Nature-Inspired Design

Strategies for Sustainable Product Development

Ingrid de Pauw

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Strategies for Sustainable Product Development

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PREFACE

Children love to play, and in our prosperous society, there's an abundance of toys around. There is a particular toy I like a lot, even though it is disposable. It is especially valued by younger children who, given the opportunity, will try to get their hands on as many as possible. Like Easter eggs and chocolate letters, they're only available part of the year, which probably contributes to their success. But in addition to their effectiveness, they are a great example of sustainable design; made of 100% renewable materials, using water-based processes, without toxic additives, and produced using solar energy only. This toy, the Blowball (or Blaasbloem in Dutch), has no adverse sustainability impacts whatsoever, something which in our field is usually thought of as being impossible to achieve. Moreover, the use of this toy even seems to have a beneficial impact in sustaining a specific species of flowers, the dandelion. In turn, the dandelion contributes to the ecosystem of which it is part, with its flowers providing nectar and pollen for bees early in the season. And finally, after its blooming phase, the dandelion evolves into something new, a wonderful children's toy.

This thesis is about Nature-Inspired Design Strategies; strategies that are based on implementing knowledge from nature into the field of sustainable product design. By exploring the effects of their application in product design projects, I aim to contribute to the further development of sustainable design strategies, and thereby to the development of products as intelligent as the Blowball[1].

[1] In the remainder of this thesis, I will use 'we' instead of 'I' when describing specific research activities. Although the thesis is the result of my work, my supervisors and others have helped me throughout the study to achieve this result. The 'we' thus refers to the research team. Specific contributions are included in the Acknowledgements.

SUMMARY

Product designers can apply different strategies, methods, and tools for sustainable product development. Nature-Inspired Design Strategies (NIDS) offer designers a distinct class of strategies that use 'nature' as a guiding source of knowledge and inspiration for addressing sustainability. Biomimicry and Cradle to Cradle, two NIDS, are already being applied in product development practice and have been integrated in the curricula of higher education. However, little research has been conducted on *how* NIDS are applied and how they actually help designers with sustainable product development. Consequently, these design strategies are not supported by an empirical understanding of their applicability, benefits, and limitations. To facilitate the effective application of NIDS for sustainable product development, a first step is to explore and understand the current NIDS design practice. Accordingly, the main research question of this thesis is:

> **How do Nature-Inspired Design Strategies (NIDS) help designers in developing 'sustainable products'?**

To answer the research question, a multiple case study approach was adopted, analysing NIDS-projects to reveal how the application of the design strategies affected the design process and its outcomes. First, a comparative study was performed using student design projects, to explore which effects could be attributed to the application of NIDS. The results were used in the subsequent study of four 'real-life' design cases. Based on the analysis of in-depth interviews and project documentation, this second study generated a thorough understanding of the effects of applying NIDS in design practice.

The first three chapters of the thesis describe the research leading up to the case studies. In **Chapter 1**, we first frame the wider context of sustainable design thinking within which

NIDS have been developed. We argue that NIDS support a changing perspective towards the aim of sustainable design which has been described as a move from 'reducing unsustainability' towards 'achieving sustainability'. Both Biomimicry and Cradle to Cradle build on this perspective of achieving sustainability and share key characteristics. In **Chapter 2** we define the term Nature-Inspired Design Strategies (NIDS) as design strategies that "base a significant proportion of their theory on 'learning from nature' and regard nature as the paradigm of sustainability". Following the definition, we analyse which design strategies can be classified as NIDS and what these strategies offer for product design, resulting in the selection of Biomimicry and Cradle to Cradle as suitable NIDS for case study research.

To be able to assess how NIDS help designers in developing 'sustainable products', we evaluate the sustainability of the case-study designs. However, as described in **Chapter 3,** current life-cycle based assessment methods are not geared towards capturing some of the main results that NIDS strive to accomplish. Consequently, for the purposes of this study, we developed an adapted method, presented in Chapter 3, which evaluates the extent to which a product (bene)fits a sustainable environment, using assessment criteria for (environmental) sustainability.

In **Chapter 4**, we describe the case study findings from the student design projects. We compared Biomimicry and Cradle to Cradle with a more established design strategy (Ecodesign) and elicited differences specific to the application of NIDS. The results from these case-studies show how the application of different design strategies coincides with differences in a) the design focus of the student groups, b) the level at which the design assignment was interpreted, and c) the resulting solution levels. NIDS helped the design students to broaden their solution space and to include designs that provided alternative ways for fulfilling product functions, system functions, and user needs. The analysis highlighted two distinct features of NIDS contributing to these findings. Both Biomimicry and Cradle to Cradle offer challenging 'absolute' design principles for guiding the design process, and both strategies trigger the integration of context-specific solutions that reach beyond the design of the product, for instance solutions that include a recycling infrastructure coupled to specific local companies. In addition, the study showed that the student groups did not apply all steps offered by the design strategies, which may have led to partial implementation of the design philosophy on which the strategies are based. In the case of NIDS, this finding is particularly relevant, as Biomimicry and Cradle to Cradle currently lack quantitative design tools for evaluating the environmental impact of the designs, when compared to Ecodesign.

Chapter 5 presents the results from the case-studies of real-life projects. These cases confirm that application-level is an important variable to consider: designers have their 'own way' of applying the design principles, methods, and tools that NIDS offer and do not apply all of the strategy elements. However, the design principles they applied activated the designers to set ambitious targets and to adopt a 'systems approach'. In each of the four real life cases, the designer/design teams engaged in designing parts of the 'material cycle'. These results were achieved by cooperating with suppliers, by selecting different materials or even developing new material combinations, and in some cases by implementing functional innovations that eliminated materials containing potentially harmful ingredients for which no cycle could be established.

In **Chapter 6**, we evaluate the outcomes of the real-life cases using the assessment method and criteria for environmental sustainability developed in Chapter 3. The assessment shows that NIDS helped designers meet specific sustainability criteria on the level of product components and, to a limited extent, achieve beneficial impacts. The designers thus achieved more than a reduction of environmental impacts for specific components. These results indicate that, in principle, NIDS are capable of helping designers to 'achieve' one or more criteria for environmental sustainability, especially with respect to establishing material loops. However, at a product level, none of the case study projects succeeded in meeting all criteria; the designers focused on specific principles at the expense of others. This poses the risk that the solutions, while realising break-through solutions in terms of specific issues such as cycling of resources, may generate increased environmental impacts within the current system in which they are produced, used, and cycled.

