CIRCULARITY INDICATORS
An Approach to Measuring Circularity

METHODOLOGY

ELLEN MACARTHUR FOUNDATION

GRANTA
MATERIAL INTELLIGENCE

Life

About the Authors

Ellen MacArthur Foundation

The Ellen MacArthur Foundation launched in 2010 to accelerate the transition towards the circular economy. The Foundation believes that a circular economy provides a coherent framework for systems level redesign and, as such, offers us an opportunity to harness innovation and creativity to enable a positive, regenerative economy.

The Foundation's team is grateful for the support by expert advisor Chris Tuppen and his contributions throughout the project.

Granta Design

Granta Design is a materials engineering software company, spun-out in 1994 from the work of Mike Ashby and David Cebon at the University of Cambridge.

Granta works with leading engineering enterprises worldwide. Its Education Division supports teaching at over a thousand universities. Granta takes a collaborative approach, particularly through its Consortia. The Materials Data Management Consortium (MDMC) and Environment Materials Information Technology (EMIT) Consortium guide development and effective application of Granta technology. These projects, with members such as Airbus Helicopters, Boeing, Emerson Electric, NASA, and Rolls-Royce, have supported development of the GRANTA MI™ materials information management system, and of tools such as MI:Product Intelligence for minimising product risk and design-stage environmental assessment. The LIFE collaboration extends the scope to product circularity.

LIFE is the EU's financial instrument supporting environmental and nature conservation projects throughout the EU, as well as in some candidate, acceding and neighbouring countries. Since 1992, LIFE has co-financed some 3954 projects, contributing approximately EUR 3.1 billion to the protection of the environment.

More information on the project, including a project overview report and a collection of non-technical case studies, are available for download from the Circularity Indicator Project website http://www.ellenmacarthurfoundation.org/circularity-indicators/.

In addition, an Excel-based model to illustrate the functioning of the methodology at the product level and a spreadsheet for aggregation at the company level are provided for convenience.

For more information on the Webtool, please contact info@grantadesign.com.

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.

Until now, there has been no established way of measuring how effective a company is in making the transition from ‘linear’ to ‘circular’ models, nor have there been any supporting tools. The Circularity Indicators Project aims to address this gap and has developed indicators that assess how well a product or company performs in the context of a circular economy, thereby allowing companies to estimate how advanced they are on their journey from linear to circular. The developed indexes consist of a main indicator, the Material Circularity Indicator, measuring how restorative the material flows of a product or company are, and complementary indicators that allow additional impacts and risks to be taken into account.

The indicators can be used as 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 by intent and design. Taking a new systemic perspective, it replaces the concept of waste with the one of restoration and aims to decouple economic growth from the use of virgin resources.

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

- **Biological cycles**, in which non-toxic materials are **restored into the biosphere** while rebuilding natural capital, after being cascaded into different applications.
- **Technical cycles**, in which 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.

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

The successful implementation of circular models depends on the combined leveraging of four key building blocks:

- Rethinking **product design** facilitates the recovery of components and materials.
- Innovative **business models** enable changes of incentives and the collection of products.
- New **reverse logistics** need to be put in place, recovering products back from consumers or users and into the supply chain, and treatment methods need to be improved.
- A number of **system conditions** can help businesses to make the transition, such as education, policy frameworks, collaboration platforms or metrics.

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 tremendous, totalling, for example,

[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.

USD 630 billion of savings for medium-lived complex goods in the EU[2] and USD 706 billion for fast-moving consumer goods globally.[3] Additionally, more circular models allow businesses to mitigate risks from material price volatility and material supply.

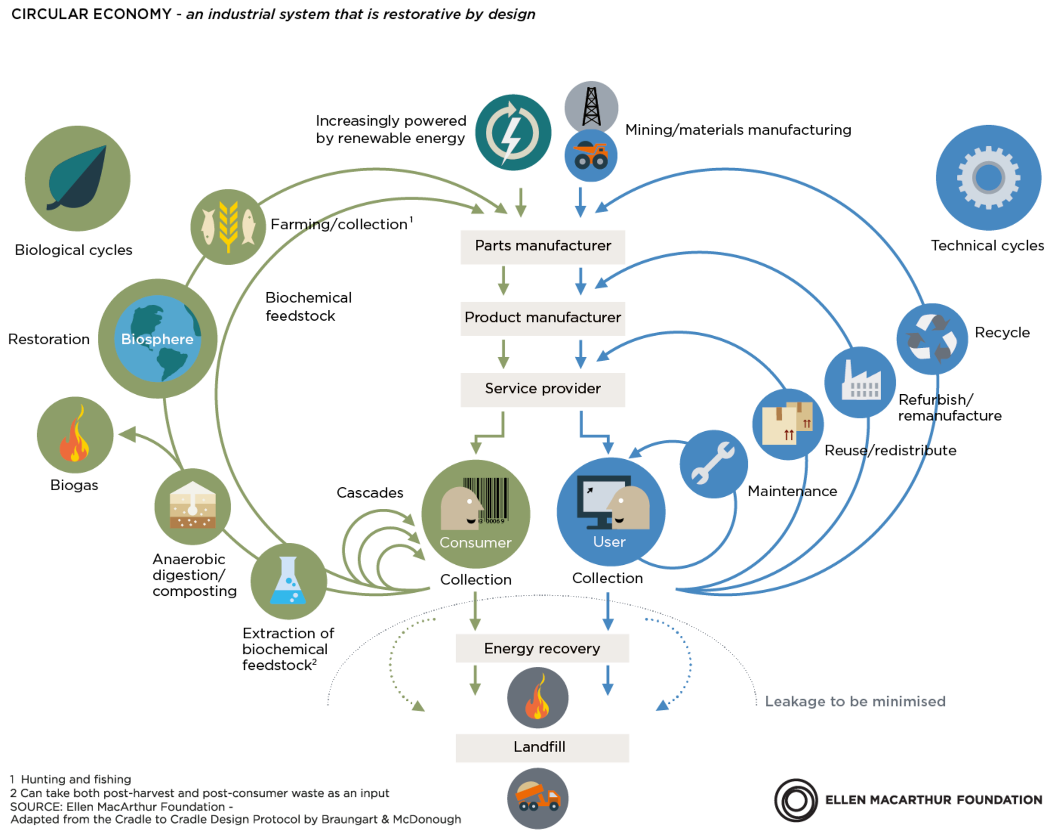

Figure 1: Circular economy systems diagram

Methods of measurement are necessary in a large number of applications, such as tracking progress (e.g. Key Performance Indicators (KPIs)), supporting internal decision making or informing 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 products and companies. This will allow companies to understand how far they are on the transition from ‘linear’ to ‘circular’.

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

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

1.2. Objectives and Scope

The methodology on the product level 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 circularity scores 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. Stakeholders could include **investors** interested in taking circularity into account for investment decisions, **rating companies** using circularity as a criterion, and those interested in **benchmarking** different companies within a given sector.

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]

This methodology focuses exclusively on technical cycles and materials from non-renewable sources, as their circularity strategies and associated business benefits are better understood. However, Appendix E gives some guidance on how wood and paper – materials from renewable sources that are frequently used in products of a technical nature and cycled in technical cycles – could be integrated into the methodology.

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 four principles:

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

i) using feedstock from reused or recycled sources
ii) reusing components or recycling materials after the use of the product
iii) keeping products in use longer (e.g., by reuse/redistribution)
iv) making more intensive use of products (e.g. via service or performance models)

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 systems improvement.

Evidence indicates that more economic value can often be captured in the end-of-use strategies corresponding to the inner, shorter, technical cycles.[5] 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%.

The question arises whether principles iii) and iv) 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[6]). 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 i) and ii)) 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 iii) and iv) 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.

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).

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

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

- **Complementary impact indicators** giving an indication of some of the benefits of circular models. They include a measure of the **energy and water** impacts of a given setup.

As 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.

The MCI presents the following differences and communalities 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).
- 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[7] 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 a number of extensions and refinements could be addressed in future developments, as explained in Section 1.4.

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[7] For example, PAS 2050:2011, *Specification for the assessment of the life cycle greenhouse gas emissions of goods and services* (www.bsigroup.com/PAS2050), PD CEN ISO/TS 14067:2014, *Greenhouse gases. Carbon footprint of products. Requirements and guidelines for quantification and communication, Greenhouse Gas Protocol Product Life Cycle Accounting and Reporting Standard.*

1.3. Development of the Methodology

This paper describes a methodology for calculating a Material Circularity Indicator for manufactured products and companies. It has been developed by the Ellen MacArthur Foundation and Granta Design under a two year LIFE+ project co-funded by the European Commission. This paper constitutes one of the principal deliverables of the project.

The **Ellen MacArthur Foundation** was founded in 2010 and works in education, business and insight and analysis to accelerate the transition to a circular economy. The Foundation believes that a circular economy provides a coherent framework for systems level redesign and, as such, offers an opportunity to harness innovation and creativity to enable a positive, regenerative economy.

Granta Design is the world leader in materials information technology. Their software tools, materials data and materials database solutions help engineering enterprises to manage vital materials data, enable better materials decisions, design for environmental objectives and regulations, and provide materials support for engineering design, analysis and simulation.

The prime purpose of this paper is to describe the thinking behind the methodology, alongside a derivation of the equations that lead to the calculation of the Material Circularity Indicator.

In addition to this methodology, a Circularity Indicators tool has been developed by Granta Design Ltd. and integrated with the MI:Product Intelligence package, which enables users to analyse and evaluate a range of environmental, regulatory and supply chain risks for their designs and products via a browser application, MI:BoM Analyzer.[8] The tool uses the product-level comprehensive approach and encompasses a number of complementary indicators. This tool will be available under commercial terms. As part of the project, the Ellen MacArthur Foundation has provided an easy to use Excel-based model to illustrate the functioning of the methodology on the product level. This is downloadable from the Circularity Indicator Project website[9] and is intended to be useful for people interested to see how the various parameters in the methodology interact with each other.

As part of the project, the methodology has been 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 pilot companies are listed in Appendix F.1.

In addition, several other stakeholders from investors, regulators, consultancies, and universities were involved in the project through workshops held in London to discuss the approach taken and to seek input into expected use cases. In total, stakeholders from about 30 organisations attended the workshops, many attending more than one and with several delegates. The stakeholders participating in these workshops are listed in Appendix F.2.

