can be reused in a functional way. Within this methodology this is considered through the fraction F_U of the mass of feedstock for the product from reused sources and the fraction C_U of mass of the product going into component reuse.
Service model	A business model in which customers pay for services instead of products. For example, this would include leasing, short-term hire or performance-based usage contracts.
Sub-assembly	A unit assembled separately but designed to be incorporated with other units into a larger manufactured product.
Sustained Production	In biological cycles, the extraction of natural materials at volumes and employing practices which aim to maximise the regeneration of natural systems in the indigenous ecosystems by for example supporting the development of healthy soils. Recognising that proving this can be challenging, as an intermediate step this definition includes extraction that does not reduce the capacity for future production of that material below its present capacity and also does not reduce the natural capital of the associated or dependent indigenous ecosystems.
Technical cycles	In technical cycles, products, components and materials are restored into the market at the highest possible quality and for as long as possible, through repair and maintenance, reuse, refurbishment, remanufacture, and ultimately recycling.
Total mass flow	The total mass flow for a product is derived as the sum of the amounts of material flowing in a linear and a restorative fashion.
Unrecovered waste	Unrecoverable waste includes waste going to landfill, waste to energy and any other type of process after the use of a product where the materials are no longer recoverable.
Upcycling	Upcycling denotes a process of converting materials into new materials of higher quality and increased functionality.
Use phase	The use phase of a product starts when it reaches its first users and ends when it is not reused any more as a whole. After the use phase, components can be reused and the rest of the product can go into recycling, energy recovery or landfill.
Utility	The utility of a product measures how long and intensely it is used compared to an average product of the same type. The utility is derived from the lifetime and functional units of a product (compared to an industry-average product of the same type).
Virgin material	Material that is not from reuse, recycling or, for the purposes of this methodology, biological materials from Sustained Production.

Symbol	Definition
M	Mass of a product
F_R	Fraction of mass of a product’s feedstock from recycled sources
F_U	Fraction of mass of a product’s feedstock from reused sources
F_S	Fraction of a product’s biological feedstock from Sustained Production. Biological material that is recycled or reused is captured as recycled or reused material, not biological feedstock.
V	Material that is not from reuse, recycling or, for the purposes of this methodology, biological materials from Sustained Production.
C_C	Fraction of mass of a product being collected to go into a composting process
C_E	Fraction of mass of a product being collected for energy recovery where the material satisfies the requirements for inclusion.
C_R	Fraction of mass of a product being collected to go into a recycling process
C_U	Fraction of mass of a product going into component reuse
E_C	Efficiency of the recycling process used for the portion of a product collected for recycling
E_E	Efficiency of the energy recovery process for biological materials satisfying the requirements for inclusion.
E_F	Efficiency of the recycling process used to produce recycled feedstock for a product
B_C	The carbon content of a biological material, by default a value of 45% is used unless supported by evidence to the contrary.
W	Mass of unrecoverable waste associated with a product
W_0	Mass of unrecoverable waste through a product’s material going into landfill, waste to energy and any other type of process where the materials are no longer recoverable
W_C	Mass of unrecoverable waste generated in the process of recycling parts of a product
W_F	Mass of unrecoverable waste generated when producing recycled feedstock for a product
LFI	Linear Flow Index
$F(X)$	Utility factor built as a function of the utility X of a product
X	Utility of a product
L	Actual average lifetime of a product
L_{av}	Average lifetime of an industry-average product of the same type

U	Actual average number of functional units achieved during the use phase of a product
U_{av}	Average number of functional units achieved during the use phase of an industry-average product of the same type
MCI_P	Material Circularity Indicator of a product
N_i	Normalising factor used to aggregate product-level MCIs using a weighted average approach; the index i refers to a specific product range or department
MCI_C	Material Circularity Indicator of a company

2. Product-Level Methodology

2.1. Material Circularity Indicator

The Material Circularity Indicator (MCI) for a product measures the extent to which linear flow has been minimised and restorative flow maximised for its component materials, and how long and intensively it is used compared to a similar industry-average product.

The MCI is essentially constructed from a combination of three product characteristics: the mass V of virgin raw material used in manufacture, the mass W of unrecoverable waste that is attributed to the product, and a utility factor X that accounts for the length and intensity of the product's use.

The associated material flows are summarised for technical materials in Figure 3.

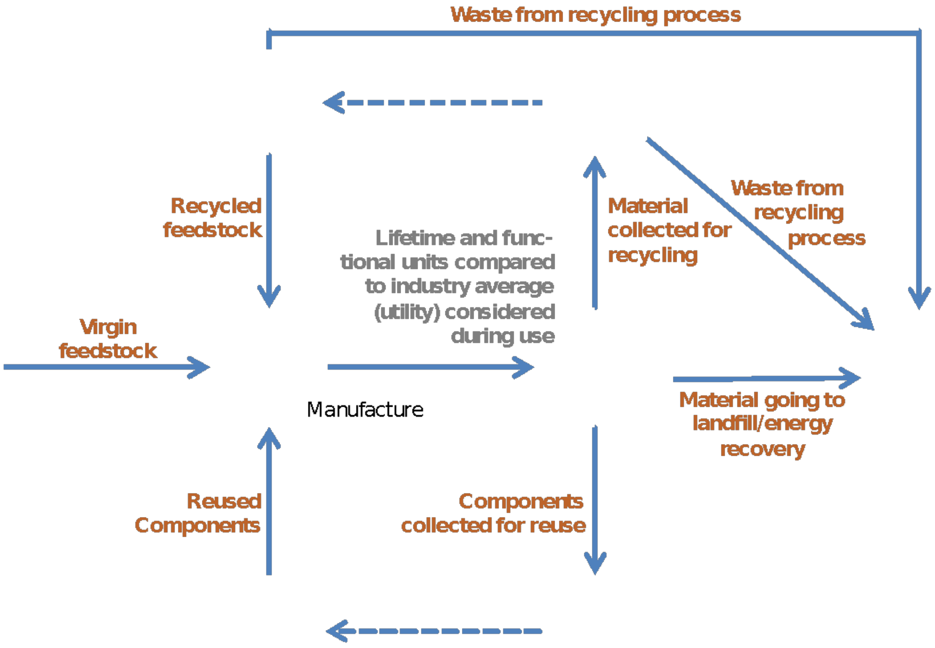

Figure 3: Diagrammatic representation of material flows

Any product that is manufactured using only virgin feedstock and ends up in landfill at the end of its use phase can be considered a fully 'linear' product. On the other hand, any product that contains no virgin feedstock, is completely collected for recycling or component reuse, and where the recycling efficiency is 100% can be considered a fully 'circular' product. In practice, products will sit somewhere between these two extremes and the MCI measures the level of circularity in the range 0 to 1.

The dashed lines in Figure 3 indicate that the methodology does not require a closed loop. That is to say, for example, that recycled feedstock does not have to be sourced from the same product but can be sourced on the open market. This is a deliberate feature and reflects the grounding of the methodology on the mass-flow within the product system - the calculation for which is the same regardless of whether it is an open or closed loop.

Note that the material flows shown in Figure 2 are associated exclusively with those materials that end up in the final product. There will be further material flows, such as waste streams that occur during the manufacturing process(es). These are subject to special consideration in Section 2.1.4.

In most cases, it is expected that the MCI will be calculated using detailed knowledge of a product's component parts and materials. However, in order to explain the basic formulation in a simpler way, Section 2.1.2 first derives the formula for the MCI using a **whole product approach** that is not differentiating between the different components and materials of a product. Section 2.1.3 then adapts it to consider a breakdown of components and materials, referred to as the **comprehensive approach.**

For quick reference, Section 1.8 lists definitions of all the principal terms and variables. Furthermore, Figure 4 summarises the different variables influencing the Material Circularity Indicator for technical materials.

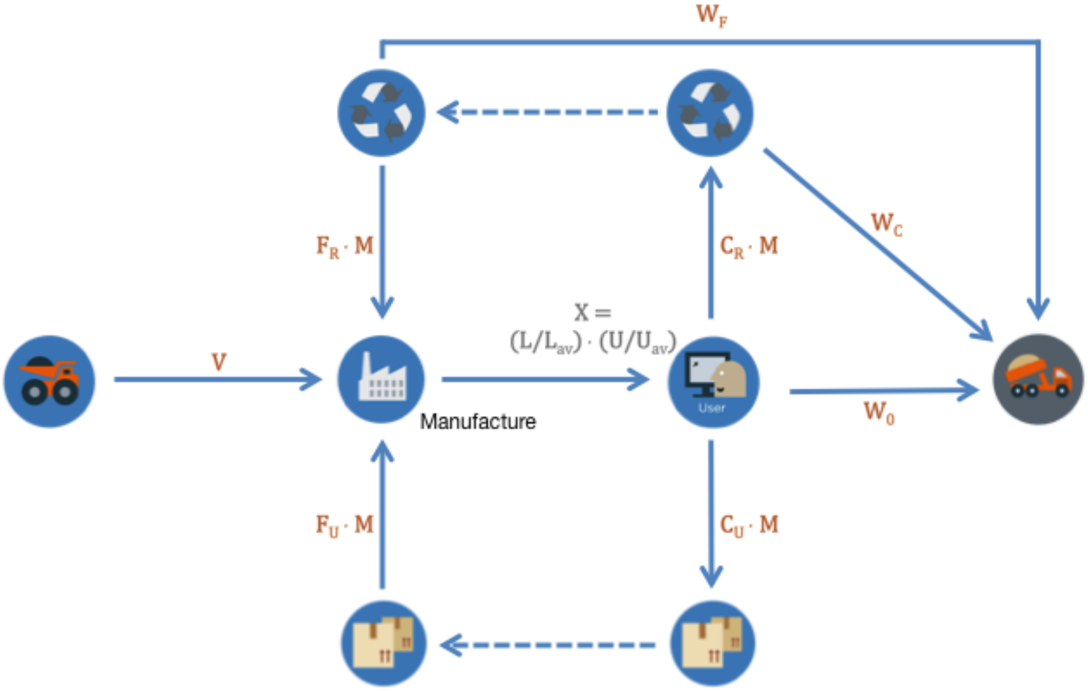

Figure 4: Diagrammatic representation of material flows

2.1.1. Data Input

This methodology is designed for use with product data representative of what actually happens in the marketplace. Data input into the model should ideally be based on knowledge of the product being assessed. Where this information is not known, generic industry data or best approximations may be used instead, as described more fully in Section 2.2.

Whilst the methodology may be used in a ‘what if’ mode to guide product design and to set product circularity targets, design data should not be used in calculating the MCI of an actual product. For example, a product may be 100% recyclable, or it may be the objective of the company to attain 100% reuse, but actual recycling rates should be used in the calculations when reporting on the actual product. Likewise, in the case of a product that is designed for a longer life than the actual product experiences in practice, the actual lifetime should be used in the calculations, not the design lifetime. This is further explained in Section 1.4.

2.1.2. Whole Product Approach

The Material Circularity Indicator is constructed by first computing virgin feedstock and unrecoverable waste, then building in the utility factor.

2.1.2.1. Calculating Virgin Feedstock

Consider a product in which F_R represents the fraction of feedstock derived from recycled sources, F_U represents the fraction from reused sources and F_S represents the fraction of the biological materials used which originate from Sustained Production. The fraction of feedstock from virgin sources is then $(1 - F_R - F_U - F_S)$ and the mass of virgin material is given by

$$V = M(1 - F_R - F_U - F_S) \qquad (2.1)$$

where M is the mass of the finished product.

Differentiating between biological materials according to origin is an important principle of this update to the methodology. The differentiation exists to prevent perverse outcomes such as deforestation, soil degradation and habitat loss which would otherwise disrupt the circularity of the material flows[9]. It also recognises that biological systems are often complex and symbiotic in nature, requiring additional considerations within this methodology.

