CONTINUING THE BUILDING'S MATERIAL CYCLE
A LITERATURE REVIEW AND ANALYSIS OF CURRENT SYSTEMS THEORIES IN COMPARISON WITH THE THEORY OF CRADLE TO CRADLE

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Keywords: Cradle to Cradle, building, closed cycle, continuous cycles, materials, systems theory

Abstract

Recently, the Cradle to Cradle (C2C) theory set ground in the Netherlands, propounding that environmental impact reduction can provide a positive economical impulse to stakeholders. The building industry has warmly received this approach and considers it to be a solution to the above-mentioned burden.

However, if the building sector wants to implement C2C into their practice, a paradigm shift is required. Therefore, the sector must overcome the many difficulties it encounters while striving for an eco-effective built environment.

Current sustainability strategies focus on reducing the negative environmental impact of buildings. The systems theory of C2C however aims at a positive impact; this could suggest that the state-of-the-art becomes inadequate when adopting C2C as a strategy for improvement.

This paper reviews contemporary systems theories and analyses them in the light of C2C, focusing on closed or continuous materials cycles. The paper finalises by describing the hiatus in and correspondence between these current theories and C2C theory.

From the study we found that C2C provides new features that help continue materials cycles, just as the contemporary theories provide potentially useful additional material for C2C. Moreover, it reveals a striking difference between the state-of-the-art and C2C.

For this paper, the Dutch building practice and industry were taken as case study. Approaches and results nevertheless are replicable to be used in other countries striving for optimised management of resources.

Introduction

1.1. Background

The growth in world population and prosperity and the resulting increase in demand for food, energy and materials give rise to major environmental issues. If the pressure on the environment should be halved within 50 years after 1990 [Speth, 1989; Ehrlich & Ehrlich, 1990], whilst coping with the predicted trends in global population and prosperity growth, the environmental impact by unit of prosperity needs to be reduced by a factor 20, or by 95% [Dobbelsteen, 2004]. The building industry's share in these issues is significant. For example, the Dutch building sector consumes 33% of all energy [Lichtenberg, 2006] and produced almost 40% of the 62 million tonnes of waste in 2008 [Agentschap NL, 2011a].

Previous studies have been searching for ways to reduce the environmental impact of the built environment, mainly on the issues concerning energy and water use, or building material waste. Strategies that were developed over time are for instance the Trias Ecologica or three stepped strategy – (1) reduce the demand, (2) generate from sustainable sources and (3) use finite sources clean and efficiently – by Duijvestein [1990], the Trias Energetica derived from that [Lysen, 1996], the DCBA method [Teeuw et al., 2010], the 3R waste hierarchy – (1) Reduce, (2) Reuse and (3) Recycle –, Lansink's ladder and it's successor, the Dutch waste treatment programme (*Landelijk afval beheerplan 2002-2012 (LAP))* [VROM, 2007].

Although all these current strategies aim for impact reduction, they leave room to harm the environment: the final steps incorporated in all of the above strategies provide "escape routes" (e.g., immobilisation, incineration & disposal (Lansink's Ladder) or "process waste wisely" (Trias Ecologica)). So far, the building industry could only use these strategies as a guidance to come to a sustainable building (design). However, it has the tendency to rearrange the guiding principles within these strategies. For example, with the Trias Energetica – (1) energy saving design, (2) energy efficient technology and (3) renewable resources –, building practice confuses the first with the third step, whereas it often skips the second step [Dobbelsteen, 2008]. Moreover, the availability of the "escape route" could well be delaying the change to a truly sustainable building practice.

In 2008 for instance, 98% of the 25 megatonnes of rubble that came from Dutch demolition sites was recovered [Agentschap NL, 2011a]. This amount of rubble could found almost 1580 miles of a 6-lanes highway: from Amsterdam (the Netherlands) to Moscow (Russia), every year. Because the supply of debris exceeds Dutch demands – e.g. for road- and railway sub-base – it is partially exported. This transportation of Dutch construction and demolition waste (C&DW) consumes energy. Furthermore, to meet local shortage of natural resources for concrete, recycling of concrete C&DW as substitute for natural resources spares nature and reduces the environmental impact of transport by limiting raw material extraction.

Therefore, a hierarchy such as Lansink's ladder – (1) prevention, (2) re-use, (3) recycling, (4) incineration (for energy production and waste condensation) and (5) disposal (through landfill) – should preferably contain only steps (1), (2) and (3) and discard the remaining two – end-of-pipe – options. This asks for an approach in which waste doesn't exist, and in which flows of, for instance, materials stay in a continuous system: in continuous materials cycles.

1.2. The building industry

During the last decade, especially after Dutch television broadcasted the influential *Tegenlicht* documentary "*Afval is Voedsel*" (Waste equals Food) [Hattum & Meyer Swantee, 2006], the Cradle to Cradle (C2C) theory has set ground in the Netherlands, presenting a new 'eco-effective' theory inspired by the systems of nature. It propounds that environmental impact reduction can provide a positive economical impulse to stakeholders, in contrast to current sustainable approaches, which are considered to be costly investments and limiting prosperity. C2C has already been practiced internationally in industrial process design and building related projects, for companies such as Herman Miller, Ford, Philips, Nike and the Republic of China. The Dutch building industry also warmly received this approach, and has been considering it as a solution to the problems discussed above.

At the time C2C slowly settled in the Netherlands, it got criticised by several professionals and scholars from the field of sustainability [Zeilmaker, 2008; Vos, 2009; Amelung & Martens, 2007; Keuning, 2008]. The main comment was that this new theory was not something new. Korevaar argues, for instance, that several decades ago at least five concepts for sustainable design were already developed and that, according to him, C2C is the most poorly detailed one of them [Zeilmaker, 2008]. Similarly, Haas states that it is old ideas parading as new ones [Vos, 2009].

Further, the building industry is struggling to put the theory into practice. Some municipalities and regions enthusiastically took up the challenge of implementing C2C as basis for their plans. However, after stating their intentions concerning eco-efficiency and arranging these intentions in project principles, the municipality's and region's agencies had difficulties adopting them in practice. This suggests that C2C can be difficult to comprehend.

