NL Agency
Ministry of Infrastructure and the Environment

Usability of Life Cycle Assessment for Cradle to Cradle purposes

Position Paper

December 2011

Executive summary

Life Cycle Assessment (LCA) is a measurement tool that has been used since the 1970s as a means of assessing the environmental impact of products or services. Cradle to Cradle (C2C) is an innovation framework used since the 1990s in order to design products and services which are beneficial in economic, health and environmental terms.

Introduction

A group of companies in the **Cradle to Cradle (C2C) Learning Community** in the Netherlands are working with both these tools and wish to determine whether C2C and LCA are compatible. How and to what extent these companies work with C2C and LCA varies for each company. In the experience of these companies, the LCA method of comparing products – particularly the use of Environmental Product Declarations, EPDs – dominates in the marketplace, while the beneficial C2C qualities they are aiming for are not reflected properly by these LCA standards.

Terms of reference

The remit of this assessment is '*to evaluate the usability of LCA as a measurement tool for the development and measurement of C2C products.*'

This assessment focuses primarily on the methods and systems that are currently in general use in the field of LCA. It looks at LCA only from the perspective of implementing C2C, not at the use of LCA for other purposes.

Concerning the *usability of LCA in a C2C process*, companies that implement C2C principles need a measurement instrument that can be used for three key purposes: *setting goals*, *monitoring* development, and *external communication*.

The usability of LCA for C2C purposes requires a better understanding of C2C *dimensions in relation to LCA*. C2C's innovation framework aims for a *beneficial future* footprint based on defined *qualities*.

These defined qualities are based on the guiding principles of C2C. In fact, this assessment involves an exploration of *C2C's guiding principles and the extent to which they can be measured using LCA*.

Summary of findings

How useful is LCA in the C2C process?

The conclusions concerning the use of LCA for C2C purposes are:

- **Setting goals**, the C2C inventory: LCA can add to the C2C inventory: 'know what you have' (The C2C inventory includes data that goes beyond the environmental data gathered in an LCA, e.g. it starts with a complete content declaration for a product);
- C2C **Monitoring**: LCA can help determine whether burdens are shifted when changes are made to the product or process.
- C2C **Monitoring**: LCA is not designed to indicate how much progress has been made with a C2C product. The C2C roadmap and associated measurable milestones are more important for that.
- **External communication**: LCA is not suitable for communicating the 'C2C-ness' of a product, and thus not suitable for external C2C communication.

For companies that wish to apply C2C principles, it may be useful to know internally how a C2C design scores using an LCA to put it into the context of government criteria (sustainable procurement) and other communication based on LCA, such as EPDs, an industry-standard LCA with sector-specific product criteria.

C2C dimensions in relationship to LCA

During the expert discussions on measuring the 'C2C-ness' of a product, three basic contradictions were identified between the C2C innovation framework and the LCA measurement tool, which are encapsulated in the following sentence.

'*Measuring a* ***qualitative***^{A} ***plan***^{B} *for creating a* ***beneficial***^{C} *footprint by using a* ***quantitative***^{A} *instrument designed to measure an* ***existing***^{B} *environmentally* ***damaging***^{C} *footprint.*'

Each of the contradictions is explained further.

*A. Measuring **qualitative** solutions with a **quantitative** measurement tool*

Under C2C, the principle of 'waste equals food' or 'everything serves as a resource for something else' is taken to mean 'the right material, at the right place at the right time'. 'Right' basically means that the materials are suitable for the use defined for them. This valuation depends on the interaction of both the solution-offering side (i.e. a product) and the solution-using side (i.e. the user, his surroundings and other environments the product will come into contact with during its life). Whether something is 'right' depends on how these qualities, the references for good and bad, are defined. Some of these can be quantified using an LCA, while others cannot.

Conclusion: The extent to which the defined qualities of a C2C product can be measured with LCA depends on how far they can be quantified for measurement in LCA terms. In other words, on how far they can be described in specific terms rather than conceptually.

*B. Measuring a **future** solution using **current** data*

The C2C framework concerns future solutions and therefore innovation. Targets and milestones towards those solutions are identified and act as innovation drivers. At the starting point, the exact nature of the ultimate solution is not always known.

Conclusion: The 'C2C-ness' of products can be measured if they are defined using data that reflect the likely nature of the future C2C design solution. However, the measurability of that data depends on the ability to forecast future outputs accurately. LCA is designed as a snapshot of a particular point in time on the basis of current impacts. It is not designed to evaluate a company's progress in completing steps towards a qualitative expected goal.

*C. Measuring a **beneficial** environmental footprint with an instrument that is designed for measuring an environmentally **damaging** footprint.*

The goal of the C2C framework is to develop a product in such a way that it creates a beneficial (positive) environmental footprint. Three guiding principles are used to define this beneficial footprint: 'waste equals food', 'use current solar income', and 'celebrate diversity'.

Conclusion: Although LCA has been designed to measure the damaging (negative) environmental impact of products, it can also be used to measure the established beneficial (positive) footprint of a C2C product. However, there are limits to the applicability of the current LCA approach.

The guiding principles of C2C and measuring these with LCA

C2C's defined qualities are based on the three guiding principles '*waste equals food*', '*use current solar income*' and '*celebrate diversity*'. Whether the 'C2C-ness' of a product can be measured with LCA depends on the extent to which the stated qualities of a C2C product can be quantified in current LCA terms. Taking a closer look at these qualities (on the basis of C2C's guiding principles), results in:

- **Waste equals food** (C2C recycling, cascades, materials pooling):
  Under C2C a product will be recyced after use. C2C works with end-of-use scenarios and not with end-of-life scenarios as under LCA. Under LCA, it is *difficult* to measure the recyclability of a product and calculate the benefits of recycling that relate to a single product in the materials cascade. Under LCA, stakeholders still differ about how to account for this benefit and to whom it should be credited.
- **Waste equals food** (toxicity aspects determined with C2C's ABC-X method):
  In many cases, it is *not possible* to calculate to what extent a material is suitable for its context. Under LCA, this is done on the basis of the actual impact of toxic emissions into the environment over the entire lifecycle. Currently the LCA community is looking for ways to model more types of environmental impact more accurately. For example, measuring the impact on indoor air quality and local aspects are being developed under LCA.
- **Use current solar income**:
  A quick LCA on several renewable energy-production systems will lead to the same general conclusions as C2C. The energy consumed for a C2C product *can be measured* with an LCA. However, the 'waste equals food' principle within energy production systems is not part of a 'regular' LCA.

Conclusions

The exploration of the usability of LCA for C2C purposes has led to the following conclusions:

- Commonly used LCAs, and especially EPDs, are not suitable for assessing and communicating the beneficial qualities of a C2C product.
  - C2C emphasizes the suitability of a 'nutrient' (material) to its context (the right material at the right time at the right place), throughout all the use cycles / loops through which it passes;
  - What is 'right' cannot be measured in LCAs currently in use; within C2C it is based on specific value-based quality-statements that are not generally suitable for measurement with LCA;

  - How C2C deals with cascading, toxicity and (local) suitability is reflected differently from commonly used LCAs.
- LCA can only contribute to the C2C inventory for internal company purposes. Under certain circumstances, it can then help to identify whether burdens are shifting when developing a C2C product, but this contribution is not universal and is limited by the LCA methods currently used.
- New developments in LCA - such as assessing social impacts and assessing the impact of materials on indoor air quality - may bring measuring 'C2C-ness' a step closer. However, it will not be possible to measure the entire 'C2C-ness' of a product, since LCA is not designed for this purpose.

Recommendations

The main recommendations of this paper are:

- Companies wanting to use C2C, but who also want to present the environmental impact of their product to other LCA users or to use EPDs, are advised to use LCA as a separate track to identify unforeseen hotspots and avoid burden shifting.
- Purchasers wanting to compare products on the market should look at the functionality of the product, and which environmental, social and health benefits they want to achieve by buying and using a product, especially if they want to favour a particular end-of-use strategy (re-use, recycling, incineration, land-fill).
- Experts in the field of C2C and environmental assessment are advised to look into which measurement tools could be used or developed to evaluate milestones in a C2C roadmap.
- For companies looking for ways to communicate the benefits achieved with a C2C product they are developing, it can be helpful to look for a (new) communication standard together, based on an assessment of environmental, economic and social issues.
- For companies familiar with LCA, it might be useful to reformulate the question: 'How can LCA practitioners benefit from C2C?'

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1 Introduction

In response to a growing awareness that our current systems of production, consumption and disposal are damaging the environment, methods such as eco-design and measurement tools such as Life Cycle Assessment were developed in order to quantify and mitigate environmental damage. The concept of sustainable development served as a guide in this: 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs', Brundtland[1].

Among industrial producers, the desire to minimize the damage caused by the production, use and disposal of products has grown because manufacturers wish to avoid image problems and meet legal requirements. Increasingly, businesses are adopting corporate social responsibility policies and taking advantage of the market opportunities that they can offer.

Now, another approach is attracting the attention of pioneering companies. The Cradle to Cradle® Innovation Framework, C2C®[2], is enabling companies to develop products which actually create a positive environmental footprint. The C2C design framework, with its three guiding principles, gives clear direction to (product) development. It functions as a driver for innovation in the product chain.

1.1 The Cradle to Cradle innovation framework ...

The Cradle to Cradle® Innovation Framework has rapidly become the focus of increasing attention. It was originally developed in the late 1980s, and matured during the 1990s as a positive approach to reconciling human activity and its environmental impact. Current thinking on the environment encourages us 'to reduce, reuse and recycle'. However, according to Michael Braungart and William McDonough, founders of the C2C concept, this will lead only to a continuation of the traditional 'Cradle to Grave' production model that has already been the cause of such enormous amounts of waste and pollution. As they see it, we should stop trying to do bad things 'less badly' and instead start doing things that are intrinsically beneficial to the environment instead.

1.2 ... and Life Cycle Assessment as a measurement tool

In the Netherlands, a growing number of companies and local authorities are striving to implement the ideas behind C2C. They are familiar with using Life Cycle Assessment, LCA[3], as a support tool for decisions that involve sustainability. LCA is also used as a measurement tool in eco-design[4] processes. LCA calculations aim to model the full lifecycle of a product (whether from 'cradle to grave' or from 'cradle to cradle') and to measure the many ways in which it will impact on the environment along the supply chain. As such, LCA is not a design tool but measures environmental impact. LCA does not relate to a vision of what the world should look like; it measures the impacts of decisions already made.

1.3 Context of this paper

In 2009, a group of 17 pioneering companies in the Netherlands came together to share their experience of implementing the principles of C2C in the '**Learning Community C2C**'. Most of these companies wanted to answer the question: '*Why does LCA sometimes not reflect the improvements expected from C2C?*'. They felt strongly that C2C needed to be made more professional with a measurement tool that was accepted among the LCA community to incorporate eco-effectiveness into their LCA-based decision-support tools. Additionally, in their experience LCA's method of comparing products – particularly through the use of Environmental Product Declarations, EPDs – dominates the marketplace, while the beneficial C2C qualities they are aiming for are not reflected properly in these LCA standards.
The degree to which each company works with C2C varies. Some companies simply use C2C as a source of inspiration when developing their products. Others are going all out to become a C2C company. The results of the Learning Community and the experiences of the participating companies were published in the booklet entitled '**Cradle to Cradle pays off!**'[5].

Companies apply C2C in different ways
Some companies have developed their own environmental toolkits with which they evaluate the environmental impact of their products and processes. LCA is one element in these toolkits. These companies may also see C2C as an interesting new concept with which to expand their toolkit. C2C challenges existing assumptions and introduces a completely new way of thinking. For these companies, C2C is primarily a design methodology or an R&D concept. This document will help those companies see the different perspectives taken on specific aspects of environmental sustainability under both C2C and LCA.

Other companies involved in this work have adopted the C2C philosophy in full and integrated it into all aspects of their business model. The conclusions and recommendations at the end of this document are mainly relevant for those companies that have adopted C2C in full and are interested in integrating LCA while continuing to follow the C2C methodology.

The working group, expert panel and sounding board
The participating companies stated that they were interested in the use of LCA as a decision-making tool when developing C2C policies. Several expert sessions were held to discuss the feasibility of using LCA to measure C2C products and processes. This process was supported and moderated by NL Agency (*Agentschap NL*), a Dutch government agency that aims to promote innovation and sustainability. This position paper describes the main conclusions of these expert panels, and has been reviewed by an international sounding board.

1.4 Terms of reference

This assessment aims '*to evaluate the usability of LCA as a measurement tool for the development and measurement of C2C products.*'

We focus primarily on the methods and systems generally used in LCA, since this is the main concern for businesses and governments that use LCA. The remit of this document includes using LCA to implement C2C, but excludes the use of LCA for other purposes.