It is also important to note that the validation required to demonstrate that a biological material has been extracted from a source of Sustained Production will be an administrative burden on the manufacturer claiming their source to be circular and may require chain of custody of specific material batches to appropriately verify. The authors of this study did not try to analyse or identify all the possible programs, schemes and indicators that could be utilised to demonstrate Sustained Production as that was outside the scope of this study. There was however a clear preference for the adoption of regenerative practices - as outlined in the definition of Sustained Production - moving above and beyond what could simply be considered as ‘sustainable extraction’.

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[9] It is also important to note that this approach does not specifically rule out the complete extraction of a biological species from a specified source - for example a non-indigenous invasive species.

Manufacturers and users should be careful to perform their due diligence in selecting appropriate chain of custody certifications so as to avoid the use of schemes that are not properly vetted or respected. Specific schemes for demonstrating appropriate chain of custody have not been specified in this paper. In some cases, the use of supplier or industry average figures for sustainable sourcing may be the only data available and, if used, it would be appropriate to state this clearly alongside the result. It is up to the user of the methodology to demonstrate to their customers that the data they have relied upon is appropriate and sufficiently robust data to support and justify their result.

2.1.2.2. Calculating Unrecoverable Waste

If C_R represents the fraction of the mass of the product being collected for recycling at the end of its use phase, C_U represents the fraction of the mass of the product going into component reuse[10] , $C_C$represents the mass of the product comprising uncontaminated biological materials that are being composted and C_E represents the mass of the product comprising biological materials from Sustained Production being used for Energy Recovery. Then the amount of waste going to landfill or energy recovery is:

$$W_0 = M(1 - C_R - C_U - C_C - C_E). \qquad (2.2)$$

The inclusion of composting naturally only applies to biological materials and only to the extent that these materials are considered compostable according to recognised standards and are non-toxic to, and biocompatible with, the ecosystems to which the compost is subsequently introduced. The by-products of composting must also be made biologically available, a restriction that exists to prevent the landfilling or sequestering of otherwise valuable nutrients that are required by the biological cycle to produce new materials as part of a circular bioeconomy. Where these conditions are met, the composting of biological materials may be treated as being up to 100% efficient depending upon the application of the resulting solid and liquid nutrients to specific ecosystems and the degree to which these are retained by those ecosystems, taking into account losses through leaching and run-off post-application.

The inclusion of energy recovery as part of a circular strategy only applies to biological materials and the following conditions must **all** apply:

1. Other end of life options for the material, besides landfill, must have been demonstrably exhausted (e.g. the product is not practically or economically recyclable or compostable).
2. The material must be from a biological source.
3. The biological material must be demonstrably from a source of Sustained Production.
4. The biological material must be completely uncontaminated by technical materials, (including coatings, preservatives and fillers except when these are demonstrably inert and non-toxic).
5. Energy recovery must be optimised, and this must be usefully employed to displace non-renewable alternatives.

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[10] Component reuse refers to individual components being reused in a functional way. Reuse in this definition excludes a direct use of the product as a whole, which is taken to be part of the use phase. It is also assumed that there are no material losses in preparing components of collected products for reuse.

6. The by-products of the energy recovery must themselves be biologically beneficial - for example as a soil conditioner - and must not be detrimental to the ecosystems to which they are introduced.

If any of the above conditions are not met, or cannot be evidenced, then the resulting energy recovery is not considered as being part of the circular economy and cannot be included in the calculation as such.

In the case of mixed origin materials, credit cannot be claimed for energy recovery for the portion that does not adhere to all of the above conditions.

Where energy recovery is applicable, the value of C_E is calculated based upon the efficiency of the energy recovery process E_E and the carbon content of the biological material meeting the above requirements B_C, thus:

$$C_E = (E_E * B_C) \tag{2.3}$$

$$E_E = (E_R /(HHV * M_B)) \tag{2.4}$$

Where E_R is the energy recovered (in MJ or BTU) HHV is the Higher Heating Value (in MJ or BTU) and M_B is the mass of eligible biological material adhering to the requirements for inclusion, above.

The typical carbon content of most biological species used in structural applications has been observed to be between 40% and 50% and a default value of 45% may therefore be used in the absence of other, more accurate, data.

The rationale behind including energy recovery as part of the circular economy within this stringent set of constraints is that there exists within nature the capacity to absorb CO_2 from the atmosphere and this forms part of the natural biological cycle. There is of course also an over-abundance of CO_2 produced globally and it is not the intention of this methodology to promote further unnecessary emissions. By restricting energy recovery to materials from Sustained Production the methodology ensures that the ecosystem capacity to absorb the resulting CO_2 has already been assured by the sourcing of the material. By placing strict requirements on the residue, and its reintroduction to support biological systems, the methodology promotes the avoidance of contaminants that might inadvertently harm indigenous ecosystems and promotes the retention of other non-CO_2 nutrients within the biological systems. Energy recovery is retained as the lowest form of circularity by the emphasis on exhausting other alternatives first and also by the lower relative contribution to circularity when compared with alternatives.

Including energy recovery provides a valuable end-of-life option for suitable bio-based materials for which no other option, besides long-term landfill, may currently exist - as long as the above requirements are all met. Such materials include suitable bio-based, durable polymers, which may not naturally degrade in domestic or commercial composting, may not be readily recycled alongside synthetic polymers and might otherwise pollute the land or sea for an extended period if not reused or remanufactured.

If E_C is the efficiency of the recycling process used for recycling the product at the end of its use phase, the quantity of waste generated in the recycling process is given by

$$W_C = M(1 - E_C)C_R. \tag{2.5}$$

There will also have been waste generated to produce any recycled content used as feedstock. This is given by

$$W_F = M\frac{(1 - E_F)F_R}{E_F}, \tag{2.6}$$

where E_F is the efficiency of the recycling process used to produce the recycled feedstock.

In contrast to the equation for W_C, the equation for W_F has the recycling efficiency E_F in the denominator. This is because the quantity $M \cdot C_R$ in the derivation of W_C is the mass of material *entering* the recycling process, whereas the quantity $M \cdot F_R$ in the derivation of W_F is the mass of material *leaving* the recycling process. To produce this amount $M \cdot F_R$ of recycled material, a mass $\frac{M \cdot F_R}{E_F}$ of material entering the recycling process is needed.

Values for E_C and E_F are material and recycling process specific and will depend on a wide range of factors, as described in Section 2.2.3.

In a closed loop, $E_C = E_F$. However, this methodology does not require a closed loop, so the recycled feedstock may come from sources other than the original product. Hence, E_C is not necessarily equal to E_F, and it is important to make a distinction between the recycling process used to produce the feedstock and the one used to recycle the product after collection.

In calculating the overall amount of unrecoverable waste W, it is important to consider both W_C and W_F. For example, if a product uses recycled feedstock but none of that product is collected for recycling, there would be no waste created while recycling the product, but $W_F > 0$ (assuming $E_F < 1$). Similarly, if the product uses 100% virgin feedstock but is collected for recycling, $W_F = 0 \text{ and } W_C > 0$. However, in general, if one were to simply add W_C and W_F together, this would double count some or all of the waste generated during the two recycling processes.

This problem is most easily explained by considering a closed-loop example, where E_C. and E_F both refer to the same recycling process. Consider a product that is made from 50% recycled material ($F_R = 0.5$), wholly collected for recycling at the end of its use phase ($C_R = 1$) and then used for new product manufacture such that $E_C = E_F = 0.5$. Because the recycling process in this example is 50% efficient, it is only possible for a single product to produce enough material at end-of-use to provide 50% of the feedstock for a new product. This is why, in this closed-loop example, only 50% of the feedstock is derived from recycled sources. Using the definitions above, it now follows that W_C $(= M \cdot 0.5 \cdot 1 = 0.5M)$ is equal to W_F $(= M \cdot 0.5 \cdot 0.5/0.5 = 0.5M)$ and considering both W_C and W_F in full would clearly double count the waste from the recycling process.

To avoid this problem, one could consider only W_C and ignore W_F, but to do this places unequal penalties on recycling at the end of the use phase over use of recycled feedstock.

A 50:50 approach is therefore used, such that $W_C \text{ and } W_F$ are given equal emphasis, and the quantity of waste generated by recycling that is associated with this product is given by

$$\frac{W_F + W_C}{2}, \tag{2.7}$$

This approach effectively assigns 50% of W_F to the product(s) that the recycled feedstock came from, and 50% of W_C to the product that will use the material which is collected and recycled.

Hence, the overall amount of unrecoverable waste is given by

$$W = W_0 + \frac{W_F + W_C}{2}. \tag{2.8}$$

Guidance on deriving E_C and E_F and how to deal with materials that are downcycled is given in Sections 2.2.3 and 2.2.4, respectively.

2.1.2.3. Calculating the Linear Flow Index

The Linear Flow Index (LFI) measures the proportion of material flowing in a linear fashion, that is, sourced from virgin materials and ending up as unrecoverable waste. So the LFI is computed by dividing the amount of material flowing in a linear fashion by the sum of the amounts of material flowing in a linear and a restorative fashion (or total mass flow, for short). The index takes a value between 1 and 0, where 1 is a completely linear flow and 0 a completely restorative flow.

The index is derived as follows:

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}} \tag{2.9}$$

The derivation of this equation is best explained by first considering the case where $E_C = E_F = 1$. This gives $W_C = W_F = 0$ and

$$LFI = \frac{V + W}{2M}. \tag{2.10}$$

Also, in this case $0 \leq V \leq M$ and $0 \leq W \leq M$ and the total mass flow is equal to $2M$.

In this case, the maximum value of 1 for LFI occurs when V and W are both equal to M, that is, when there is no recycled (or reused) content and no collection for recycling (or reuse). The minimum value for LFI (i.e., zero) occurs when $V = W = 0$, that is when there is 100% recycled (or reused) content and 100% collection for recycling (or reuse).

In order to ensure that that $0 \leq LFI \leq 1$ and that the LFI still represents the right proportion for situations when $E_C < 1$ and/or $E_F < 1$, the term $\frac{W_F - W_C}{2}$ needs to be included in the denominator of Equation 2.7. This is because:

- Owing to the 50:50 approach, half of W_C is neither part of the linear nor the restorative flow as it is not assigned to the product being recycled, but to a different product that will use the recycled material as feedstock. Hence $\frac{W_C}{2}$ is not part of the total mass flow and needs to be subtracted from $2M$ in the denominator of Equation 2.7.

- W_F is not part of the mass M of the product, but is needed additionally to create the recycled feedstock. Therefore it is part of the total mass flow. Again, because of the 50:50 approach, the actual amount that needs to be added to the denominator of the expression in Equation 2.7 is $\frac{W_F}{2}$.

A more detailed derivation of the formula can be found in Appendix B. There now follows a demonstration that it yields the right results for the closed loop example given in Section 2.1.2.2. In this case, all waste created in the recycling process is assigned to this product by the 50:50 approach (either as waste created when recycling the product, or as waste created when producing feedstock for it), and all waste considered comes from the material of the product. Hence the total mass flow should be $2M$, which is indeed the case as $W_F = W_C$; however, if, for example, E_F was less than 0.5 (or $F_R > 0.5$) an additional amount of material would be required to create the recycled feedstock and the mass flow would increase, but only by the marginal difference, that is, $\frac{W_F - W_C}{2}$.

2.1.2.4. Calculating the Utility

The utility X has two components: one accounting for the length of the product's use phase (lifetime) and another for the intensity of use (functional units).[11]

The length component L/L_{av} accounts for any reduction (or increase) in the waste stream in a given amount of time for products that have a longer (or shorter) lifetime L than the industry average L_{av}. This is based on the premise that if the lifetime of a product is doubled, the waste created and the virgin materials used per year by the linear portion of a product's flow are halved. Similarly, if the lifetime of the product is halved, the waste created and the virgin materials used per year by the linear portion of a product's flow are doubled.

The intensity of use component U/U_{av} reflects the extent to which a product is used to its full capacity. In this case, U is, on average, the number of functional units[12] achieved during the use of a product, while U_{av} is, on average, the number of functional units achieved during the use of an industry-average product of similar type. Increasing a product's use intensity results in a more efficient use of any resources that take a linear path in the material flow, and hence an improvement in the final Material Circularity Indicator.