This paper has also been through two detailed peer review phases by an expert panel of reviewers as listed in Appendix F.3.

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

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[8] http://www.grantadesign.com/products/mi/bom.htm

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

1.4. Potential Future Developments

The methodological approach presented here could be written up as a scientific paper and published in an appropriate journal. Additionally it could be developed into an official standard. 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.

As described earlier, the current methodology has focused on technical cycles and materials from non-renewable sources. An important next step would be to extend it to embrace biological cycles and materials from renewable sources, including consumables like food. This might also include a proper consideration of conversion of end-of-use materials into energy, for example, via producing biofuels from food waste or burning wood.

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

- 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.

1.5. 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.

The paper closes with an appendix containing case studies that explain the use of the methodology (Appendix A), a description of our proposed method to include production waste (Appendix B), some details on the derivations of the Linear Flow Index and the utility factor (Appendices C and D) and a list of project stakeholders (Appendix F).

1.6. 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 biological cycles, non-toxic materials are restored into the biosphere while rebuilding natural capital, after being cascaded into different applications.
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 is restorative by design, and aims to keep products, components and materials at their highest utility and value, at all times.
Closed loop	In a closed loop, used products come back to the original 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.
***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.
Feedstock	Feedstock is anything used to produce a new product. This in particular includes raw materials (from either virgin or recycled sources) but can also include components from old products used in a new product.
Functional unit	A functional unit is a measure of the product’s use. For example, it could be one kilometer driven for a car, or one wash cycle for a washing machine.

Term	Definition
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, $LFI = 1$.
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 restorative or linear 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 can be 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 for the original purpose or for other purposes. The materials recovered 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.

Term	Definition
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	To reuse a product is to reintroduce it 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.
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 has not been previously used or consumed, or subjected to processing other than for its original 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
V	Mass of virgin feedstock used in a product
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_F	Efficiency of the recycling process used to produce recycled feedstock for a product
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}	Actual 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}	Actual 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 in Figure 2.

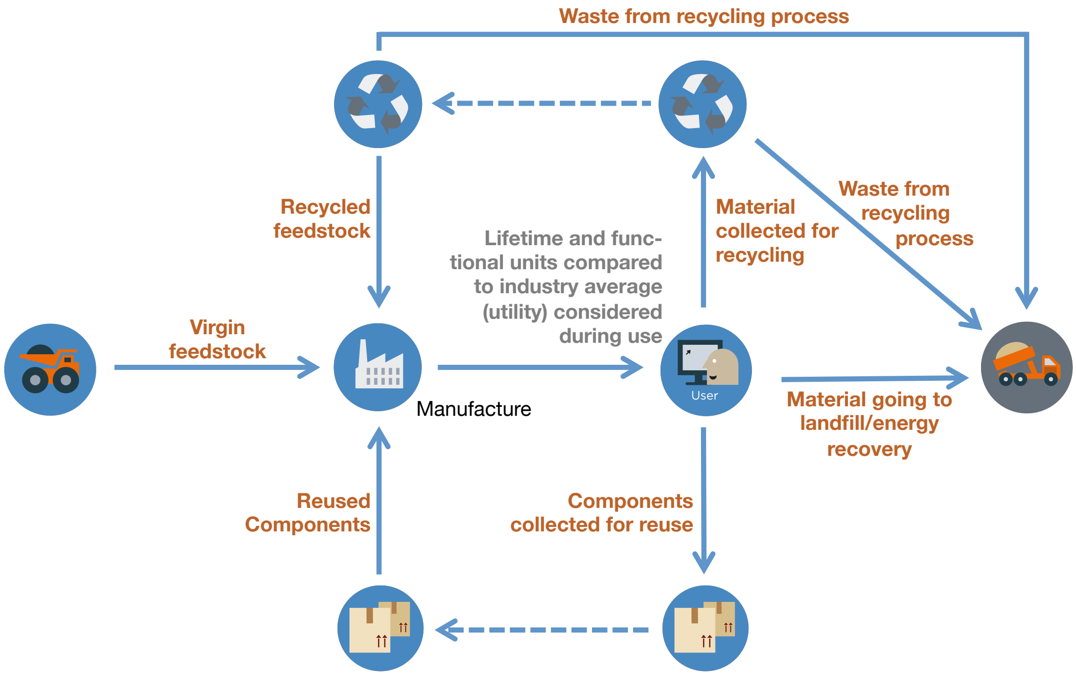

Figure 2: Diagrammatic representation of material flows

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, most 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 2 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.

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 1.6 lists definitions of all the principal terms and variables. Furthermore, Figure 3 summarises the different variables influencing the Material Circularity Indicator.

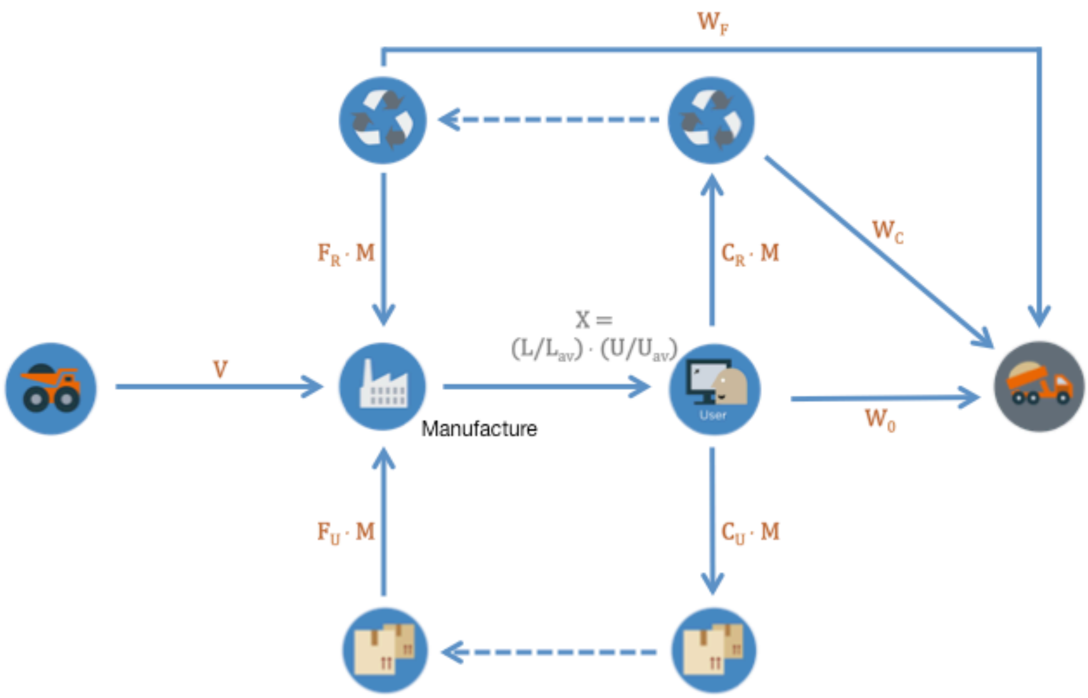

Figure 3: Diagrammatic representation of material flows

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, design data should not be used in calculating the MCI of an actual product. For example, a product may be 100% recyclable, but actual recycling rates should be used in the calculations. Or, in the case of a product that is designed for a longer life than – for whatever reason – the actual product experiences in practice, the actual lifetime should be used in the calculations, not the lifetime the product is designed for.

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 and F_U represents the fraction from reused sources. The fraction of feedstock from virgin sources is then $(1 - F_R - F_U)$ and the mass of virgin material is given by

$$V = M(1 - F_R - F_U), \tag{2.1}$$

where M is the mass of the finished product.

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 and C_U the fraction of the mass of the product going into component reuse,[10] the amount of waste going to landfill or energy recovery is

$$W_0 = M(1 - C_R - C_U). \tag{2.2}$$

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

$$W_C = \mathrm{M}(1 - E_C)C_R. \tag{2.3}$$

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

$$W_F = M\frac{(1 - E_F)F_R}{E_F}, \tag{2.4}$$

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

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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.

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, $W_F = 0$ 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 and W_F are given equal emphasis, and the quantity of waste generated by recycling that is associated with *this* product is given by

$$\frac{W_F + W_C}{2}, \tag{2.5}$$

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

$$W = W_0 + \frac{W_F + W_C}{2}. \tag{2.6}$$

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:

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}} \tag{2.7}$$

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

$$LFI = \frac{V + W}{2M}. \tag{2.8}$$

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 C. 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

$$X = \left(\frac{L}{L_{av}}\right) \cdot \left(\frac{U}{U_{av}}\right). \tag{2.9}$$

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.

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 on deriving the utility factor (see Appendix A.2) illustrates this by way of an example.

[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 kilometer driven for a car, or one wash cycle for a washing machine.

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 mass.

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

$$MCI^*_P \;=\; 1 - LFI \;\cdot F(X). \tag{2.10}$$

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

$$MCI_P \;= \max(0, MCI^*_P). \tag{2.11}$$

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 (i.e., $X = 1$).

So F takes the form:

$$F(X) = \frac{0.9}{X} \tag{2.12}$$

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

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.

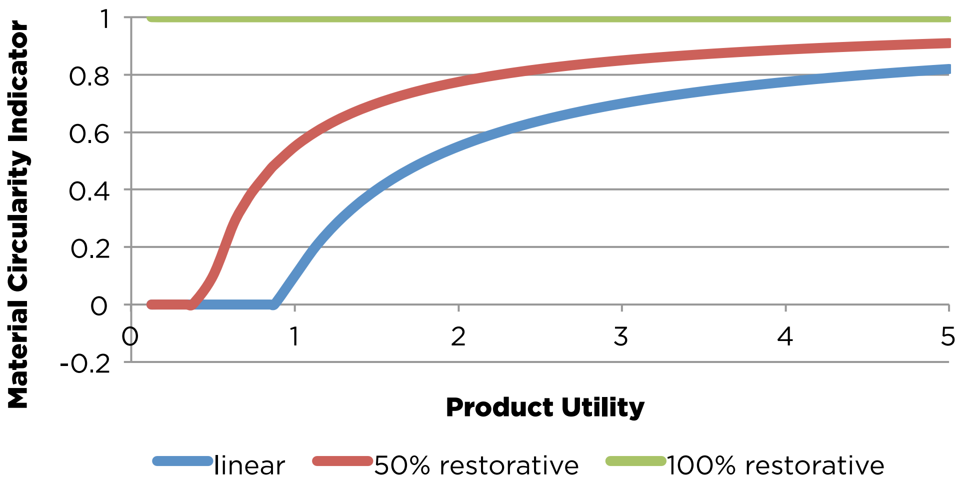

Figure 4: Chart showing impact of product utility on the Material Circularity Indicator

[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).