1.3. Objective and methodology

The aim of this paper is to provide an overview of current theories, concepts or strategies, in order to grow a greater understanding of the C2C theory's context and its implications and opportunities for the built environment. If we want it to be accepted as a theory we can build upon, we need to embed the theory in its field. To which extent is the critique by the scholars correct? Are the other systems theories indeed similar to C2C? To which extent do they harmonise? Furthermore, because of the market's expressed difficulty of applying C2C, the other – according to Korevaar – more detailed theories might ease the practical application of it. What means can other systems theories provide that accord with C2C?

In addressing the above questions, this paper reviews and compares seven early and contemporary systems theories or concepts in section 2. These theories or concepts include guiding principles or criteria, which were collated. Consequently, each principle or criterion corresponding to one of the C2C categories – (1) waste equals food, (2) use current solar income and (3) celebrate diversity – is classified as such. Subsequently, the principles and criteria linked to the first C2C category are isolated. Then, section 3 derives criteria from three C2C-approved resources: principles of green engineering [McDonough et al., 2003], C2C certification program [MBDC, 2008] and C2C criteria for the built environment [Mulhall & Braungart, 2010]. Subsequently, each criterion and its corresponding principles are analysed in section 4: what are the similarities and differences between these principles and the C2C criteria. Finally, the complying principles and criteria are collected and categorised in an inventory, providing additional principles/criteria for continuous materials cycle in accordance with the C2C theory. Furthermore, the differences revealed from this analysis will provide additional insight concerning the continuous materials cycles.

Although the scientifically established Life Cycle Assessment (LCA) is used as a tool to analyse and evaluate the environmental impact of materials, it was not taken into account in this research. LCA gives an indication of *current* impacts, whereas systems theories focus on designing *future* solutions for the current environmental problems [Agentschap NL, 2011b].

2. Closing the cycle

The idea of closed loops in mankind's systems finds it's origins in nature's ecology. Nature has balanced systems, in which all elements are connected and interdependent. Because of this interdependency, the systems are robust: although regularly some species become extinct, this is usually caused by an external intervention (natural disasters or humans) and seldom causes an imbalance in nature. What is more, nature's remainder from the biosphere becomes food for other natural processes. All the nutrients used by living organisms in ecosystems are a part of a closed continuous system. In contrast, the flow of energy in nature is an example of an open system; the sun provides living organisms with light and heat and is needed to engine the growth of the natural system. It is a system in which waste does not exist; everything is related to something else.

With the industrial revolution a new system arose: one of quantitative development. It is a system of technological cycles, in which nutrients and resources from the natural metabolism are used for industrial processes. After processing and manufacturing these resources into products for human use, they usually have become unfit to return to nature's cycles. It is an open system, just as with the flow of energy in the biosphere. However, in contrast to the energy flow, the industrial output does not logically provide other industrial processes or nature with useful residues. It relies upon end-of-pipe solutions, frequently ending up as waste in landfills or incinerators, even in current times.

The complexity of products and the globalisation of trade make it challenging to shift to another way of thinking. Continuing the cycle therefore asks for effort in understanding the complexity of material, energy and economic flows to comprehend how resources can be (re)cycled more effectively within the system. Since the 70s, several theories and approaches have been developed to work toward closed cycles from an environmental, economic and often societal perspective. The following sections describe 7 systems theories: Laws of Ecology, Looped (later known as Performance) Economy, Regenerative Design, Biomimicry, Industrial Ecology, Cradle to Cradle and Blue Economy.

2.1. Cradle to Cradle

“The Cradle to Cradle design framework moves beyond the goal of only reducing an organization’s negative impacts (eco-efficiency), to provide an engaging vision for [stakeholders] to create a wholly positive footprint on the planet— environmental, social and economic (eco-effectiveness)” [MBDC, 2010a].

William McDonough drew the first outlines of Cradle to Cradle (C2C) with the Hannover Principles [William McDonough architects, 1992]. Half a decade earlier, Michael Braungart – founder and former leader of Greenpeace’s chemical division - established the Environmental Protection Encouragement Agency (EPEA). This institute’s key ambition is to encourage improved environmental performance by co-operation with industry. Together, they composed the book “Cradle to Cradle - remaking the way we make things”, which – combined with the documentary “*Afval is Voedsel*” (Waste equals Food) [Hattum & Meyer Swantee, 2006] – eventually lead to the current wide acceptance of the theory in Dutch practice. Current examples of C2C projects in the Netherlands are the C2C inspired design of Park 20|20 [William McDonough + Partners, 2012], the Almere Principles [Gemeente Almere, 2008], Venlo Principles [Doorn, 2012] – which were inspired by the Hannover Principles – and the Klavertje 4 C2C framework [William McDonough + Partners, 2012].

To measure the built environment’s sustainability, the contemporary methods used are mostly LCA based, as it is a scientifically established assessment method. However, the current LCA methods focus on minimising the impact on the environment. It is being referred to as ‘less bad’, because production, use and disposal of products continue to generate toxic elements that end up as waste in the human environment MBDC, 2010b]. C2C on the other hand asks for a new way of thinking: instead of striving for a reduction of negative impact (i.e. reducing waste quantities or transforming waste into useful substances), it aims for a positive impact. In other words, instead of striving for “fine-tuning a fundamentally flawed system”, C2C aims at “… a […] system powered by renewable energy in which materials flow in safe, regenerative, closed loops" [McDonough et al., 2003].

Sustainable development [Brundtland et al., 1987] is often perceived in terms of reducing the impact on the environment, and it is usually put into practice by optimising existing solutions or re-engineering the system. According to Braungart & McDonough [2002] this is called eco-efficient engineering, and does not supply in a sufficient long-term goal. It may reduce pollution and resource consumption in the short term, but it does not address the source of the problem: the design defect of current industry. According to McDonough & Braungart [2002] it is therefore sustaining a defective system.

The C2C framework aims to redefine the problem based on the rules of nature. It suggests a new, *eco-effective* approach to anthropogenic systems in which economic growth and environmental health will not be in mutual conflict. For this, they defined three key tenets that lie at the basis of C2C:

- *Waste equals food* - everything is a nutrient for something else
- *Use current solar income* - Energy that can be renewed as it is used
- *Celebrate diversity* - Species, cultural and innovation diversity

Waste equals food
In the C2C theory, waste virtually does not exist. It refers to the regenerative systems of nature, in which organic waste provides nutrients to other metabolisms. Concurrently, industrial processes can be mirrored as such: materials from industrial processes and products provide nutrients for the biological or technical metabolisms. However, to either provide a biological or technical nutrient, a product or process should be designed to enable the decomposability of the product into single nutrients.