These two components are combined to form the utility X as

$$X = \left(\frac{L}{L_{av}}\right) \cdot \left(\frac{U}{U_{av}}\right). \tag{2.11}$$

Increasing the lifetime L when the industry average L_{av} remains fixed leads to an increase in X and, correspondingly, to an increase (and thus an improvement) in the product's MCI. Conversely, if the industry average increases (e.g. because most producers start producing more durable or repairable products) while the assessed product's lifetime remains constant, its MCI will decrease. While this means that the MCI is affected by factors outside of a producer's control, this feature has the benefit of encouraging continuous improvement. The same argument applies to functional units.

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[11] Note that these should be actual values and not theoretical maxima or guaranteed values.

[12] A functional unit is a measure of the product's use. For example, it could be one kilometre driven for a car, or one wash cycle for a washing machine.

It is expected that in most cases either lifetimes or functional units, but not both, will be used to calculate X. If lifetimes are used exclusively, this means assuming that $U/U_{av} = 1$. If functional units are used exclusively, this means assuming that $L/L_{av} = 1$. If the user wishes to use both lifetimes and functional units, it is important to make sure that any given effect is only considered once – either as an impact on lifetimes, or on intensity of use – but not both.

A case study is available on the derivation of the utility factor illustrating this by way of an example.

Light-weighting

A further way of improving the efficiency of a product's portion of linear material flow is to reduce its weight whilst retaining all other product characteristics. One possible approach to incorporate this option is to include a factor M/M_{av} alongside L/L_{av} and U/U_{av} in the utility factor, where M is the product mass and M_{av} is the mass of an industry-average product of similar type.

This was not pursued for several reasons:

- Light-weighting is most likely to happen for standard economic reasons and hence most products would naturally follow M_{av}.
- While increases in a product's serviceable life and functional unit may enable large-scale material savings, light-weighting strategies usually only enable minor impacts, thus only leading to 'saving some time'.
- Defining M_{av} is not straightforward as most products come in a wide range of sizes and types, which automatically affects the

2.1.2.5. Calculating the Material Circularity Indicator

The Material Circularity Indicator of a product can now be defined by considering the Linear Flow Index of the product and a factor $F(X)$, built as a function F of the utility X that determines the influence of the product's utility on its MCI. The equation used to calculate the MCI of a product is

$$MCI^*_P = 1 - LFI \cdot F(X). \tag{2.12}$$

However, given the definition of the function F (Equation 2.12 below), this value can be negative for products with mainly linear flows ($LFI \approx 1$) and a utility worse than an average product (X <1). To avoid this, the Material Circularity Indicator is defined as

$$MCI_P = (0, MCI^*_P)\ . \tag{2.13}$$

Note that this means that two 'very linear' products cannot properly be compared to each other using this methodology (as they both might get an MCI of 0). However, as it is not anticipated that this methodology would normally be used for these kinds of product, there should not be any problems with this approach.

By having the utility factor $F(X)$ only affecting the linear part of the material flow (remember that the LFI measures the proportion of material flowing in a linear fashion), Equation 2.10 is designed to ensure that the higher the share of restorative flows in the product, the lower the influence of the product's utility. Therefore, MCI_P takes the value 1 when W and V are both 0 (i.e., $LFI = 0$), irrespective of the utility. In all other cases, F is designed to penalise products with short lifetimes and poor utilisation, and *vice versa.*

The function F is now chosen in such a way that improvements of the utility of a product (e.g. by using it longer) have the same impact on its MCI as a reuse of components leading to the same amount of reduction of virgin material use and unrecoverable waste in a given period of time[13]. This means that decreasing the linear flow by a constant factor c should have the same impact as increasing the utility by a factor c. Given the computation of MCI^*_P as of Equation 2.10, the function F should hence have the form $\frac{a}{X}$ for some constant a. Setting $a = 0.9$ ensures that the MCI takes, by convention, the value 0.1 for a fully linear product (i.e. , $LFI = 1$) whose utility equals the industry average ($\text{i.e.}, X = 1$).

So F takes the form:

$$F(X) = \frac{0.9}{X} \qquad (2.14)$$

A detailed derivation of F can be found in Appendix C.

If the utility of a product is lower than industry average, (i.e., $X < 1$), this decreases the Material Circularity Indicator. This means that for a product with $LFI = 1$ and $X < 1$, the MCI will be smaller than 0.1 and will quickly approach zero. This allows the MCI to differentiate between a fully linear product whose values for lifespan and functional units are equal to an industry – average product of similar type (i.e. , $X = 1$ resulting in $MCI_P = 0.1$) and a fully linear product with lower lifespan or functional units than industry average (resulting in $0 \leq MCI_P < 1$) as indicated by Equations 2.10 and 2.11. This explains why the MCI of a fully linear product with industry average utility has been chosen to be 0.1 instead of 0.

The following chart shows how the Materials Circularity Indicator of a fully linear product varies according to its utility.

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[13] For example, a product produced from virgin material and discarded into landfill after two years of use produces the same amount of virgin material and produces the same amount of unrecoverable waste in those two years as a similar product that is only used for one year but is produced from 50% reused components (otherwise virgin material) and of which 50% of components are reused (with the rest going into landfill).

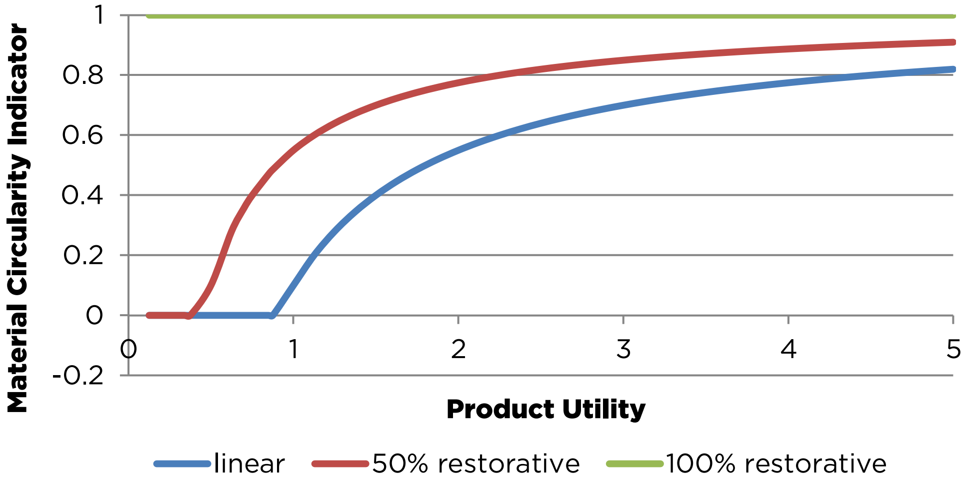

Figure 4: Chart showing impact of product utility on the Material Circularity Indicator

Note how MCI_P receives the full score of 1 for a product with fully restorative flow irrespective of the product's utility. Also note that a product's utility has much more influence on its MCI for a fully linear product compared to one with a 50% restorative (i.e. 50% linear) flow.

2.1.3. Comprehensive Approach

In reality, most products will be produced using a number of components: sub-assemblies, parts, and/or materials. If this level of detail is known, for example, via a detailed bill of materials, the Material Circularity Indicator can be built up by summing over each individual sub-assembly, part, and/or material χ.

This leads to a revised set of equations. A subscript (χ) on all the symbols previously defined is used to denote a quantity for a specific sub – assembly, part, or material χ. For example, $M_{(\chi)}$ refers to the mass of sub – assembly, part, or material χ, and the total mass M is then the sum over all $M_{(\chi)}$.

Based on the previous equations, the following quantities are defined:

The amount of virgin material for each sub-assembly, part, and/or material:

$$V_{(\chi)} = M_{(\chi)}(1 - F_{R(\chi)} - F_{U(\chi)} - F_{S(\chi)}) \qquad (2.15)$$

The total amount of virgin material (derived by summing across all sub-assemblies, parts, and/or materials):

$$V = \sum_{\chi} V_{(\chi)} \qquad (2.16)$$

The amount of waste generated at the time of collection for each sub-assembly, part, and/or material:

$$W_{0(\chi)} = M_{(\chi)}\left(1 - C_{R(\chi)} - C_{U(\chi)} - C_{C(\chi)} - C_{E(\chi)}\right) \tag{2.17}$$

The quantity of waste generated in the recycling process:

$$W_{C(\chi)} = M_{(X)}\left(1 - E_{C(\chi)}\right)C_{R(\chi)} \tag{2.18}$$

The waste generated to produce any recycled content used as feedstock:

$$W_{F(\chi)} = M_{(\chi)}\frac{\left(1 - E_{F(\chi)}\right) \cdot F_{R(\chi)}}{E_{F(\chi)}} \tag{2.19}$$

The total amount of waste generated:

$$W = \sum_{\chi} \left(W_{0(\chi)} + \frac{W_{F(\chi)} + W_{C(\chi)}}{2}\right), \tag{2.20}$$

and the Linear Flow Index:

$$LFI = \frac{V + W}{2M + \sum_{\chi} \frac{W_{F(\chi)} - W_{C(\chi)}}{2}}. \tag{2.21}$$

Calculation of the MCI remains as per Equations 2.10 and 2.11.

It is also possible to consider several levels: a product may be constructed from sub-assemblies, where each sub-assembly is built up from a number of components (which may themselves be sub-assemblies or parts), and each part is made from one or more materials. This would involve multiple levels of nested summations.

Going into additional levels of detail offers much more insight into the product, and this approach should be used for all but very simple products completely dominated by one material. In particular, if the Material Circularity Indicator is used in conjunction with complementary indicators as described in Section 2.3, a thorough understanding of the material composition is necessary, and acquiring the knowledge on this will also help generally in gaining a better understanding of a company's products and supply chains.

2.1.4. Material Losses in the Supply Chain

The methodology so far is based purely on the material present in the final product. A more complete approach would be to also take the material losses that occur throughout the supply chain of the product into account – from raw material extraction and refinement, through all manufacturing stages, to final assembly. Whilst such an approach is to be encouraged, in practice it is often limited by a shortage of available data. For practical reasons, it is therefore not included in the main part of this methodology. However, those wishing to incorporate supply chain material flows may follow the expanded methodology detailed in Appendix A.

In the future, if companies build up more knowledge about the material flows in their supply chains, it may prove possible for complete chain approaches to become incorporated in a future version of this methodology.

2.1.5. Assumptions and Limitations

The model has been built on the following assumptions, many of which have been addressed more completely elsewhere in this document:

- The indicator does not explicitly favour closed loops. That is to say, for example, that material recovered for recycling does not need to return to the original manufacturer.[14]
- It is assumed that recovered material at the end of use can be processed to a similar quality as the original virgin material. For further information, see Section 2.2.3.
- It is assumed that there are no material losses in preparing collected products for reuse.
- It is assumed that the mass of the product does not change from manufacture to the end of use. In particular, this means that no part of the product is 'consumed' (e.g. eaten or burned) during its use.

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[14] However, closed loops usually allow purer material streams, increasing the recycling efficiency. Also, closed loops are necessary for component reuse. This means that implementing closed loops will increase the MCI without requiring explicit consideration in the methodology.

2.2. Guidance for Use of this Methodology

When applying this methodology, users are asked to reference this document as the source of the methodology.

Whenever possible, input data should be specific to the product under assessment. Where product-specific data is unavailable, generic data may be used. Users are requested to be as transparent as possible on the input parameters they have used, especially where generic data has been deployed.

The following guidance can also be used when applying the methodology.

2.2.1. Recycled Feedstock

If the recycled content of feedstock is unknown, it is reasonable to use a relevant regional average or the global average if this is also unknown.