Chapter 7 presents the main conclusions from the study. They capture the understanding of NIDS we generated from this study, which we summarize here:

- Nature-Inspired Design Strategies offer a design philosophy for integrating environmental sustainability in product development, building on the perspective of 'achieving sustainability'. This perspective challenges designers to develop products that, like their natural counterparts, fit within and even benefit the 'ecosystem' of which they are part.
- At an operational level, Biomimicry and Cradle to Cradle provide design principles and tools conveying ecosystem knowledge for implementing this philosophy within the design process. This study illustrates how the principles helped designers to set ambition levels and to guide the design process.

- The cases included in this study show that NIDS helped designers to achieve solutions that include more than the design of the product (the artefact), thereby tackling hurdles for realising environmental sustainability, especially concerning the cycling of resources.
- However, NIDS offer no tools that help designers to pinpoint potentially adverse impacts of their designs across the product life cycle. The study demonstrated how the partial application of NIDS by designers can lead to such impacts.

This PhD study has generated several propositions for the way in which NIDS affect the design process and its outcomes, thereby providing starting points for follow-up research. Furthermore, the findings gave rise to recommendations for the development of tools that can remove current obstacles in the application of NIDS. The thesis ends with the author's recommendations for designers who are currently putting NIDS into practice, and for the educators who are encouraging the next generation of designers to learn from and be inspired by nature.

CHAPTER 1

Introduction

This chapter frames the context of Nature-Inspired Design and presents the outline of the research described in this thesis. Nature-inspired Design Strategies have been developed within a wider context of sustainable design thinking, and fit a changed perspective on how to address sustainability in product design. In this chapter, we frame this context (section 1.1), and show how we have developed the research questions and scope of the study (section 1.2). Next, we describe the research design that is used for answering the research questions (section 1.3). The chapter ends with an outline of the thesis (section 1.4).

Chapter 1 and 2 are based on: DE PAUW, I., KANDACHAR, P., KARANA, E., PECK, D. & WEVER, R. 2010. Nature inspired design: Strategies towards sustainability. In: WEVER, R., QUIST, J., TUKKER, A., WOUDSTRA, J., BOONS, F. & BEUTE, N., eds. 2010 ERSCP-EMSU conference, October 25-29 2010 Delft. 1-21.

1.1 A changing perspective within Sustainable Product Design

The potential role of designers in addressing sustainability and the contributions they could make in creating a sustainable world have long been recognized (Ehrenfeld, 2008, Manzini, 2009, Margolin, 1998, Papanek, 1971, Rahimifard and Clegg, 2008). The field of practice that integrates sustainability within product design is referred to as sustainable product design or design for sustainability, and has been characterised as "balancing economic, environmental and social aspects in the creation of products and services" (Charter and Tischner, 2001, p.121)[1]. In the literature, several studies have considered how product design can contribute to sustainability in line with the well-known concept of sustainable development[2] (e.g. Bakker, 1995, Brezet et al., 1997, Dewberry, 1996, Hallstedt, 2008). At the same time, part of the design community have started to include sustainability criteria within their work, with a focus on the environmental aspects of sustainability (Charter and Tischner, 2001, Dewberry and de Barros, 2009).

The focus on environmental sustainability originates from the historical development of sustainable product design, which evolved from approaches for reducing the environmental impacts of products throughout their life cycle, including Ecodesign, Design for Environment, and Life Cycle Design (e.g. Alting, 1995, Brezet et al., 1997, Dewberry, 1996). The rationale for addressing environmental aspects stems from the realisation that humans are responsible for changing ecosystems, to meet their demands, in ways that are not sustainable. According to the Millennium Ecosystem Assessment:

> *"The changes [...] have contributed to substantial net gains in human well-being and economic development, but [...] at growing costs in the form of the degradation of many ecosystem services, increased risks of nonlinear changes, and the exacerbation of poverty for some groups of people. These problems, unless addressed, will substantially diminish the benefits that future generations obtain from ecosystems" (2005, p.5)*

This context clarifies the dominant position of environmental sustainability within current approaches for sustainable product design.

To integrate sustainability in the design process, eco-efficiency is widely applied as a strategy for addressing environmental aspects. The aim of eco-efficiency, "creating more goods and services with ever less use of resources, waste, and pollution" (WBCSD, 2000, p.1), endorses the perspective that 'reducing the impacts of products' is the way to approach (environmental) sustainability. Nevertheless, as we elaborate on further in this section, several sustainability and design thinkers have questioned this perspective and put forward an alternative point of view on how to address sustainability in product design.

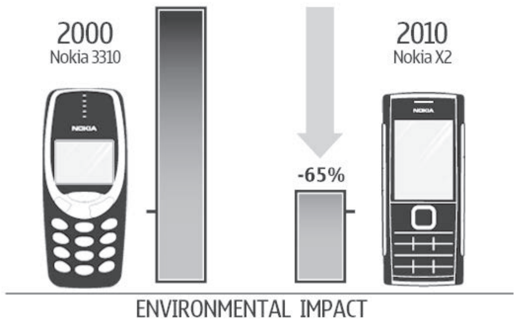


Figure 1.1: Example of eco-efficiency (Nokia 2013)

The application of eco-efficiency has led to great improvements in environmental product performance. The example shown in Figure 1.1 illustrates the gains that can be achieved when redesigning a product with 'the environment in mind' (Nokia 2013). However, despite the success eco-efficiency can have at a product level, the improvements have not resulted in an overall decrease of environmental impacts: many have not been reduced; some have even increased. Causes for this increase in impacts include the growing population, the growing number of (smaller) households, as well as increased affluence, resulting in increased sales volumes that outweigh the reductions achieved at product-level (Dietz et al., 2007, Ehrlich and Holdren, 1971, Kandachar, 2012). Additionally, the design of a product can cause unintentional increases in impact. A well-known type of unintended effects in energy-consuming products is referred to as the 'rebound effect'[3]. This effect occurs when an increase in product efficiency, which is expected to reduce the impact of the product throughout its life cycle, has the unintended consequence of increasing product consumption. This increase in consumption may reduce or even undo the anticipated impact reduction (Herring and Roy, 2007). To illustrate this effect, Figure 1.2 shows an example of the energy consumption of electric lamps for public lighting in the UK. While the energy consumption of these electric lamps (in Watt/lumen, light-grey line) shows a declining trend, overall energy consumption for public lighting has not decreased, but has increased instead (dark-grey line), due to the increase in overall illumination levels (in lumen/km, middle-grey line).