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:

$$V_{(\chi)} = M_{(\chi)}(1 - F_{\mathrm{R}(\chi)} - F_{\mathrm{U}(\chi)}) \tag{2.13}$$

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

$$V = \sum_{\chi} V_{(\chi)} \tag{2.14}$$

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

$$W_{0(\chi)} = M_{(\chi)}\left(1 - C_{\mathrm{R}(\chi)} - C_{\mathrm{U}(\chi)}\right) \tag{2.15}$$

The quantity of waste generated in the recycling process:

$$W_{C(\chi)} = M_{(\chi)}\left(1 - E_{C(\chi)}\right)C_{R(\chi)} \tag{2.16}$$

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

$$W_{F(\chi)} = M_{(\chi)} \frac{\left(1 - E_{F(\chi)}\right) \cdot F_{R(\chi)}}{E_{F(\chi)}} \tag{2.17}$$

The total amount of waste generated:

$$W = \sum_{\chi} \left(W_{0(\chi)} + \frac{W_{F(\chi)} + W_{C(\chi)}}{2} \right), \tag{2.18}$$

and the Linear Flow Index:

$$LFI = \frac{V + W}{2M + \sum_{\chi} \frac{W_{F(\chi)} - W_{C(\chi)}}{2}}. \tag{2.19}$$

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 B.

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:

- 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.

[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.

- It is assumed that there are no material losses in preparing collected products for reuse.
- It is assumed that all material is cycled in technical cycles; biological cycles are not taken into account.
- 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.

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 the global (or relevant regional) average.

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, EPLCD (the European Reference Life-Cycle Database), 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

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

overall concentrations. Recycling efficiency is also affected by the presence of pollutant in material scrap and/or the presence of coatings.
- 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.*

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

- *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).

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 infant mortality 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.

2.3. 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...			

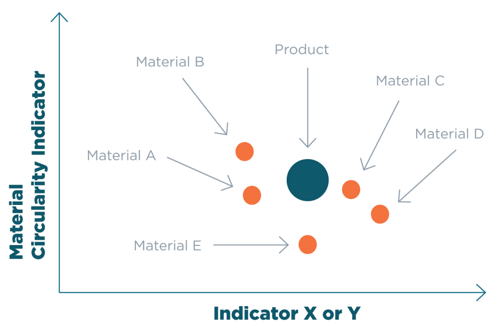

Figure 5: Example of comparing indicators to aid decision-making: (a) comparative table; (b) graphical representation specifically for comparing MCI values to the results of one complementary indicator.

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

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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.

[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)

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]

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.
- 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]

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.

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

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]

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

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[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.

[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.

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.

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

[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/).

[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.

2050:2011,[36] PD CEN ISO/TS 14067:2014,[37] and GHG Protocol Product Life Cycle Accounting and Reporting Standard.

- The 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.

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.

[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] PD CEN ISO/TS 14067:2014, *Greenhouse gases. Carbon footprint of products. Requirements and guidelines for quantification and communication*.

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

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

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.

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

[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/.

designs is especially important for these strategies and is sometimes needed to create a positive business potential.

Similar to resale, revenue opportunities can also be captured by exploring **new revenue streams or increasing market share**. Performance models can be especially interesting for a company to retain ownership of the product and therefore facilitate its recovery while offering options for different pricing and service models to customers.

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		• 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.
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	

[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.

An Alternative Approach

Manufacturing companies that produce their products directly from raw materials (as opposed to assembling components manufactured elsewhere) should have a good knowledge of the total mass flows entering and leaving the business, broken down by material type. In principle this offers an alternative approach to calculating a company-level MCI. However, this approach has not been used because:

- It is not applicable to all types of business.
- It does not allow for component manufacture.
- It does not provide a method of consolidating products with varying utility factors.

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.

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.

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 $P_{(\alpha,r(\alpha))}$.

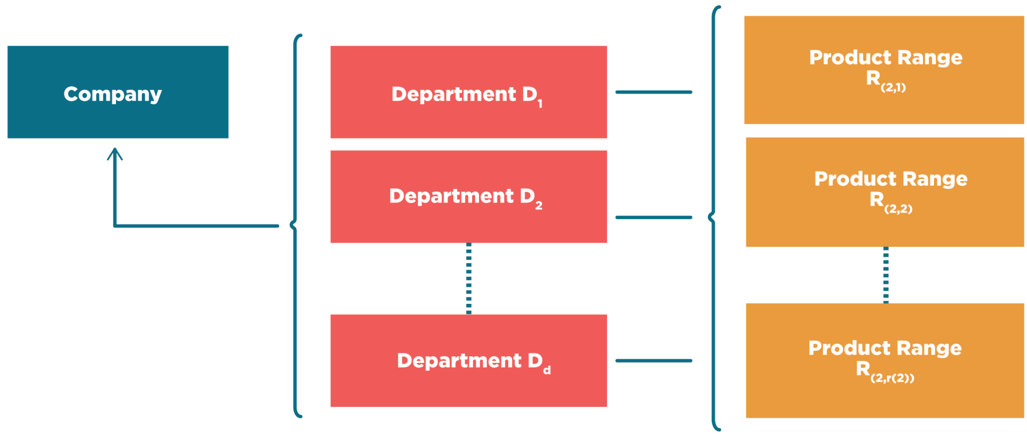

Figure 6: Example company structure

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

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

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

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

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

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]

[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.

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 Global Reporting Initiative (GRI) guidelines.[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 standard disclosures as displayed on the next page.

Some of these standard disclosures are very closely linked to the MCI. For example, *G4-EN1: 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 standard disclosures are similar to the complementary indicators described in the product methodology (Section 2.3). For example, G4-EN15: Direct Greenhouse Gas (GHG) Emissions (Scope 1), G4-EN16: Energy Indirect Greenhouse Gas (GHG) Emissions (Scope 2) and G4-EN17: Other Indirect Greenhouse Gas (GHG) Emissions (Scope 3) together relate to Section 2.3.2.1, Energy and CO_2.

Full definitions of the GRI standard disclosures are provided in the GRI Implementation Manual available from the GRI website.[47]

[46] Global Reporting Initiative, *G4 Sustainability Reporting Guidelines,* https://www.globalreporting.org/reporting/g4/.

[47] https://www.globalreporting.org/reporting/g4/

TABLE 1: CATEGORIES AND ASPECTS IN THE GUIDELINES

Category	Economic	Environmental
Aspects[iii]	• Economic Performance • Market Presence • Indirect Economic Impacts • Procurement Practices	• Materials • Energy • Water • Biodiversity • Emissions • Effluents and Waste • Products and Services • Compliance • Transport • Overall • Supplier Environmental Assessment • Environmental Grievance Mechanisms

Category	Social			
Sub-Categories	Labor Practices and Decent Work	Human Rights	Society	Product Responsibility
Aspects[iii]	• Employment • Labor/Management Relations • Occupational Health and Safety • Training and Education • Diversity and Equal Opportunity • Equal Remuneration for Women and Men • Supplier Assessment for Labor Practices • Labor Practices Grievance Mechanisms	• Investment • Non-discrimination • Freedom of Association and Collective Bargaining • Child Labor • Forced or Compulsory Labor • Security Practices • Indigenous Rights • Assessment • Supplier Human Rights Assessment • Human Rights Grievance Mechanisms	• Local Communities • Anti-corruption • Public Policy • Anti-competitive Behavior • Compliance • Supplier Assessment for Impacts on Society • Grievance Mechanisms for Impacts on Society	• Customer Health and Safety • Product and Service Labeling • Marketing Communications • Customer Privacy • Compliance

APPENDIX

Appendix – Table of Contents

A. Case Studies

A.1. Case Study – Simple Product

Widget Store is a company producing widgets and associated products. They have a range of widgets including a standard product SW_d and a premium product PW_b and want to compare their circularity.

A.1.1. Bills of Materials

The bills of materials of the two products look as follows:

Product SW_d:

Component	Material	Mass (kg)
Component 1	Aluminium (Al)	2.0
Component 2	ABS[1]	8.0

Product PW_b:

Component	Material	Mass (kg)
Component 1	Aluminium (Al)	8.0
Component 2	ABS	2.0

A.1.2. Virgin Feedstock

The ABS that the company uses comes from virgin sources. The aluminium is sourced from a supplier that uses 50% recycled and 50% virgin material. In terms of the notation used in

[1] Acrylonitrile Butadiene Styrene, a common thermoplastic polymer.

the methodology, this means $F_{R(ABS)} = 0.5$ and $F_{R(Al)} = 0$. As no reuse is occurring, we have $F_{U(ABS)} = F_{U(Al)} = 0$.

Equation 2.1 of the methodology is used to compute the mass of virgin feedstock.

For product SW_d, this yields

$$V_{(Al)} = 2 \cdot (1 - 0.5) = 1 \text{ and } V_{(ABS)} = 8 \cdot (1 - 0) = 8\,,$$

whereas for Product PW_b, we get

$$V_{(Al)} = 8 \cdot (1 - 0.5) = 4 \text{ and } V_{(ABS)} = 2 \cdot (1 - 0) = 2\,.$$

A.1.3. Unrecoverable Waste

Collection data for the markets the company operates in show that the recycling rate for ABS is 25% ($C_{R(ABS)} = 0.25$), while 75% of aluminium usually ends up in recycling, ($C_{R(Al)} = 0.75$). The recycling efficiency rate for aluminium is $E_{C(Al)} = E_{F(Al)} = 0.9$ and that for ABS is $E_{C(ABS)} = E_{F(ABS)} = 0.4$.[2]

For product SW_d, Equation 2.2 of the methodology gives us

$$W_{0(Al)} = 2 \cdot (1 - 0.75) = 0.5 \text{ and } W_{0(ABS)} = 8 \cdot (1 - 0.25) = 6,$$

so the amount of waste generated for SW_d at the time of collection is

$$W_0 = W_{0(Al)} + W_{0(ABS)} = 6.5\,.$$

The quantity of waste generated in the recycling process, is given by

$$W_C = W_{C(Al)} + W_{C(ABS)} = 2 \cdot (1 - 0.9) \cdot (0.75) + 8 \cdot (1 - 0.4) \cdot (0.25) = 1.35\,,$$

and the waste generated to produce the recycled content is

$$W_F = W_{F(Al)} = 2 \cdot \frac{(1-0.9) \cdot 0.5}{0.9} = \frac{1}{9}.$$

The total amount of unrecoverable waste for product S is then given by

$$W = W_0 + \frac{W_F + W_C}{2} = 6.5 + \frac{1/9 + 1.35}{2} \approx 7.23$$

according to Equation 2.6.