Those companies that are implementing the principles of C2C need a measurement instrument that can be used for three key purposes in the C2C process:
- *Setting goals* (vision/ambition);
- *Monitoring* the development;
- *External communication*.

The starting point for these companies is to use what is currently the most widely accepted measurement tool, Life Cycle Assessment (LCA). LCA, unlike the LCA-based Environmental Product Declaration (EPD), is an open framework that can be very flexible. EPDs, by contrast, are more rigid and their Product Category Rules are based on sector consensus.

1.5 Target audience

This paper is essentially meant for companies which are considering implementing C2C but are more familiar with LCA. It addresses managers, designers and eco-designers, environmentalists, LCA specialists and CSR specialists working in companies who want to develop products according to the guiding principles of C2C. But it is also relevant for others who come into contact with both C2C and LCA, who can benefit from the comparison of the two concepts. As such, it will also be relevant for policymakers and purchasers within local and national government who are aiming to implement C2C, to help them understand what an LCA can be used to measure. The paper deals mainly with using LCA as an input for C2C, but some sections also relate to using C2C as an input for or alongside an LCA process. Eco-designers familiar with LCA as a tool will benefit from the information on the role of C2C and LCA in product-development processes. There is more practical information in the appendices about this and how managers, designers and CSR specialists can make use of both concepts.

1.6 Structure of the position paper

As stated, the objective of this assessment is '*to evaluate the usability of LCA as a measurement tool for the development and measurement of C2C products.*'

Chapter 2 explores how C2C and LCA operate in business development and the product design processes. Chapter 3 focuses on three important dimensions of C2C in relation to LCA as a measurement tool. It describes how LCA could be used to measure a beneficial future footprint on the basis of defined qualities which are in turn based on the guiding principles of C2C. Chapter 4 explores the usability of LCA for C2C purposes by examining the guiding principles of C2C and the potential usefulness of LCA when assessing the application of these principles. The main conclusions and recommendations can be found in Chapter 5.

The main body of this position paper describes the theoretical aspects of using LCA for the purposes of C2C, while the appendices include further practical information on LCA and C2C.

2 C2C and LCA in the context of business development and eco-design

To explore the usefulness of LCA as a tool for developing and evaluating C2C products, this chapter of the paper will first examine how C2C and LCA operate in business development and the product design processes.

2.1 Cradle to Cradle as a framework for design and innovation

C2C is a design framework for innovation. It is based on a philosophy, guiding principles and application tools. Appendix 2 shows a comparison between C2C and LCA, including the development of new materials, processes, products and systems. Companies take varying approaches to implementing C2C. Some opt to have their existing products certified, others choose to optimize their products first and then have them certified individually, and others still adopt C2C across the entire company including all products and processes.

There are *three guiding principles* within the C2C framework for innovation:

1) **Waste equals food**: products and by-products are designed to act as defined 'nutrients' in a biological or a technical 'metabolic system';
2) Energy requirements must be met using sources derived from **current solar income** (either direct or derived, thus including geothermal and kinetic energy);
3) **Celebrate diversity** (biodiversity, cultural diversity, conceptual diversity). A diversity of actors and concepts will ultimately make it possible to implement C2C while adhering to these principles.

When developing C2C products and processes, these principles are applied in an integrated manner. For example, when developing a C2C carpet, materials are selected according to their healthiness during use as well as their compatibility with defined future uses. Both the production and recycling of carpets involve using a range of renewable energies. Applying the principles in an integrated manner also means that these renewable energy production systems are designed according to the 'waste equals food' principle.

The objective of a beneficial environmental footprint is fundamental to the C2C approach. C2C aims for products and processes that improve the environment and society, add value and are 'eco-effective'. Progress towards this goal is directed by the three principles outlined above. Companies begin a C2C process by stating their qualitative intentions according to these guiding principles.

2.1.1 Setting goals (vision/ambition)

Companies often define corporate goals to reflect their values. A corporate strategy or policy may include eco-effectiveness (such as contributing to soil restoration) and eco-efficiency (zero waste) goals.

Implementing C2C begins with the formulation of eco-effectiveness goals based on the guiding principles of C2C. The extent to which corporate goals are consistent with the C2C innovation framework and its guiding principles may be reflected in the company's KPIs.

The process starts with the C2C inventory ('know what you have'). Depending on its scope, this may include data on an existing product or portfolio (in the case of a redesign) or on a product concept. It starts with a precise and comprehensive understanding of 1) the composition of the product; 2) material flows to which it contributes (or would contribute) and 3) the actors involved and their attitudes. The C2C inventory includes a complete content declaration of a product to 100 ppm (parts per million).

C2C uses a *back-casting approach*. This means that it begins with the objective, and works backwards to define the conditions necessary to achieve this objective. Elements are bundled to form milestones.

In this context, eco-effectiveness encompasses not only the final result but also the *interim results* achieved along the way, which represent the conditions for reaching the final objective. From the customer's perspective, buying products from a company which has not yet achieved its final objective but which has stated its intention to achieve that objective also represents an eco-effective contribution to a better environment under the C2C approach (but an additional challenge in evaluating the 'C2C-ness' of products).

2.1.2 The C2C Roadmap and monitoring progress

Goal-setting is at the heart of the C2C design and innovation framework. It is the process through which the core principles of C2C are applied to a product or process. The C2C Roadmap is an important application tool that describes the pathway that the organization will take to achieve its goals. It includes clearly identifiable and measurable milestones, or key performance indicators (KPIs), which can be used to assess the extent to which the goals have been achieved.

Under C2C, *KPIs* might include activities outside the company's own boundaries. For example, for service products with post-use management of the used products and materials, the system of KPIs could encompass:

- at a milestone: Logistic partners contracted for future collection of used products and materials;
- at a later milestone: Rate of collection and rate of recovery of materials from the used products collected.

Those milestones (e.g. percentage of recycled content, percentage of solar income, and so on) are measurable, but do not usually require a full LCA. More targeted tools could be used instead and a screening LCA or a carbon footprint may be enough, for example. It would be useful to explore how selected LCA tools could be used to evaluate the milestones on a C2C roadmap. The selective use of tools could avoid costly duplication on occasions when a full LCA is not needed.

2.1.3 C2C certification (external communication)

Products made from materials which are environmentally safe, healthy and recyclable are awarded the C2C certificate. C2C certification gives companies a way of demonstrating the success and progress of their products. Consumers may seek out products on the basis of whether they have met this quality requirement. Additionally, the use of renewable forms of energy, a responsible attitude to water usage and other social aspects are also considered. A C2C certificate remains valid for one year, after which recertification is needed. A higher level of certification may be awarded if progress has been made. Certification shows the extent to which a product has satisfied the requirements of C2C and there are four different levels of certification: basic, silver, gold and platinum. Certification is planned to be carried out by an independent NGO, the C2C Product Innovation Institute in California[6]. The institute is currently implementing a critical review of the certification process and is planning to release an updated version (3.0) in early 2012.

2.2 Life Cycle Assessment as a measurement tool

Life Cycle Assessment tools have been developed within a broad and open community of experts and companies. No one individual or organization owns the method, although several privately and publicly owned software tools and databases are used, and a number of organizations have produced LCA handbooks. Global guidance is provided through ISO standards 14040 and 14044, and through the UNEP/SETAC Lifecycle initiative. In Europe, the JRC in Ispra runs an LCA centre that has developed its own methods and database[7].

The aim of LCA is to provide a tool to help decision makers understand and improve the environmental impact of products and services. Systematic measurement is essential if we want to assess and mitigate the impact of human activity on the environment. LCA is not a design concept: it focuses on understanding products, whether they are already in production or will be produced in the future.

LCA includes all possible aspects of environmental impact, from the raw materials consumed during manufacturing (cradle) to disposal of the product after use in a landfill or incineration site (grave), or – in the case of recycling – its new lifecycle (the next cradle). It is necessary to isolate the impact of a single product because production processes and product systems are often interlinked.
Three key issues that must be addressed are:

- **System boundaries:** 1) Where do we stop modelling? 2) What can be omitted without distorting results?
- **Allocation**: Industrial processes often result in more than one product (or service). For example, if we want to model the product 'milk', we find that cattle farming also produces meat, leather, bones etc. How do we allocate a share of the environmental impact of cattle farming to 'milk' in particular?
- **Regional differences**: The electricity consumed by a company in France will use energy from a different source (mainly nuclear) to a company in Denmark (mainly coal and some wind power) or Norway, (mainly hydro-electric power). This means that identical production processes that consume electricity can have a different environmental impact depending on where they are carried out.

These are a few of the complexities involved with 'modelling the world', whether this is the model of a C2C world or

not. How LCAs are conducted depends on the decision context.

It is important to note that different choices or forecasts of how industrial processes interact and how the market responds to changes can lead to different models and therefore different results.

The best way to handle the ambiguity that results from this complexity is to be transparent, clear and consistent on how choices and interpretations are made. This means that in an LCA study, the purpose and goal of the study, which are often based on the decision context of the LCA, need to be clearly described and justified in a *goal and scope document*. The goal and scope document also describes the choices and assumptions made (including the system boundaries), the required depth of the analysis as well as the use of future scenarios and the main methodological choices. Consequently, when performing an LCA for a C2C product, it is essential to specify which aspects of C2C will be assessed and how. It is also wise to state which C2C aspects are not taken into consideration. This information needs to be included in the goal and scope document. Despite criticism of its ambiguity, LCA has been accepted and adopted as an important tool enabling us to measure the environmental impact of products and processes systematically.

The world of LCA is constantly improving as methods evolve to assess environmental impact ever more accurately. This position paper focuses on commonly used LCA methodology at the time of writing.

2.2.1 Setting goals

LCA can be used as a measurement tool in eco-design processes. One of the purposes of LCA in eco-design is to identify environmental *hotspots*. Hotspot analysis helps product developers to prioritize areas for improvement after an LCA has been conducted.

A *key difference* from the C2C approach is that when conducting an LCA, priorities are not set *a priori*. Depending on the hotspot analysis, it is possible to focus on product development to improve recycling of the used materials, but equally the focus may be on minimizing energy use, reducing the amount of materials used, improving logistics, replacing toxic materials, and so on.

2.2.2 Monitoring progress and the benefits of C2C

Another use for LCA in eco-design processes is in comparing alternative design solutions and identifying an alternative that has a lower environmental impact. It is also possible to compare the initial product design with a redesigned product to reveal how much progress has been made in reducing the environmental impact. LCA can be used in C2C to show whether environmental burdens are being shifted.

LCA-related standards are often unable to reveal the benefits of C2C products. The short guide in appendix 7 includes a number of points which may be relevant when analysing C2C products using an LCA, including the aspects relevant to C2C. The usefulness of LCA in measuring specific indicators depends on the flexibility of LCA models. If they are flexible enough, LCA can play a more useful role in C2C.

2.2.3 Communication: LCA as a basis for Environmental Product Declarations

The ambiguity of LCA results and its misuse in 'greenwashing' have prompted the development of a series of ISO standards. Greenwashing is common among companies that wish to improve their green credentials. The 'sins of greenwashing' website[8] publishes a regular overview and found that only 5% of all products investigated were innocent of all the 'seven sins of green washing'.

The ISO distinguishes four ways of communicating environmental information about products:

1. Full LCA reports as described above. These are used in business-to-business communication.
2. Environmental claims (ISO14024), such as 'this product is recyclable'. The standard describes the minimum requirements that must be met before this claim or other popular claims can be made.
3. Environmental labels (ISO14021), such as the EU flower, the Nordic Swan, the blue angel and the Dutch *Milieukeur*. The ISO standard stipulates that a generic LCA must be conducted. This is then used as one of the inputs for a panel of experts which sets easily verifiable requirements for products to meet before they can carry a particular label. The aim is to reward only the top 20% of products on the market.
4. Environmental Product Declarations (ISO 14025) are declarations of environmental impact that are usually printed on the product or packaging. There is some parallel with the standardized nutritional information found on many food and drink products. The idea is to empower consumers to choose for themselves, but the most important application seems to be in a business-to-business context. To minimize the problem of ambiguity, the standard describes a procedure according to which a 'Product Category Rule' (PCR) must be defined[9]. The PCR is comparable with the Goal and Scope Document used in LCA. Results must be calculated in the same way within each product category. PCRs are also developed through a transparent stakeholder consultation process. One source of confusion, however, is that these PCRs are developed on a national or regional basis.

Environmental Product Declarations

Recently some very important initiatives to streamline Environmental Product Declarations have emerged: The greenhouse gas protocol from the World Business Council

Sustainable Development[10], The Sustainability Consortium[11] and the PCR Harmonization initiative[12].

In the experience of the working group, these LCA standards are not suitable for communicating the 'C2C-ness' of a product, and thus unsuited for external C2C communication. Why they are not suitable in relation to C2C-specific qualitative benefits is explained in chapter 4.