Use current solar income
C2C sees the sun as a giant nuclear power source at a safe distance from earth. In nature, plants and trees manufacture food, using solar radiation as energy source. Likewise, the designed society can harvest solar income as solar power, solar heat, daylight, wind energy, etc.

Celebrate diversity (or stated differently, Respect Diversity [McDonough & Braungart, 2002])
As diversity in nature makes a robust system, the same goes for the designed system: Current industry favours simplification and monotony, which opposes the diversity of place and culture. As an example: this general-purpose system depletes topsoil caused by monoculture and the use of chemical fertilizers and pesticides.

Because this research reviews theories and principles that focus on continuing the *materials* cycle, this study will mainly focus on the first tenet and its relation to the other systems theories. However, figure 1 provides a full overview of the three tenets and the related systems theories principles.

2.2. Other systems theories

2.2.1. Laws of Ecology

" Human beings have broken out of the circle of life, driven not by biological need, but by the social organisation which they have devised to "conquer" nature […]. The end result is environmental crisis […] [O]nce more, we must close the circle. We must learn how to restore to nature the wealth that we borrow form it". [Commoner, 1971]

One of the first to describe principles on closed cycles for human technology was biologist and environmental economist Barry Commoner. He established the Centre for the Biology of Natural Systems (CBNS) in 1966. Its mission is "to identify and rectify environmental and occupational threats to human health" [CBNS, 2012]. Consequently, in his book "Closing the Circle" Commoner [1971] tried to bring environmental logic and the chaotic economic and political system into contact; he depicted the relation of the world population's growing prosperity and its environmental impact as the cause of environmental problems. This later formed the basis for the formula of the pressure on the environment – introduced by Ehrlich & Ehrlich [1990] and Speth [1990] – to be able to quantify the objectives of the Brundtland Commission.

table 1. Laws of Ecology

1. everything is connected to everything else	3. nature knows best
2. everything must go somewhere	4. there is no such thing as a free lunch

Commoner stated that the present industrial system is self-destructive and suggested that the American economy should be restructured according to the four "laws of ecology" [1971], which are illustrated in table 1. For example, he rejected the conventional measures to judge the "affluence" of life – such as Gross Net Product (GNP) – as a reflection of human welfare. He suggested that with a new economic system people can continue living their affluent way of life; however, it asks for reforms without seriously reducing the current level of useful products available to the individual. Together with this example, several other ideas of Commoner are echoed in the ideas of C2C.

2.2.2. Looped Economy

Looped Economy (LE) "creates an economy based on a spiral-loop system that minimizes matter, energy-flow and environmental deterioration without restricting economic growth or social and technical progress". [Walker, 2011]

In 1976, Walter Stahel – a former architect – and Genevieve Reday drew the first sketches of the vision of LE describing its impact on waste prevention, resource saving, economic competitiveness and job creation. Since then, Stahel has been working on convincing the establishment that economic actors in a circular economic system become more profitable than their competition in a linear one. In 2006, Stahel launched the book "the Performance Economy" (PE), which extends LE and translates it to current economic times and practice. Walker describes four key principles, pioneered by Stahel and co-scholars. These are formulated in table 2.

table 2. Principles of the Looped Economy

1. product design optimized for durability, adaptability, remanufacturing and recycling	3. business models based around "product leasing" as opposed to "product selling", where ownership remains with the manufacturer over the entire product life cycle, thereby encouraging product durability and improved quality approaches to product design, manufacture and maintenance
2. remanufacturing that preserves the frame of a product after use, replacing only the worn-out parts	4. extended product liability/stewardship/responsibility: encouraging manufacturers to guarantee low-pollution-use and easy-reuse products

Supposedly, the term "Cradle back to Cradle" was first used by Walter Stahel in the 1980s as an alternative to the common linear product responsibility "Cradle to Grave", which he saw as "a marketing update for gravediggers, because it still relies on end-of-pipe solutions" [Product-Life Institute, 2008]. As with the Laws of Ecology, LE addresses issues and solutions that coincide with C2C; for example, arguing for extended performance responsibility of products by manufacturers, what Stahel calls The Functional Service Economy [Stahel, 2006].

2.2.3. Regenerative Design

“While closely aligned with environmental, economic and social sustainability projects, regenerative studies places emphasis on the development of community support systems which are capable of being restored, renewed, revitalized or *regenerated* through the integration of natural processes, community action and human behavior.” [Lyle Center, 2011]

Also before the year 2000, John Tillman Lyle proposed the implementation of Regenerative Design (RD): an approach to design based on process-oriented systems theory [Lyle, 1994]. Regenerative systems are involved in complex social and natural processes and integrally serve the involved communities. According to Lyle, RD requires a pattern of thought quite different from the patterns that have become customary.” He refers to Regenerative Design as a design method aiming for renewing the earth’s resources, as opposed to sustainable design, which he claims to be merely breaking even. Lyle [1994] offers a concept and design strategies, as illustrated in table 3, which he describes as contrasting to the current, what he calls, one-way throughput or “paleotechnic” systems.

table 3. Principles of Regenerative Design

1. letting nature do the work	7. providing multiple pathways
2. considering nature as both model and context	8. seeking common solutions to disparate problems
3. aggregating, not isolating	9. managing storage as key to sustainability
4. seeking optimum levels for multiple functions, not the maximum or minimum for any one	10. shaping form to guide flow
5. matching technology to need	11. shaping form to manifest process
6. using information to replace power	12. prioritising for sustainability

The given list of design strategies expresses the RD experience up to 1994. Since experience will grow over time, Lyle stressed that this list is not a final version. However, the principles from 1994 are considered in this paper.

2.2.4. Industrial Ecology

IE mainly focuses on identifying “opportunities for reducing waste and pollution in the material-intensive sectors by exploiting opportunities for using low-value byproducts (i.e. waste) of certain processes as raw materials for others”. [Ayres & Ayres, 1996]

Referring to the design of production sites in analogy to natural ecosystems, the term Industrial Ecology (IE) and the concept of Industrial Ecosystems were first introduced by Frosch and Gallopoulos [1989]. It models socio-technological processes to ecological principles, aiming for closed material cycles by exchanging waste flows as input for other technological systems.