Figures for the global average recycled content of different materials can be obtained from a number of sources, such as trade associations, commercial lifecycle analysis databases, and published tables – for example, the Inventory of Carbon & Energy (ICE) published by the University of Bath, LCDN (the Life Cycle Data Netwok), or the US LCI database published by the NREL (National Renewable Energy Laboratory).[15]

2.2.2. Recycling Collection Rates

In the absence of product-specific data, sector collection rates may be used. This may be facilitated by the fact that some products in some jurisdictions are subject to regulations governing collection for recycling. For example, the European Union sets collection targets for Waste Electrical and Electronic Equipment (WEEE), vehicles and packaging. It is also important to recognise that recycling collection rates may be influenced by the market price of virgin material.

2.2.3. Recycling Process Efficiencies

The variable E denotes the efficiency of the recycling process for a specific material and recycling process. Values for E will depend on a wide range of factors such as:

- The material(s) – some materials, for example metals, are inherently easier to recycle and will often have higher recycling efficiency.
- The quantity of material(s) involved – when a product is recycled the principal components by mass are often recycled with higher efficiencies than those at lower overall concentrations. Recycling efficiency is also affected by the presence of pollutant in material scrap and/or the presence of coatings.

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[15] http://www.nrel.gov/lci/

- The recycling preparation process – higher efficiency can be expected when product disassembly takes place prior to material recovery; lower values are more likely when a product comprises a number of components of different material types and is fragmented prior to some form of materials separation process.

Once a range of material streams has been produced from a product with multiple components, different material recovery processes will have different efficiencies.

A good understanding of the typical recovery and recycling processes for a given product will be required to obtain accurate values for E. Ideally, there should be a value for each material and for each specific recycling process (e.g. mobile phone recycling, or scrapping of vehicles). In cases where application – specific values for E are unavailable, generic values can be used, and users of the methodology should state this.

Generic values for E have limitations because the real values are likely to vary with time, by application, recycling technology and demand. However, those values for the recycling efficiency can be derived from various sources, for example:

- Reference Documents on Best Available Techniques from the European IPPC Bureau[16]
- U. Arena, LCA of a Plastic Packaging Recycling System, the International Journal of Life Cycle Assessment, March 2003, Volume 8, Issue 2, pp. 92-98
- P. Shonfield, LCA of Management Options for Mixed Waste Plastics, WRAP, 2008

2.2.4. Downcycling

The term downcycling is often used to describe a recycling process that reduces the quality and economic value of a material or product. Similarly, upcycling is used to describe a recycling process that increases the quality and economic value of a material or product. Both terms are open to very wide interpretation and no standard definitions have been generally adopted.

In practice, there exists a continuum of varying degrees of down- and upcycling. This methodology does not incorporate any form of sliding scale to accommodate these (although this may change in future developments). Rather, the following rules and guidance should be followed when material is considered as being collected for recycling.

General requirement

The collected material should be able to be separated into its component materials using a proven, financially viable process. It should not remain as an inseparable mixture of different materials.

Guidance

- A mixing of colours and minor contaminations are acceptable.
- If it can be proven that the material mix is used in products for which a further recycling process exists that allows the material mix to be recovered and recycled again, the downcycling into the material mix can be considered recycling.

If downcycled material is used as a feedstock, it is generally acceptable to consider this as recycled material (bearing in mind that the material cannot be considered as collected for recycling at the end of use unless the above requirements are satisfied).

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[16] See http://eippcb.jrc.ec.europa.eu/reference/; for example, Reference Document on Best Available Techniques in the Non Ferrous Metals Industries.

For example, consider a product that contains aluminium and plastic that cannot be economically separated after the product's use. The mix of those two materials could theoretically be used in similar applications as the plastic on its own. However, in this example, it is assumed that currently there is no market for this material and also no recycling stream at the end of use for a product using this mixed material as a feedstock. Hence the portion of the mass of the original product represented by these two materials cannot be considered as collected for recycling.

2.2.5. Utility (Lifetimes and Functional Units)

Companies are expected to have a reasonable understanding of the typical lifetime L of their products. This is often assessed from warranty return rates and product testing using well-known product reliability models, such as the classic 'bathtub' curve which indicates initial levels of early product failures as manufacturing defects manifest themselves, followed by the serviceable life and finally the wear-out phase.

The industry-average lifetime L_{av} of a product of similar type may be more difficult to establish. However, estimates may be obtained if market size in terms of sales per annum and market penetration levels are both known.

If it is not possible to provide a good estimate of L/L_{av}, the average lifetime L_{av} should be deemed equal to L so that $L/L_{av} = 1$.

Companies may also be expected to have a reasonable understanding of the typical number of functional units U for their product. These values will, like L, be evaluated from warranty return rates and product reliability testing.

If it is not possible to provide a good estimate of U/U_{av}, the average utility U_{av} should be deemed equal to U so that $U/U_{av} = 1$.

As already mentioned, it is expected that in most cases one would use either lifetimes or functional units. If both lifetimes and functional units are used, it is important to make sure that any given effect is only considered once – either as an impact on lifetimes, or on intensity of use, but not both.

2.2.6. Shared Consumption Business Models

The utilisation of a product may be improved if it is shared across a significant number of consumers during its use phase. For example, a product may be supplied on short-term hire to a large number of people. If the average number of functional units per hire is U_h, the total number of functional units used during its use phase will be $U = H \cdot U_h$ where H is the number of times it has been hired. If this results in U being larger than U_{av}, the product will demonstrate an improved level of circularity.

2.2.7. Consumables Related to a Product

In most cases, consumables (e.g. the cartridges of a printer or the capsules of a coffee machine) will have different utility factors compared to the product they relate to. This means it is not possible to incorporate them directly into a product assessment. It is therefore recommended that separate MCIs are calculated for consumables related to a product.

If a consolidated MCI for the product including its consumables is required, a method for MCI consolidation similar to the one described in the company-level methodology may be used (see Section 3.1.5).

2.2.8. Material Losses in the Supply Chain

Section 2.1.4 describes how to extend the standard product MCI approach to include material losses in the supply chain. In undertaking such an evaluation the user will need to decide how far upstream to take the assessment. One option would be to cover manufacturing operations whilst excluding mining, extraction and refining operations. Another would be to include all or some of these. The user will need to decide on, and should be transparent about, the extent to which any calculation has included upstream waste.

2.2.9. Material Losses During Product Use

Although the methodology does not specifically address materials lost through consumption or processes such as wear, these can, in many cases, be considered within the methodology quite simply. For example, for a technical product such as a vehicle tyre, a substantial portion of the original mass of material is lost through wear and discharged into the environment - in such an example the lost material could be equated to material that is sent to landfill or incinerated as it is, in essence, beyond recovery. The circularity of such a product would need to account for such losses. For food materials, which are consumed by people or livestock, a similar approach would need to be taken, accounting for the typical downstream recovery of the resulting biological waste by agricultural or municipal systems and the extent to which this recovery supported the regeneration of the natural systems used for growing the resources used in the product. Reasonable assumptions could be made if the scope of the material flows is outside the immediate control of the business responsible for introducing the product to the market.

2.3. Suggested Complementary Indicators

The complementary indicators are additional indicators that can be used alongside the MCI to offer further business management insight into the product. These indicators are suggested to help prioritise circularity actions based on business risks or consequential impacts which may be of importance to a business, its stakeholders or the environment. Examples of use cases include:

- Which materials, parts or products should I focus on based on risk or impact?
- My business priorities are X, Y and Z; where is my highest risk or impact?
- Can I mitigate this risk by making my product more circular?

Although there will be some overlap between the categories such complementary indicators may be broadly categorised into:

i. Complementary risk indicators that may provide further insights into potential risks in relation to business priorities
ii. Complementary impact indicators that may provide additional information to evaluate how changing the level of material circularity affects other impacts of interest to businesses and their stakeholders

Where a comprehensive approach has been adopted (see Section 2.1.3), a more detailed analysis of the different levels of sub-assemblies, components and/or materials is possible. MCI values can also be compared against complementary indicators at these levels. Any data comparison or decision-making methods may be used, which will depend on the business' own priorities or approaches. For example, comparative tables, graphical representations or multi-criteria decision analysis approaches could be used (see Figure 5). The schematic in Figure 5 (b) illustrates one possible and simple option for comparing MCI values to a complementary indicator (e.g. supply risk or energy usage).

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...			

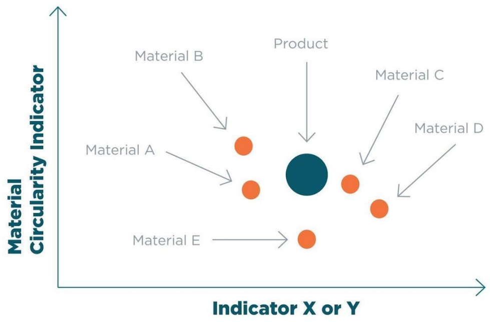

Figure 5: Example of comparing indicators to aid decision-making: (a) comparative table; (b) graphical representation specifically for comparing MCI values to the results of one complementary indicator.

2.3.1. Complementary Risk Indicators

Where a product's bill of materials has been used to evaluate the MCI using a comprehensive approach, there will be knowledge of the quantity of all types of material used in the production of the product. This opens up the opportunity to associate the MCI with a number of risk indicators associated with material use. The specific indicators used are optional; it is up to businesses to decide which risks are important to them. Example indicators are provided below.

2.3.1.1. Material Price Variation Risk

Knowledge of historic material prices (and/or future price projections) can be used to identify high-risk materials from price variation and price volatility perspectives. An approach has been developed for this project, termed Material Price Variation, and is detailed below. However, other approaches may be used, for example using historic price data from McKinsey Global Institute[17] or other measures of price volatility or maximum price variation for materials from relevant sources.

The Material Price Variation Indicator has been developed in conjunction with this MCI methodology. It can provide an indication of the change in material price for a given product, on an annual basis and a given time horizon, for example, the past five years. It also provides statistical analyses to indicate the trend over the same period. It represents a new indicator added by this methodology, unlike the other indicators that already exist.[18]

Considering the annual product mean price over the past 5 years, different statistical analyses are conducted to identify if the trend has been due to increment, decrease or no change, as well as to indicate level of price volatility of the product. The statistical analyses can include:

- price arithmetic mean over the past 5 years
- price delta over the past 5 years (Year 1 price subtracted from Year 5 price, a +/- sign shows the overall trend)
- price standard deviation over the past 5 years
- price range over the past 5 years (maximum price minus minimum price)

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[17] The McKinsey Global Institute publishes historic price data, variation and volatility statistics for a number of commodities at http://www.mckinsey.com/insights/energy_resources_materials/resource_revolution_tracking_global_commodity_markets/.

[18] Sources for existing material criticality risk indicators include:

- J.R. Goddin, J. O'Hare, A. Clifton and N. Morley, The materials supply risk: digging deeper, Materials World – Institute of Materials, Minerals and Mining, June 2013, p. 23.
- J.R. Goddin, Material Tools for Product Design, COST-Materials in a resource constrained world, Proceedings, 2013, Slide 125, (http://collegerama.tudelft.nl/Mediasite/Play/9ba73dfdb0684ab2a846dd5b439ef6b21d time stamp 01:08:00).
- J.R. Goddin, W. Martin, K. Marshall and A. Clifton, Identifying Supply Chain Risks for Critical and Strategic Materials, Shechtman International Symposium, 2014,
- European Commission, Report of the Ad-hoc Working Group on defining critical raw materials, 2014.
- S.J. Duclos, J. P. Otto and D. G. Konitzer, Design in an Era of Constrained Resources, Mechanical Engineering-CIME, September 2010.

- average annual price variation over the past 5 years[19]

2.3.1.2. Material Supply Chain Risks

Risks concerning the continuity of supply of a material for a product are related to the availability of that material for purchase by the product's manufacturer. In practice, there exists a complex interaction between the availability of a material, the competing markets for the use of that material, supply and demand within each of those markets, regulatory limitations for legal extraction, political stability of states rich in the material and the ability of their respective product purchasers to absorb increases in cost due to these factors.

Hence, supply chain risk can be associated with a number of factors. For example, high risks may be experienced in supply of materials where countries:

- have a monopoly, or near monopoly, of supply
- have weak legal and governance systems
- have poor environmental standards
- are sources of conflict minerals as specified under the Dodd Frank Act[20] or the European Union Conflict Minerals Regulation.