[2] The low recycling efficiency is due to the ABS going into a generic recycling waste stream and the difficulty of detecting and separating ABS from other plastics.

Similarly, for product PW_b, we compute

$$W = 3.5 + \frac{4/9+0.97}{2} \approx 4.17 \ .$$

A.1.4. Linear Flow Index

Now we can compute the Linear Flow Index of the two products via Equation 2.7 of the methodology:

Product SW_d:

$$LFI = \frac{V+W}{2M+\frac{W_F-W_C}{2}} = \frac{9+7.23}{20+\frac{1/9-1.35}{2}} \approx 0.84 \ .$$

Product PW_b:

$$LFI = \frac{6+4.17}{20+\frac{4/9-0.97}{2}} \approx 0.51 \ .$$

A.1.5. Utility Factor

Customer surveys have shown that the standard widgets are usually used for 8 years, while the premium widgets are more durable and last an average of 12 years. The industry-average lifetime is ten years. There is no suitable measurement of functional units for widgets, so only the lifetime is taken into account in the utility. By Equation 2.9, we therefore get

$$X = \frac{L}{L_{av}} = 0.8 \text{ and } F(X) = \frac{0.9}{0.8} = 1.125$$

for Product SW_d and

$$X = \frac{L}{L_{av}} = 1.2 \text{ and } F(X) = \frac{0.9}{1.2} = 0.75$$

for Product PW_b.

A.1.6. Material Circularity Indicator

Finally, we can compute the Material Circularity Indicator for the two products as per Equations 2.10 and 2.11.

Product SW_d:

$$MCI_P = \max \ (0, 1 - 1.125 \cdot LFI) \approx 0.06.$$

Product PW_b:

$$MCI_P = \max \ (0, 1 - 0.75 \cdot LFI) \approx 0.61.$$

A.1.7. Comment

The premium widget has a substantially higher MCI compared to the standard product. This is due to replacing a lot of the ABS – which does not come from recycled sources and has a low recycling rate and efficiency – with aluminium, which comes from mixed sources and has a higher recycling rate and recycling efficiency. Also, the higher lifetime of the more premium product increases its Material Circularity Indicator.

A.2. Case Study – Utility Factor

This case study calculates the utility factor $F(X)$ as described in Section 2.1.2.4 of the methodology for a high quality washing machine. The value X is defined according to Equation 2.9:

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

where:

L = average lifetime of the product

L_{av} = on average, the lifetime of an industry-average product of similar type

U = average number of functional units achieved during the use phase of the product

U_{av} = on average, the number of functional units achieved during the use of an industry-average product of similar type

Most of the figures used in this case study are based on published information and actual, but confidential, company and market research data.

A.2.1. Washing Machine Data

The manufacturer designed the washing machine to deliver a minimum of 5,000 wash cycles and has stress tested it up to 7,500 wash cycles.

Taking a conservative approach, the use intensity variable U is thus assigned a figure of 5,000 functional units where one functional unit is equal to a single wash cycle.

A.2.2. Calculating the Industry Averages

The following data for the UK market has been used to assess industry averages.

Table 1: UK market data for washing machines

Quantity	Value	Source
Number of units sold into UK market per year (millions)	2.5	Market research statistic
% of households with a washing machine	96%	Office of National Statistics
Number of households in UK (millions)	26.4	Office of National Statistics
Average number of washes per home and year	270	Energy Savings Trust and 'Which?'
Number of use cycles for mid-range washing machine	2,000	http://www.ukwhitegoods.co.uk/

With a 96% market penetration rate, it is assumed that new sales are essentially replacing machines that have reached the end of their use phase. This allows us to calculate one possible figure for the life of an industry-average washing machine according to:

$$L_{av} = \frac{26.4 \cdot 0.96}{2.5} = 10.1 \text{ years}$$

An alternative approach is to assume that the number of use (wash) cycles for a mid-range washing machine represents the industry average, that is, U_{av} = 2000. In this case, knowledge of the average wash cycles per year per household provides:

$$L_{av} = \frac{2000}{270} = 7.5 \text{ years}$$

According to the White Goods Trade Association "*the average lifespan [of a washing machine] has dropped from over ten years to under seven years and it is not unusual for cheaper appliances to only last a few years now*".

Taking into account all the above evidence, the following figures are taken forward:

$$L_{av} = 7.5 \text{ years}$$

$$U_{av} = 2000 \text{ cycles}$$

A.2.3. Calculating the Utility Factor

Knowing the average number of functional units achieved during the use phase of the product $(U = 5{,}000)$ and the average number of wash cycles per year per household allows a calculation of the average lifetime of the product according to:

$$L = \frac{5000}{270} = 18.5 \text{ years}$$

The two ratios that comprise X can now be calculated according to:

$$\frac{L}{L_{av}} = \frac{18.5}{7.5} = 2.5$$

and

$$\frac{U}{U_{av}} = \frac{5000}{2000} = 2.5$$

As the methodology states *"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."* In this case the ratios are indeed indicative of the same thing (i.e. the much improved durability of this washing machine compared to the industry average) and using them both in calculating X would account for them twice. To avoid this one ratio should be set to 1. For example if L/L_{av} is used, U/U_{av} is set to 1, yielding:

$$X = 2.5 \cdot 1 = 2.5$$

The utility factor can now be calculated according to Equation 2.12 of the methodology according to:

$$F(X) = \frac{0.9}{X} = \frac{0.9}{2.5} = 0.36$$

For comparison, the equivalent calculation for an industry-average washing machine where $\left(\frac{L}{L_{av}}\right)\left(\frac{U}{U_{av}}\right) = 1$ would give:

$$F(X) = \frac{0.9}{X} = \frac{0.9}{1} = 0.9$$

A.2.4. Impact on the Material Circularity Indicator

To illustrate how this impacts on the Material Circularity Indicator let us assume a Linear Flow Index (LFI) of 0.5. This assumption is considered valid for illustrative purposes given the large amounts of metal in washing machines that will typically have a reasonably high recycled content in the feedstock, and given the reasonably high recycling levels for white goods.

Equations 2.10 and 2.11 of the methodology define the MCI according to:

$$MCI_P = \max(0, 1 - LFI \cdot F(X))$$

Thus, using the utility values derived above, this gives an MCI of 0.82 for the high quality washing machine and 0.55 for the industry-average washing machine.

A.3. Case Study – Shared Consumption Business Model

This case study calculates the utility factor $F(X)$ as described in Section 2.1.2.4 of the methodology for cordless power drills purchased and owned by a DIY consumer, and compares this to an equivalent drill that is hired on a short-term basis to multiple customers.

The value X is defined according to Equation 2.9:

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

where:

L = average lifetime of the product

L_{av} = on average, the lifetime of an industry-average product of similar type

U = average number of functional units achieved during the use phase of the product

U_{av} = on average, the number of functional units achieved during the use of an industry-average product of similar type

The case study is based on the widely quoted, although somewhat apocryphal assertion that on average a power drill is used for just six minutes a year. The figures used in the case study have no further evidence base and are simply used to illustrate how to undertake the calculations.

A.3.1. Power Drill Data

This case study is based on a DIY cordless power drill that is used by the average consumer for just six minutes a year. Table 2 gives the utility factor data for an owned drill and a hired drill.

Table 2: UK market data for power drills

Attribute	Symbol	Owned drill	Hired Drill
Average serviceable life of the product (years)	L	8	3
Life of an industry-average product of similar type (years)	L_{av}	8	
Average number of functional units achieved during use phase of the product (number of holes)	U	80	600
Number of functional units during the use of an industry-average product of similar type (number of holes)	U_{av}	80	

An average serviceable life of eight years is assumed on the basis that batteries have a finite life and are difficult/expensive to replace once the model is no longer sold. The hired drill has a much shorter life as the hirer has a policy of taking all equipment out of circulation after three years.

It would be reasonable to expect approximately ten holes to be drilled in six minutes. This makes the average number of functional units for the owned drill:

$$U = 8 \cdot 10 = 80 \text{ holes.}$$

Assuming the hired drill is rented out twenty times per year and that each time ten holes are drilled, the average number of functional units for the hired drill (U) equals 600 holes.

$$U = 3 \cdot (10 \cdot 20) = 600 \text{ holes.}$$

A.3.2. Calculating the Utility Factors

The two ratios that comprise X along with X itself can now be calculated for the two business models. See the Utility Factor case study (Section A.2) for more information on these calculations.

Business Model	$\frac{L}{L_{av}}$	$\frac{U}{U_{av}}$	X
Ownership	1	1	1
Hiring	1	7.5	7.5

Note that although the hire drill only lasts three years in this case $\frac{L}{L_{av}}$ has been set to 1. This is because it is assumed that the main value in a power drill lies in the functional units (number of holes) it provides and a longer life; without any actual usage it does not provide a significantly higher value.

The utility factor for the ownership approach can now be calculated according to Equation 2.12 of the methodology according to:

$$F(X) = \frac{0.9}{X} = \frac{0.9}{1} = 0.9$$

and for the rental approach according to:

$$F(X) = \frac{0.9}{X} = \frac{0.9}{7.5} = 0.12$$

A.3.3. Impact on the Material Circularity Indicator

To illustrate how this impacts on the Material Circularity Indicator in this example, we assume an LFI of 0.75 (see Section 2.1.2.3 for more information).

Equations 2.10 and 2.11 of the methodology define the MCI according to:

$$MCI_P = \max(0, 1 - LFI \cdot F(X))$$

Thus, using the utility values computed above, we derive $MCI_P = 0.33$ for the owned machine and $MCI_P = 0.91$ for the rented machine.