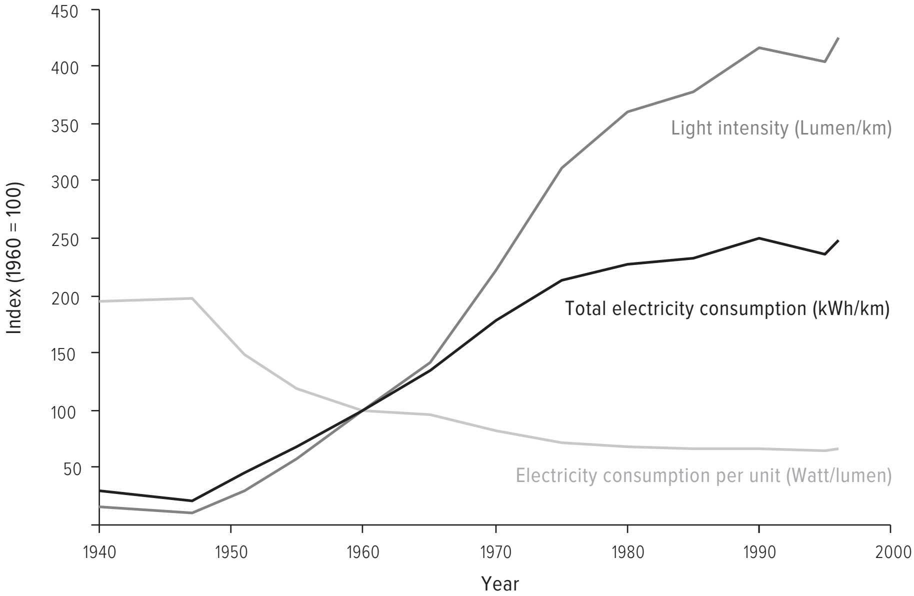


Figure 1.2: Development in energy consumption for public lighting in the United Kingdom, based on Herring (1999)

Overall, the need for more drastic efforts to achieve sustainability is increasing. The WWF, in their Living Planet reports, have tried to quantify the degree to which humanity 'consumes' the planet's living resources, using an ecological footprint methodology. Their analysis shows the world demand for these resources is progressively increasing beyond the planet's regenerative capacity (Figure 1.3) and according to WWF "the resulting [effects] are putting the well-being and development of all nations at increasing risk" (2008, p.2).

Different approaches have been proposed to address the increasing overall environmental impacts within the field of product design. Building on eco-efficiency, 'factor-thinking' approaches pursue drastic efficiency improvements of factor 4, 10, or even 20 (Jansen et al., 1997, Schmidt-Bleek, 1993, von Weizsäcker et al., 1998). The aim of these improvements is to reduce overall environmental impacts by a factor 2, whilst increasing prosperity by a factor 2-5 (the latter including a 'fair' distribution of prosperity worldwide), and taking into account that the world population will increase by a factor 2[4]. To achieve these drastic efficiency gains, design approaches have been suggested and developed to aid designers in new product development, and in the development of entirely new 'product service systems' that focus on fulfilling customer demands (e.g. Crul and Diehl, 2009, Goedkoop, 1999, Manzini, 1995, Manzini and Vezzoli, 2002, McAloone and Andreasen, 2002).

However, several thinkers in the field have argued that eco-efficiency design has a fundamental flaw, as it is founded on the perspective of 'reducing unsustainability' (Braungart et al., 2007, Ehrenfeld, 2008, Gladwin et al., 1995, Manzini, 1994). Manzini observed that 're-designing what exists' results in systems that are 'less polluting' than present systems and that redesigning will not help designers in discovering truly sustainable solutions (1994). More recently, Ehrenfeld emphasized that "...reducing unsustainability, although critical, does not and will not create sustainability" (2008, p.7). Both Ehrenfeld (ibid) and Braungart, McDonough et al. (2007) go even further by stating that an eco-efficiency strategy may even have adverse effects if the underlying problems are not addressed. To support designers in thinking beyond efficiency, they propose a shift in the aim of design - a changing perspective- that can be described as moving from 'reducing unsustainability' towards 'achieving sustainability'.

Views differ on which strategy product designers should pursue for 'achieving sustainability'. 'Transformational' design strategies have been proposed for bringing about social change, or for transforming behaviour and mind-sets of designers (Manzini 2009, Ehrenfeld 2001, 2008). Conversely, 'nature-inspired' design strategies that take nature as a model for developing products and systems have also been suggested

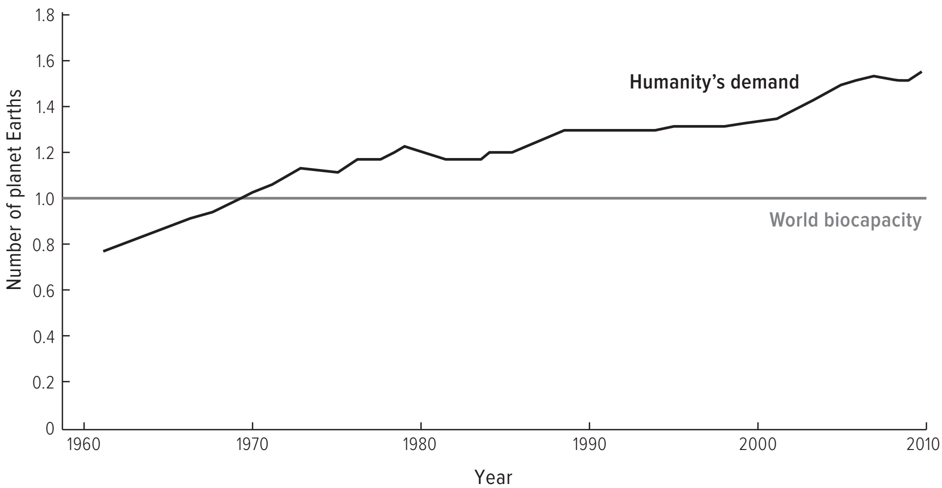


Figure 1.3: Humanity's demand on the planet's living resources (WWF 2014)

(Benyus, 1997, McDonough and Braungart, 2002). Despite the apparent differences in the suggested strategies, they promote the same change in perspective within sustainable product design. How the aim for 'achieving sustainability' may shape the design profession and the outputs of its work remains largely unknown, as many of the strategies have yet to be implemented in design practice.