The following specific indicators related to the above may be used:

- The Herfindahl-Hirschman Index (HHI) is an indicator of monopoly of supply for an element. It is defined by the sum of the squares of the market share for the producers of that element.[21]
- The Sourcing and Geopolitical HHI is a modified and scaled version of the HHI that embodies the geopolitical risk of the producing countries, as well as the monopoly in the supply of the material. It uses the World Bank's Worldwide Governance Indicator (WGI),[22] which represents six dimensions of governance for each producing country. The dimensions of governance have been aggregated to provide a single indicator (WGI) that is expressed for 213 economies.
- The Environmental Country HHI is a modified and scaled version of the HHI that embodies the producing countries' environmental performance as well as the degree of monopoly in the supply of the material. It uses the Environmental Performance Index (EPI)[23] produced by Yale University as the measure for the environmental performance associated with each country.

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[19] In order to take into account both long-term and short-term risk, an estimation of price variation within each year (used for the 5 year variation calculation) is recommended. The annual price variation should be estimated according to at least one of the following statistical analyses:

- price standard deviation of prices from mean annual price
- price range over the year (maximum price minus minimum price)

The analyses should be performed on monthly, weekly or daily prices according to the specific needs of the case or the availability of data.

[20] Dodd–Frank Wall Street Reform and Consumer Protection Act, Public Law 111–203, July 2010, Section 1502.

[21] European Commission, Report of the Ad-hoc Working Group on defining critical raw materials, 2014.

[22] The World Bank, Worldwide Governance Indicators (WGI) project, 2010 (see http://info.worldbank.org/governance/wgi/index.asp).

[23] Yale University, Environmental Performance Index, http://epi.yale.edu.

- An indicator that reports the risk that an element has been obtained from a 'conflict mineral'. The concept of a conflict mineral is enshrined under the US Conflict Minerals Law and at present includes: columbite-tantalite (coltan), cassiterite, gold and wolframite or any derivative of these, and any other mineral or derivative determined by the US Secretary of State to be financing conflict in the Democratic Republic of Congo.[24]

2.3.1.3. Material Scarcity

Future supply may be constrained for particularly scarce materials (in the earth's crust). There are a number of approaches to assess scarcity, each of which having its own benefits and constraints. These include:

- crustal abundance
- reserves to production ratios
- the results of the EU Ad-hoc Working Group on Defining Critical Raw Materials[25]

Specific indicators related to the above include:

- abundance in the Earth's crust as an estimate of the element's abundance in the Earth's upper continental crust (in parts per million, by mass) which can be obtained from a range of sources, including British Geological Survey[26] and US Geological Survey[27]
- availability of critical raw materials, as described in the EU Report of the Ad-hoc Working Group on defining critical raw materials[28]

The notion of 'absolute scarcity' or that we are likely to run out of a specific resource has been widely debunked for most technical resources, although there is a more specific risk of economic scarcity as the cost of extracting materials becomes more expensive as the easily available resources are consumed and the typical yield decreases as a result. The concept of absolute scarcity for biological materials may however be far more real as the world continues to experience mass extinction and whole ecosystems are threatened by climate change and severe weather events. At present there are no known metrics which deal with the scarcity of biological materials.

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[24] J.R. Goddin, W. Martin, K. Marshall and A. Clifton, Identifying Supply Chain Risks for Critical and Strategic Materials, Shechtman International Symposium, 2014.

[25] European Commission, Report of the Ad-hoc Working Group on defining critical raw materials, 2014; Annex V to the Report of the Ad-hoc Working Group on defining critical raw materials, 2010 (available at http://ec.europa.eu/enterprise/policies/raw-materials/files/docs/report-b_en.pdf).

[26] British Geological Survey, World Mineral Production, http://www.bgs.ac.uk/.

[27] US Geological Survey, Minerals Information, http://minerals.usgs.gov/.

[28] European Commission, Report of the Ad-hoc Working Group on defining critical raw materials, 2014.

2.3.1.4. Toxicity

Products and materials containing toxic substances can be subject to current regulation and are susceptible to future restrictions. It may also disrupt the extended use of the material, hence limiting its use and potential future economic value. This includes identifying materials and/or substances that may fall under legislation or standards that may restrict their use in products.

Some examples of substances legislation and lists that could be considered when looking into material toxicity are:

- EU REACH regulation:[29] The Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) is a regulation in the European Union, adopted to improve the protection of human health and the environment from the risks that can be posed by chemicals, while enhancing the competitiveness of the EU chemicals industry. It also promotes alternative methods for the hazard assessment of substances in order to reduce the number of tests on animals.
- EU RoHS directive:[30] The Restriction of the Use of Certain Hazardous Substances (RoHS) directive bans the placing on the EU market of new EEE containing more than the agreed levels of lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE) flame retardants.
- Substitute It Now! (SIN) List from the International Chemical Secretariat (ChemSec):[31] The chemicals on the SIN List have been identified by ChemSec as Substances of Very High Concern based on the criteria established by the EU chemicals regulation REACH.
- Cradle to Cradle Certified™ Banned List of Chemical: [32] This list contains those chemicals and substances that are banned for use in Cradle to Cradle Certified™ products as intentional inputs above 1000 ppm due to their tendency to accumulate in the biosphere and to lead to irreversible negative human health effects.

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[29] REACH Legislation (see http://echa.europa.eu/regulations/reach/legislation), REACH Regulation, Registration, Evaluation, Authorisation and Restriction of Chemicals, EC No 1907/2006, in particular Article 33.

[30] Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment, Dir. 2011/65/EU.

[31] ChemSec, SIN (Substitute It Now!) List, 2014, http://sinlist.chemsec.org/.

[32] Cradle to Cradle Products Innovation Institute, *Cradle to Cradle Certified™ Banned List of Chemicals*, 2013 (see http://www.c2ccertified.org/resources/detail/cradle-to-cradle-certified-banned-list-of-chemicals/).

2.3.2. Complementary Impact Indicators

Increasing (or decreasing) the Material Circularity Indicator of a product may have consequential impacts, which may be of importance to a business and its stakeholders. The specific indicators used are optional; it is up to businesses to decide which impacts are important to them. Example indicators are provided below.

2.3.2.1. Energy Usage and CO_2 Emissions

In most cases increasing the circularity of a product would be expected to decrease the energy used for raw material production and product manufacture – and consequential CO_2 emissions. However, this should be evaluated on a case-by-case basis. The calculation of this requires knowledge of the energy and carbon intensity of materials[33] as well as the energy used in the product's manufacture and disposal.

Well-established standards and methodologies for energy and CO_2 emissions already exist, for example:

- Life Cycle Assessment approaches can be used to assess the energy consumption for each stage of a product life (e.g. see the ISO standard on Environmental management[34]). It is important to use an approach that avoids double counting of energy savings. The mentioned ISO standard as well as other experts[35] recognise this issue and offer a range of optional approaches. CO_2 emissions would follow a similar approach being an extension of energy consumption. Following international recognised product carbon footprinting methodologies, these would include PAS 2050:2011,[36] ISO 14067:2018 [37] and GHG Protocol Product Life Cycle Accounting and Reporting Standard.
- An environmental product declaration (EPD) is a standardised way of quantifying the environmental impact of a product or system. EPD is a verified document that reports environmental data of products based on LCA and other relevant information and in accordance with the international standard ISO 14025 (Type III Environmental Declarations)[38]. Declarations include information on the environmental impact of raw material acquisition, energy use and efficiency, content of materials and chemical substances, emissions to air, soil and water, and waste generation.

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[33] See for example, University of Bath, Inventory of Carbon & Energy (ICE), 2008, and European Commission, European reference Life Cycle Database (ELCD), http://eplca.jrc.ec.europa.eu/ELCD3/.

[34] ISO 14044:2006. Environmental management – Life cycle assessment – Requirements and guidelines; Covers life cycle assessment (LCA) studies and life cycle inventory (LCI) methodology.

[35] C.I. Jones, Embodied Impact Assessment: The Methodological Challenge of Recycling at the End of Building Lifetime, Construction Information Quarterly (CIQ), The Chartered Institute of Building, 11 (2009), no. 3.

[36] PAS 2050:2011, Specification for the assessment of the life cycle greenhouse gas emissions of goods and services (see www.bsigroup.com/PAS2050).

[37] ISO 14067:2018, Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification

[38] ISO 14025:2006, Environmental labels and declarations – Type III environmental declarations – Principles and procedures (see also http://www.environdec.com/).

2.3.2.2. Water

In most cases changes to the circularity of a product are expected to change the amount of water used for raw material production and product manufacture. There is an ISO standard for reporting water footprints (ISO 14046:2014[39]). The calculation of this for products requires knowledge of the water intensity of materials. It should be noted that true impact of water usage is dependent on the location(s) it is extracted from and the level of water stress in those locations.

2.3.2.3. Toxicity

Harmful chemicals can be contained in the material composition or may be added to the composition to impart specific properties (e.g. fire retardants, plasticisers or pigments). They can also be applied to products within coatings or preservatives. Such chemicals have the potential to disrupt biological species when released into the environment in even comparatively small amounts. Chemicals can also be concentrated through the food chain resulting in much higher levels of exposure. It is important to note that this can be true as much for recycled materials as for virgin materials and it would be appropriate to consider the likely exposure scenarios for circular economy products as part of the overall assessment and to seek to minimise such consequential impacts through avoidance or appropriate recovery.

2.4. Guidance on Profitability Impact of Circular Initiatives

As the three 'Towards the Circular Economy' reports by the Ellen MacArthur Foundation[40] have demonstrated, businesses can capture significant economic benefits from circular economy principles: materials and energy cost savings, new markets and sources of revenue, and a greater resilience to external shocks. A number of companies are already leveraging these opportunities across sectors.[41] How profitable a circular initiative is will depend on a number of factors, and, most likely, there won't be a simple correlation between an increase in the Material Circularity Indicator of a product and the associated business benefits.

This section aims to provide guidance to help estimating the profitability of circular economy initiatives in the technical cycle. Section 2.4.1, provides an overview of the main insights for four main strategies. When using a combination of strategies, for example, for the different components of a product, consideration of the different aspects of these guidelines will be useful. Section 2.4.2 gives further information on the drivers of revenue and costs and approaches to consider optimising profitability.

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[39] ISO 14046:2014, Environmental management — Water footprint — Principles, requirements and guidelines.

[40] The Ellen MacArthur Foundation, Towards a Circular Economy, Volumes 1-3, 2012-2014.

[41] Some examples can be found at http://www.ellenmacarthurfoundation.org/case_studies/.

2.4.1. Overview of Profitability for Four Key Strategies

2.4.1.1. Resale and Use Period Extension

Reselling a product in its entirety or extending its use period is the strategy that preserves most of its integrity and complexity. This is therefore the approach that can give rise to the greatest economic benefits compared to a linear model. In most cases, the increase in profitability will come from capturing new markets, for example, by offering a more cost effective option for a high-performing product. In some models (e.g. if product quality and price point only change marginally), it may also be interpreted as a cost reduction instead.

Activities such as repair and maintenance help to achieve the product’s best performance for as long as possible, and when these are offered as services, they can translate into new revenue streams. Tweaks or more radical changes in product design can further optimise the benefits by helping extending a product's lifetime.

2.4.1.2. Refurbishment and Remanufacturing

Refurbishment refers to returning a product to good working condition by replacing or repairing major components that are faulty and can also include making ‘cosmetic’ changes to update the appearance of a product. Remanufacturing restores at a component level: reusable parts are taken out of a used product, potentially repaired and rebuilt into a new one. This process usually includes quality assurance and products can be sold ‘as-new’. Both of these approaches retain major parts of the integrity and complexity of a product, and therefore can also enable savings in materials and energy costs. Rethinking product designs is especially important for these strategies and is sometimes needed to create a positive business potential.