A.4. Case Study – Complementary Indicators

This case study is based on a generic personal tablet that is used for two years by the average consumer. The baseline design tablet described below is evaluated by this Circularity Indicators methodology (MCI and complementary indicators) to determine its circularity and potential risks, and then design changes are proposed with the aim to improve the circularity and lower the risks found while, at the same time, not increasing others.

In more detail, the objectives, hypotheses and limits of this case study are as follows:

Product design objectives:

- Improve Material Circularity Indicator
- Reduce or stabilise other product risks and impacts

Main hypotheses and limits of this case study:

- The focus of the analysis is based on the casing and the front glass cover of the LCD display, which are assumed to be more easily changeable in the short term.
- All feedstock materials (with the exception of reuse) are coming from virgin sources.
- For the baseline tablet, it is assumed that it is completely discarded to landfill after its use to highlight the influence of recycled and reused components in the indicators assessment for the redesign options. In Europe this would usually not be the case, as electronics disposal needs to meet the requirements of the WEEE directive.
- For the redesigned tablets involving reuse, it is assumed that 100% of tablets sold are returned to the manufacturer where some components are reused with the remainder of materials going to landfill.
- A streamlined estimation has been provided for the carbon footprint of the electronic components production, as this is particularly difficult to analyse in detail owing to the lack of information about the specific composition of the components.[3]

Table 3: Baseline tablet characteristics

Bill of materials	Generic tablet bill of materials[4]
Mass	0.68 kg
Average lifetime	2 years
Average lifetime of an industry average product of similar type	2 years

[3] Some additional information can be found in the document repository of the JRC, *Development of European Ecolabel and Green Public Procurement Criteria for Personal Computers & Notebook Computers*, http://susproc.jrc.ec.europa.eu/computers/stakeholders.html.

[4] P. Teehan and M. Kandlikar, *Comparing Embodied Greenhouse Gas Emissions of Modern Computing and Electronics Products*, Environ. Sci. Technol, 2013, no. 47, p. 3997–4003.

Feedstock materials	Virgin materials
Destination after use	All materials to landfill

A.4.1. Circularity Indicators for the Baseline Design

The indicators calculated for this case study are:

- Material Circularity Indicator
- REACH Article 33 Obligations
- RoHS Compliance
- Average annual price variation over the past 5 years
- Conflict material risk
- Carbon footprint

A.4.1.1. Material Circularity Indicator

Due to the assumptions above (100% virgin material input and 100% landfill after use), the Linear Flow Index (LFI) of the baseline tablet has a value of 1.0 (see Section 2.1.2.3). The utility X takes a value of 1 from L/L_{av}, and assumes 1 for U/U_{av}. Equations 2.10 and 2.11 of the methodology then define the MCI according to:

$$MCI_P = \max(0, 1 - LFI \cdot F(X))$$

Thus, we derive: $MCI_P = 0.10$ for the tablet baseline design.

A.4.1.2. REACH Article 33 Obligations – Complementary Risk Indicator

Based on the bill of materials, the composition of each material and the EU Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) obligations on Article 33,[5] it is possible to determine if there is a potential restricted substance risk based on the substances that a material may contain[6] using the candidate list for inclusion in Annex XIV of REACH Candidate List of Substances of Very High Concern (SVHCs).

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[5] 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.

[6] Substances that can be associated with this material, but are not guaranteed to be present in this material; applicable to materials that have flexible compositions that are dictated by their specific engineering application and regulatory constraints, for example, materials with proprietary formulations such as polymers, rubbers, and adhesives.

For all SVHCs that may be present in the finished article at more than 0.1% (by weight) across the product, it was determined that the highest substance by weight of the article is 1.3% by weight.

Looking into the materials and their composition, it was found that there was a flame retardant, decabromodiphenyl oxide, which may be present with up to 10% of mass in the polycarbonate (PC) used in the casing of the tablet. This falls into the SVHC candidate list since it is present at high levels, and it is also present in the polyvinyl chloride (PVC) used in the power supply cables.

A.4.1.3. EU RoHS Directive – Complementary Risk Indicator

Based on the bill of materials, the composition of each material and the Restriction of the Use of Certain Hazardous Substances (RoHS) directive[7] that bans placing new electronic equipment containing more than certain levels of lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE) flame retardants on the EU market.

As can be expected, in order to be sold in countries that have adopted the RoHS, all parts of the tablet are compliant with these requirements and there is no presence of hazardous substances as listed in RoHS.

A.4.1.4. Average Annual Price Variation – Complementary Risk Indicator

According to the material composition of the tablet's components, the historical price variation of the tablet has been analysed using data for the past five years. The maximal price variation has been estimated equal to 30% of the average price of the material used for the tablet.

The main causes of the price variation are due to the presence of precious metals (e.g., gold and silver) and critical materials (e.g. cobalt for batteries or neodymium for speakers).

A.4.1.5. Sourcing and Geopolitical Risks – Complementary Risk Indicator

Among the specific indicators for material supply chain risks discussed in this methodology (see Section 2.3.1.2), the sourcing and geopolitical risk according to the sourcing and geopolitical Herfindahl-Hirschman Index (HHI) has been analysed. According to the material used in the tablet, about 22 of the 150 parts contain elements that are classified with high sourcing and geopolitical risks.

For example, about 0.08 grams of tantalum have been estimated to be in the capacitors mounted on the mainboard of the tablet. Tantalum has a very high sourcing and geopolitical risk, due to a high value of sourcing and geopolitical HHI. In this case, the index indicates a

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

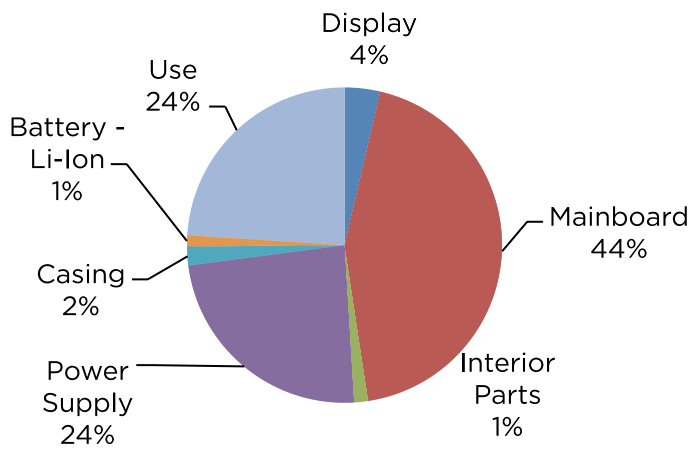
high supply disruption risk due to political factors, based on the countries in which the element is produced (e.g. in terms of political stability and control of corruption) and the concentration of worldwide production.

A.4.1.6. Carbon Footprint – Complementary Impact Indicator

Based on the bill of materials, generic tablet manufacturing processes, and a two-year use of the product, the total energy usage has been calculated. The calculations were based on the Life Cycle Assessment standard ISO 14044: 2006.[8]

The total carbon footprint along all the Life Cycle Phases (Cradle to Grave) is about 20.0 kg of CO_2 equivalent. Of this, about 75% are due to the production of the materials and electronic components as seen in Figure 7, while the use phase accounts for about 25%. The production of the electronic components, in particular the printed circuit boards, contributes to the high carbon footprint.

Figure 7: Carbon footprint of the baseline tablet (breakdown of the main parts)



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

A.4.2. Summary of Complementary Risk and Impact Indicators

According to the analysis performed, it is possible to summarise the main risks analysed and link them to the parts that are the main cause of risks as seen in Table 4.

Table 4: Summary of risks

Main parts	Carbon footprint	Price variation and material supply chain risk	Restricted substances risks
Display	High	High	Low
Electronic components	High	High	Medium
Power Supply	Medium	Medium	High
Casing	Low	Low	High
Battery	High	Medium	Low

A.4.3. Product Redesign

In order to increase the circularity of the tablet and mitigate the regulatory compliance issue on REACH above, the material used in the casing, which contains a flame retardant, needs to be substituted with a non-flammable material.[9,] Several materials could be used to substitute for the polycarbonate used in the base.[10] In this specific case, the objectives of the substitution are to increase the circularity of the product and reduce the potential presence of substances regulated by REACH. The constraints are not to increase the environmental impact, that is, the Carbon Footprint, and not to increase the price and risks associated with the materials.

In order to make the product more circular, three different scenarios have been developed as detailed in Table 5. The first redesign just changes the material used for the casing, while the second variant also reuses the casing. The third redesign is such that it also enables the front glass cover of the LCD display to be dismantled for reuse while still keeping the same proportions of materials used to manufacture the tablet.

[9] Greenpeace, *Safer Chemicals with REACH*, White Paper, 2001.

[10] M. F. Ashby, *Materials Selection in Mechanical Design*, Elsevier, USA, 2005, p. 251.

Table 5: Tablet characteristics - Baseline and redesign options

	Baseline	Redesign: material change	Redesign: material change and reuse of casing	Redesign: material change and reuse casing and front glass cover
Bill of materials	Generic tablet BoM with PC casing	Generic tablet BoM with aluminium casing	Generic tablet BoM with aluminium casing	Generic tablet BoM with aluminium casing
Mass	0.68 kg	0.74 kg	0.74 kg	0.74 kg
Feedstock materials	Virgin materials	Virgin materials	Reuse of casing, otherwise virgin materials	Reuse of casing and front glass cover, otherwise virgin materials
Destination after use	All materials to landfill	Aluminium casing recycled, rest to landfill	Aluminium casing reused, rest to landfill	Aluminium casing and front glass cover reused, rest to landfill

A.4.4. Comparing Circularity Indicators between Designs

Using the above information on the different designs, the same indicators were calculated for each of them, as can be seen in Table 6.