1.2 Research questions and research scope

Two design strategies -Biomimicry and Cradle to Cradle[5]- have already been developed and applied in design practice within commercial business settings (Chapter 2). These strategies, which we designate in this thesis as Nature-Inspired Design Strategies (NIDS), have generated interesting results in terms of 'achieving sustainability', such as designs that are free of harmful substances, designers that seek to 'design out waste', and companies that have re-formulated their company mission to reflect this perspective. Furthermore, designers are being trained, on a small scale, in Biomimicry and Cradle to Cradle, and a number of design and engineering schools have introduced these strategies in their curriculum. The uptake of NIDS in design practice and education indicates that they meet a specific need for design support. However, few studies have analysed the application of NIDS for product development: there is a lack of research on *how* these design strategies are used and *how* they actually help product designers in 'achieving sustainability'. Consequently, designers and design educators would benefit from well-founded knowledge on the specific merits and limitations of this class of design strategies.

To facilitate the effective application of NIDS for sustainable product development, a first step is to explore and understand the current design practice of NIDS. The purpose of this study is to provide a critical understanding of the application of NIDS within sustainable product development. Accordingly, the main research question of this study is:

> **How do Nature-Inspired Design Strategies (NIDS) help designers in developing 'sustainable products'?**

As described in the previous section, the general understanding of the term 'sustainable product design' has become synonymous with reducing adverse sustainability impacts. To include the perspective of 'achieving sustainability' in the definition, we define sustainable product design as *design aimed at the development of products that are beneficial to people, planet and profit.* Consequently, 'sustainable products' can only be considered as such when they are beneficial to people, planet, and profit.

To be able to answer the main research question, the following four sub-questions have been formulated:

RQ 1. Which Nature-Inspired Design Strategies and which elements within these design strategies, are being applied in sustainable product development?

This thesis introduces and defines the term Nature-Inspired Design Strategies (NIDS). In our literature study, we analyse the NIDS that are currently available for sustainable product development, and specify the elements they offer to designers, including methods and tools. This analysis led to a selection of Nature-Inspired Design Strategies to be included in the research.

RQ 2. What are the criteria for assessing the sustainability of Nature-Inspired Design?

Based on our literature study, a set of criteria has been developed to be able to assess whether and how NIDS contribute to the realisation of sustainable products. These criteria focus on the extent to which NIDS help designers in the development of products that contribute to ‘achieving sustainability’. Answering research question 2 enables us to operationalise what is considered a ‘sustainable product’ in this thesis. The assessment criteria are used in the following research activities to answer RQ4.

RQ 3. What are the effects of applying NIDS on the design process and design outcomes?

To understand how NIDS affect sustainability, we need to first understand the effects that NIDS have on the design process and on the design outcomes. Two main studies, each consisting of multiple cases, were conducted to explore the effects of NIDS in design practice:

a) To obtain insights into which effects may be attributed to the application of NIDS, we analysed the use of NIDS in *student design projects*. Two case studies are included that analysed the results of student work from three consecutive courses at Delft University of Technology, in which students designed a product using either a Nature-Inspired Design Strategy, or a more conventional Ecodesign strategy. The differences in effects when applying different design strategies enable the identification of effects that are specific to NIDS.

b) For gaining in-depth insights into the effects that occur in design practice, four case studies were conducted of *real-life (longer-term) projects* in which product designers applied a Nature-Inspired Design Strategy for sustainable product development.

RQ 4. In view of the assessment criteria (RQ2), what are the effects of applying NIDS on the sustainability of the designs?

In each study, the measures that affect the sustainability of the designs were analysed to provide insights into the effects that the application of NIDS has had on the outcomes of the design process. Furthermore, the results of the real-life cases were assessed using the criteria for sustainable product development (RQ2). The results are linked to the effects that resulted from the application of NIDS (RQ3) to show whether, and to what extent, the NIDS helped the development of sustainable products, and to reveal how the individual design strategies differ from each other.

The scope of this PhD research is the application of NIDS within product development, with a focus on product design activities. Numerous models have been developed to represent the product development process and the product innovation process of which it is part (for instance Cross, 2000, Pahl and Beitz, 2013, Roozenburg and Eekels, 1995, Ulrich and Eppinger, 2012). The model of Roozenburg and Eekels (1995), which is being taught at Delft University of Technology, specifically describes how product development and design are embedded within the overall product innovation process, and is therefore shown here to illustrate the scope and focus of the study (Figure 1.4). Within this model, *product development* refers to all activities from generating an idea for a new business activity, up to the development of the product design, the production plan, and the marketing plan (Roozenburg and Eekels, 1995). *Product design*[6] is that part of the product development process where the new business idea is transformed into a detailed product design. For the remainder of this thesis, the terms product design and product development are used interchangeably to refer to activities performed by product designers. In turn, a *product designer* is defined as a person qualified to execute product design and product development activities. Novice designers who are being trained to become product designers (i.e. students) are also included in the study. For the remainder of this thesis, we will use the term *designers* to refer to the target group described here.