According to Stremke et al. [2011], IE proclaims four primary concepts: (1) modelling industrial systems on ecological principles, (2) closed material cycles, (3) waste exchanges and (4) design for environment, with the natural ecosystem serving as a model for industrial processes. Ayres & Ayres [1996] describe three elements for IE, similar to the 3R anthology. Furthermore, it has four basic strategies for increasing material resources’ productivity. All are listed in table 4.

table 4. Principles of Industrial Ecology

1. reduce, and eventually eliminate, inherently dissipative uses of non-biodegradable materials, especially toxic ones (like heavy metals)	4. dematerialisation
2. design products for easier disassembly and reuse, and for reduced environmental impact, known as ‘design for environment’ (DFE)	5. substitution of a scarce or hazardous material by another material
3. develop much more efficient technologies for recycling waste materials, so as to eliminate the need to extract ‘virgin’ materials that only make the problems worse in time	6. repair, re-use, remanufacturing and recycling
	7. waste mining

Although the Industrial Ecology concept aims for waste reduction, Ayres & Ayres [1996] raise an important dilemma: the development of profitable markets for waste might effect a higher production and could limit innovation of processes that would generate no waste at all.

It is likely that because of its relatively narrow scope – focussing on industrial processes only – the theory of IE was able to find its way into practice. It has been applied in ‘eco-industrial parks’, in which industries cooperate and exchange energy and by-products, avoiding exergy destruction and reducing waste [Ehrenfeld & Gertler, 1997]. A well-known example of can be found in Kalundborg, Denmark.

2.2.5. Biomimicry

The term biomimetics was first defined as: "the study of the formation, structure, or function of biologically produced substances and materials (as enzymes or silk) and biological mechanisms and processes (as protein synthesis or photosynthesis) especially for the purpose of synthesizing similar products by artificial mechanisms which mimic natural ones" [Websters Dictionary, 1974].

Benyus [1997] envisions the following: “Unlike the Industrial revolution, the biomimicry revolution introduces an era based not on what we can *extract* from nature, but on what we can *learn* from her”.

Learning from nature is the core concept of biomimicry and it has a long tradition; Leonardo daVinci is one of history’s great examples having nature inspiring him in his inventions. Along with him the concept has many adherents in a wide field of technology. Nature has been growing, surviving and innovating for 3.8 billion years and has produced the most astonishing inventions on earth: light-producing fish in deep seas, self-cleaning leaves, microscopic solar collectors, naturally-cooled (small scaled) buildings in desert area’s, etc. Benyus [1997] describes eleven principles, which are illustrated in table 5.

table 5. Principles of Biomimicry

1. nature runs on sunlight	6. nature banks on diversity
2. nature uses only the energy it needs	7. nature demands local expertise
3. nature fits form to function	8. nature curbs excesses from within
4. nature recycles everything	9. nature taps the power of limits
5. nature rewards cooperation	

Biomimicry eventually leads to systems that go beyond human control [Kelly, 1995]. Kelly describes systems from the analogy of the hives mind: a single bee has little brain capacity, whereas the beehive’s community forms a “neurological web” of small processing capacities; they grow a collective mind. It enables them to collect food, search for new meadows and report them to the family, collectively migrate and create & nurture offspring; things that single bees are incapable of. Although man can develop the single bee’s cognitive capacities, they can never predict nor control the hives mind.

Where Commoner [1971] describes the “elaborate network of interconnections in the ecosphere” and the ability of humans to comprehend these networks through as what he calls “cybernetics”, biomimicry implies that these “cybernetics” can create systems beyond human control. Benyus stipulates that if we want to mimic nature, people have to accept that mankind is a part of the natural system instead of in control of it.

2.2.6. Blue Economy

“[Blue Economy] stands for a new way of designing business: using the resources available in cascading systems, where the waste of one product becomes the input to create a new cash flow. In this way, jobs are created, social capital is built and income rises – while the environment that provides the basis for our lives is no longer strained and polluted.” [Konvergenta Interzero, 2011]

The Blue Economy (BE) has its origins in the initiation of the *Zero Emission Research Initiative* by Gunter Pauli in 1994, from which the ZERI foundation was commenced. This foundation strives for finding sustainable solutions for societal problems, inspired by the principles of nature [Konvergenta Interzero, 2011]. The foundation collected 2131 promising peer-reviewed articles on natural technologies and these were evaluated on various criteria such as feasibility, intellectual property, etc. The 100 best ideas, collected in the book “The Blue Economy”, contain elements of system design, which means that instead of focussing on only one problem they aim at solving multiple issues. This shows that BE’s focus is on implementing feasible innovations and helping fundamentally change the contemporary economy to a more sustainable one, due to the added value of the projects.

ZERI [2011] identifies 5 “Kingdoms of Nature” (bacteria, algae, fungi, animals and plants), 5 design principles and 12 axioms of economics (purpose, growth, productivity, cash flow, price, quality, competitiveness, place, innovation, diversification, management and thermodynamics), which form the basis for the 21 principles of the BE illustrated in figure 1. This figure compiles all systems theories discussed in this paper.

figure 1. Principles of the seven systems theories discussed and related to Cradle to Cradle.

2.3. Discussion

figure 1 collates the principles from the seven systems theories and categorises each principle into one of the three tenets of C2C. The aim of many of the principles can be easily identified: classifying these principles needs no further discussion. However, some of them are ambiguous; this section provides rationale to enable categorisation of these principles. The paper only discusses the principles that aim to close the materials cycles.

Nature knows best – Laws of Ecology
Nature is composed of an abundance of diverse organic compounds that have been synthesised over billions of years. Man-made substances as a variant to natural ones, Commoner [1971] argues, will presumably be damaging to the environment, since these compounds do not exist in nature. This extensively refers to (material) design for the biological cycle.