2.4.1.3. Recycling

If there is no possibility for reuse, refurbishment or remanufacture, the materials in a product can still be recycled. While in this case all the integrity and complexity of the product is lost, the value of the materials contained in the product can be preserved. A company might decide to sell the recyclable parts of a product to a third party treatment plant or reuse the recycled materials for its own production. In the first case, the company creates a new revenue source, while in the second case, it captures materials cost savings but it also secures a safe supply of materials. Improvement in design can greatly improve the profitability of the model, for example by enabling easier disassembly or using pure and easy-to-recycle materials. This can help to optimise the revenue or saving costs depending on the case.

2.4.1.4. Service and Performance Models

Service and performance models allow companies to preserve ownership of their products and facilitate their after-use recovery. They include models such as rentals (e.g. clothing rental model), pay-per-use (e.g. a pay-per-wash model for a washing machine) or a service offering including the maintenance, repair and upgrade of the product. These can be combined with the other strategies mentioned above and can help to facilitate the collection of the products while creating new sources of revenues (e.g. by combining the model with a service offering) and capturing larger market share (e.g. by making a product available at a low initial investment).

2.4.2. Revenue and Cost Drivers

The two tables below synthesise the key drivers of revenue (in the first table) and costs (in the second table) across the different strategies. The first column of each table gives the new revenue or cost saving while the second column details possible drivers of revenue reduction or new costs, respectively. The last column suggests approaches by which a company can optimise the profitability of the model.

2.4.2.1. Impact on Revenue

Potential drivers of revenue increase	Potential drivers of revenue decrease	Approaches to consider to optimise profitability
Capturing new revenue streams	Verifying Sustained Production of materials used (e.g. FSC labels)	• Moving to service models can help companies to capture new revenue streams, for example, by starting a leasing solution or offering complementary services.
		• New revenue streams can also be achieved through the sales of end-of-use products or by-products to third parties (e.g. a recycling plant). In some cases, improvement in designs can help to improve the relationships with the third parties or to land a better contract. • Reduced exposure to downstream product liabilities, (e.g. Extended Producer Responsibility, climate change related lawsuits.)
Capturing new markets or a greater market share		• Through circular economy principles, companies can improve the attractiveness of their products by offering cheaper, more convenient or higher quality solutions. The right pricing will help to reach the right segments and maximise total revenue. • In the case of industries with a grey market capturing value from the company's products, there is an opportunity of expanding market share while keeping better control of the use of the company’s brand.
	Cannibalising existing sales	• When offering new product lines, companies need to mitigate the risk of cannibalisation (i.e. the loss of existing sales). Targeted marketing can also be helpful here.

2.4.2.2. Impact on Costs

Potential drivers of cost decrease	Potential additional costs	Approaches to consider to optimise profitability
Reducing the costs of production by preserving embedded energy, materials and labour		• Inner circle approaches, such as reuse or refurbishment, preserve more of the integrity and complexity of products, which can be seen as their embedded energy, materials and labour. These approaches therefore enable greater cost savings. • More durable products also make better use of embedded materials, energy and labour. The planned product lifetime should also take into account the intended use. For example, the design of a high tech product should take into account that technologies will evolve in the coming years.
	Costs of collection and reverse logistics (in particular labour and transportation)	• Most circular approaches require some sort of product collection. Innovative business models, such as take-back schemes or performance models can facilitate the collection of products. • In some cases, idle space can be leveraged in return trips from forward logistics (e.g. empty trucks returning from a delivery). This can significantly reduce logistics costs. • Collaboration is often essential at this stage.
	Costs of treatment (e.g. remanu-facturing or recycling process)	• Changes in design and treatment approaches help to reduce the costs of reverse treatment (e.g. design for disassembly). Already small tweaks requiring minimal investment and relying on existing technology can significantly improve the business case.[42]
	Potential other costs: initial design or R&D investment; marketing	

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[42] See, for example, Figure 11 B in: The Ellen MacArthur Foundation, Towards a Circular Economy, Volume 1, 2012

3. Company-Level Methodology

3.1. Material Circularity Indicator

The development of the company Material Circularity Indicator (MCI) is based on the hypothesis that the material circularity of a company can be built up from the material circularity of the company's products. As such, the MCI for a company follows the same general approach as the MCI for a product. The company-level MCI is then obtained as a weighted average of product level MCIs. A complementary view on a company's circularity beyond material flows, to empower strategic decisions and open up opportunities to generate brand value can be obtained using Circulytics, an Ellen MacArthur Foundation method that will be launched in early 2020. Circulytics focuses on a holistic set of indicators that describe a company's ability to capture CE opportunities in the future, as well as how circular the company is today. Section 3.3. explains in more detail how MCI and Circulytics complement each other.

3.1.1. Time Period Covered by the Assessment

The assessment may cover any time period. In most cases this is likely to be one year but it could be longer or shorter. The user of the methodology should state the time period used for the calculation.

3.1.2. Reference Products

For many businesses it would not be practical to undertake an MCI assessment for every single product placed on the market. This company-level methodology therefore takes a reference product approach where each reference product represents a range of similar products.

On the one hand, the greater the number of reference products, the more accurate the assessment is likely to be. On the other hand, the lower the number of reference products, the more efficient the process becomes. Therefore, it is not possible to give general rules on how many reference products to use. It is up to the user of the methodology to find the right balance between accuracy and practicality. However, they should describe the process undertaken and criteria used for reference product selection.

For a product to be part of a product range represented by a reference product, it should be sufficiently similar to this reference product. In particular it should exhibit:

- similar material composition in terms of the type of material and their relative masses
- similar levels of recycled and reused content in the feedstock
- similar levels of recycling and reuse after use
- similar utility characteristics

3.1.3. De Minimis Rule

Any product that cannot be included in one of the product ranges represented by the selected reference products, can be excluded from the assessment under this de minimis rule provided that:

- the total of the mass of all de minimis products is not greater than 5% of the total mass of shipped product, and
- the total revenue arising from de minimis products is not greater than 5% of the total revenue arising from shipped product.

If either of these is not satisfied, further reference products need to be created.[43]

3.1.4. Calculating the Material Circularity Indicator for a Reference Product Range

The MCI for each reference product should be determined using the product level approach described in Section 2.1. Given the requirements for inclusion in a product range listed in Section 3.1.2, it follows that the MCI for the reference product is an approximation for the MCI of all products in the product range represented by this reference product. Hence this MCI can then be used for all products in the reference product range.

3.1.5. Aggregating Material Circularity Indicators

In order to combine the MCIs for a number of product ranges, a normalising factor is used to determine a weighted average of the product's MCIs.

3.1.5.1. Normalising Factors

There exist a number of candidates to be used as the normalising factor. For reasons of usefulness and practicality, product mass and sales revenue as defined below have been selected for use in this methodology.[44]

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[43] It is here assumed that it is not known at this stage of the process which normalising factor is going to be used. If this has already been determined, it is acceptable if the criterion is only satisfied for the quantity used as normalising factor.

[44] Other options include, for example, cost of goods sold or raw material costs.

Factor	Definition	Comments
Product Mass	The mass of the final manufactured product. Equal to the parameter M used in the product-level methodology.	- Mass is the option most consistent with the product-level MCI. - Heavy products can dominate the final result. - Input data is readily available.
Sales Revenue	Revenue (turnover) generated from the sale of the product.	- Input data is easily obtainable from company accounting systems. - High value products can dominate the final result

The user should state the normalising factor selected and the reasons for their choice.

3.1.5.2. Calculating the Material Circularity Indicator for a Department or Company

Consider a company comprising d departments labelled D_1 to D_d (cf. Figure 6). Each department α has $r(\alpha)$ unique product ranges, each of which has a reference product. The product ranges for department α are labelled $R_{(\alpha,1)}$ to $R_{(\alpha,r(\alpha))}$ and the corresponding reference products $P_{(\alpha,1)}$ to $P_{(\alpha,r(\alpha))}$.

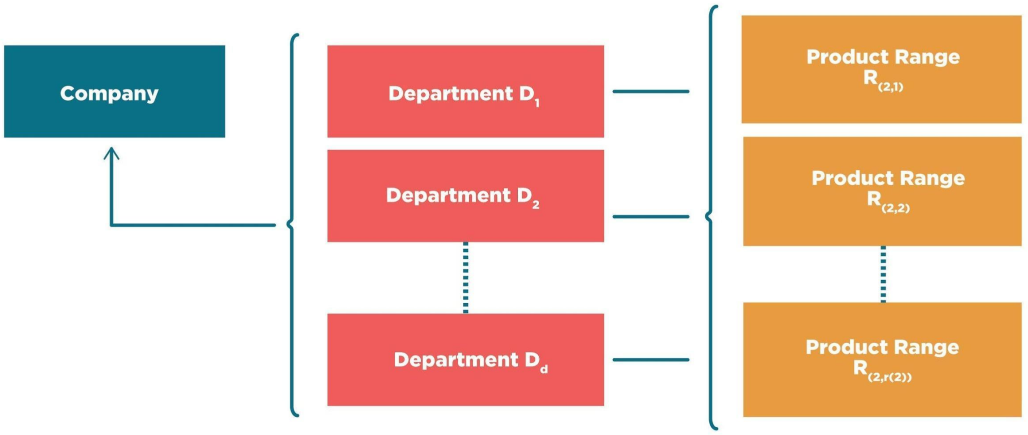

Figure 6: Example company structure

To combine the MCIs of all product ranges in department α into the Material Circularity Indicator for this department, one first has to calculate the total normalising factor $N_{D(\alpha)}$ for that department according to

$$N_{D(\alpha)} = \sum_{\beta} N_{R(\alpha,\beta)}, \tag{3.1}$$

Where $N_{R(\alpha,\beta)}$ is the normalising factor for product range $R_{(\alpha,\beta)}$.

The Material Circularity Indicator $MCI_{D(\alpha)}$, for department α, is now calculated as a weighted average according to

$$MCI_{D(\alpha)} = \frac{1}{N_{D(\alpha)}} \sum_{\beta} \left(N_{R(\alpha,\beta)} \cdot MCI_{P(\alpha,\beta)}\right), \qquad (3.2)$$

Where $MCI_{P(\alpha,\beta)}$ is the Material Circularity Indicator for the reference product $P_{(\alpha,\beta)}$.

The Material Circularity Indicator MCI_c for the company is now derived similarly as a weighted average, according to

$$MCI_c = \frac{1}{N_c} \sum_{\alpha} \left(N_{D(\alpha)} \cdot MCI_{D(\alpha)}\right), \qquad (3.3)$$

where $N_c = \sum_{\alpha} N_{D(\alpha)}$.

3.2. Guidance for Use of this Methodology

When applying this methodology, users are asked to reference this document as the source of the methodology.

Users are also requested to be as transparent as possible with regard to the input parameters they have used and any approximations made where the actual data is unknown.

The following guidance can also be used when applying the methodology.

3.2.1. Normalising Factors

The normalising factor should be selected to give the best representation of the overall company as possible. In particular, users should avoid using a normalising factor that results in a particular product set affecting the result in a way that is not reflective of its place in the overall product portfolio.

For example, if one product set is particularly heavy but of low economic value, this could dominate a company-level MCI calculated using mass as the normalising factor. In this case, using revenue as the normalising factor may be more appropriate.

3.2.2. Aggregating Material Circularity Indicators

A simple spreadsheet has been developed for aggregating a set of reference product MCIs according to the equations outlined in this Chapter. This is available to download from the Circularity Indicator Project website.[45]

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[45] http://www.ellenmacarthurfoundation.org/circularity-indicators/

3.3. Suggested Complementary Indicators

As in the case of the product-level indicators, complementary indicators can be used alongside the MCI to provide additional insight.

The complementary indicators described in Section 2.3 of the product-level methodology can all be used at the company level provided there is a suitable way of combining the complementary indicators for each product range.