Within a product development project, many factors can determine the extent to which a design strategy helps, or hinders, designers achieve a specific goal. Strategies provide the general plan of action for a project and the tactics (i.e. design methods) for reaching the design goal (Cross, 2000). In design literature, different factors have been described that influence the adoption and usability of design methods and tools, including: type of content provided, presentation style and format, time requirements, and accessibility (Byggeth and Hochschorner, 2006, Daalhuizen, 2014, Hornbuckle, 2010, Lofthouse, 2006). In this thesis, those factors that influence the sustainability measures taken by designers are of key importance. Consequently, we anticipate the content provided by NIDS to be most relevant.

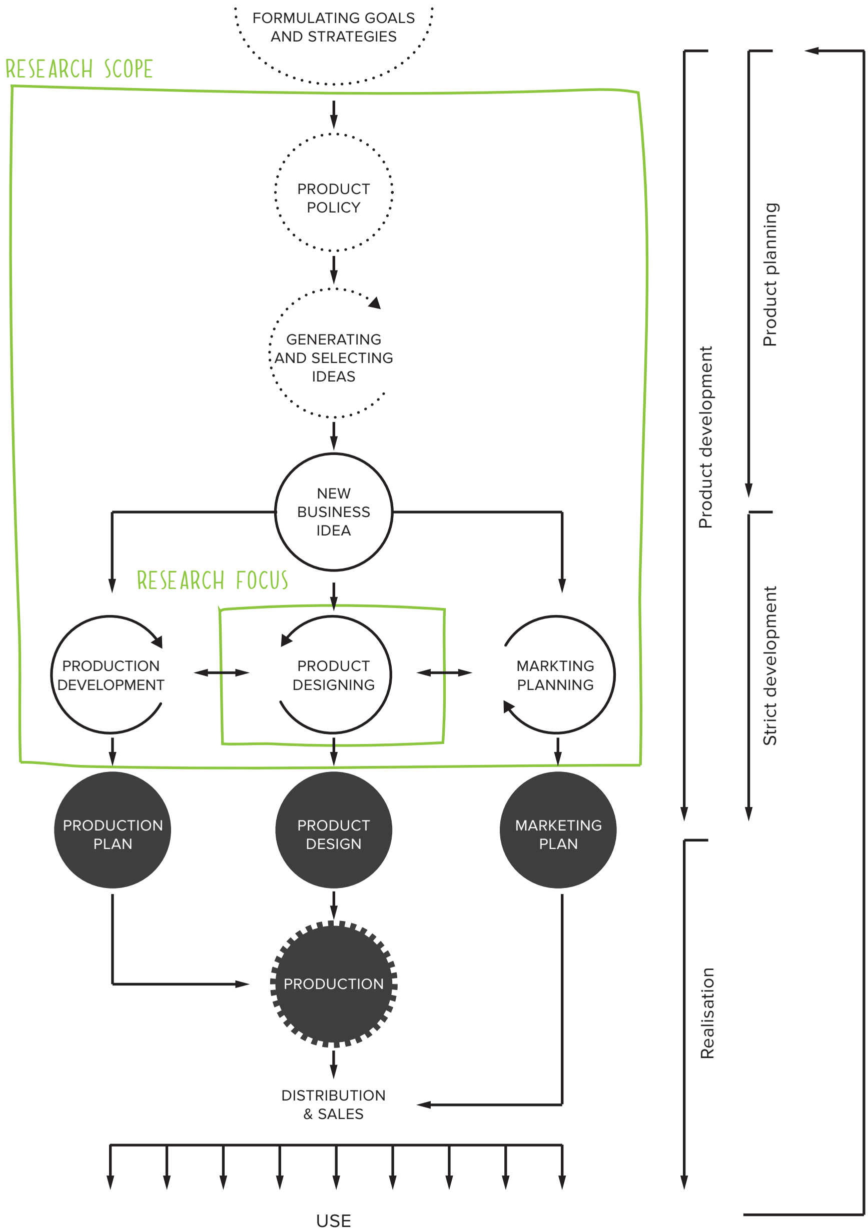


Figure 1.4: Scope and focus of the study within the product innovation process, after the model of Roozenburg and Eekels (1995, van Boeijen, Daalhuizen et al. 2013)

1.3 Research design

Based on the research questions and scope, we developed a research design for the study. This section describes why a practice-based approach was adopted, and why an exploratory, multiple case-study research was used to investigate the application of NIDS.

A practice-based approach

The PhD-project started from the observation that alternative design strategies for sustainable product development have emerged in design practice that seem different to strategies commonly used for that purpose. Both the Delft University of Technology and the author had developed an interest in this contemporary phenomenon, with the (instrumental) aim of discovering what these strategies may bring for design practice.

The study into different NIDS, as described in Chapter 2, shows that in-depth knowledge into the application of NIDS for sustainable product development could be obtained from design practice. A growing number of projects in which either Biomimicry or Cradle to Cradle have been applied, are available for study purposes. Being an inquiry *of* design practice *for* design practice, this project has a practice-based approach (Verschuren et al., 2009).

Multiple case-study research

Case study research aims to provide a thorough understanding of research phenomena in order to answer 'how' or 'why' questions (Yin, 2009). The main question of this project is a 'how'-question formulated as: "How do Nature-Inspired Design Strategies help designers in developing sustainable products?" The greatest advantage of case study research is its specific suitability for understanding 'rich' phenomena in which the real-life context is important, allowing for the exploration of relationships and processes within a realistic setting (Thomas, 2011, ibid). Applying NIDS will affect the design process, with outcomes that are anticipated to have multiple, and possibly interconnected features. Furthermore, the context in which the design project takes place is expected to be relevant to the findings. Consequently, the study fits the characteristics of case-study research.

As stated earlier in this section, design practice can provide empirical data on the application of NIDS, currently still limited in terms of the number of cases, but rich in nature. In this situation, case study research is suited to generating and analysing data. Furthermore, with the availability of existing cases, case study research was preferred above action research (in which the researcher also initiates and executes cases) as it allows the researcher to spend more time analysing cases.