2.3 Development of materials, processes, products and systems

Both C2C and LCA can be used to develop materials, processes, products and systems. The guiding principles of C2C are based on the notion that materials, products and processes form part of a wider system – a biological system and/or a technological system – in which materials are defined as 'nutrients' that interact with humans, the open environment and future generations. This is not to be confused with C2C certification, which is only available for materials and products. The C2C process focuses on changing a product throughout its functional and environmental uses, taking account of the societal context in which it is embedded. The process aims at system change and there is no rule about where in the supply chain to start, or where to end. The inventory will move up and down the chain. Under this method of system change, the starting point is usually irrelevant.
LCA looks at the whole product chain when analysing the environmental performance of a product. If an LCA covers the system in which a product operates, this defines the boundaries of the LCA.

2.3.1 Product development process

C2C and LCA can both be used in the product-development process. LCA can be used as one of the tools in an eco-design process, to measure the environmental impact of products. C2C is a guiding framework for the design process. The table below gives an overview of both in relation to eco-design.

C2C and LCA can complement one another. An important difference is that in LCA the direction for design solutions is depending on the analysis of the impacts, and not on the basis of guiding principles. Appendix 3 focuses on how C2C and LCA operate at each stage of the product development process.

	C2C	Eco-design / LCA
Aim	Make good products (eco-effectiveness).	Take environmental impact into account when designing products; LCA can help determine this impact.
Design tool	Give a **clear direction**, through the three guiding principles.	Give a clear direction by identifying hotspots using a range of information sources, of which LCA may be one.
Beginning, generation of idea, divergence	C2C gives a clear direction at the start of the design process (divergence phase). This direction is based on its innovation framework and the corresponding guiding principles. They define the beneficial qualities to aim for.	LCA can be used to give a clear direction at the start of the design process and support designers in making choices.
Final stage, evaluation, convergence	Qualitative check: does the C2C product meet the stated intentions?	LCA mainly comes in at the final stage of the design process to **assess** a number of design options in quantitative terms, and use this for retrospective learning and communication.

Table 1: C2C and LCA in a (eco-)design process.

The companies' experiences
The companies participating in the working group reported that when following the C2C framework completely, it was sensible to carry out an LCA in order to know how consumers and governments who use LCA would view their product. An LCA can help to:

- add in-depth knowledge and eliminate any burden shifting (i.e. reducing one environmental impact while increasing another one);
- explain the differences and advantages of your product;
- explain very clearly why certain choices were made when questions are asked, in the event that the product has a worse environmental impact.

For those companies not following the full C2C framework, we did not identify elements that could be added to the environmental analysis toolkit during this assessment because within C2C this is presented as an overall approach, in which everything is connected and it is therefore not possible to isolate specific parts.

Once a company has decided to deliver a C2C-certified product, an LCA is much easier to carry out because the data needed for the LCA will be much more easily available. C2C involves knowing exactly what is in your product, and this is precisely the data that is needed to conduct a proper LCA.

2.3.2 When do we need an LCA, when do we not need an LCA?

LCAs are useful if an environmental impact assessment relating to the entire lifecycle is needed, or when the environmental impacts of multiple products are to be compared.
This means they are only useful in the context of C2C if there is a clearly defined goal to measure, analyse and compare life-cycle impacts. If such a goal has not been clearly identified, a detailed LCA may be redundant. But even when there is such a goal, there may be other and simpler ways to achieve the desired result. A simple mass-flow analysis, energy analysis, the use of LCA-based eco-indicators, or plain common sense may be enough.
A short guide to LCA, which also addresses the relevant aspects of C2C, is included in appendix 7.

2.4 Summary

Findings of this chapter
Exploring C2C and LCA more closely in a business development and eco-design context, we have learned that LCA can be used for C2C purposes when *setting goals* (LCA can contribute to the C2C inventory) and for *monitoring* whether burdens are shifting. However, current LCA standards are not suitable for communicating the 'C2C-ness' of a product, and thus *not suitable for external C2C communication*. Neither are there any plans to make this a goal, as far as the participants of this project are aware of.

Remaining questions
Monitoring the progress made in a C2C process by using a measurement tool like LCA requires a more detailed exploration. We need to know more about the relevant dimensions of C2C in relation to LCA. Can a *beneficial future* environmental footprint based on defined *qualities* be measured with an instrument like LCA? Chapter 3 will address this question.

3 The dimensions of C2C in relation to LCA

Exploring whether LCA can be used for C2C purposes means understanding the principles of C2C and how they relate to LCA. During the expert discussions on measuring the 'C2C-ness' of a product, three basic contradictions were identified between the C2C innovation framework and the LCA measurement tool.

These contradictions are captured in the following sentence:

'Measuring a **qualitative**[A] **plan**[B] *for creating a* **beneficial**[C] *footprint using a* **quantitative**[A] *instrument designed to evaluate an* **existing**[B] *environmentally* **damaging**[C] *footprint.'*

Each of these contradictions will now be explained in more detail and illustrated with examples.

3.1 Using a quantitative measurement tool to measure qualitative solutions (A)

C2C is based on the qualitative goals set out in its three guiding principles. Any particular course of action is evaluated against these qualitative goals, which serve as benchmarks. Some of these can be quantified using LCA, but others cannot.

For example, qualities such as the health benefits of natural light and access to fresh air and its influence on human productivity are an integral part of C2C but are difficult to incorporate under current LCA methodology. Contributing to a green environment is another quality that is hard to measure in a quantitative manner in current LCA measurement terms.

However, qualities that are being accounted for under current LCA methodology can be included if they are well defined. For example, if the production process of textiles is developed in such a way that the water leaves the process cleaner than it came in (containing fewer chemicals).

The extent to which the defined qualities of a C2C product can be measured with LCA therefore depends on the extent to which they can be quantified for LCA measurement. In other words, it depends on the extent to which they can be described in current LCA measurement terms rather than conceptually or in non-LCA measurement terms.

The measurability of C2C developments and products according to C2C's guiding principles (on which the defined qualities are based) is discussed in greater detail in Chapter 4.

3.2 Using current data to measure a future solution (B)

The C2C innovation framework is about future solutions. Targets are set, and milestones defined along the path to achieving those targets. These function as drivers for innovation. Under the current situation, exactly what the final solution will look like is often unknown; however, this is common in product development and by no means unique to C2C and LCA.

How can we evaluate future development? It is possible to conduct an LCA on future technologies if a scenario for that technology can be created. Once a future scenario has been agreed (including backcasting and interim milestones), it is possible to evaluate future technologies using an LCA. However, data for future technologies can never be certain and all uncertainties (model uncertainties, subjective choices, sensitivity analysis comparing product a+b) need to be documented.

Attempts are being made to address these uncertainties. The Prosuite project[13] is currently working to develop sustainability estimates for four technology cases (carbon storage, nanotechnology, bio-refinery and multifunctional mobiles) in close consultation with the stakeholders involved.

The 'C2C-ness' of products can be measured if they are defined using data that reflect the C2C design solution likely to be used in the future. However, the measurability of that data is subject to the ability to measure future outputs accurately. LCA is designed to measure a point in time based on existing impacts. It is not designed to evaluate a company's progress in completing steps towards a qualitative goal.

For example, the predicted percentage of recycled content can be calculated where detailed figures are available (on how the material is transported and recycled), and the expected toxicity can be measured if detailed information on the material is available. However, if new materials and processes will need to be developed to meet the qualitative goals set, LCA can only evaluate this if environmental data can be estimated on the basis of a concrete scenario.

The same applies to energy production. Available data should be used, if necessary assuming that some innovations will be achieved (e.g. the complete recycling of solar cells or wind turbines, including how they will be recycled).

3.3 Measuring a (positive) beneficial environmental footprint with an instrument that is designed to measure a (negative) environmentally damaging footprint (C)

The basic goal of the C2C innovation framework is to develop products that will leave a beneficial environmental footprint. This positive footprint could be achieved by, for example, using solar income so that products generate more energy than they consume over their whole life cycle. The three guiding principles are used to define a beneficial footprint: waste equals food, use current solar income, and celebrate diversity.

3.3.1 Eco-effectiveness under C2C

Within the C2C framework, 'eco-effectiveness' means product designs with an intended *beneficial impact* and the development processes to achieve them. A 'desired state' or ambition is formulated: implementing the three basic guiding principles (waste equals food, use current solar income, celebrate diversity) within the design for the product or service. For example, a carpet may be designed with a functional use (covering the floor) as well as other beneficial objectives such as 'cleaning the air', 'cleaning the water', or 'supporting biodiversity' (whether during the production process or while in use).

Eco-effectiveness does not necessarily exclude eco-efficiency and in specific cases, eco-efficiency can even lower the threshold for eco-effective solutions. This applies particularly to energy use:

- When efficiency increases allow for the decentralized use of energy (example: office lighting powered by photovoltaic cells integrated into the building).
- The relative contribution of a given amount of energy derived from current solar income in a mix increases as energy use becomes more efficient.

3.3.2 Measuring C2C's eco-effectiveness with LCA

When using LCA to evaluate a product as part of an eco-design process, the approach is to measure environmental impact. Under C2C, LCA would not be used to calculate 'damage' but to calculate the benefits of 'solutions' (the evaluation of ideas) or in other words, the extent to which solutions contribute to the stated intentions.

Measuring C2C's eco-effectiveness, for example, means measuring the benefits of collecting fine dust, cleaning water, or restoring depleted soil. Some of these benefits can be measured using LCA. The benefits of energy-producing buildings for example can be measured using LCA. However, measuring the environmental benefits of related C2C results such as design for disassembly and materials pooling is limited using LCA.

To conclude, LCA has been developed specifically to measure the damaging environmental impact of products; however, elements of LCA can also be used to measure the established beneficial (positive) footprint of C2C products, although there are limits under the current LCA approach. These limits relate to LCA's ability to measure quality: some aspects of quality can be measured under LCA, but not all.

LCA aggregates the materials emission and resource use figures on environmental damage. C2C also addresses the quality of products as nutrients. This means that the extent to which the benefits of C2C can be measured depends on the extent to which the stated (beneficial) qualities can be quantified (contradiction A). How LCA can be used to measure quantified beneficial qualities is described in the short guide on LCA (appendix 7).

3.4 Summary

Findings of this chapter

An overview of the contradictions between C2C and LCA:

	C2C	LCA
Quality –Quantity	**Qualitative** statements are the starting point.	**Quantitative** assessment.
Future – Present	**Future** solutions.	**Current** data generally used.
Benefits – Damage	**Create and develop** a **beneficial** environmental footprint.	**Measurement tool** developed to measure **damaging** environmental impact.

This chapter has shown that the extent to which the defined qualities of a C2C product can be measured using LCA depends on how far they can be quantified for LCA measurement. In other words, it depends on how far they can be described in terms of current LCA measurements rather than conceptually or in non-LCA measurement terms.

Remaining questions

Further exploration is needed on whether and how C2C-defined qualities can be quantified in concrete current LCA terms. These qualities are defined on the basis of C2C's guiding principles, so exploring the usability of LCA for C2C purposes therefore brings us back to C2C's guiding principles and how compatible they are with LCA assessment. In other words, which indicators, based on the guiding principles of C2C, can be measured? Chapter 4 will consider this question.

4 The guiding principles of C2C and their measurability with LCA

The C2C innovation framework is based on three guiding principles, and these also form the basis for C2C certification. A closer look at these guiding principles can indicate whether LCA can be used to measure the 'C2C-ness' of a product. It should be noted that in this paper we only focus on the first two principles of C2C. The third guiding principle, 'Celebrate diversity', was not studied during the expert sessions due to time constraints.

4.1 The first guiding principle of C2C: 'Waste equals food'

According to C2C, 'waste' should serve as 'food', meaning that 'nutrients remain nutrients' or 'everything should become a resource for something else'. It is understood as '*the right material, at the right place at the right time*', where '*right*' means the suitability of materials for a defined use in a defined context. This evaluation depends on the interaction of both the solution-offering side (the product) and the solution-using side (the user and its environment). The product and the materials it contains may have an impact in a strict sense (its effect on the user) and in a wider sense (such as fertilizing the soil after use).

For example, in the *case* of the **paper cascade** (biosphere, see also figure 1), office paper can be recycled up to seven times as office paper. When the fibres become too short, the next stages in the cascade include reuse as cardboard, tissues or toilet paper before the material returns to the biosphere as a nutrient (via waste water, compost or ash). This requires all products in the cascade to be developed in such a way that they can safely enter the biosphere and be used for fertilization and soil reconstruction. This helps the cultivation of new trees, and a new cascade starts.

The example of the paper cascade illustrates that 'the right material in the right place at the right time' is highly context-dependent and localized. It also shows that all used materials are defined as 'food' (=resource) for something else and that 'emissions' can nourish organisms that they come into contact with. In case of the paper cascade, the design and composition of office paper already takes into account the subsequent stages of the paper cascade, i.e. all the ingredients used to manufacture the office paper must be suitable as nutrients/resources for the next steps of the cascade, including the last step which could be composting, defined combustion or digestion.