Letting Nature do the work – Regenerative Design
Natural systems have been in equilibrium before the industrial revolution. Since then, mankind has been trying to overcome nature by means of artificial interference, harming the environment. However, Lyle [1994] asserts that "[o]ften the necessary services could be performed just as well by simply augmenting the already operational natural processes". Furthermore, he refers to using natural processes on location. In analogy: short distribution routes for industrial processes, limiting energy consumption. To Lyle, the key first step in Regenerative Design is inventorying the local processes and resources. This refers to integrated material flows. Moreover, the locality aspect can be arranged in the C2C-tenet "Celebrate Diversity".

Consider Nature as both model and context – Regenerative Design
Nature can serve as inspiration for designed systems as an overarching theme. It refers to interconnectedness of systems.

Seeking optimum levels for multiple functions, not the maximum or minimum for any one – RD
Lyle [1994] states that current industrial systems tend to maximise one goal, such as food production, profit, etc., neglecting other goals or concerns. This could lead to social and environmental concerns, such as highly toxic products. By balancing multiple goals, quantities will have optimal value. Therefore, this principle can be appointed to toxicity reduction measures.

Matching technology to need – Regenerative Design
This principle refers to overdesign of industrial support systems and asks for revising the technological means. Lyle [1994] exemplifies this with the change in providing human comfort in buildings. Before the 1970s, fossil fuels heated and cooled buildings; during the 1970s, however, architects began to use other measures to provide comfort, such as sunshades, insulation, controlled ventilation, etc.. In essence, this principle focuses on changing technology to become less wasteful.

Using information to replace power – Regenerative Design
Information collection and monitoring provides opportunities to design a system that suits a specific situation. This helps optimising products or processes thus minimising use of material, energy, water, etc.

Seeking optimal solutions to disparate problems – Regenerative Design
Essentially, Lyle [1994] proposes trying to connect industrial processes. By connecting processes, "problems" in separated disciplines of industrial systems can be a solution to other disciplines of industry: waste of one system can be a nutrient to the other. This refers to integrated material flows.

Shaping form to guide flow – Regenerative Design
Utilising the rules of physics, material and energy consumption can be reduced. As an example, when the air in a space heats up, it rises. Instead of cooling the air or mechanically removing it from the space with a ventilation system, releasing the hot air by opening a window near the ceiling could also suffice. The principle aims for reduction.

Dematerialisation – Industrial Ecology
Scholars on IE share different opinions on the term "dematerialisation". Many suggest a reduction of material (and energy) consumption – the so-called resource efficiency. However, some argue that the term is misleading. They rather describe dematerialisation as "transmaterialisation" [Labys & Wadell, 1988; Bruyn, 1998]: new types of materials substitute contemporary materials.

3. Cradle to Cradle versus the other systems theories

3.1. C2C: Waste equals food

In an ecosystem organisms process practically all the waste that is produced within this ecosystem, implying that in nature waste virtually does not exist. Insight into natural regenerative systems raises awareness of the opportunities of this interrelatedness for designed metabolisms [McDonough & Braungart, 2002]. Nature's effluents and food only cycle in the so-called biological metabolism; designed systems of output and input can, however, both comprise the biological and a technical metabolism. In the viewpoint of Cradle to

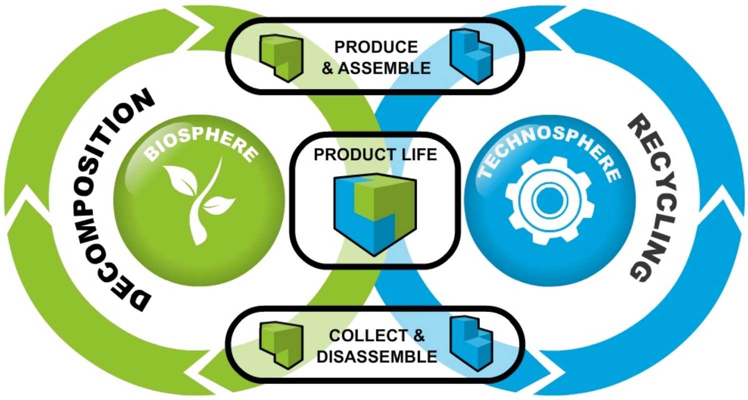

figure 2. A simple model of the biosphere and technosphere of designed systems [Güiza Caicedo, 2009]

Cradle the technical metabolism should be a continuous-loop system, which circulates high-quality synthetic and mineral resources in cycles of production, use, recovery and remanufacture. Both the biological and technical metabolism are illustrated in **Fout!Verwijzingsbron niet gevonden.** as the anthropogenic system.

In order to further this research, the first principle needs to be specified. Therefore, this paper brings its focus on continuing the material cycle and discusses three sources of criteria and principles that have been referred to by C2C scholars.

3.1.1. 12 principles of green engineering

In order to integrate eco-effectiveness in the design process, McDonough et al. [2003] refer to the 12 principles of green engineering (GE) [Anastas & Zimmerman, 2003]. The principles focus on the aspects concerned with the engineering of products. Although more of the principles of green engineering might lead to continuous cycles, McDonough et al. specifically draw a parallel between the GE principles 1, 3, 7 and 10 and the C2C principle "waste equals food", as shown in table 6. These four principles will be considered in this research.

From these four principles a collection can be derived and, in regards to continuous material cycles, recapitulated as the Condensed list of Green Engineering (CGE):

1. Non-hazardous material input and output;
2. Minimise production process' energy consumption and material use;
3. Durability as a goal;
4. Integration and interconnectivity of material flows.

table 6. Principles of Green Engineering

Principle 1 Designers need to strive to ensure that all material and energy inputs and outputs are as inherently nonhazardous as possible.	**Principle 7** Targeted durability, not immortality, should be a design goal.
Principle 2 It is better to prevent waste than to treat or clean up waste after it is formed.	**Principle 8** Design for unnecessary capacity or capability (e.g., "one size fits all") solutions should be considered a design flaw.
Principle 3 Separation and purification operations should be designed to minimise energy consumption and materials use.	**Principle 9** Material diversity in multi-component products should be minimised to promote disassembly and value retention.
Principle 4 Products, processes and systems should be designed to maximise mass, energy, space and time efficiently	**Principle 10** Design of products, processes and systems must include integration and interconnectivity with available energy and material flows.
Principle 5 Products, processes and systems should be "output pulled" rather than "input pushed" through the use of energy and materials.	**Principle 11** Products, processes and systems should be designed for performance in a commercial "afterlife".
Principle 6 Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse or beneficial disposition	**Principle 12** Material and energy inputs should be renewable rather than depleting.