Table 6: Circularity Indicator results for all designs

	Baseline	Redesign: material change	Redesign: material change and reuse of casing	Redesign: material change and reuse casing and front glass cover
Material Circularity Indicator	0.10	0.17	0.26	0.46
REACH Article 33 Obligations	Highest risk substance 1.3% by weight	Highest risk substance 0.53% by weight	Highest risk substance 0.53% by weight	Highest risk substance 0.53% by weight
Average annual price variation over the past 5 years	±30% of average price	±30% of average price	±30% of average price	±30% of average price

	Baseline	Redesign: material change	Redesign: material change and reuse of casing	Redesign: material change and reuse casing and front glass cover
Material supply risk	22 parts containing elements with high risk	22 parts containing elements with high risk	22 parts containing elements with high risk	22 parts containing elements with high risk
Carbon footprint (CO_2eq)	20.0 kg	20.2 kg	19.9 kg	19.5 kg

From this comparison of indicators, we can see that the redesign reduced the amount of substances exceeding the REACH Article 33 threshold, improved the Material Circularity Indicator of the product and did not negatively impact the other risks considered. From the carbon footprint analysis, we can see that changing from the non-recyclable polycarbonate with flame retardants to aluminium did not significantly increase the impact since the aluminium can easily be recycled, as can be seen in the first redesign. (In the carbon footprint estimation, the potential benefits of aluminium recycling are already taken into account.) Moreover, as shown in the last redesign, the possible reuse of the casing and front glass cover contributes to a slight reduction of the emissions of greenhouse gases compared to the baseline scenario. That reduction is quite low owing to the fact that the contribution of the casing and front glass cover to the overall carbon footprint is low compared to that of the electronic components (See Figure 7).

A.5. Case Study – Simple Company

Widget Store is a company producing widgets and associated products. It has three product departments:

i) Widgets Department

The widgets department has three product ranges comprising:

- a range of five standard widgets
- a range of two premium widgets
- a recently introduced range of two circular widgets that have a closed loop return system[11]

ii) Flanges Department

Widget Store also produces one flange that can be used to connect any of the widgets.

iii) Accessories Department

The accessories department has two product ranges comprising:

i. a range of two covers to protect widgets
ii. a widget cleaning cloth

The standard and premium widgets are described in detail in the Simple Product Case Study, Section 4.1.1. The circular widgets are in a closed loop return system, meaning that *Widget Store* collects all old widgets after their use. The recovered aluminium parts are split between those suitable for further reuse (83%) and those sent for recycling (17%). All the ABS goes for recycling as a clean, mono-material waste stream.

Table 7: Standard accounting information for *Widget Store*

Depart-ment	Range	Model	Units Sold	Unit Price (EUR)	Unit Mass (kg)	Total Mass Sold (Tonnes)	Total Revenue (EUR 1000)
1. Widgets						**3395**	**28775**
	Standard Widgets					**1370**	**7100**
		SW_a	25000	50	10	250	1250
		SW_b	30000	65	12	360	1950
		SW_c	15000	80	14	210	1200
		SW_d	45000	50	10	450	2250
		SW_e	10000	45	10	100	450

[11] For the sake of simplicity, and for the purposes of this case study, it is assumed that, despite being a new product, the circular widget range has already reached a steady state whereby there are sufficient products recovered after their use to provide components for reuse in new products.

Depart-ment	Range	Model	Units Sold	Unit Price (EUR)	Unit Mass (kg)	Total Mass Sold (Tonnes)	Total Revenue (EUR 1000)
	Premium Widgets					**1300**	**12000**
		PW_a	50000	120	12	600	6000
		PW_b	70000	110	10	700	6000
	Circular Widgets					**725**	**9675**
		CW_a	65000	90	7	455	5850
		CW_b	45000	85	6	270	3825
2. Flanges						**177.5**	**1775**
	Flanges					**177.5**	**1775**
		F_a	355000	5	0.5	177.5	1775
3. Accessories						**4.25**	**190**
	Protective Covers					**2.25**	**150**
		PC_a	10000	10	0.15	1.5	100
		PC_b	5000	10	0.15	0.75	50
	Cleaning Cloths					**2**	**40**
		CC_a	20000	2	0.1	2	40
Company Totals:						**3576.75**	**30740**

A.5.1. Applying the De Minimis Rule

The Accessories Department accounts for just 0.12% of the total mass of product shipped and 0.62% of total sales revenue. In both cases these sit well below the 5% de minimis threshold. So to simplify the approach and reduce the amount of input information required, the Accessories Department is not considered any further.

A.5.2. Reference Products

The selection of reference products should follow Section 3.1.2 of the methodology. This states that:

"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 the their relative masses*
- *similar levels of recycled and reused content in the feedstock*
- *similar levels of recycling and reuse at the end of the use phase*
- *similar productivity function characteristics"*

The material compositions, recycling and reuse rates and productivity function characteristics of the various product ranges (as shown in the next section) are quite different, so each product range needs at least one reference product. However, within each range the main thing that distinguishes the different products is size, with all other characteristics remaining essentially identical. This means that one reference product per product range is sufficient.

In light of this assessment the following products have been selected as the reference products: SW_d, PW_b, CW_a and F_a. These particular products were chosen, as they are the products with the highest numbers of shipped units in their respective product range.

A.5.3. Bills of Materials

The bills of materials for the four reference products are as follows:

Table 8: Bill of materials for Reference Product SW_d

Component	Material	Mass (kg)	%Recycled feedstock	%Reused feedstock	%Recycled after use	%Reused after use
Component 1	Aluminium (Al)	2.0	50%	0%	75%	0%
Component 2	ABS	8.0	0%	0%	25%	0%

Table 9: Bill of materials for Reference Product PW_b

Component	Material	Mass (kg)	%Recycled feedstock	%Reused feedstock	%Recycled after use	%Reused after use
Component 1	Aluminium (Al)	8.0	50%	0%	75%	0%
Component 2	ABS	2.0	0%	0%	25%	0%

Table 10: Bill of materials for Reference Product CW_a

Component	Material	Mass (kg)	%Recycled feedstock	%Reused feedstock	%Recycled after use	%Reused after use
Component 1	Aluminium (Al)	6.0	17%	83%	17%	83%
Component 2	ABS	1.0	100%	0%	100%	0%

Table 11: Bill of materials for Reference Product F_a

Component	Material	Mass (kg)	%Recycled feedstock	%Reused feedstock	%Recycled after use	%Reused after use
Component 1	Aluminium (Al)	0.5	50%	0%	60%	0%

A.5.4. Material Circularity Indicators

In order to calculate the MCIs the product lifetimes are required as listed below. The market-average product lifetime (L_{av}) for a widget is 10 years, and for a flange 20 years.

In the case of the circular widget the materials sent for recycling are uncontaminated compared to the mixed plastics associated with standard and premium widgets. As a result the recycling efficiency for ABS is increased from 0.4 to 0.8.

The MCIs have been calculated according to Section 2.1 of the product methodology, and as illustrated in full detail for SW_d and PW_b in the Simple Product Case Study (Section A.1).

Table 12: Reference product lifetimes and MCIs

Reference Product	Lifetime (years)	MCI
SW_d	8	0.06
PW_b	12	0.61
CW_a	12	0.98
F_a	20	0.57

The standard widget has the lowest MCI due to its reduced lifespan and the fact that it is mostly made from virgin ABS which is not recycled at end of use. The premium product has a higher MCI because of its longer life and the fact that it is mostly made from aluminium, which has high levels of recycled content and high collection rates for recycling. The flanges are completely made from aluminium giving them a relatively high MCI. The very high MCI of the circular widget reflects the high levels of reuse and recycling.

A.5.5. Combining the Widget MCIs

In order to calculate the company-level MCI, one must first derive the MCI for the Widgets Department. This is illustrated here using mass as the normalising factor.

The total mass of widgets sold is 3,395 tonnes as shown in Figure 8. The table also shows the total mass of standard widgets sold (1,370 tonnes), premium widgets (1,300 tonnes) and circular widgets (725 tonnes).

The MCI for the Widgets Department is now calculated as described in Section 3.2.2 of the methodology:

$$MCI_W = \frac{1}{3395}\,(\,1370 \cdot 0.06 + 1300 \cdot 0.61 + 725 \cdot 0.98\,) = \ 0.47$$

This calculation can also be undertaken using the aggregator tool available from the Circularity Indicator Project website.[12] This tool also plots a chart as shown below.

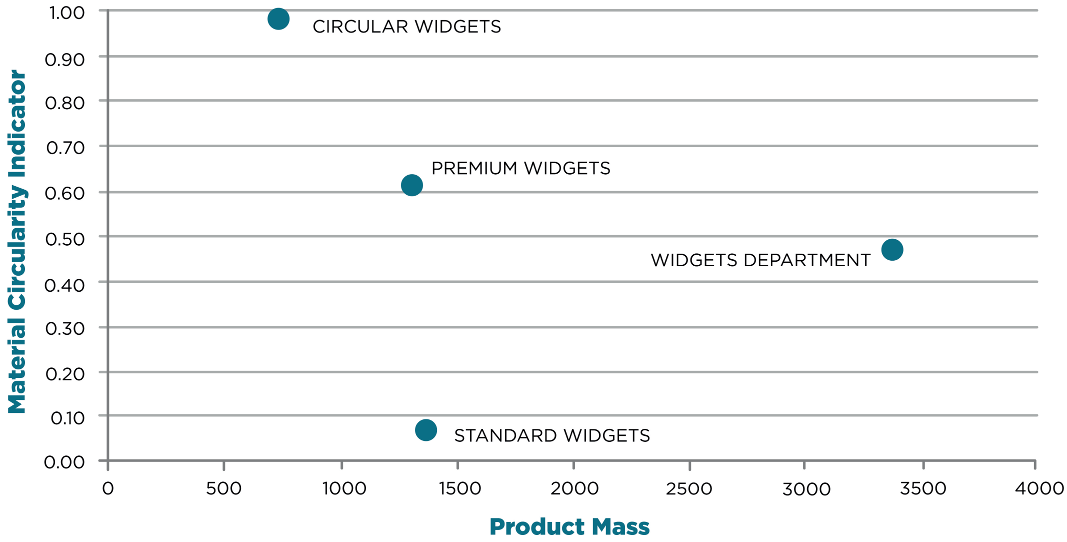


Figure 8: Combining widget product ranges using mass as the normalising factor

A.5.6. Combining the Department MCIs

In order to calculate the company MCI, the MCI of the Widget Department (0.47) is now combined with the MCI of the Flanges Department (0.57). Note that, as the Flanges Department has only one product range, its MCI is equal to the MCI of the flange reference product F_a. The total mass of widgets sold is 3,395 tonnes and the total mass of flanges sold is 177.5 tonnes. According to Section 3.2.2 of the methodology, the company level MCI is now derived as

$$MCI_C = \frac{1}{(3395 + 177.5)}(\,3395 \cdot 0.47 + 177.5 \cdot 0.57) = \ 0.47.$$

Again the Aggregator Tool can be used to undertake this calculation thus producing the following graph:

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

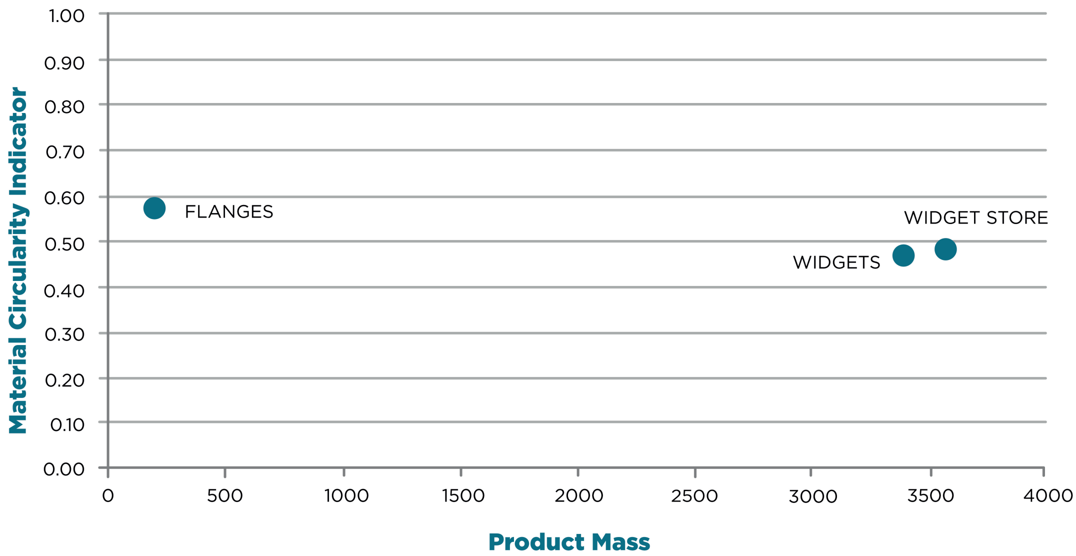


Figure 9: Combining widget and flange departments using mass as the normalising factor

The widgets dominate the final result reflecting the much higher amount of product shipped in terms of mass.

A.5.7. Investigating an Alternative Normalising Factor

Using the information provided in Table 12, it is straightforward to repeat the calculations using sales revenue as the normalising factor. In this case the combination of widget MCIs is summarised in the following chart:

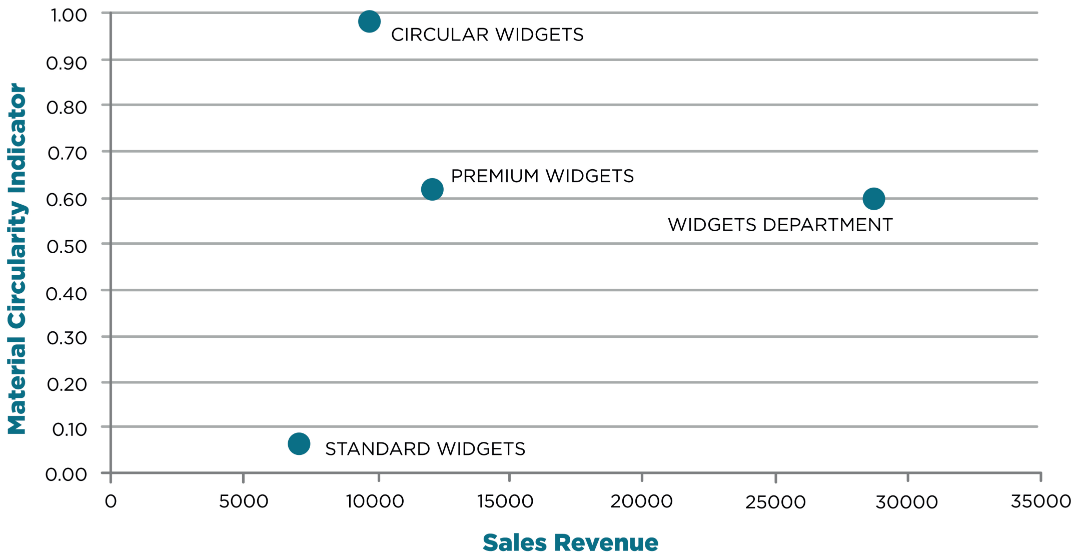


Figure 10: Combining widget product ranges using sales revenue as the normalising factor

… and the combination of widgets and flanges as follows:

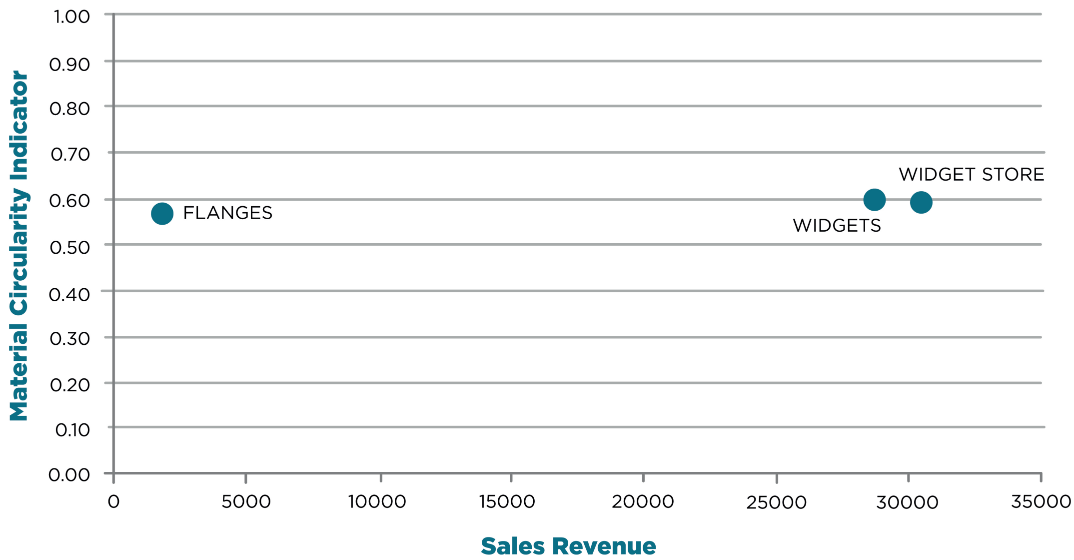


Figure 11: Combining widget and flange departments using sales revenue as the normalising factor

For this particular company, the final result from using sales revenue as the normalising factor is not vastly different to that obtained using mass. It is therefore concluded that either normalising factor would be appropriate to use in this case.

A.6. Case Study – Normalising Factors

In the simple company case study (Section A.4) there is not much difference between using mass and revenue as the normalising factor, but this case study provides an example where there is an important difference.

It is based on a fictitious plumbing pipe supplier with two product ranges: one comprising copper pipes, and the other polybutylene[13] pipes. Similar quantities (in terms of length) of pipe are sold each year for each range.

The revenue figures are representative of current retail prices. The mass figures are based on commercially available plumbing pipes.

The MCI values have been calculated elsewhere and reflect:

- the high recycled content of copper feedstock and the high recycling rates of the copper pipes after their use
- no recycled content of plastic feedstock and very low recycling rates for polybutylene pipes

Table 13: Summary of input data for a plumbing pipe supplier

	Mass Sold (tonnes)	Revenue (£m)	MCI
Copper pipe	8,500	60	0.61
Polybutylene pipe	2,112	41	0.14

Using the Aggregator Tool, it results that, using mass as a normalising factor, the MCI of the company would be 0.52, whereas using revenue it would be 0.42. The following figures show the output of the Aggregator Tool for the two normalising factors.

In this example, it is clear that because of its higher density the MCI for copper pipe dominates the combined result when mass is used as the normalising factor. On the other hand, using revenue gives a more balanced view of the company and should be chosen as the preferred option in this case.

[13] A saturated polymer (plastic).