All this requires a very clearly *defined use scenario* for a product. After use, every part or substance in the product should serve as a 'nutrient' for something else. A 'nutrient' is a resource, a substance that contributes towards the production of a 'new' beneficial product in a 'new' context. This means that the materials used must be suitable to all the contexts that it will pass through, from the extraction of raw materials, the production process to the various usage cycles that are planned for the materials. It will thus be decided at an early stage whether a material will be used in a technical context or in a biological context. C2C's suitability to context is a carefully balanced combination of cascading and toxicity. C2C's nutrient management thus relates to resource management, which takes account of recycling and toxicity from a sustainability perspective. The following sections will examine both of these topics more closely.

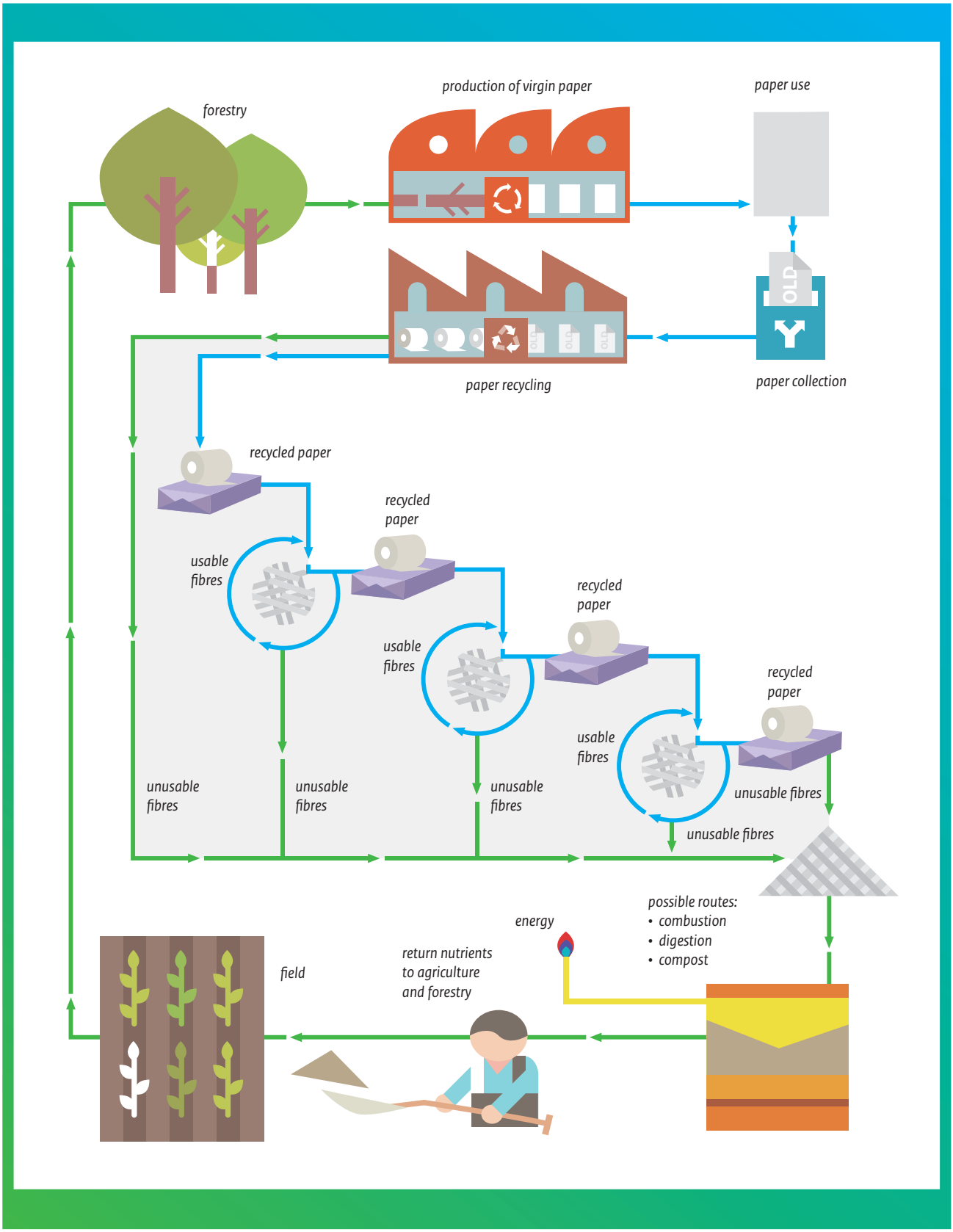

Figure 1: Example of a cradle to cradle paper cascade.

4.1.1 Nutrient management: recycling, cascading and upcycling

Nutrient management is a key issue when designing and developing a C2C product. Nutrient management scenarios are defined for biological and/or technical systems, and include past, present and future cradles. Depending on the scenario, parts or materials may be re-used in the same type of product, so a carpet tile may become a carpet tile again, for example. Sometimes materials flow through a pre-defined cascade.

Nutrient management in product design means defining a product and the materials it contains according to their potential to act as nutrients in biological systems, or 'technical nutrients' for future generations of technical products. Whether a product is a source of technical nutrients is the result of investment on the part of the producer. The producer of a first-generation product therefore has an interest in managing the materials (nutrients), whether himself or through third parties, so that he can benefit from this investment.

How can we measure recycling or a defined cascade use with an LCA? In an LCA, recyclability in a technical system can only be measured if the assumption of recycling is made. LCA is traditionally used to measure impacts that actually occur; intentions do not count. In this context, recyclability is only relevant if the product is actually recycled; whether materials are suitable for recycling is not relevant. A recyclable product that is incinerated has the same status as a non-recyclable product. Design for biological recycling or design for disassembly can be measured with an LCA, provided the recycling scenario can be modelled.

Under LCA, recyclability is not necessarily positive. The benefit of recycling can only be measured when the recycled material is actually used to replace virgin ones. Under LCA, there is some discussion about how to account for this benefit and to whom it should be credited. This is related to the question of which stakeholder makes the effort, and can thus claim the reward for recycling.

For example, when aluminium is recycled, the question is who to credit for this – the party responsible for making the secondary aluminium or the party that uses the secondary aluminium? Although there are some guidelines, there is no clear consensus yet within the LCA community and its stakeholders on this.

The modelling of recycling under LCA must be clearly explained in the goal and scope document. It is possible to take into account the entire cascade (including transportation, the recycling process and the use of virgin materials that is avoided) or only part of it. The decision will depend on the goal and scope of the study.

C2C aims for continuous flows of materials in the biosphere or the technosphere. This makes it very difficult to define the system boundaries, which is required for LCA.

Under eco-design, a long *lifespan* is usually preferable. Under C2C, a 'defined period of use' is established that takes into account rapid technological developments, patterns of use, etc. If a product is designed for a long lifespan, as for example a wastewater pipe would be, this should also be taken into account.

Suitability to the context of the biological system implies that biological nutrients should return to the biosphere, even if they contain no 'nutritional' elements. At the same time, biomaterials are acceptable as a source of 'current solar income'. Under LCA, paper could be incinerated as long as this does not give rise to problematic emissions. In fact, an LCA would clearly show that the incineration of paper for the production of electricity is preferable to composting, for example. In C2C terms, paper contains valuable nutrients or bio-resources, such as carbon. Here a broad definition of biological nutrition is used. In the example of the paper cascade above, the cascade does not exclude dedicated combustion at the last stage of the cascade, provided that the paper has been designed for combustion (in terms of the used additives or inks etc.). The remaining ashes (carbon) could then be returned to the soil.

4.1.2 Nutrient management: toxicity, ABC-X, health and environmental aspects

The example of the paper cascade shows that the content of the product requires thorough consideration at each level of the cascade. At each stage of 'defined use', the material should fit the purpose of the overall cascade. So if the paper is destined for compost in the last stage of the cascade, all previous stages need to take account of that final stage, i.e. the paper should be healthy for the soil. Within C2C, the evaluation of the biological resource value of materials that are intended to have a new cradle in biological systems makes use of toxicological data on chemicals.

In many cases, it is not possible to calculate to what degree a material is suitable for its context. Under LCA, this is don e on the basis of the actual impact that occurs as a result of releasing toxic substances (emissions) to the environment over the lifecycle of the product (not the toxic content). Research is on-going in the LCA community for modelling a wider range of environmental impacts more accurately, such as measuring the impact on indoor air quality and local aspects.

Under LCA, toxicity is viewed in terms of emissions into the environment. C2C, however, also looks at the value of materials as biological or technical nutrients and not only at the toxicity of emissions. If we look at toxicity in terms of

emissions (LCA), this is a totally different viewpoint then the content approach of C2C. In effect, these two toxicity approaches are not comparable with one another at all.

Another point is that very low levels of emissions are often omitted from an LCA if they seem irrelevant. However, if very low emissions occur over the entire life cycle, they must be included. In this case, where no data is available, an estimate must be made. This brings uncertainty in an LCA. Under C2C, if these low emissions also represent scarce resources, the risk for the future availability of resources (nutrient management) must also be estimated.

Around 145,000 chemicals are used in industry (REACH preregister). About 6,000 of these are subject to regulation due to proven toxicity. Some chemicals are not regulated because they have been deemed to be non-toxic. The vast majority, however, are simply not classified. The most comprehensive LCA impact assessment method, Usetox, includes profiles for 5,000 substances. Much less emphasis is put on toxicity issues compared with C2C. Under LCA, ISO generally requires a cut-off that fits the goal and scope of the LCA study. Normally 99% of all environmental impact must be accounted for. This means that any substance that is relevant in terms of its environmental impact will be included in an LCA, regardless of the level of emissions. In C2C, material composition is known to a level of at least 100 ppm (parts per million).

Certain *health issues* are important in C2C that have yet to be defined under LCA. For example, aspects relating to the sensitization potential for skin or the respiratory system are excluded in an LCA. Not all aspects of C2C can be included in an LCA.

Local effects: LCA impact assessment can be criticized for its lack of site-specificity, and its linearity. This is a simplification, although much work is now being done to tackle this. Future databases will support GIS-based (Geographic Information System) coordinates for better modelling.

It is difficult to measure toxicity with precision and this problem is not LCA-related but extends to all systems that aim to assess toxicity. The two main problems are:

- *Exposure*: what fraction of an emission is ingested or inhaled? This depends on the climate, population density, and in the case of indoor emissions, ventilation. Indoor exposure is not assessed as standard under LCA, but it is being worked on.
- *Toxic impact*: once the exposure has been established, the toxic impact needs to be assessed. Human testing is not feasible, so toxicologists extrapolate on data for lower organisms or test animals. Extrapolation to humans involves uncertainty of up to three orders of magnitude.

4.1.3 Nutrient (mis)management: the example of CO_2

Under LCA, CO_2 and its role in climate change play a very important role. Major releases of CO_2 are related to energy production from fossil fuels. Energy is also required to establish material flows. Under C2C, energy should be produced from sources derived from current solar income. The energy necessary for materials pooling (transport and recycling processes) should come from these sources as well. So energy consumption and production is part of the C2C supply chain partnership. Section 4.2 examines C2C's second guiding principle on energy.

From a C2C point of view, CO_2 is a nutrient that has been mismanaged during recent decades. There is too much CO_2 in the atmosphere, which is causing climate change. When CO_2 is released during the continuous material flows surrounding products, this CO_2 also needs to be managed as a material. For example, greenhouses for growing vegetables and fruit will benefit from CO_2. They could be positioned near a factory that emits CO_2 as a by-product. Algae turn CO_2 into valuable nutrients which can be converted into plastics, fuels and many other materials. Atmospheric carbon can be sequestered through the plant cycle and turned into stable humus carbon, where it can be stored long term.

4.1.4 Findings: 'Waste equals food'

It is very difficult or impossible to quantify the 'waste equals food' principle using LCA:

Recycling and Cascading:

- Under LCA, part of the *materials cascade* is usually calculated, but is difficult to calculate when recycling is involved. Who is credited for the recycling process – the recycler, the user or the source of the recycled material? Among the commissioners of LCA studies, there is no consensus on this yet.
- LCA cannot measure the recyclability of a product. Furthermore, recyclability has no meaning under LCA. The recycling process can only be taken into account in an LCA if realistic assumptions can be made about the anticipated recycled percentage.
- So, if a C2C product (which is part of a materials cascade) is assessed using LCA, this should be clearly described in the goal and scope definition. In the assumptions and scenario definition, the percentage of recycling and figures in the transport and recycling processes can be included.

Toxicity:

Very different approaches are taken to toxicity under C2C and LCA. C2C looks at the suitability of a material to the context in which it is used and at the properties of the material. LCA focuses on emissions of the material during its life cycle.