3.1.2. Cradle to Cradle certification criteria

To be able to repeatedly circulate synthetics and minerals with a preserved high quality, the MBDC formulated C2C certification categories. The MBDC [2008] describes a total of five categories, which are material health, material reutilisation, water stewardship, renewable energy and social responsibility (figure 3); these categories cover all three basic principles. Each category comprises multiple clear criteria from which producers can compile a "roadmap" towards an eco-effective product. Because of the lucidity of the criteria and their quantifiability, the research continues with these categories.

However, this paper aims for continuous material cycles; therefore, it will only consider the criteria that concern materials and their cycle. From the five categories of the certification program, the categories Material Health and Material Reutilisation are taken into consideration. The basic principle of *Waste equals Food* also accompanies Water Stewardship and its concern for water quality might suggest that it is influential in closing the material cycle. However, the quality is directly linked to the effluents of production: if the materials used for fabrication and the production processes are clean and safe, the water quality will be preserved. Therefore, this study does not take this category into consideration. The last two categories of Renewable Energy and Social Responsibility accompany the second and third basic principles and can accordingly be left aside for this study. Consequently, this paper considers the categories of Material Health and Material Reutilisation. table 7 provides the criteria that go with these categories.

table 7. Cradle to Cradle criteria for Material Health and Reutilisation, adopted from [MBDC, 2008]

Material Health	Material Reutilisation
1. Material Transparency	1. Define appropriate cycle
2. Biological/Technical nutrient	2. Well-defined recovery plan
3. Ingredient characterisation	3. Actively closing the loop
4. Material avoidance	4. Nutrient reutilisation
5. Optimising strategy	
6. Optimisation of Product formulation	
7. Cradle to Cradle emission standards	
8. Percentages of "green" components	

Many criteria from both material categories cluster around the same topic; the clustered criteria form a roadmap to get to an end goal. For example, before eliminating toxic materials from a product (use non-toxic materials), information on the content of the materials needs to be defined first (material transparency) and characterised according to their toxicity: one follows the other. Similarly, the producer needs to draw up a "well-defined recovery plan" before he can start "actively closing the loop"; without product recovery the producer will never be able to close the loops.

Continuing in this line of reasoning, from the category of Material Health (MH) criteria 1 to 6 form a roadmap-to-goal, as well as criteria 1 to 4 from the category of Material Reutilisation (MR). Criteria 7 and 8 of MH are separate goals. Consequently, the criteria can be narrowed down to the topics (1) Optimising product formulation, (2) Cradle to Cradle emission standards, (3) Percentages of "green" components and (4) Actively closing the loops.

This study excludes topic 3 from the enumeration above, even though sound agriculture is essential for stopping depletion of topsoil and deforestation. Since this paper focuses on continuing material cycles, it only reviews those criteria that contribute to this goal. This third criterion tends to be situated somewhere in the area of social and environmental responsibility. To illustrate, both FSC and non-FSC wood will return to nature, assuming that it has not been permanently combined with a technical nutrient or contaminated with a toxic: nature does not judge upon any labels.

This leads to the following list of adapted certification criteria (ACC):

1. Optimising product formulation (MH 1-6);
2. Cradle to Cradle emission standards (MH 7);
3. Nutrient reutilisation (MR 1-4).

3.1.3. Cradle to Cradle criteria for the built environment

In 2010, Mulhall & Braungart [2010] composed a set of criteria, specifically focusing on the built environment. They describe C2C principle criteria and formulate implementation criteria, intending to accelerate implementation of the C2C tenets. This publication formulates four criteria around the *waste equals food* principle, corresponding to the criteria mentioned in the first column of table 8.

In addition, the implementation criteria's list provides the criterion "integrate systems and application tools" which essentially suggests that systems integration enhances a building's success. Mulhall & Braungart [2010] exemplify systems integration by enhancing air quality through combining Heating Ventilation and Air Conditioning (HVAC) systems with products that metabolise pollutants. In this way, these products (such as wall coverings) display an additional performance by cleaning the air: they have added quality. Moreover, Mulhall & Braungart describe a set of examples of what they call C2C Application Tools (AT), which aim for continuous material cycles. This collection is illustrated in table 8 as well.

table 8. C2C principle criteria and Application Tools for the built environment [Mulhall & Braungart, 2010]

Waste equals food	**Application Tools (AT)**
1. Define materials and their intended use pathways	1. Actively beneficial qualities
2. Integrate biological nutrients	2. Defined product recycling
3. Enhance air and climate quality	3. Defined use pathways
4. Enhance water quality	4. Defined use periods
	5. Design for assembly, disassembly and reverse logistics
	6. Materials pooling
	7. Preferred ingredients lists (P-lists).

In the AT list, points 2, 3, 4, 5 and 6 more specifically describe aspects of the third adapted certification criterion (ACC) in the previous paragraph. The P-lists "application tool" is closely related to the first ACC criterion, referring to composing a list of preferred ingredients for the built environment. Moreover, the first "application tool", *actively beneficial qualities,* provides an addition to the so far mentioned list of C2C criteria.