We recognise that case study research allows no generalization of the results towards a population, but 'only' allows the development of an understanding, described by Yin as 'generalisation to theory' (2009, p.38)[7]. In other words, the results from this study are used to develop propositions, an understanding, of *how* Nature-Inspired Design Strategies have helped designers in developing sustainable products, and will not be used to generalize how NIDS will help (any) designer that applies them. The findings are specific to the cases, and only by gaining converging results from multiple cases and perspectives, will we be able to develop a rich, generalizable, understanding of the research phenomenon. This research is exploratory in nature: no specific findings are anticipated, no causal relationships have been proposed in literature. Therefore, the exploration has to identify key issues and variables. Exploratory case studies are suggested when little preliminary knowledge is available on the phenomenon (Thomas, 2011), or when the researcher anticipates "no clear, single set of outcomes" (Yin, 2009, p.20). A multiple-case study design was selected to allow comparison of the empirical data across different projects, which offers analytical benefits from case replication. As described in the previous section, the research design includes two main studies, each consisting of multiple cases. This allows for theory building throughout the research and for cross-case analysis.

Basic elements key to the research approach to enhance the study quality include: purposeful sampling of cases, systematic data collection, and clear data analysis procedures. Within each case, multiple sources of data are included, and for the real-life cases the approach integrates a process of member checking (Baxter and Jack, 2008) in which the results are discussed with the key informants for validation, and to allow the addition of perspectives. Details on the research set-up for each particular study are provided in the consecutive chapters.

1.4 Thesis outline

The basic outline of this thesis is presented in Figure 1.5. The first chapters provide background information on NIDS and how they will be analysed: Chapter 2 explores NIDS, and determines which of these design strategies are used in sustainable product development (to answer RQ1). Chapter 3 describes the development of the criteria by which the results of the design projects will be assessed (RQ2). These criteria determine the contribution that NIDS have for sustainable product development.

Chapters 4 to 6 describe the results from the empirical studies (to answer RQ3 and 4). Chapter 4 describes and analyses the effects of using NIDS in student design projects (RQ3a); Chapter 5 the effects that occur during real-life projects (RQ3b). In Chapter 6, the effects of applying NIDS are analysed by assessing the designs from the real-life cases against the criteria for sustainable product development, in order to answer the last research question (RQ4).

Chapter 7 presents the discussion and conclusions generated by the study, thereby answering the main research question. Furthermore, this final chapter provides an outlook of the implications this research can have for integrating NIDS in design practice.

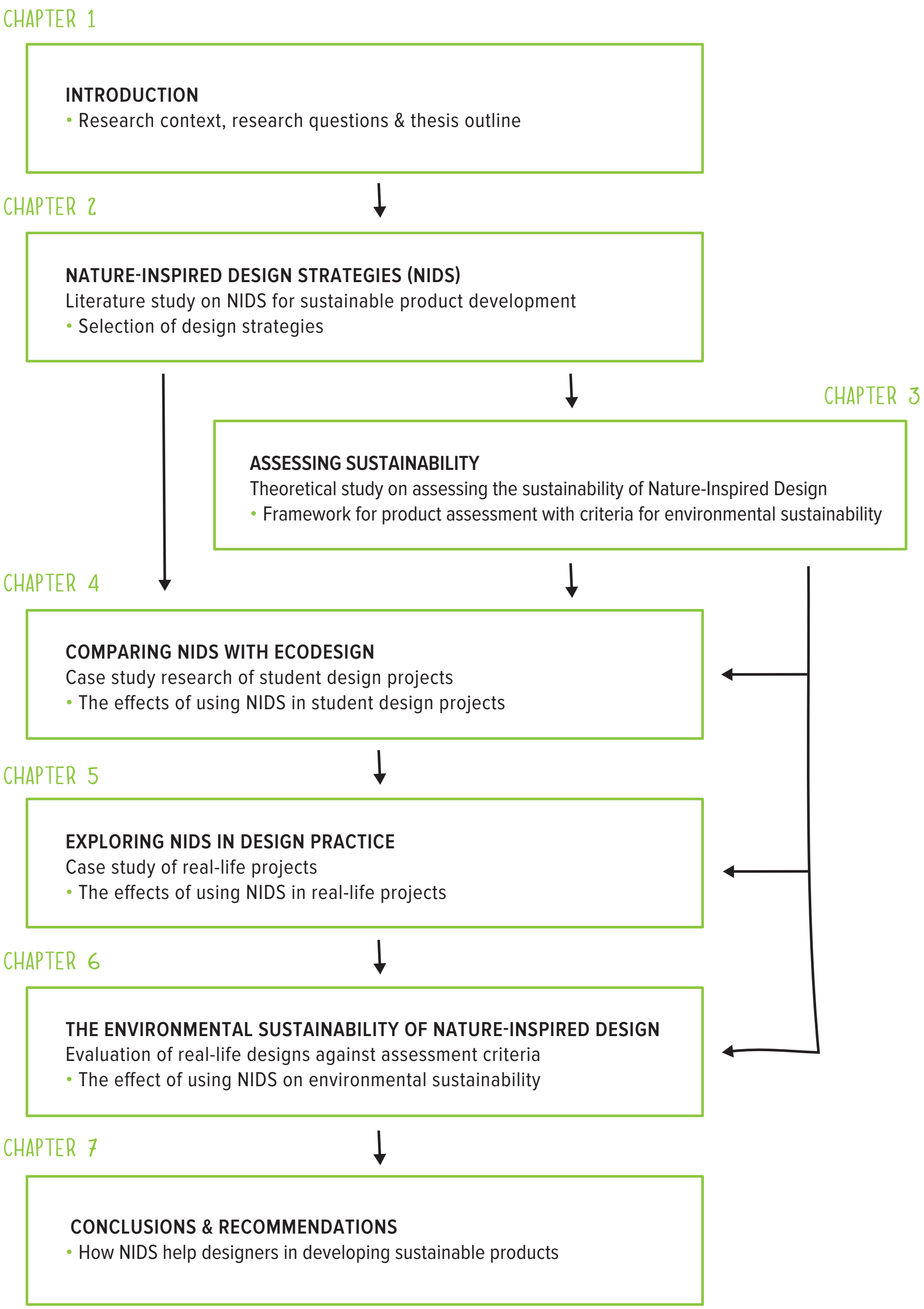


Figure 1.5: Thesis outline

1 This definition links to the 'triple bottom line' concept for sustainable business introduced by Elkington in 1994, in which companies consider value creation across three bottom lines: social value (people), environmental value (planet) and financial value (profit) (Elkington, 1997).