While company-level MCI represents an accurate view of the circularity of a company's material flows, a complementary view on a company's circularity beyond material flows can be obtained using EMF's Circulytics, which will be launched in early 2020. Circulytics provides a single score on a company level to describe a company's circularity that is designed to empower strategy development, provide tracking year to year, and offer opportunities to generate value with key stakeholders. This score breaks down into two categories: enablers and outcomes. Enablers is a set of indicators that form a view on a company's ability to become more circular in the future (e.g., through strategic prioritisation and innovation), and outcomes indicators display a company's circularity today. For companies that directly deal with materials or products in their business processes, outcomes is mainly focussed on the circularity of input and output material flows. Here, the information required to produce company level MCI is directly usable to inform the indicators in Circulytics as well. In this way, MCI provides accurate analyses on the circularity of a company's products, and when aggregated onto a company level, accurate view of company level material flows. Circulytics complements this view with additional elements such as energy and circularity of services, and by indicating how likely it is for this company to become even more circular in the future (and in doing so, how likely it is to increase its MCI score). Circulytics can also be applied to companies or business units that do not directly deal with materials in their business, such as consultancies or financial institutions.

Circulytics allows companies to use readily aggregated material flow data to generate a score, and therefore companies who wish to understand their material flow circularity on a more granular level, are encouraged to use MCI for this purpose. Additionally, it may be appropriate to use relevant complementary indicators that have already been established at the company level. For example, many companies report according to the GRI Sustainability Reporting Standards (GRI Standards).[46] Whilst the actual indicators used in a GRI report will depend on the materiality of the different issues with respect to the business and its stakeholders, they are likely to include many of GRI's topic specific disclosures.

Some of these topic disclosures are very closely linked to the MCI. For example, Disclosure 301-1 Materials used by weight or volume is a measure of the company's total weight or volume of materials used to produce and package its primary products and services split into non-renewable materials and renewable materials.

Some of the GRI topic specific disclosures are similar to the complementary indicators described in the product methodology (Section 2.3). For example, Disclosure 305-1 Direct (Scope 1) GHG emissions, Disclosure 305-2 Energy indirect (Scope 2) GHG emissions and Disclosure 305-3 Other indirect (Scope 3) GHG emissions together relate to Section 2.3.2.1, Energy and CO_2.

Full definitions of the GRI disclosures and lists of the relevant standards are available from the GRI website.[47]

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[46] https://www.globalreporting.org/standards

[47] https://www.globalreporting.org/Pages/default.aspx

APPENDIX A – Production Losses

Often, material is discarded during production. In other words, for some or all of the materials, the total mass M' of material used throughout the production process is larger than the mass M of material contained in the final product. This will almost certainly be the case if material discarded during raw material extraction (e.g. mining) is considered. For understanding the material flows in detail, a similar model to that described in ISO 14051, Material flow cost accounting, can be used.[48]

Single Production Step

First, consider the simple case taking the whole product approach as described in Section 2.1.2 with all production taking place at a single point. In this case the total mass of unrecoverable waste becomes

$$W' = W + W'_0 + \frac{W'_F + W'_C}{2} \, ,$$

where W is the waste arising at the end of its current use phase as defined in Equation 2.6. Unrecoverable waste resulting from the manufacturing process is given by

$$W'_0 = (M' - M)(1 - P_R' - P_U') \, ,$$

where P_R' and P_U' are the collection rates for recycling and reuse during production.

Similar to Section 2.1.2.2, the waste arising from the production process associated with the portion of recycled feedstock that does not go forward into the final product is given by

$$W'_F = (\mathrm{M}' - \mathrm{M}) \frac{(1 - \mathrm{E}_F)\mathrm{F}_R}{\mathrm{E}_F} \, ,$$

and the waste arising during the recycling process for manufacturing waste sent for recycling is

$$W'_C = (\mathrm{M}' - \mathrm{M})(1 - \mathrm{E}'_C)P'_R \, ,$$

where E'_C is the recycling process efficiency for the waste arising during manufacturing.

The total mass of virgin material used is now based on the total mass of material input into the manufacturing process

$$V' = M'(1 - \mathrm{F}_R - \mathrm{F}_U) \, ,$$

where, as previously, F_R and F_U are the fractions of feedstock coming from recycled and reused sources, respectively.

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[48] ISO14051:2011, Environmental management – Material flow cost accounting – General framework

The Materials Circularity Indicator including production $\mathrm{MCI'}_P$, can then be computed as

$$\mathrm{MCI'}_P \; = \max\left(0, 1 - \frac{\mathrm{W'} \; + \; \mathrm{V'}}{2\mathrm{M'} + \frac{W_F - W_C}{2} + \frac{W'_F - W'_C}{2}} \; \mathrm{F(X)}\right).$$

Multiple Production Steps

In reality, most products will involve a more complex supply chain with a number of production steps across multiple suppliers, each involving separate inputs of materials. Since the materials may not come from homogeneous sources and waste might be disposed of in various manners, a proper assessment of the masses of unrecoverable waste and virgin material requires a consideration of all production steps ψ.

Mass of Unrecoverable Waste

Each step ψ begins with a mass $M^{'}_{(\psi)}$ and ends with a mass $M_{(\psi)}$ thus giving rise to an amount of material discarded $M^{'}_{(\psi)} - M_{(\psi)}$. Note that for the last step of the production ψ_L, the mass $M_{(\psi_L)}$ is equal to the mass M of material in the product. The equation for W' thus becomes

$$W' = W + \sum\nolimits_{\psi} \left(W_{0(\psi)} + \frac{W_{F(\psi)} + W_{C(\psi)}}{2} \right),$$

where

$$W_{C(\psi)} \quad = \left(M'_{(\psi)} - M_{(\psi)}\right)\left(1 - P_{R(\psi)} - P_{U(\psi)}\right);$$

with $P_{U(\psi)}$ and $P_{R(\psi)}$ representing the recycling and reuse rates during production step ψ.

$W_{F(\psi)}$ and $W_{C(\psi)}$ are given by:

$$W_{F(\psi)} = (M'_{(\psi)} - M_{(\psi)}) \frac{(1 - \mathrm{E}_{F(\psi)})\mathrm{F}_R}{\mathrm{E}_{F(\psi)}}$$

and

$$W_{C(\psi)} = \left(M'_{(\psi)} - M_{(\psi)}\right)\left(1 - E_{C(\psi)}\right)\mathrm{P}_{R(\psi)}.$$

Here $E_{C(\psi)}$ is the recycling process efficiency for the waste arising out of manufacture step ψ and $\mathrm{E}_{F(\psi)}$ the recycling process efficiency to create the recycled feedstock used in step ψ.

Mass of Virgin Materials

At production step ψ, the mass $M^{'}_{(\psi)}$ consists of the materials from the previous step(s)plus an additional input of new raw material of mass $I_{(\psi)}$. The equation for V' thus becomes

$$V' = \sum\nolimits_{\psi} I_{(\psi)} \left(1 - F_{U_{(\psi)}} F_{U(\psi)} - \; F_{R(\psi)}\right),$$

where $F_{U(\psi)}$ and $F_{R(\psi)}$ are the fractions of feedstock coming from recycled abd reused sources at production step ψ.

Expressing the Mass of New Input

In a production line where every new step follows only one previous step, I_{ψ} is given by

$$I_{(\psi)} = M'_{(\psi)} - M_{(\psi-1)} \, ,$$

except for the first step $\psi = 1 \text{ where } I_{(1)} = M'_{(1)}$.

However, there may also be cases where $I_{(\psi)}$ is given by a more complicated expression when several production steps lead into one next step. The mass of new input may take the following form:

$$I_{(\psi)} = M'_{(\psi)} - \sum\nolimits_{\bar{\psi}} M_{(\bar{\psi})} \, ,$$

where the sum runs over all the steps ψ that lead into step ψ . For all starting steps ψ_S, one gets $I_{(\psi_S)} = M'_{(\psi_S)}$.

Updated Material Circularity Indicator Equation

The materials circularity including production MCI'_P, can then be computed as

$$\mathrm{MCI}'_P \; = \max\left(0, 1 - \frac{\mathrm{W}' + \; \mathrm{V}'}{2\mathrm{M}' + \dfrac{W_F - W_C}{2} + \sum_{\psi} \dfrac{W_{F(\boldsymbol{\psi})} - W_{C(\boldsymbol{\psi})}}{2}} \; \mathrm{F(X)} \right),$$

where M' is given by the sum

$$M' = M + \sum\nolimits_{\psi} \left(M'_{(\psi)} - M_{(\psi)}\right).$$

Comprehensive Approach for Production Waste

Production waste can also be included in the comprehensive approach described in Section 2.1.3, which allows the incorporation of any number of sub-assemblies, components and/or materials. If this level of detail is known, for example, via detailed bills of materials for each production step, the MCI can be built up by summing over all production steps at a level of granularity that takes into account each individual sub-assembly, component and/or material.

APPENDIX B – Derivation of the Linear Flow Index

This appendix gives more details on the derivation of the Linear Flow Index (LFI) in Section 2.1.2.3

LFI without Consideration of Waste Created in Recycling Process

The LFI describes the proportion of material flowing in a linear as opposed to a restorative fashion. This fraction is obtained by dividing the amount of virgin material and waste created (the linear part of the material flow) by twice the product mass (once for the mass of material at production stage and once for the mass of material after use, the total mass flow). This is illustrated in Figure 14.

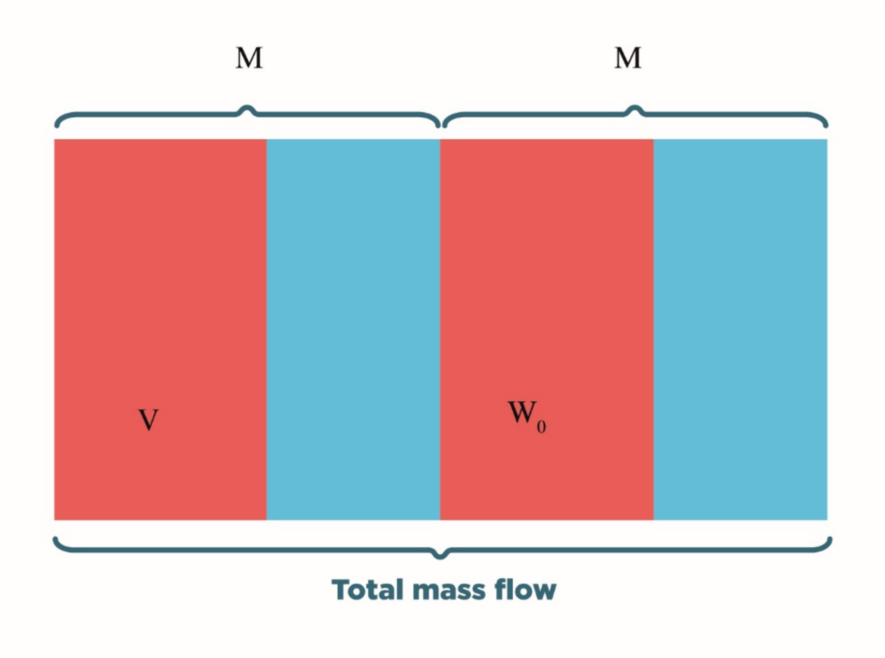


Figure 14: Derivation of the LFI without considering waste from recycling processes – the red area represents the linear part of the flow while the blue area represents the restorative part

So we arrive at

$$LFI = \frac{V + W_0}{2M}.$$

Considering the Waste Created while Recycling the Product

As of Equation 2.3, the mass of the waste created in the process recycling the product is W_C. All of this waste comes from the material that was part of the product as illustrated in Figure 15. However, because of the 50: 50 approach described in Section 2.1.2.2, only 50% of this is counted as part of the waste generated by the product being recycled, the other 50% is counted as part of the waste created by a product using the recycled material. This means that an amount of $W_C/2$ will never be counted as waste generated by the product and neither can it form part of the restorative flow. It is therefore excluded from the total mass flow.