3.2. Summary of C2C criteria for specific comparison

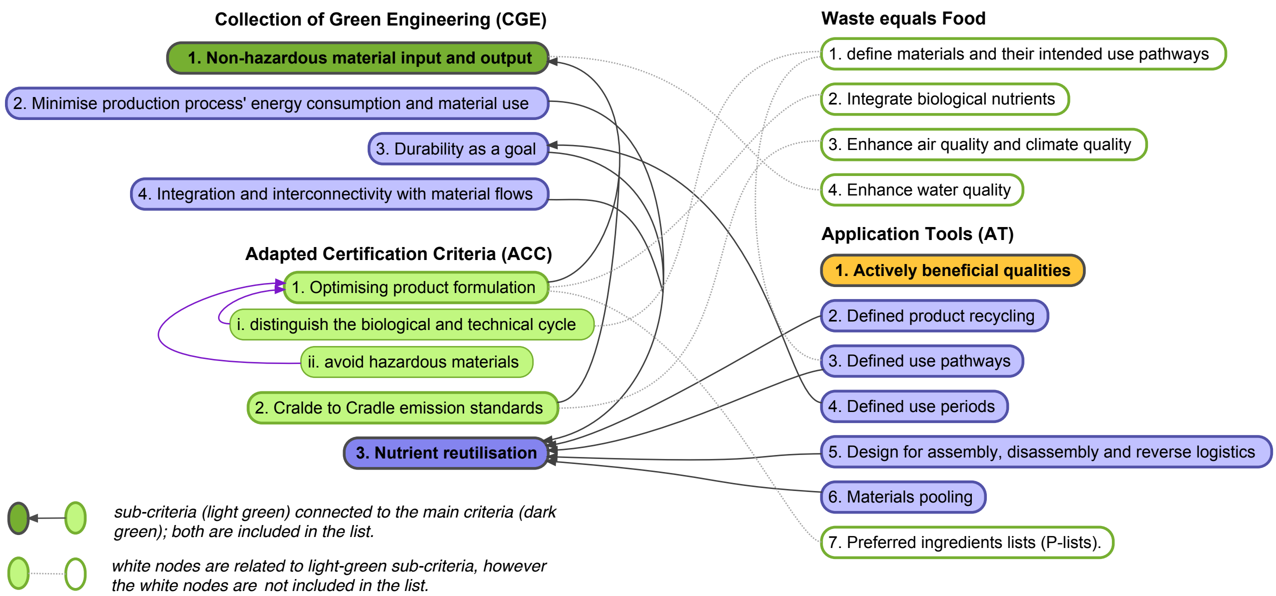

figure 3. Graphical representation of the overarching C2C criteria list

Elaborating on the previous three paragraphs, this paper combines the three criteria selections into one overarching list, which is represented in figure 3 and summarised below:

1. Non-hazardous material input and output (GE1);
    a. Optimising product formulation (MH1-6);
        i. Distinguish the biological and technical cycle (MH2);
        ii. Avoid hazardous materials (MH4);
    b. Cradle to Cradle emission standard (MH7 and GE1);

2. Nutrient reutilisation (MR1-4);
    a. Integration and interconnectivity with material flows (GE4);
    b. Defined product recycling (AT2);
    c. Defined use pathways (AT3);
    d. Durability as a goal (GE3);
        i. Defined use periods (AT4);
    e. Design for assembly, disassembly and reverse logistics (AT5);
    f. Material pooling (AT6);
    g. Minimise energy consumption and material use for production;
3. Actively beneficial qualities (AT1).

4. Comparing criteria and principles: similarities and differences

This chapter compares and categorises the systems theories' principles from chapter 2 which concentrate on continuous materials cycles (green dots in figure 1) with the abstracted criteria from the previous chapter. These principles are illustrated in figure 4, together with the Cradle to Cradle (C2C) criteria. Each principle is labelled with a number, which correspond with the numbers of the C2C criteria list in §3.2. The green tags describe the main criterion "non-hazardous material input and output" and the orange markers refer to the main criterion "nutrient reutilisation" and yellow tags to "actively beneficial activities". However, the figure also gives blue labels to three of the principles. These principles do not harmonise with the listed C2C criteria and are therefore tagged as "non-considered criteria".

As shown figure 4, the principles share considerable similarities to the C2C criteria; most of the principles are

Main (C2C) **material cycle criteria**

- non-hazardous material input and output (green)
- nutrient reutilisation (orange)
- actively beneficial activities (yellow)
- *non-considered criteria* (blue)

Laws of Ecology

everything must go somewhere	2a
nature knows best	1a

Looped Economy

product design optimized for durability, adaptability, remanufacturing and recycling	2d/e
remanufacturing that preserves the frame of a product after use, replacing only the worn-out parts	2d/e
business models based around "product leasing" as opposed to "product selling", where ownership remains with the manufacturer over the entire product life cycle, thereby encouraging product durability and improved quality approaches to product design, manufacture and maintenance	2d-NEW
extended product liability/stewardship/responsibility, encouraging manufacturers to guarantee low-pollution-use and easy-reuse products	1a/2d

Regenerative Design

letting nature do the work	2a
considering nature as both model and context	2a
seeking optimum levels of multiple functions, not the maximum or minimum for any one	OPTIMISE
matching technology to need	2g
using information to replace power	2g
seeking common solutions to disparate problems	2a
managing storage as key to sustainability	2-NEW
shaping form to guide flow	2g

Industrial Ecology

1a	reduce, and eventually eliminate, inherently dissipative uses of non-biodegradable materials, especially toxic ones (like heavy metals)
2e	design products for easier disassembly and reuse, and for reduced environmental impact, known as "design for environment" (DFE)
2b/2g	develop much more efficient technologies for recycling waste materials, so as to eliminate the need to extract "virgin" materials that only make the problems worse in time
MINIMISE	dematerialisation
1a	substitution of a scarce or hazardous material by another material
2b/2e	repair, re-use, remanufacturing and recycling
2-NEW	waste mining

Biomimicry

2b	nature recycles everything

Blue Economy

2g	substitute something wih Nothing - question any resource regarding its necessity for production
2a/-NEW	natural systems cascade nutrients, matter and energy - waste does not exist. Any by-product is the source for a new product
1a	water is the primary solvent (no complex, chemical, toxic catalysts)
1-NEW	Nature responds to basic needs and then evolves from sufficient to abundance. The present economic model relies on scarcity as a basis for production and consumption
2a	natural systems are non-linear
1a	in Nature everything is biodegradable - it is just a matter of time
2a	in Nature everything is connected and evolving towards symbiosis
OPTIMISE	Nature searches for the optimum for all involucrated elements

figure 4. Systems theories principles concentrating on closed materials cycles and main C2C criteria.

marked green or orange. The sub-criterion "optimising product formulation" corresponds to six. A noticeable difference between some systems theories is their scope of focus; for example, Looped Economy mainly focuses on durability and related aspects, while Regenerative Design clearly aims for minimising material use for production. The following section discusses the differences between the principles and the C2C criteria.

4.1. Differences

First, figure 4 clearly shows that the last C2C criterion – actively beneficial qualities – does not recur in the other systems theories. What Mulhall & Braungart [2010] imply with this application tool is that a designer should try to add extra value to its product by adding beneficial qualities. They exemplify this with the development of a new type of green roof moss that captures and metabolises fine dust – current mosses merely function as filter and fine dust runs off the roofs with rainwater. By applying such mosses on roofs the air quality of the outdoor environment increases and the fine-dust residues are metabolised instead of polluting the environment. Although the principles of Blue Economy do not discuss this aspect, Blue Economy considers innovative projects in which these added qualities occur [Pauli, 2010].