2 Introduced by the World Commission on Environment and Development (WCED, 1987). See also Appendix 1 for a glossary of main terms and their definitions as used in this thesis.

3 The example presented here illustrates the existence and potential impact of unintentional effects. The size of the rebound effect, and the resulting implications for energy-efficiency policies is subject of continuing debate, see for example (Gillingham et al., 2013), versus (Frondel and Vance, 2013).

4 See for instance Crul and Diehl (2009) and Reijnders (1998) for a discussion on factor thinking.

5 Cradle to Cradle® and C2C® are registered trademarks held by EPEA Internationale Umweltforschung GmbH (EPEA) and McDonough Braungart Design Chemistry, LLC.

6 In the overview of product development activities by Roozenburg and Eekels, shown in Figure 1.4, product design is referred to as product designing to distinguish the activity from the outcome.

7 However, as described by Flyvbjerg (2006) case study results, even from single cases, can be generalised when the study deals with 'falsification'.

CHAPTER 2

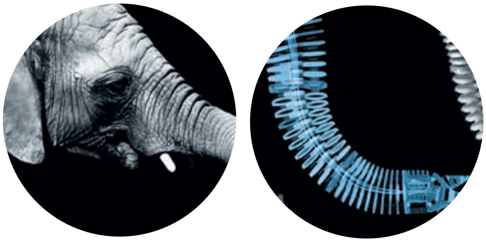
Nature-Inspired Design Strategies

As described in the Introduction, the goal of this research project is to explore how Nature-Inspired Design Strategies (NIDS) help designers in developing 'sustainable products'. Chapter 2 first delineates the concept of NIDS and identifies the specific design strategies included in this PhD study.

In section 2.1, the specific characteristics of NIDS are explored, resulting in a definition for this class of strategies. Using this definition, currently available strategies for sustainable product design are analysed to determine which of the strategies can be classified as NIDS. In the following sections, three NIDS are introduced and analysed: Biomimicry (section 2.2), Cradle to Cradle (section 2.3), and Natural Capitalism (section 2.4). The chapter ends with the conclusion that two NIDS, Biomimicry and Cradle to Cradle, are at the forefront of nature-inspired design, are already being applied in design practice, and sufficiently well developed in terms of principles, methods, tools and expertise available to this research. Consequently, both Biomimicry and Cradle to Cradle will be explored throughout the remainder of this thesis (section 2.5).

Chapter 1 and 2 are based on: DE PAUW, I., KANDACHAR, P., KARANA, E., PECK, D. & WEVER, R. 2010. Nature inspired design: Strategies towards sustainability. In: WEVER, R., QUIST, J., TUKKER, A., WOUDSTRA, J., BOONS, F. & BEUTE, N., eds. 2010 ERSCP-EMSU conference, October 25-29 2010 Delft. 1-21.

Bionic handling assistant
by Festo, 2010



Hydrofoil by
Colani, 1973

Shady Lace by Chris
Kabel, 2004

Burr and the product it inspired,
Velcro by de Mestra, 1955

Public light by
Innolumis, 2008

Go chair by
Lovegrove, 1998

Lily impeller for mixing fluids by
PAX Scientific, 1996

Figure 2.1: impression of nature-inspired products

2.1 What are 'Nature-Inspired Design Strategies'?

Throughout history, many designers have taken inspiration from the natural world to create new products, new forms, and innovative technical solutions. In the field of sustainable product development, natural forms such as trees or bone structures have inspired the development of material efficient solutions, and 3-dimensional logarithmic spiral shapes, as found in water flows, water lilies and shells, have been applied to render products more energy efficient (Harman, 2013, Mattheck, 1990, Pax Water Technologies, 2011). While these solutions may reduce environmental impacts, a 'nature-inspired' design process does not render products that are more sustainable than conventional designs by default. Products that mimic the natural form of an organism can still contain materials that cause adverse environmental impacts, or be used in a way that may increase overall energy consumption.

The degree to which designers implement lessons from nature varies from simple, sometimes superficial analogies, to in-depth studies into the emulation of natural forms, processes, and systems (among many others e.g. Buijs et al., 2009, Colani, 2015, Festo, 2012, Jin et al., 2009, Kabel, 2004, Lovegrove, 1998, World Intellectual Property Organisation, 2014). To allow systematic implementation of this knowledge into the design process, dedicated design strategies have been proposed and applied in design practice. Throughout this study, we have seen these strategies evolving, with more extensive information and tools becoming available to designers. The design strategies we include in this thesis specifically address *sustainable product design* and are based, in one way or another, on 'learning from nature': using design principles from nature to develop sustainable solutions. We have introduced the term 'Nature-Inspired Design Strategies' (NIDS) to describe this class of design strategies, with the following definition:

> *Nature-Inspired Design Strategies are design strategies that base a significant proportion of their theory on 'learning from nature' and regard nature as the paradigm of sustainability.*

This definition distinguishes NIDS from Ecodesign and many other strategies for sustainable design, which we elaborate on in the following chapters. In order to include all the relevant design strategies in the study, we first analysed which of the design strategies that are currently available to sustainable product designers can be classified as NIDS. The analysis is based on a comprehensive list of 30 sustainability approaches compiled in 2009 by AIGA[1]. This list consists of 'the major sustainability visions, manifestos, principles, frameworks, and tools that have been developed over the past 50 years and that are relevant to design' (Brink et al., 2009). Not all of the approaches in the list constitute design strategies. However, a vision or tool that bases a significant proportion of its theory on 'learning from nature' can point to the existence of a related Nature-Inspired Design Strategy, and has therefore been included in the selection procedure.

The following criteria have been applied as consecutive filters for the selection: (1) the approach refers explicitly to nature; (2) the approach refers to the use of 'nature' in the design process, that is, it explicitly couples the use of 'nature' to the design process as a source of inspiration, of design principles, tools and/or methods for product development; (3) the approach has been applied for sustainable product development, which excludes approaches only used in other design fields such as architecture, graphic or fashion design. Figure 2.2 lists the sustainable design approaches and illustrates the selection process.