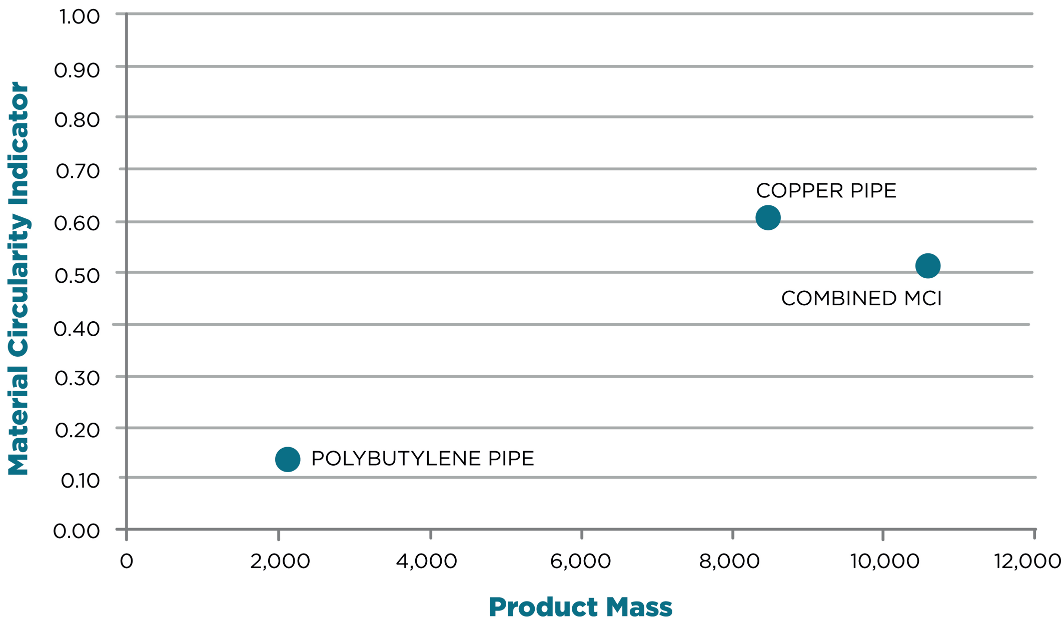


Figure 12: Combining the MCIs using mass as the normalising factor

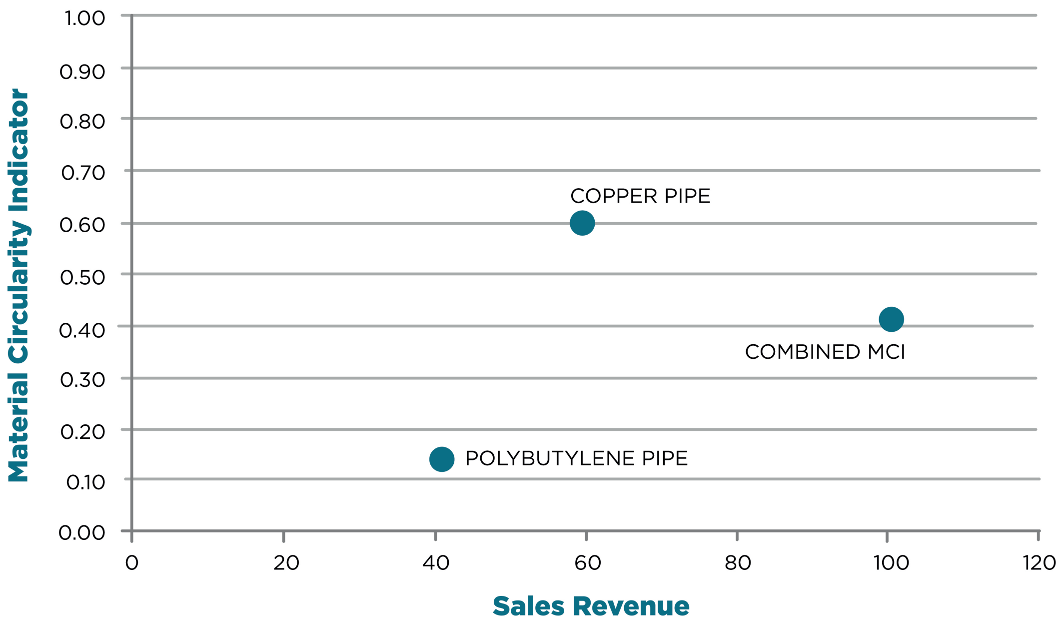


Figure 13: Combining the MCIs using sales revenue as the normalising factor

B. Proposed Method to Include 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.[14]

B.1. 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.

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

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.

The Materials Circularity Indicator including production MCI'_P, can then be computed as

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

B.2. 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.

B.2.1. 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

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

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.

B.2.2. 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

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

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

B.2.3. 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 $\psi = 1$ 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:

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

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

B.2.4. Updated Material Circularity Indicator Equation

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

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

where M' is given by the sum

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

B.3. 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.

C. 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

C.1. 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.

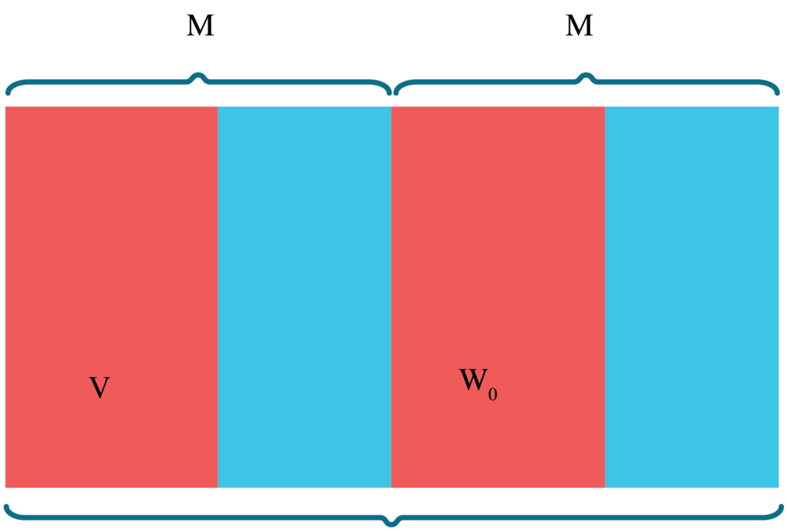


Figure 14: Derivation of the LFI without considering waste from recycling processes – the red area represents the linear part of the flow while the blue area represents the restorative part

So we arrive at

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

C.2. 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.

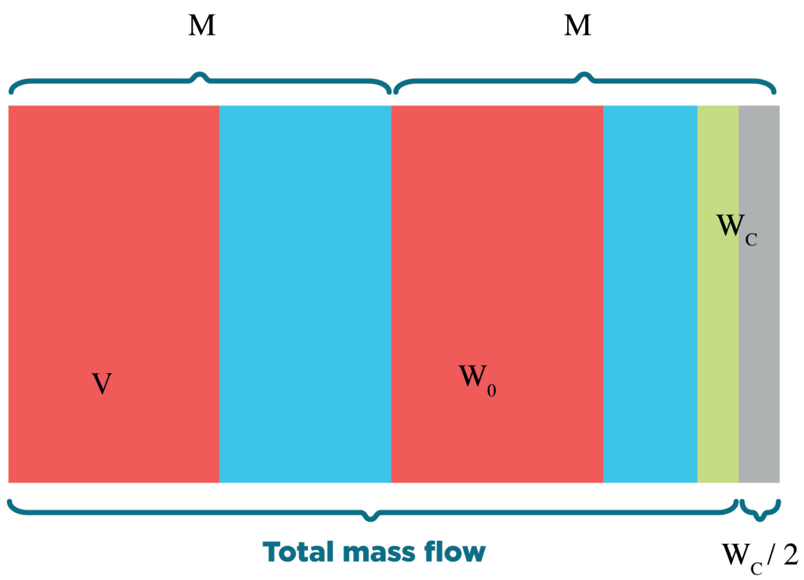


Figure 15: Derivation of the LFI considering waste created while recycling the product - the red and green area represented the linear part of the flow while the blue area represents the restorative part; the grey area is not considered part of the total mass flow for this product

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

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

C.3. 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.

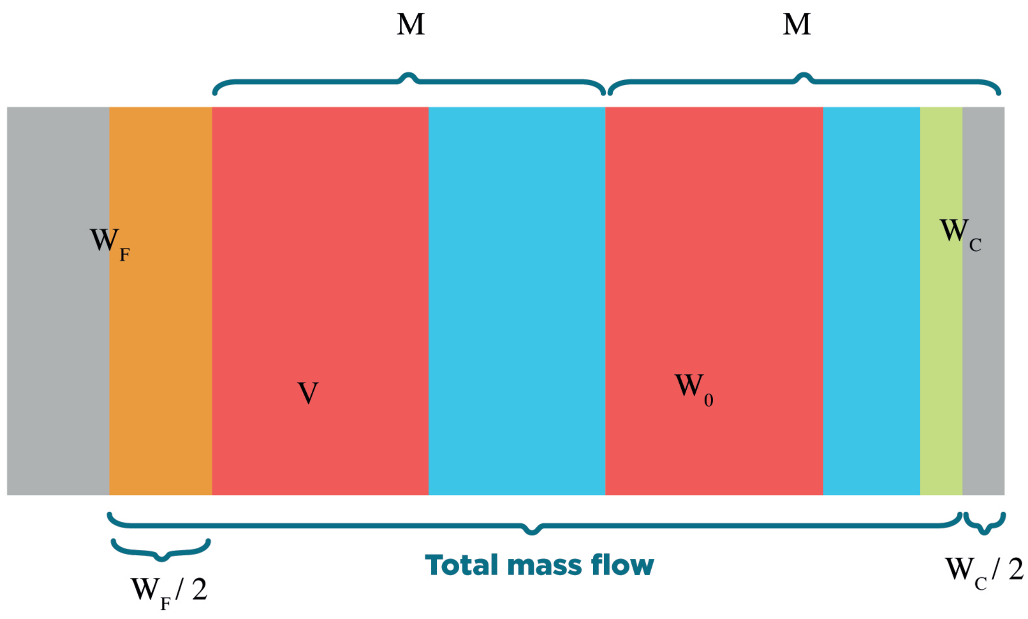


Figure 16: Derivation of the LFI additionally considering waste generated to produce recycled feedstock - the red, green and orange area represented the linear part of the flow while the blue area represents the restorative part; the grey areas are not considered part of the mass flow for this product

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.

D. 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 $1/k$ of them need to be 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 and the amount 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 $X = 1$ 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.

E. Wood and Paper

This methodology only addresses technical products and materials in technical cycles. However, materials like paper and wood – although biologically sourced – are frequently used in technical products and can circulate in the technical cycle. This appendix describes considerations and provides some guidance on how such materials could be incorporated into this methodology.

It should be noted that this appendix just gives some guidance and cannot replace a proper methodology of how biologically sourced materials are to be considered as part of a circularity indicator. In particular, the recommendations made for wood and paper here do not necessarily generalise to other biologically sourced materials. In addition, other factors including land use and impact on ecosystems including biodiversity would need to be considered, for example via further complementary indicators.

E.1. Feedstock from Renewable Sources

At a basic minimum, biologically sourced materials can only be considered part of a circular economy if materials are not used faster than they can be restored naturally. Phrased differently, for timber-based materials, "the rate of harvest of forest products shall not exceed levels which can be permanently sustained."[15]

Additionally, forestry can also have a variety of other impacts that are not compatible with a sustained use of resources, which is necessary for a circular economy to be possible in the long-term. Therefore using only sustainably certified paper or wood, for example, by satisfying the principles of the Forest Stewardship Council or equivalent certifications. This feedstock from renewable sources can then be considered separately from virgin feedstock in the methodology.

E.2. End-of-use Materials

For materials like wood and paper that are used in technical products, circulating them in technical cycles via recycling or reuse should be considered the preferred method, since this allows for longer material use and hence retains the most value.

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[15] Forest Stewardship Council, *FSC Principles and Criteria for Forest Stewardship*, 2012, Principle 5.6 (see https://ic.fsc.org/principles-and-criteria.34.htm).

However, at the end of use, alternatively to being recycled, materials like wood and paper can be restored to the biosphere if there is no contamination with toxic or non-degradable materials such as paint or chemical preservatives. For wood-based products, for example, this can be via composting. (Note that anaerobic digestion is not a suitable decomposition method for wood-based products as those contain high portions of lignin.) This is in general preferable to disposal via landfill and can be considered separately in the methodology.

F. Project Stakeholders

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F.1. Pilot Companies

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

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Desso

Dorel

Hewlett-Packard

Kingfisher

Nespresso

Rolls Royce

F.2. 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

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NGOs

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