- LCA bases toxicity on emissions into the environment. C2C on the other hand looks at the toxicity of the materials. LCA often omits minor substance flows, which appear to be irrelevant in comparison to the overall environmental impact along the whole life cycle. The C2C strategy is to choose materials which are suitable for their pre-defined use and context. There is a lack of data, which means that products with a low impact measured with LCA, can include highly toxic chemicals which constitute a substantial local risk. LCAs can therefore appear inadequate when it comes to toxicology.
- Toxicity as a general theme is relatively unimportant under LCA compared to C2C. If toxicity accounts for less than 1% of the total environmental impact in an LCA, it is not taken into account. Under C2C the composition of a material should be known to at least 100 ppm (parts per million).
- So, the suitability of a material to its context cannot be calculated under LCA. A very specific LCA can only be made in some very well-defined cases. For instance, calculating the impact of a material on indoor air quality with an LCA is difficult at the initial phase of development, but not impossible.

4.2 The second guiding principle of C2C: 'Use current solar income'

The principle of using 'current solar income' is largely consistent with the concept of 'renewable energy' as it is generally understood. Sources that use current solar income include wind turbines, solar panels, wave-powered, bio-powered, kinetic and shallow geothermal energy systems.

Around 10,000 times more solar energy is available on earth today than is consumed. Hitherto, the only limitation has been our ability to harness this energy. In effect, this is another issue that relates to the management of material flows and as such the second principle of C2C is closely linked to the first: renewable energy is only renewable when the materials used for producing energy are renewed in the same period as they are used. The implementation of C2C's second principle tends towards increasingly decentralized energy production.

Companies can incorporate the second principle into their strategy by using renewable energy, but just as important is their capacity to influence suppliers by including it as part of their purchasing criteria for raw materials. C2C thus encourages making current solar income usable by industry while applying the 'waste equals food' principle to all materials including those used to generate and distribute energy.

The approach of using renewable energy in the whole product chain is one of greatest challenges and also one of the main reasons why C2C products do not always perform well in an LCA. The current underutilization of current solar income in the supply chain often generates a negative outcome under LCA. C2C aims for a quality statement which considers how energy is produced and how effectively it is used, whereas LCA considers the amount of energy used throughout the lifespan of the product. In LCA, the production and use of fossil energy is seen as a main source of many of today's environmental problems. Energy use throughout the life cycle appears to be the most important cause of environmental damage for many products.

4.2.1 Measuring energy production systems with LCA

The environmental impact of different energy production systems (solar panels, wind mills, regular mix (coal etc.) and nuclear) was calculated using currently available data. The chart below shows the results.

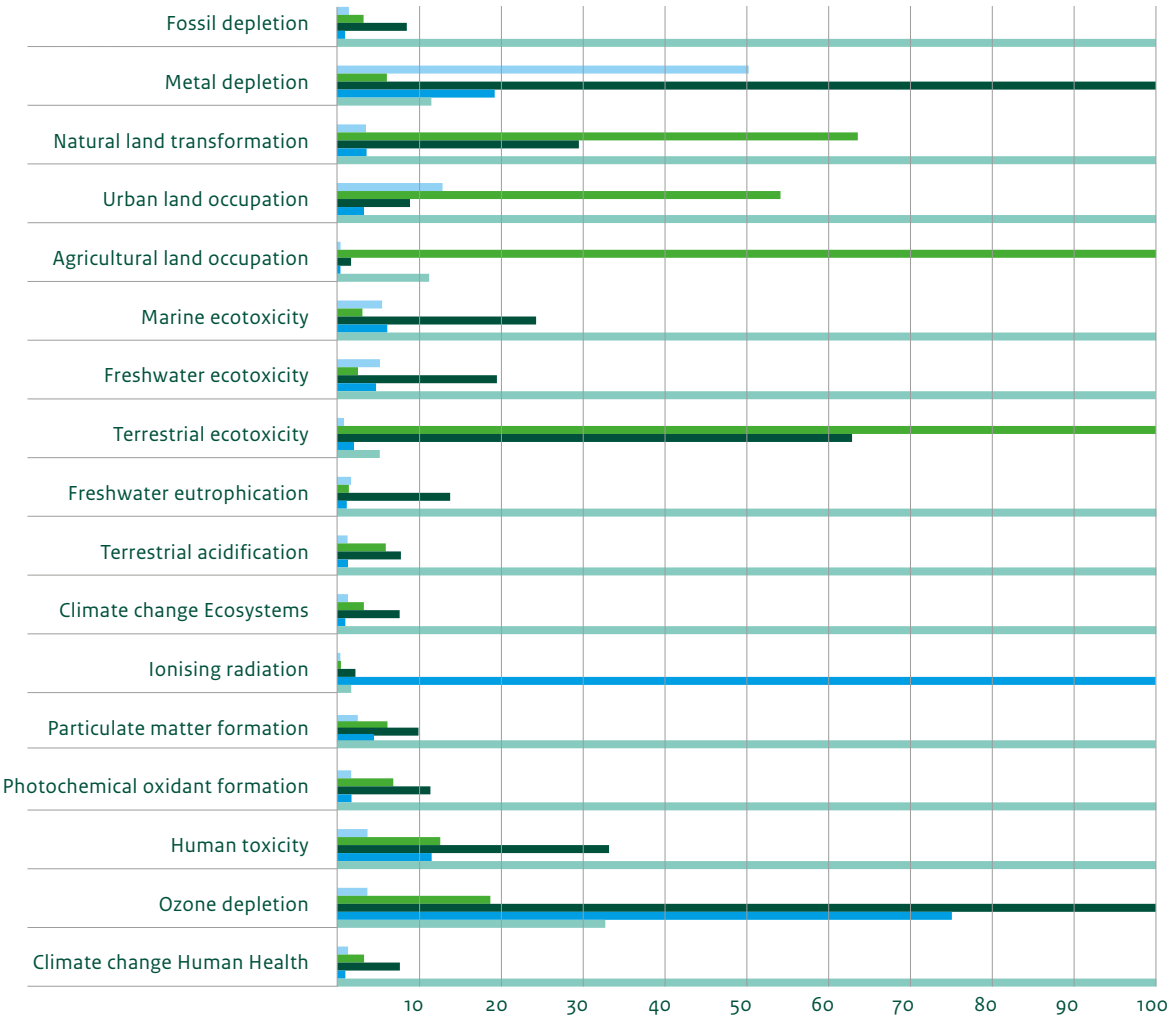

Figure 2: Comparison of environmental impact of energy production systems in SimaPro.

Clarification to the figure:

- Comparing the energy system for each impact category: = wind (EU average); = biofuel, in this case wood (Sweden); = solar (the Netherlands); = nuclear (EU average) and = coal (EU average).
- The chart compares the production of 1KWh using different energy sources.

Please note: the highest alternative is rated at 100% for each impact category. This does not mean each impact category scores equally highly or that both are equally important. The impact of solar cells occurs mainly during production and disposal. The latest technology enables solar panels to be 85% recycled, but this is not included.

4.2.2 Energy and LCA

The option that has the least environmental impact varies according to the location. The data on the chart shows that using current technology, German wind power has less environmental impact than German solar power, but in the Sahara solar power may be much better than wind for example. Also it can be seen that under an LCA comparison, renewable sources like solar power still have an impact. This impact occurs mainly during the production and disposal of solar panels. Furthermore, solar panel technology is developing rapidly and this is hard to keep up with in LCA databases. So at the moment of calculation, data can quickly become out-dated compared to the newest solar technology.

However, LCA does not claim to be exact or comprehensive, as the discussion on nuclear energy demonstrates. LCA usually excludes the possibility of accidents and considers only the environmental impact of normal operation. It does not consider the birds killed by wind turbines or the between 10,000 and 100,000 deaths that occur in coal mining every year, for example. As such, LCA cannot be followed blindly. Decision makers use a range of tools and approaches and the scope of any LCA should be considered carefully.

4.2.3 Energy and C2C

The three basic principles of C2C clearly incentivize the development of certain energy options and the elimination of others.

Nuclear energy is not an option under the C2C approach because it is inconsistent with both the first principle ('waste equals food') and the second ('use current solar income'). Furthermore, nuclear power is associated with risks which are unacceptable within the C2C innovation framework (as illustrated by the nuclear accidents in Chernobyl, Ukraine and Fukushima, Japan), which are not included in the current LCA model.

Neither is energy sourced from burning fossil fuels acceptable under C2C because it is inconsistent with both the second principle (coal is not current solar income) as well as the first (the waste products from fossil fuel combustion do not currently find a productive fate in the environment, quite the contrary). There are also other significant aspects such as the injuries and fatalities that occur in the mining industry. This kind of 'damage' is not included in the current LCA model. Under C2C, CO_2 is a nutrient that should be managed – by supplying it to green houses or sequestering it into organic forms for use in topsoil, for example.

The impact figures associated with supplying renewable energy are calculated using the non-renewable energy forms that are currently used to produce the required infrastructure (wind turbines, solar panels and so on). As such, they represent a snapshot for a given point in time. As the infrastructure needed to capture renewable energy becomes more widespread, the share of renewable energy used to produce the next generation of renewable energy infrastructure will also increase, causing a reduction in its impact profile. The apparent objectivity of current (or slightly out-dated) figures can impact negatively on decisions to develop this infrastructure. This tendency to slow down the introduction of a potentially effective shift in energy production is intrinsic to the more conservative LCA approach. An observer is never objective. He influences a system by the way he observes it. It is therefore important to describe the goal and scope of the LCA. The Prosuite approach[13], which involves calculating feasible future scenarios (including the recyclability of the energy delivery systems), may help to introduce more 'objectivity'.

4.2.4 Findings: 'Use current solar income'

Energy production: A quick LCA shows that solar energy has the lowest overall environmental impact; this is consistent with C2C's second guiding principle, 'Use current solar income'.
Restrictions with current LCA methodology: measuring solar energy with LCA does not include the latest technological developments; information on the recyclability of production systems is also missing.

4.3 Materials management, energy used and LCA measurement

Under C2C, the prevailing lack of energy derived from solar power in an industrially usable form is not a valid excuse for failing to develop the 'Waste equals food' dimension of products in areas other than energy supply. For example, transportation energy, which currently meets neither the 'Waste equals food' nor the 'Use solar income' criteria, is no reason for not beginning the post-use management of products to recover the scarce resources they contain.
The application of LCA inventory methods for mapping energy demand in supply chains makes a great deal of sense from a C2C perspective when it comes to identifying opportunities for the rational use of energy (irrespective of whether it is obtained from current solar income or not) and changing how energy is supplied.

5 Conclusions and recommendations

This position paper has explored not only whether LCA can be useful at key moments in the process of C2C business development (setting goals, monitoring and external communication), but also the limitations of the compatibility between the two systems. This section sums up our findings and includes a number of recommendations for companies and experts in C2C and LCA about the usability of LCA for C2C purposes.

5.1 Conclusions

Cradle to Cradle is a framework for innovation based on three guiding principles. Life Cycle Assessment, by contrast, is an assessment tool and not a universal design approach. It is designed for use as a measurement tool in eco-design processes.

Overall, it has proved very difficult to make an objective comparison between LCA and C2C, because the two concepts do not share the same aims:

- C2C states clear objectives at the beginning of the design process and is an innovation driver that aims to bring about quality improvements. C2C objectives are based on three guiding principles and C2C amounts to a way of thinking, creating normative guidelines and giving credit for what are deemed to be steps in the right direction and thereby contributing to a future where products have a positive environmental footprint.
- LCA measures the environmental burden of a product or service (which may or may not have been designed with the environment in mind), identifying hotspots and/or comparing the environmental impact of potential design solutions. It leaves the interpretation of these measurements to those assessing the findings and sets down no normative standards. Under LCA, normative conclusions are left to the analyst.

Considering this, we can conclude:

- C2C and LCA can be used to complement one another.
- LCA can only be used to evaluate clearly defined quantitative goals.
- The usefulness of LCA for measuring specific indicators based on the guiding principles of C2C depends on the flexibility of LCA models. The rigid Product Category Rules of EPDs in particular often fail to reflect C2C qualities properly, since some important established environmental benefits are not included (e.g. recycling and health benefits).
- Overall, LCA cannot be used to assess or communicate the 'C2C-ness' of a product. The 'Waste equals food' principle in particular, which is about nutrient management, cannot be measured effectively using LCA. Cascading and toxicity, which are given particular emphasis in C2C, cannot be considered adequately using LCA.

Furthermore, it may be useful to know how a C2C design scores under LCA in order to compare it to government criteria (sustainable procurement) and other LCA-based communication such as EPDs, an industry-standard LCA with sector-owned product criteria.

Daily practice has taught us that once a company has reached the stage of delivering a certified C2C product, an LCA is much simpler to carry out.

5.2 Recommendations

On the basis of this exploration, we can make two recommendations to improve the usability of LCA for C2C purposes. A recommendation is also made on the usability of C2C for LCA purposes.