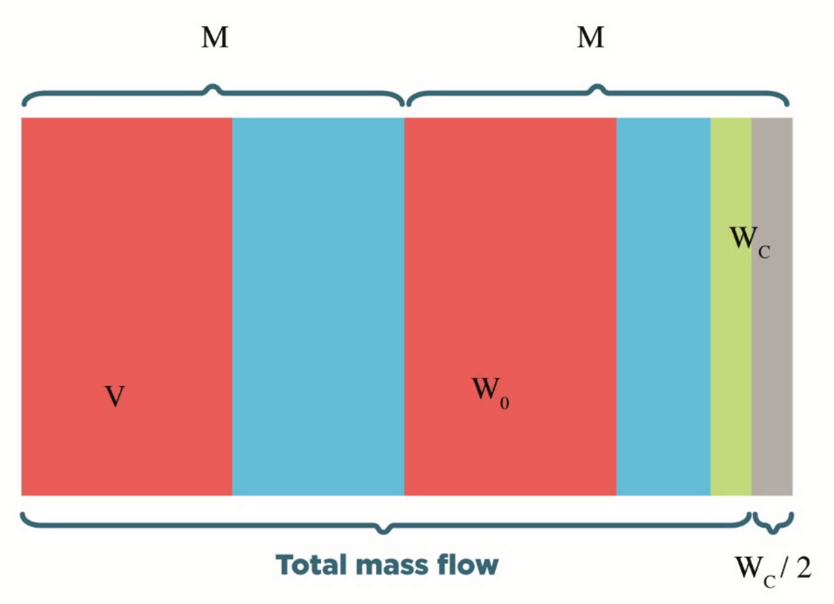


Figure 15: Derivation of the LFI considering waste created while recycling the product - the red and green area represented the linear part of the flow while the blue area represents the restorative part; the grey area is not considered part of the total mass flow for this product

As can be seen from Figure 15, the LFI is now

$$LFI = \frac{V + W_0 + \frac{W_C}{2}}{2M - \frac{W_C}{2}}.$$

Considering the Waste Created while Producing Recycled Feedstock

As of Equation 2.4, the mass of the waste created while producing recycled feedstock is W_F. As W_F is the amount of additional material needed to create an amount $M \cdot F_R$ of recycled feedstock (cf. Section 2.1.2.2), it does not come from the material that is part of the product. As it is part of the linear flow, the total mass flow needs to increase by W_F. However, in the same way as described above for W_C, only 50% of this is counted as part of the waste generated by the product, so only $W_F/2$ needs to be added to the linear part of the flow and total mass flow as illustrated in Figure 16.

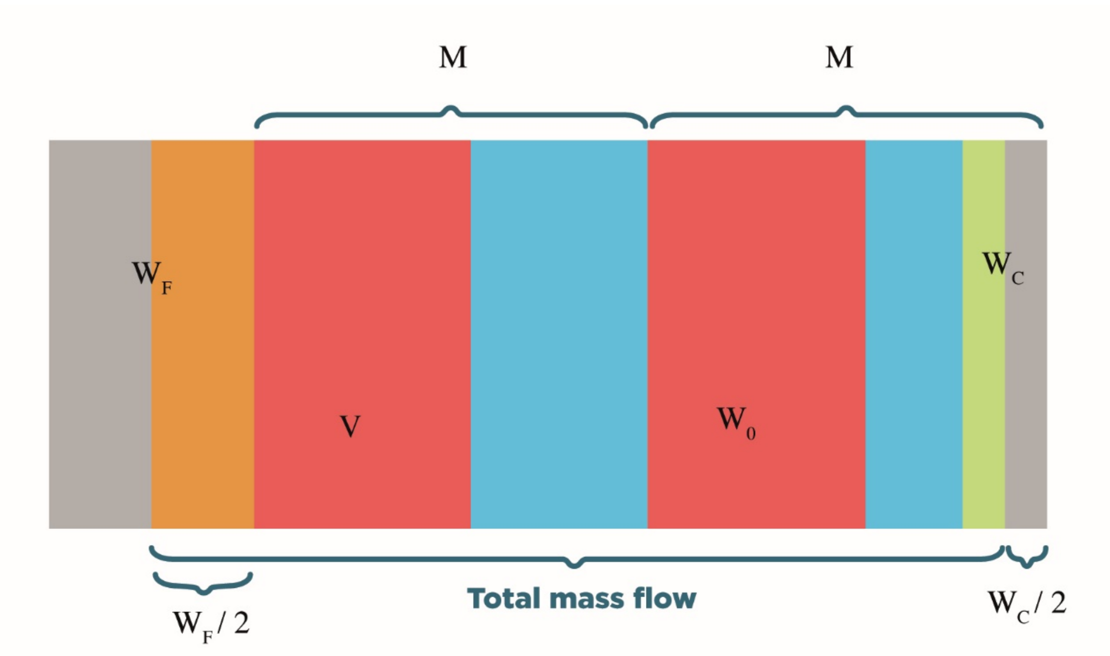


Figure 16: Derivation of the LFI additionally considering waste generated to produce recycled feedstock - the red, green and orange area represented the linear part of the flow while the blue area represents the restorative part; the grey areas are not considered part of the mass flow for this product

So the final formula for the LFI is

$$LFI = \frac{V + W_0 + \frac{W_C}{2} + \frac{W_F}{2}}{2M - \frac{W_C}{2} + \frac{W_F}{2}},$$

which exactly corresponds to Equation 2.7.

APPENDIX C – Derivation of the Utility Factor

This appendix gives more details on the derivation of the function F that defines the influence of the utility X of a product on its MCI.

As explained in Section 2.1.2.5, the influence of the utility should be defined in such a way that improvements of the utility of a product (e.g. by using it longer) have the same impact on its MCI as a reuse of components leading to the same amount of reduction of virgin material use and unrecoverable waste in a given period of time. So consider a product that is not using any recycled feedstock, is not collected for recycling ($F_R = C_R = 0$), and is reused on average k times before it is discarded. During one of its uses, lifetime and functional units are equal to an industry-average product of similar type. There are two ways to look at this product:

- In Case A, assume the product has no component reuse ($F_U = C_U = 0$) and the utility is equal to $X = k$, where $k > 1$.
- In Case B, the product has a utility equal to the industry average ($X = 1$). It is also considered as being in a closed – loop system consisting of a single component that is being reused. It is assumed that all products are collected for reuse and that $1k$ of them need to discarded in each production cycle, reflecting that a product can be reused on average k times. This yields $F_U = C_U = 1 - 1/k$.

Careful consideration of the mass flows shows that the treatment of k above means the use of virgin material of unrecoverable waste arising goes down by the same amount in both cases. It then follows that the MCIs for the two cases should be equal. Following this logic allows for the derivation of the function F as follows.

In Case A, the LFI is equal to 1 and

$$MCI^*{}_P \ = \ 1 - F(k)$$

as of Equation 2.10.

In Case B, Equation 2.7 yields

$$LFI \ = \frac{M(1 - F_U) + M(1 - C_U)}{2M} = \frac{M/k + M/k}{2M} = \frac{1}{k},$$

and hence

$$MCI^*{}_P \ = \ 1 - \frac{F(1)}{k}.$$

Equating $MCI^*{}_P$ for Case A with $MCI^*{}_P$ for Case B means that function F needs to satisfy the condition

$$F(k) = \frac{F(1)}{k},$$

Hence, F has to be of the form

$$F(X) = \frac{F(1)}{X}.$$

The methodology chooses to set the MCI for a fully linear product with $X = 1 \text{ to } 0.1$ such that

$$MCI_P \;=\; 0.1 = \; 1 - 1 \cdot \frac{F(1)}{k},$$

has to hold, resulting in $F(1) = 0.9$ as used in Section 2.1.2.5.

APPENDIX D - Calculating material circularity indicator as a percentage

Using a percentage figure to calculate the Material Circularity Indicator (MCI) makes it easier for organisations in different sectors to understand and compare their circularity. It clearly shows where a product stands in terms of circularity. However, the challenge is that in the original MCI scale (0 to 1), a linear system has a value of 0.1. This does not work well in percentage terms, as a non-circular system should be 0%.

As a reminder, the MCI calculation is:

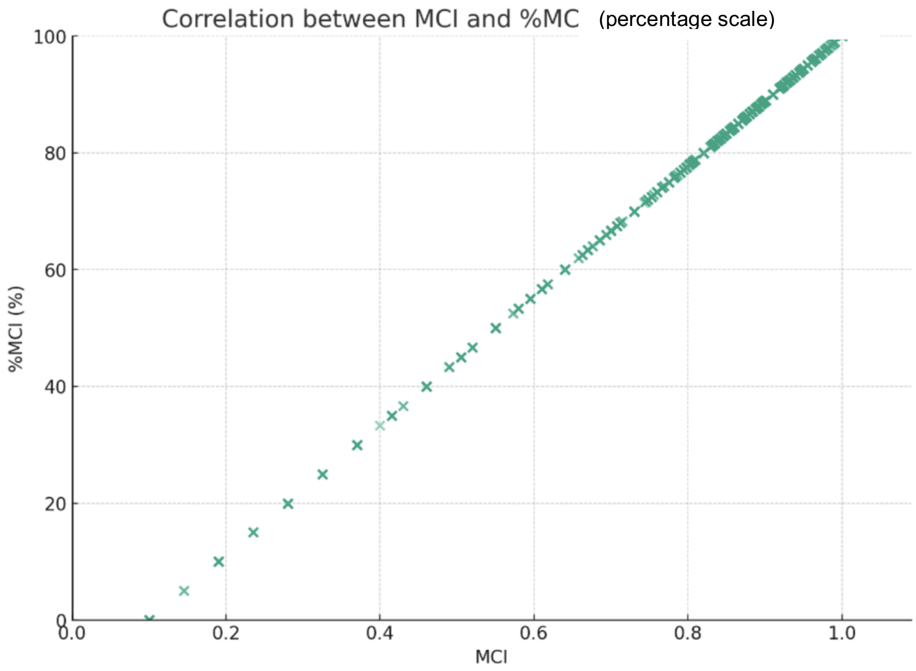
$$MCI = 1 - \left(\frac{V + W}{2M}\right) * \left(\frac{0.9}{X}\right)$$

Where M is the product's mass, V is its virgin content, W is waste not recovered, and X is the utility function.

To calculate MCI as a percentage, we have changed the equation to:

$$\%MCI = \frac{\left(M - \left(V * \frac{1}{X}\right)\right) + \left(M - \left(W * \frac{1}{X}\right)\right)}{2 * M}$$

This method continues to reflect important factors such as virgin material use and waste reduction. It also reflects the value of extending the life of products, for example by shared use. Comparing the two calculations for a wide range of combinations of V, W, and X enables a correlation between the two approaches. It also means that MCI values lower than 0.1 are no longer considered as part of the %MCI scale:



The correlation also means we can translate directly from the original MCI and the %MCI, as follows:

$$\%MCI = \frac{(MCI - 0.1)}{0.9}$$

$$MCI = (0.9 * \%MCI) + 0.1$$

This allows for easy translation between the two scales and means we can convert previously calculated MCI figures into %MCI directly.

APPENDIX E – Project Stakeholders (2015 Methodology)

The authors would like to continue to recognise the following organisations for their time, support and feedback during the 2013-2015 project which gave rise to the original methodology:

Pilot Companies

The following organisations shared product data to help develop the tool and the reporting of the indicators:

- CHEP
- Cisco Systems
- Desso
- Dorel
- Hewlett-Packard
- Kingfisher
- Nespresso
- Rolls Royce

Other Stakeholders

Investors

- Aviva Investors
- PGGM
- Rob Lake Advisors
- SRI Connect

Universities

- Bradford University
- Cranfield University
- Imperial College London
- Leeds University
- Surrey University
- TU Delft
- University College London

Government, Standards Bodies and Regulators

- British Standards Institution (BSI)
- City of Bradford
- Suffolk County Council
- Zero Waste Scotland

Businesses

- Anthesis Group
- BT
- Kyocera
- Philips
- Resource Futures
- Ricardo AEA
- Royal Haskoning DHV
- Tata Steel

NGOs

- Aldersgate Group
- Circle Economy
- Circular EcologyForum for the Future
- Green Alliance
- RSA
- WRAP

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