The second striking difference is that some of the other systems theories' principles could not be fitted under the umbrella of one of the C2C criteria. They are tagged blue in figure 4. What these exceptions mainly have in common is that they aim for material reduction. Although C2C asks for material minimisation in production processes – see criterion 2g –, it does not acknowledge the need to minimise material use of products, since a system according to the theory uses materials over and over again. However, due to diminishing resources and the fact that we do not live in a Cradle to Cradle society, many scholars have a different opinion and do argue for material efficiency [Allwood et al. 2011].

Regenerative Design's third principle and the Blue Economy's last principle in figure 4 aim at achieving optimum levels for multiple functions instead of maximum or minimum level for a single function of the product at the expense of all other functions. Lyle [1994] refers to the analogy of regenerative systems in nature, which "always have more than one goal, some in conflict with the other." This "product optimisation" does not occur in the C2C criteria; however, these principles show similarities with one of the statements of C2C scholars that instead of aiming for minimisation, C2C strives for optimisation [Agentschap NL, 2011b].

Furthermore, despite the great correspondence, the principles do not cover the full scope of the C2C criteria of §3.2; none of the principles cover the sub-criteria (1b) Cradle to Cradle emission standard, (2c) Defined use pathways and (2f) Material pooling. Nevertheless, most systems theories – although not emphasised in their principles – to some degree consider these aspects of closed materials cycles in the background.

Finally, five principles that consider "nutrient reutilisation" provide possible new criteria that could be added to the list for continuous materials cycles, being (1) managing storage, (2) business models based around product leasing, (3) waste mining, (4) cascade nutrients and (5) use the abundantly available materials. These sub-criteria do not contradict the ideas of the C2C theory. In fact, the C2C founding fathers have been advocating sub-criterion 2 since C2C's initiation and more recently they argued for cascading products and nutrients [Agentschap NL, 2011b] – sub-criterion 4. A remark to this fourth sub-criterion is that C2C does not propose cascading nutrients that are unfit to return to their biological or technical metabolism. It only supports cascading if the nutrient can be retrieved after cascading in a clean and effective way, resulting in the initial pure and healthy nutrient for the natural or designed cycle.

5. Conclusions

The objective of this paper has been to help further continuous material cycle for the built environment by providing an overview of current theories, concepts or strategies, in order to grow a greater understanding of the Cradle to Cradle (C2C) theory's context and its implications and opportunities. It raised the following questions: To which extent is the critique by scholars correct, who argue that C2C is old wine in new bottles? Are the other systems theories indeed similar to C2C? To which extent do they harmonise? What means can other systems theories provide that accord with C2C?

This paper discussed seven systems theories from the 1970s up until today: Laws of Ecology, Looped Economy, Regenerative Design, Industrial Ecology, Biomimicry, Cradle to Cradle and Blue Economy. It categorised their guiding principles from a C2C's perspective, according to its tenets. Furthermore, a series of C2C criteria derived from three resources was collected and analysed. From this analysis, the overarching list of C2C criteria and sub-criteria was formulated.

1. Non-hazardous material input and output (GE1);
    a. Optimising product formulation (MH1-6);
        i. Distinguish the biological and technical cycle (MH2);
        ii. Avoid hazardous materials (MH4);
    b. Cradle to Cradle emission standard (MH7 and GE1);
2. Nutrient reutilisation (MR1-4);
    a. Integration and interconnectivity with material flows (GE4);
    b. Defined product recycling (AT2);
    c. Defined use pathways (AT3);
    d. Durability as a goal (GE3);
        i. Defined use periods (AT4);
    e. Design for assembly, disassembly and reverse logistics (AT5);
    f. Material pooling (AT6);
    g. Minimise energy consumption and material use for production;
3. Actively beneficial qualities (AT1).

Consequently, the principles from the remaining six systems theories (C2C was excluded) that correspond with the C2C tenet "waste equals food" were labelled to reveal differences and similarities between C2C and established systems theories.

This paper shows that the C2C theory has a high coherence with the other systems theories in the area of non-hazardous material input and output and nutrient reutilisation. Some systems theories show a specific focus when aiming for closing materials cycles – such as Looped Economy and Regenerative Design – while for example the Blue Economy is more generic in its approach. Moreover, both C2C and the other systems theories provide sub-criteria that have not been considered in the principles or the C2C criteria. These principles provide new means that could invigorate the C2C criteria. They are (1) managing storage, (2) business models based around product leasing, (3) waste mining, (4) cascade nutrients and (5) use the abundantly available materials.

Furthermore, contradictory to the criticism that C2C received, it can be concluded that it propounds a new idea that other systems theories have not referred to: actively beneficial activities. Moreover, it addresses three sub-criteria that did not correspond with the other systems theories' principles, being (1b) Cradle to Cradle emission standard, (2c) Defined use pathways and (2f) Material pooling. However, most systems theories – although not emphasised in their principles – to some degree consider these aspects of closed materials cycles in the background.

Finally, as opposed to many scholars and current political agendas that argue for material efficiency or dematerialisation, C2C does not share this opinion, since a natural or designed system – according to the C2C theory – can use materials over and over again. It does, however, recommend energy and material minimisation for production processes. Nevertheless, since resources are diminishing and since only signs of a Cradle to Cradle society are manifesting, alternatives that limit the material squander of current times should be searched for.

By showing the coherence between C2C and other systems theories, this paper embedded C2C in the systems theories practice. Furthermore, an analysis of the systems theories resulted in new principles that could invigorate the current C2C measures to come to a continuous material cycle. Moreover, this paper strongly contributes to the C2C discussion among scholars.

Bringing these principles and (sub-)criteria into practice will be a challenge for the future, although some innovative entrepreneurs have been able to bring C2C into operation in their businesses. Nevertheless, many companies involved in the building industry find C2C quite intangible and have difficulties to put it in practice because of the complexity of building projects. Further research is needed to provide means to the building industry to translate the C2C theory for practical implementation.

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