5.2.1 Recommendation on using LCA tools to monitor a C2C process

Future applicability of selected LCA tools to the C2C Roadmap

The milestones on a C2C Roadmap (section 2.1.2) are measurable, but do not usually require a full LCA. More targeted tools can be used.

→ Experts in the field of C2C and LCA should jointly indicate how selected LCA tools could be used to evaluate milestones on a C2C roadmap. The selection of tools could help companies to avoid costly repetition a full LCA at various stages of a roadmap if a full LCA is not necessary.

Improving the measurability of C2C, beginning with its guiding principles

Progress is necessary on making C2C more measurable, for companies and governments that want to commit to the C2C framework. Transparency on what can and what cannot be measured will enable companies applying C2C to communicate with their customers and with government bodies.

- Experts in the field of C2C and LCA should investigate the extent to which C2C's guiding principles can be quantified. Which of the intentions stated in advance (based on the guiding principles) can be measured using LCA, and how can this be done. The guide (appendix 4) and Chapter 4 (guiding principles) are a first step in this direction.

5.2.2 Recommendation on using EPDs to compare products on the market

Applying EPDs to compare products on the market

Purchasers who want to compare products on the market, should be very careful if they are aiming for C2C or other C2C-related objectives, such as a healthy environment or a circular economy. The rigid Product Category Rules of EPDs (that are being defined in a multi-stakeholder process) do not usually reflect beneficial C2C qualities effectively.

- Purchasers should look at the functionality of the product, and think of which environmental, social and health benefits they want to achieve by buying and using the product in the first place, especially if they want to favour a particular end-of-use strategy (re-use, recycling, incineration, land-fill) or a healthy (working) environment.

5.2.3 Recommendations on developing a standard for communication including the benefits of C2C

A 'new' standard for communication

For companies developing C2C products that are looking for ways to communicate the benefits achieved with a C2C product, it would be useful to develop a new common standard for communication.

- These companies are used to working with EPDs, which generally do not include aspects typical of C2C. C2C aspects can only be described in the 'remarks' section. For communication purposes, it may be useful to develop a standard for carrying out EPDs for C2C products. The guiding principles used in C2C could then be integrated into these EPDs by describing their own specific Product Criteria Rules.
- The term EPD is restricted to the environment. The scope of C2C, however, is overall product quality with environmental quality as a specific entry. A distinction could be introduced between conventional LCA-based EPD and a C2C Quality Declaration (C2C QD) to avoid confusion. C2C experts should reflect on a meaningful structure for a C2C QD, and identify which conditions would need to be fulfilled before issuing them.

5.2.4 Recommendations on the usability of C2C for LCA purposes

Usability of C2C for LCA purposes

For companies that have not yet adopted the full C2C framework, no elements were identified during this assessment that could be added to the environmental analysis toolkit. This is because it is presented as an overall approach within C2C, in which all aspects are connected. It is therefore impossible to pick out specific parts in isolation.

- For companies familiar with LCA, it might be interesting to reformulate the question as: 'In what way can LCA practitioners benefit from C2C?'.

6 Opinions from the Sounding Board

K. Christiansen (Dansk Standard)

I do not agree that it is not possible to develop a LCA-based C2C assessment methodology, but I do agree that it is not available now. I do agree on the notion of keeping different assessment methodologies apart but as in life cycle costing (economic LCA) or social LCA, the boundary setting and data quality etc. should be the same for all methodologies to assure a common basis for decision making.
ISO 14040/44 clearly states to be for environmental aspects and impacts only, but also that the methodology can be used for assessment of other aspects or impacts e.g. social and economic. If the qualities of C2C can be quantified, they can be included in the LCA, and if not how can you then assess an improvement?
ISO 14040/44 introduces shortly different approaches to LCA and consequential LCA is actually future oriented. This approach is not assessed in the document.
ISO 14040/44 is about potential environmental impacts. Using wording like "existing environmentally damaging" or "current impacts" is therefore misleading and mis-interpreting the standards.
ISO 14000 series uses "impact" as both potentially positive and negative. ISO 14040/44 does not explicitly include positive impact categories but this can be done without conflicting with the standards. Adequate methods have been described e.g. in the Danish EPA funded methodology for the handling of recyclability and in consequential LCA.
ISO 14025 sets a framework for EPD including "Additional environmental information" – therefore it would easily be possible to add information from a C2C assessment as qualitative or semi-quantitative data.

M.Z. Hauschild and A. Bjørn (Technical University of Denmark)

This is a very important document for companies inspired by C2C that look for guidance on synergetic effects and conflicts between C2C and Life Cycle Assessment. We think the document has a high level of detail and addresses the main issues on the subject in a professional manner. Overall the document does tend to be somewhat biased towards C2C and does not always describe LCA objectively (most notably the sections on toxicity and energy use). Also the classification of C2C as 'qualitative' (as opposed to the quantitative LCA) is artificial, since most aspects of C2C can in fact be quantified.

E.J. van Hattum (O2 Global Network)

The conclusions and recommendations are of high interest for (industrial) designers, innovators and any other person involved in Eco-design, LCA and C2C. Also worthwhile to mention are the discussions and schemes in the paper as support for the design process.

L. Heine (Clean Production Action, Alaska, USA)

This paper makes the important distinction between results from product design and development based on design principles intended to provide social and environmental benefits including sustainable material flows- and product design and development optimized to minimize certain measurable environmental and/or human health-related impacts. It illustrates the challenge of using efficiency-based metrics when not all benefits are tangible or efficient – especially when new material flow systems are first being established. At the same time it recognizes the importance of metrics for communication and for driving progress toward any goal. This paper will provide fodder for discussion about the various existing and developing tools for measuring attributes of chemicals, materials, products and business systems, and how they can best be used either independently or in combination to achieve desired results. Scholars in the field of decision theory and sustainability-related sciences may be familiar with the inherent synergies and conflicts described between tools such as LCA and principle based innovation frameworks such as C2C design. Likewise, there is opportunity for scholars and practitioners to further advance metrics and indicators for C2C design and to continue to prototype products based on the C2C principles and to measure and compare results over time.

G. Korevaar (Technical University of Delft, the Netherlands)

This report shows very well the usefulness of one of the fundamental tools on environmental impact analysis, Life Cycle Assessment (LCA), for a more practical and business-oriented approach like Cradle to Cradle (C2C). In this way, environmental science meets sustainable innovation and that combines the best of two worlds. It also shows weaknesses of LCA at the one hand and C2C at the other hand, which gives relevant opportunities to improve at both sides:

- The LCA community could be more open and flexible

to alternative interpretations of sustainability, like C2C, and could work more on how to incorporate those new insights along the existing impact categories.
- The C2C community could be more specific in setting a clear baseline within their projects and reporting undisputable results towards sustainability, on which the LCA field could share insights in defining system boundaries, goal, scope, and measurable impact reduction in a structured and scientific way.

With this position paper, the C2C community in The Netherlands obtains a clear challenge to cooperate more with existing fields of expertise on environmental analysis, sustainable design, and innovation management. So, I am highly interested in getting involved in that new future path that we have started here.

P. Luscuere (Technical University of Delft, the Netherlands)

The current title: "Usability of LCA for C2C purposes" gives a proper reflection of the content of the report.
The objective as stated in the "Terms of reference" is limiting itself to products. Though it is stated in the report that both C2C as LCA can support processes, the C2C approach gives a more holistic and goal oriented support of these processes as LCA can, which C2C is not credited for due to this limitation.
The summary of findings gives a good overview of the shortcomings of LCA in C2C perspective as well as a proper identification of those areas where it can be supportive. Much of the difficulties in quantifying effects using LCA refer to the basic concept of using existing data, where C2C provides a framework for innovation. Some of the resulting improvements can be quantified where others cannot or at least it is, in LCA terms, unclear who should be credited for the improvement.
The recommendations are useful and relevant, especially the last one: "How can LCA practitioners benefit from C2C?"

M. Stevenson (World Wildlife Fund)

I have worked with both systems – C2C and LCA – and their application toward the design of better products and systems. I consider neither approach a panacea toward sustainability assessment and find both to be too product-focused to result in significant, systemic change given our current global crises. This report has resulted in a solid set of recommendations identifying C2C and LCA as different approaches, but complementary and this requires further inquiries into the interface of qualitative and quantitative assessment. Globally, many discussions are underway that support these same conclusions when examining the nexus of various assessment methods and certifications. Unfortunately, in this report I found the path to these conclusions heavily biased toward the positive aspects of C2C and a misinterpretation of the LCA methodology (e.g., the data collection systems could be incredibly powerful when combined, opportunities in PCR development to represent both approaches). Many of the assertions made about LCA contradicted its methodology. I was hopeful that this position paper would result in the identification of useful complementary information – one system focused on final product and the other on the product's supply chain. However, this opportunity was not realized in favor of defending C2C as an approach.

O. Vilaca (World Business Council Sustainable Development)

This Position Paper will dramatically help businesses willing to incorporate sustainability in their core strategy better understand how LCA and C2C differ and overlap. In fact, turning sustainability into strategy can be quite challenging and complex as it requires a firm grip on new measurement tools, such as LCA, and a shift toward new strategy frameworks, such as C2C. The links between these different concepts and methodologies are not always obvious and easy to identify, and I am glad to see some of the most advanced companies in the field of sustainable development willing to share the findings of their work on this specific topic. This working group is the kind of "complex coalitions" that are needed to speed up the transition toward a more sustainable world. I hope this example will be followed by many other businesses and stakeholders.

Appendices

Appendix 1: Members of the working group, expert panel and Sounding Board

Working Group

Henk Bosch (Competence Leader LCA, DSM)
Rudi Daelmans (Sustainability Director, DESSO)
Klas Hallberg (Manager Sustainable Development, AkzoNobel Technology & Engineering)
Maarten ten Houten (Sustainability Director, Philips Lighting)
Nicole Schaffroth (Project leader for sustainability, DESSO)
Diana Seijs (CSR and Sustainability Coordinator, Royal Ahrend)
Max Sonnen (Sustainability Consultant, AkzoNobel Technology & Engineering)
Jan Verlaan (Ideation Manager, AkzoNobel)
Dorien van der Weele (Sustainability Manager, Royal Mosa)

Expert panel

Katja Hansen (Consultant, EPEA; Senior researcher, C2C chair, Erasmus University)
Mark Goedkoop (Owner, PRé Consultants)
Alain Rivière (Senior Scientist, EPEA)
Carmen Alvarado Ascencio (Consultant, PRé Consultants)

Process facilitators

Anne-Marie Bor, Walter van den Wittenboer, Guus van den Berghe (NL Agency)

Sounding Board

Kim Christiansen (Senior Consultant, Dansk Standard)
Michael Zwicky Hauschild (Professor LCA & Design for environment, Technical University of Denmark)
Ernst-Jan van Hattum (Board Member, O2 Global Network Foundation on Sustainable Design)
Lauren Heine (Science Director/Partner Clean Production Action, Science Advisory Council C2CPII, USA)
Anna Karin Jönbrink (Manager Energy and Environment, Swerea, Sweden)
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Tomas Rydberg (Swedish Environmental Institute)
Martha Stevenson (Senior Program Officer R&D Global Markets, World Wildlife Fund)
Olivier Vilaca (Sustainable Consumption and Value Chain Programme Manager, World Business Council Sustainable Development)

Appendix 2: Comparison of C2C and LCA

This appendix includes two tables to answer the questions: 'What is C2C?' and 'What is LCA?' This is meant to help understand both concepts and follow on from Chapter 2 (sections 2.1 and 2.2, 'C2C as a framework for design & innovation' and 'Life Cycle Assessment').

	C2C	LCA
Ownership	*MBDC* (Charlottesville, Virginia) owns the Cradle to Cradle Trademark and EPEA (Hamburg, Germany) has the license to use it. The C2C Product Innovation Institute (California) has the license to certify products according to version 3 of the Cradle to Cradle® certification scheme which is currently under development.	Has been developed by a *global community* of practitioners; no ownership; some *coordination* by *UNEP-SETAC* Lifecycle initiative, ISO 14040/44 defines the framework.
What is it?	*Innovation framework*; business concept.	*Method* designed to *assess* the *environmental impact* of products over their whole lifecycle.
Point of view	It is possible to create *products* in such a way that they *are beneficial* to people, the planet and profit. Nature does not know waste.	*Products pollute*. By definition, they consume resources and produce some kind of waste in the end.
	Use of materials is not necessarily a source of environmental damage.	Most solutions have trade-offs.
Philosophy	We should not seek to replicate nature but we can learn how nature constantly transforms huge amounts of matter while sustaining itself and evolving towards increasingly complex structures.	Model of production system: all impacts throughout the lifecycle of the product, from cradle to grave or cradle to cradle, are inventoried systematically and then assessed.
Goal	A delightful diverse, safe, healthy and just world, with clean air, water, soil and power - economically, equitably, ecologically and elegantly enjoyed.	A clear and unbiased view of the impact of products over their lifecycle; assessment of the impact of decisions.

Table 2: Different aspects of Cradle to Cradle and Life Cycle Assessment.

LCA is used in ecodesign processes. Some basic issues considering the way C2C and LCA are used in (eco-)design processes are given in Table 3.

	C2C	LCA
Footprint	Develop a beneficial footprint.	Measure footprint, and use findings to minimize a damaging footprint.
Initiation, idea generating, divergence	C2C gives a *clear direction* at the beginning of the design process (divergent phase). This direction is based on its innovation framework and corresponding guiding principles. Positive qualities to strive for in the product design are stated in the beginning.	LCA can be used to find hotspots and problems to solve by redesigning with an ecodesign process. These hotspots give a direction for the design process. Experienced eco-designers include LCA information when creating products.
Final stage, evaluation, convergence	A plausibility check is performed: can the C2C product idea meet the stated intentions? Are the right materials available to meet intentions.	LCA can mainly be used at the final stage of the design process to *assess* several design options quantitatively. It also looks for unwanted or unforeseen effects.
How to act	Eco-effectiveness (beneficial footprint) is to be developed. The way is the goal.	Eco-efficiency is a balance between economic value and environmental burden. Since growth means more economic value, we need to optimize this balance (do more with less pollution).
	Guiding principles.	Be transparent, be unbiased, avoid or document values choices.
	Goals on a roadmap.	Transparency of results and methods are key requirements.
KPI	KPIs for progress and success.	KPIs are often based on LCA, for better communication with non-experts.
Principles	1) Waste equals food; everything is a nutrient for something else.	Waste is a potential source of pollution or a potential input for recycling. What counts is what actually happens, or can realistically be assumed to be happening.
	a) defined nutrient metabolism: bio or techno cycle.	Every claim that cannot be based on data and proper methodology is 'green washing'.
	b) materials scarcity, real and geopolitical.	Peer-reviewing by independent experts is required when public statements are made (ISO 14040).
	c) ABC-X (A: optimal, B: satisfactory, C: tolerable, X: unacceptable).	Toxicity (including fate and exposure) is assessed on the best available science.
	2) Use current solar income; quality of energy.	The actual energy mix or 'marginal' energy mix is used.
	Also considered: waste equals food e.g. the materials that solar panels are made from, nutrient and soil restoration for biomass.	Solar energy does not come free; in LCA, the production and disposal impacts are also modelled and allocated per kWh produced.
	3) Support diversity (in nature, the more diverse a system, the more stable it is).	Assess biodiversity.
	a) Biodiversity; b) Conceptual diversity; c) Cultural diversity.	Use 'cultural theory' to take account of different worldviews of stakeholders.
Roles in the chain	Customers and suppliers as partners.	Depends on goal and scope, wide variety possible.
Steps	Eco-effectiveness: define-increase-support-optimize.	Goal and scope document → inventory analysis → impact assessment → interpretation ←

Table 3: Main issues addressing the role of C2C and LCA in a design process.

Appendix 3: C2C and LCA in a product development process

Product development processes can be described with a model based on the stages or phases of product development. The diverging and converging iterations take place over several phases: product initiative/planning, idea generation, concept development, detail definition, production preparation and communication.

How C2C and LCA can be used at each stage of the product-development process (including eco-design) is described as extended information relating to section 2.3 (product development process).

	C2C	Eco-design	LCA
In general **Per phase**	The C2C innovation framework gives a clear direction for creating a beneficial footprint according to the three guiding principles.	Eco-design is a means of designing a product in such a way that product-related environmental issues during the entire product life cycle are reduced through (re) designing.	LCA is a measuring tool designed to assess the environmental impact of products over their life cycle.
Initiative / planning ↓	*Opportunities as a compass:* C2C gives a clear direction at the initial stage of the design process. 1) State positive quality intentions/ ambitions first 2) Analyse the function: what is the product intended to do for the customer/user? (Consumption product or service product) 3) Analyse the environmental fate of materials: Where can materials flow if we do/don't take care 4) Develop a roadmap with milestones to achieve progres-sively the match between intentions and the reality. At this stage, there may already be a product that can serve as template for a redesign. Or there may only be 'pre-material' system of intentions that will direct the choice of materials and the development of solutions for managing material flows.	Eco-design usually starts with a redesign of an existing product. The whole life cycle is inventorized, looking for 'hot spots' to address in the redesign. These hotspots may involve: - several stages of the life cycle, or - certain parts or - materials used in the product. Based on this: targets are set, specifications are made: - ambition, - added value, - scope.	*Hot spots as a compass:* LCA can be used to identify environmental hotspots, thereby prioritizing potential improvements. The purpose is to help product development to focus on the priorities, as they emerge from the LCA. at this stage it is very useful to find existing LCAs, or carry out a screening LCA of an earlier design or a competing design. The purpose is to identify hotspots and begin product development to focus on the characteristics that determine the environmental footprint and for which alternatives seem possible.

Table 4: Applying C2C and LCA in a product development process [part 1].

	C2C	Eco-design	LCA
Idea	1) Plausibility check: can the C2C product idea achieve the stated objectives? Are there any materials available to achieve these intentions 2) 'Imagineering': what other innovative functions could the product perform? 3) Analyse product utilization: consumption product, service product, product as a meeting point for material flows, each of them requiring specific reflection on their management. 4) Select type of nutrients (bio-cycle or techno-cycle?). 5) Plan for cascade use considering all stages.	Depending on the hot spots identified, several product ideas are developed, to solve the environmental problems. The targets and stated function of the product also play an important role. Design strategies such as improving recyclability, reducing energy use in materials production or reducing the off-gassing toxicity of the materials used will direct the process when developing eco-design product ideas.	Idea generation does not allow for any detailed LCA; there is simply no time to calculate all alternatives. The eco-indicator calculation can be used as a surrogate for a detailed LCA. Eco-indicators are predefined single LCA score for materials, transport or energy that can be aggregated.
Concept	Verification: Based on the three principles. Define relevant assessment criteria. Apply criteria: ABC-X categorization according to selected assessment criteria → compose positive lists of ingredients in the production process. Which energy? Which targets? Which stakeholders?	When the product idea is developed further, more detail is added in the selection of materials, and how product parts are composed and linked. All these choices influence the environmental impact of a product.	There is no clear role for a detailed LCA in this phase. Eco-indicators and preliminary 'what-if' studies can be made using LCA software and standard data.
Detail	Implement: select material-flow chain, partners, timeframe for steps Document remaining distance to target.	Choices such as surface treatments, additives and packaging are finalized, still taking into account the eco-design targets stated in the planning phase. Here the product is checked against the specifications/ design criteria and released for production.	In the detailed design phase an LCA is possible, but will not be very useful in influencing the design. An LCA is done at this stage to prepare for communication. Another reason is to make an LCA to look back and learn which assessments have been useful and correct.
Production preparation	Contract the selected supply chain partners, organize return or cascade system.	Select suppliers that can deliver the specified materials / parts. Another strategy is to try to pressure current suppliers to change, by changing purchasing criteria.	LCA has no role here.
Marketing	C2C Certification may support communication and marketing efforts. Communicate: develop marketing programme to describe C2C characteristics. Emphasize the role of the customer as part of the solution by purchasing product.	The hotspots that are reduced through the redesign can be mentioned in external communication. Examples are 'uses less energy', 'uses less water'.	LCA can be used to communicate environmental benefits, or simply to state the impact as an environmental product declaration.

Table 4: Applying C2C and LCA in a product development process [part 2].

Appendix 4: Overview of recycling and cascading issues within C2C and LCA

The following table gives an overview of the main points that are considered in 'nutrient management' under C2C and LCA, particularly when it comes to recycling and cascading. This table can be seen as an extension of the information provided in section 4.1.1 (Nutrient management: recycling, cascading and upcycling).

	C2C	LCA
Nutrient management	'Waste equals Food' means that the product is suitable as a resource for next product generations. Effective post-use handling of materials produces resources for future product generations and thus improves on production paths that rely on virgin resources.	Calculating recycling or cascading is a problem. 'Who gets the credit: recycler, user, deliverer?' There is no consensus on this in the LCA community and the various stakeholders and interest groups
Defined use	*Defined use* means that the use of the product at each stage of the cascade is defined, including the environment that the product is suited to.	In LCA the use period is defined by the '*functional unit*'. It is described with 'units' that fulfil a function, e.g. contain and protect 1 litre of milk, or transport 1 person 1 km.
Scenario	A scenario describes the continuous flow of a material, including the transportation and proposed recycling processes.	A scenario describes how a material and/or product is expected to fulfil its function, including the expected life time and end-of-life strategies.
Cascade	A cascade is the way material flows can be managed through several defined uses (products) prior to their up-cycling to again highly organized forms using energy derinved from current solar income.	The quality of recycling is not taken into account. The loss of quality when recycling 'virgin' office paper to toilet paper is not calculated. This can only be done by comparing one cascade with another.
Recycling	The aim is to 'upcycle' materials, which means that materials improve in quality through recycling as the result of design decisions before starting production.	'Who gets the credit' for recycling is an issue. There is no consensus on this in the LCA community, and the various stakeholders and interest groups
Life span	The life span of a product is described in the 'defined use'. It is the period during which the product has a functional use. Expected technological developments are taken into account, i.e. when improved functionality can be expected.	There are no strict rules for defining the life span of a product. The most plausible life span should be taken into account. The environmental impact per functional unit is very dependent on the life span that used for calculations. Also see the example of sewage.

Table 5: Overview of recycling and cascading issues in C2C and LCA.

Appendix 5: Overview of toxicity issues within C2C and LCA

The following table summarizes the way toxicity (and healthiness) is interpreted under C2C and LCA. This table can be seen as an extension of the information in section 4.1.2 (Nutrient management: toxicity, ABC-X, health and environmental aspects).

	C2C	LCA
Purpose / intentions	*Classify/substitute* harmful materials for optimal results in a defined C2C nutrient flow scenario. Hazardous chemicals are detrimental from the perspective of 'biological nutrition'. Technical properties may be detrimental from the perspective of 'technical nutrient' management.	*Measure* the extent of hazardousness of emissions that occur in the various steps of the lifecycle, while not taking into account the chemical content of the material (unless this results in emissions in the use or end of life stages, with an objective (open source) expert system.
Compare	The idea is not to compare two (functionally similar) C2C products. C2C compares a given product at different stages of its optimization (redesign).	It is possible to compare products, also only on toxicity.
Strategy	'The *right* material at the right place, in the right time' (defined C2C nutrient scenario). → If toxic: 1) *look for alternative* (absolute), 2) if no alternative is available, aim to reduce the risk of exposure and retain the weak point as an opportunity for innovation within a company's industrial partners.	'*Minimize* impact' (ecodesign strategy, LCA has no design strategy). → try to design a product with *less toxic impact* (relative).
Looks at	The *adequacy of the material* as: - Biological nutrient (for biological systems that they will come into contact with (e.g. via inhalation or ingestion, humans, water, soil)); - Technical nutrient (for technical systems capable of reusing materials with defined quality).	The (toxicological) *emission* of materials, assuming some of the chemicals contained in the material will be emitted. 'Embedded toxicity' is not included in the assessment; provided there are no toxic emissions, the impact is zero.
What is assessed	The *material properties* (toxicology, chemical/physical properties) and their capacity to support the C2C scenario in a beneficial way.	*Emissions* occurring over the life cycle. It depends on the end of life scenario to what extent the content is being assessed.
Assessment means	(Quality of nutrients) *classification* into A (optimal), B (could be optimized), C (tolerable) and X (not acceptable), grey (not characterized).	(Quantitative) impact *calculation*.
Based on	1) the *properties* of the materials and 2) the suitability of the context	*Emissions* during the whole life cycle.
Model	1) The *possibility* of living systems to come in contact (oral, dermal, inhalation) with the substances/ materials during the past, present and intended future of the product with beneficial impacts; 2) The *possibility* of (theoretical/operational) technical systems to process materials with beneficial resource impacts during the past and the intended future of the technical product.	*Assess* the impact of the *actual* (and not potential emissions), and then assess the fate and exposure of the emission.

Table 6: General overview of how C2C and LCA deal with toxicity [part 1].

	C2C	LCA
Note	ABC-X is *context dependent* and based on intended use (scenario: the past, present and future cradle). Technical rather than toxicological considerations may lead to an X classification for a process input or product component.	LCA does not assess acceptable levels.
Fate	1) Bioaccumulation, biodegradation, abiotic degradation, elemental composition, radioactivity. 2) Behaviour in technical nutrient processing/recovery.	Fate model: links steady state flow of an emission to a steady state concentration. Emissions (kg) to air, water, soil → concentration * area * time.
Probability → consequence	What may happen → Avoid worst case, go or no-go decision based on effects during intended use.	What will happen → Calculate while being aware of uncertainties.
Process	First qualitative statements and scenario definition (biological / technological), then classification. → Look for weak spots then look for alternatives (other materials within the current product or completely new ways of fulfilling the purpose).	Multiply the emission by a characterization factor; the characterization factor is developed using fate, exposure and impact assessment steps.
Amount of toxic substance	A little means a lot - 'Search for alternatives if intrinsically detrimental'.	Multiply amount by characterization factor, everything counts.
Exposure	*Oral, dermal* (organisms as a whole, skin and eye tox, skin penetration) and *inhalation* Acute (single exposure), Chronic (exposure over 2 years) - include bioaccumulation.	Calculates effect based on the intake fraction (*oral, dermal and inhalation*) and fate factor, on humans and ecosystems (species in aquatic ecosystems) → Yes, always - Bioaccumulation is included in the fate model.
Local aspects	As the suitability of a material to its context is important, local aspects are considered.	Local aspects (like indoor air quality) are not considered in a 'standard' LCA. There are some new developments that could be used to calculate the impact on indoor air quality.
Climatic relevance	In ABC-X.	In climate impact category, not in toxicity assessment.

Table 6: General overview of how C2C and LCA deal with toxicity [part 2].

The following table summarized the aspects of toxicity that are taken into account in ABC-X (C2C) and Usetox (LCA).

	C2C, ABC-X	LCA, Usetox
Effect of mining	On the C2C agenda, but not the first priority. Design/redesign for the future cradle first.	Always included (biggest effects mostly in mining phase).
Human health aspects	1) Carcinogenicity 2) Endocrine disruption 3) Mutagenicity 4) Reproductive tox (disturbance of fertility and foetal development) 5) Skin irritation + mucus membranes 6) Sensitization.	1) Yes, often modelled separately 2-4) Depends on how it is reported by Environmental Protection Agency, Eco-tox, Material Safety Data Sheet, Hazardous Substances Data Base or Quantitative structure activity relationships 5) Partially 6) Not usually.
Environmental health aspects	7) Terrestrial mammals 8) Fish 9) Aquatic invertebrates (daphnia) 10) Aquatic plants (Algae) 11) Soil organism tox 12) Biodegradation 13) Bioaccumulation.	7) Yes 8) Not usually (bias to lower organisms) 9) Yes 10) Yes 11) Yes 12) Yes, in fate step, not an effect 13) No.

Table 7: Detailed overview of how C2C and LCA deal with toxicity.

Appendix 6: Overview of energy production in C2C and LCA

The following table summarized the way energy production is dealt with under C2C and LCA. This table can be seen as an extension of the information in section 4.2 (C2C's second guiding principle 'Use current solar income').

	C2C	LCA
Purpose	Have go/no-go.	Measure and assess.
Coal	No-go: 1) it is not renewable; 2) toxicity problems during mining; 3) many miners die during mining.	Energy based on coal has the highest impact in several categories.
Nuclear	No-go: high risks and the waste cannot be used as a nutrient.	The high risks from nuclear power are not taken into account.
Solar panels	Go: solar energy is renewable. Innovation is needed on substituting the scarce materials that are used and innovation and design in such a way that recycling increases from current 85% towards 100% upcycling.	Impact is mainly in production and disposal.
Wind turbines	Go: energy from wind is renewable. Design for disassembly and recycling is an innovation challenge. Some scarce materials need to be substituted.	Impact is mainly in production and disposal
Bio fuel	Go: if material is used in cascade (fuel is last step) and nutrient requirements to grow biomass that meets C2C principles, including the third principle: social impact of non-access to food.	Land use, necessary for producing the crops will be dominant in the bio fuel option.
Best option	Depends on the local situation.	Depends on impacts.

Table 8: Overview of how C2C and LCA deal with energy production.

Appendix 7: Guide to LCA and how to measure 'C2C-ness'

The short guide in this appendix relates to section 3.3.2 (Measuring C2C's eco-effectivity with LCA). It builds on the general information on LCA given in section 2.2 (Life Cycle Assessment).

Introduction

LCA was developed to provide a systematic approach for assessing the environmental impact of product systems over the lifecycle, from the production of raw materials (cradle) to the final disposal, including the impact of landfill and discharges into air and water (grave) that occur with or without partial recycling to a new lifecycle (the next cradle). Modelling a lifecycle in this way is complex, since production processes and product systems are very closely interlinked.

Often, LCA standards are not able to capture the benefits of Cradle to Cradle (C2C) products. This short guide lists a number of items which may be relevant when analysing C2C products using an LCA, including aspects that are relevant to C2C. Chapter 2 of this document summarizes the principles of LCA, and Chapter 3 describes issues relevant when assessing C2C products.

LCA applications can be categorized into four groups, shown in Figure 3.

	Analyse one system	*Compare two or more systems*
Internal	*Analyse hotspots as input for product development and future product policy strategies.*	*Choose between alternative design or purchasing solutions, or future product policy strategies.*
External	*Environmental declarations, show awareness to important stakeholders; lobby for or against legislation.*	*Claim your product is superior to a competitor or a baseline, use as a basis for policy (i.e. German packaging policy).*

Figure 3: LCA Applications.

We can differentiate a number of 'steps' in LCA

1	Define the functional unit, formulate goal & scope; system boundaries must correspond to goal and scope definition; depends on the outcome. Establishing priorities (whether materials are a problem is one of the objectives, and never a starting point).
2	Several thousands of emissions are assessed.
3	Ten to fifteen impact categories.
4	Environmental problems 'damage'.
5	Optional weighting → single score, but not allowed in public statements (ISO).

Table 9: Overview of steps to make in an LCA.

Considerations with C2C products

Of all the LCA considerations, the following are the most relevant to C2C products:

Functional Unit

In LCA, the functional unit specifies the functions of the system (product) being studied. The functional unit determines the reference flows that will be used to model the life cycle. The lifetime of a product plays an important role in the functional unit. C2C products aim to be environmentally beneficial, and they can therefore often be seen as multifunctional. For example, a carpet can purify the air and serves as a way of covering the floor in the same time.

Being an innovation framework, C2C may lead to the emergence of products with unique functionalities. The innovative character of C2C may be easily overlooked, if the product wants to be compared to traditional products or if a PCR wants to be applied. Especially if the C2C product carries a secondary function, such as an air-purifying carpet.

Because C2C products may have multiple functions, the use phase of C2C products may deserve more attention than it normally receives in LCA. Comparisons can be made on the basis of expanded systems that consider all functions. In the case of an edible plate, for example, an LCA for only the plate is not sufficient and the food replaced could be also considered, if possible.

Level of technology

The status quo is usually the starting point in LCA. Nevertheless, some studies follow the 'consequential' approach, which involves forecasting hypothetical scenarios to model life cycles, assuming that the introduction of new products and technologies will impact on the market. Under C2C, the intention to change in the future is what counts. Energy, for example, is considered to be a manageable issue since enough solar energy is available.

It is possible for LCAs to be calculated on the basis of the input of solar energy alone. This would be done, however, based on current solar-panel technology. This data could also be corrected to account for the more efficient technology expected in the future. For example, an increase in efficiency of 20% could be considered, and the 85% recycling of solar panels could also be taken into account. The same principle of efficiency increases could be used for recycling or waste treatment processes. In order to maintain transparency, the reference status quo scenario could be presented as a base line.

Recycling

Recycling poses a challenge when applying LCA to C2C. Under C2C, waste streams need to be avoided, transforming them into inputs for the same or other life cycles (in the techno sphere or in nature). This means that recycling methods are often novel and there are no regular substitution patterns for the recycled materials.

For an LCA of a C2C product, this information needs to be estimated based on similar recycling processes, the expected substitution rates, the expected collection patterns and the expected introduction of the recycled material on the market.

A second consideration is the nature of the recycled material. Not all materials allow infinite recycling. ISO 14047 includes examples on how to model the subsequent uses of recycled materials.

Benefits account

Making C2C measurable would involve measuring eco-effectiveness. The questions that need to be answered are:

1) What qualities are defined in advance (to what extent can the subjective qualitative positive future C2C scenario be translated into quantitative aims and milestones)?
2) Are they defined in a measurable way?
3) Can they be used to measure the product development results during the several design phases?

Accounting for benefits may be expressed as environmental impact avoided. This is often done to account for recycling benefits in LCA. Transparency and consistency is essential when communicating benefits in LCA, as most of the time this involves other systems than the one under study. One must be careful of accounting not only benefits but also all environmental costs that may result from pursuing the benefit.

In the case of *recycling*, the following should be included:
- The collection of materials for recycling
- The recycling processes
- Any loss of material
- Property losses (translated into a substitution factor)
- Transportation

In the case of an *air-purifying* carpet, the following should be included:
- Air-quality requirements
- Subtract the process of cleaning the air unnecessarily, due to the new carpet in use
- Link between air quality and health
- VOC emissions
- Fine dust emissions
- Differences in maintenance
- Differences in carpet production

In the case of a *water cleaning system* (e.g. in production processes), the following should be included:
- Water-quality requirements
- Subtract the process of cleaning the water unnecessarily
- Link between water quality and ecosystems quality
- Differences in water quality as a result of production processes
- Energy and raw materials required for the production processes that lead to better water quality

In the case of *soil restoration*, the following should be included:
- Soil-quality requirements
- Link between soil quality and ecosystem quality
- Differences in soil quality as a result of production processes
- Energy and raw materials required for the production processes that lead to better soil quality
- Subtract energy and materials that are not needed due to the soil restoring qualities of the C2C product / process

Result Interpretation

When interpreting results, it may be necessary to spend some time thinking about the reasons why C2C principles may not necessarily lead to an LCA-calculated environmental benefit. This should be described clearly in the goal and scope document, and possibly in the sensitivity analysis as well. Certainly, a great degree of innovation is necessary to reach sustainability. Nevertheless, innovation should not backfire leading to a larger or even an unacceptable shift in the environmental impact from one category to another. LCA can provide a good reference by which to direct innovation.

Appendix 8: References and Further reading

References

1) *Our Common Future*; **Brundtland**, Commission of the United Nations, March 20, 1987.
2) Cradle to Cradle® and C2C® are registered trademarks held by McDonough Braungart Design Chemistry, LLC (MBDC). More information can be found at: www.epea.com and www.mbdc.com;
3) www.ecobilan.com/uk_lca02.php;
4) *Iterative Screening LCA in an Eco-Design Tool*, **G. Fleischer, W.P. Schmidt**, 1997, SETAC;
5) *Cradle to Cradle pays off!* **Learning Community Cradle to Cradle**, 2011, 'publicaties' at www.agentschapnl.nl/cradle-to-cradle, or www.theterrace.nl/en/publications;
6) www.c2ccertified.org;
7) http://lct.jrc.ec.europa.eu;
8) www.sinsofgreenwashing.org;
9) www.gednet.org;
10) www.ghgprotocol.org; only greenhouse gasses are considered
11) www.sustainabilityconsortium.com; over 50 companies that have committed to develop a Sustainability Measurement and Reporting System (SMRS), defining also Sustainability Drivers and Sustainability Indicators.
12) PCR Harmonitiation initiative, initiated by PRé and the German Thema1 consultancy, has broad the globally relevant stakeholders around the table. This initiative also collaborates with GEDNET, www.gednet.org;
13) www.prosuite.org.

Further reading

- *From Life Cycle Assessment to Life Cycle Development*; **Braungart M, Rivière A, Soth J, Ketelhut R, Rinkevich J**, 1997, 97-A1454, Presentation at the Air & Waste Management Association's 90th Annual Meeting & Exhibition, June 8-13, 1997, Toronto, Ontario, Canada
- *Cradle to cradle. Remaking the way we make things*; **McDonough W, Braungart M**, 2002, North Point Press, New York
- *Cradle to cradle criteria for the built environment*; **Mulhall D, Braungart M**, 2010, CEO Media, Rotterdam, Oct 2010
- *Rocking the Cradle to Cradle Revolution in Davos*; **Lacy P, Rosenberg D**, 2011, Fast Company 2011/01/28 www.fastcompany.com/article/rocking-the-cradle-to-cradle-revolution-in-davos last accessed Oct. 22, 2011
- www.C2C-world.com
- A Semi-Quantitative Method for the Impact Assessment of Emissions Within a Simplified Life Cycle Assessment, **G Fleischer, K Gerner, H Kunst, K Lichtenvoort, G Rebitzer**, 2001, Int. J LCA 6 (3) 149 - 156.

Position paper – Usability of Life Cycle Assessment for Cradle to Cradle purposes-

This publication belongs to:
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© NL Agency | December 2011
Publication-nr. 1AFVA1106
This paper can be found at:
www.agentschapnl.nl/cradle-to-cradle and www.theterrace.nl

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