FILTER 1 - Six of the 30 approaches described by AIGA make reference to 'nature' or the natural world: The Hannover Principles, IDSA Eco Design Principles and Practices, The Natural Step, Biomimicry, Natural Capitalism, and Cradle to Cradle. For instance, The Hannover principles have several references, such as: "Evaluate and optimize the full life cycle of products and processes to approach the state of natural systems…", "treat nature as a model and mentor", and "re-establish the integral relationship between natural processes and human activity" (ibid, p.6).

FILTER 2 - Four of the six approaches -The Hannover Principles, Biomimicry, Natural Capitalism and Cradle to Cradle - refer directly to nature as a model, something to emulate, an inspiration, a mentor, an example or as a goal. For example, the description of Biomimicry includes: "*In her 1997 book 'Biomimicry: Innovation inspired by Nature', Janine Benyus invites us to reframe our thinking about innovation and argues that people should look at nature as a model, mentor, and measure*" (ibid, p.16). In Natural Capitalism, the direct link can be seen in one of the four 'shifts' which this strategy argues must be made in business practices. This shift is entitled "Ecological redesign (turning to nature as a model)" (p.16). Cradle to Cradle is described as a strategy that further develops the concept of 'eco-effectiveness', which "seeks to design systems that emulate the healthy abundance of nature" (p.17).

In contrast, the other two approaches -the IDSA Principles and The Natural Step- address nature 'only' in the sense of protecting and interacting with it. They do not mention nature as a source of knowledge, inspiration, solutions, or such. The IDSA principles indirectly refer to the use of nature by stating, *"Human society and the biosphere are interdependent"*, and *"Nature can survive without humanity but society is dependent on the biosphere for*

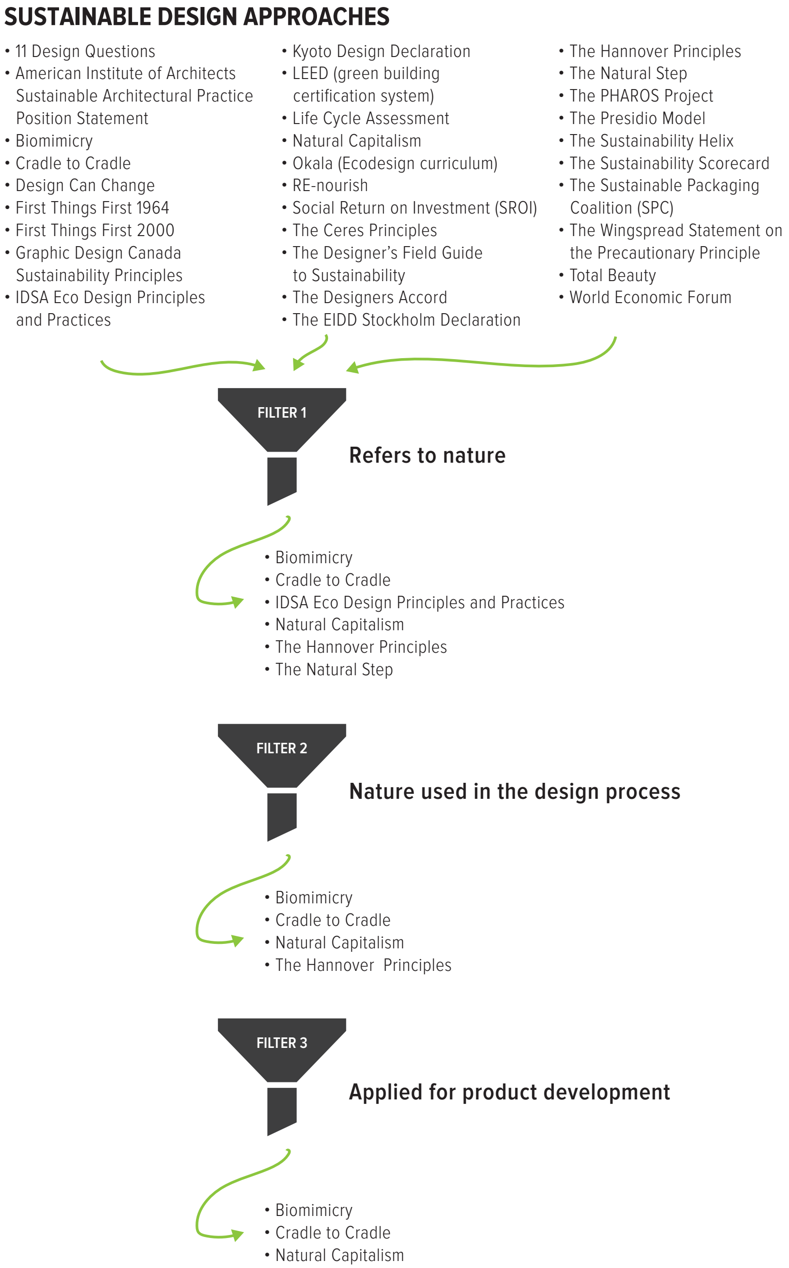


Figure 2.2: Selection of sustainable design approaches classified as Nature-Inspired Design Strategies

crucial services. Society's systematic destruction of the biosphere threatens nature's health and its capacity to sustain human society" (p.7). In The Natural Step (TNS) the name of the strategy refers explicitly to nature, and 'nature' is used to determine what is referred to as the 'system conditions' and 'principles of sustainability'. TNS focuses on what should not be done to nature in order to achieve a sustainable society, as illustrated in the description of the TNS system conditions: *"In a sustainable society, nature is not subject to systematically increasing: (1) concentrations of substances extracted from the earth's crust (2) concentrations of substances produced by society (3) degradation by physical means, and (4) in that society, people are not subject to conditions that systematically undermine their capacity to meet their needs"* (p.14).

FILTER 3 - The last criterion for the selection addresses the applicability of the approaches for sustainable product development. Both The Hannover Principles and Cradle to Cradle were developed by McDonough and Braungart. Of the two, Cradle to Cradle (C2C) was specifically developed as a strategy for sustainable product development, whereas the Hannover Principles are a set of principles written for designing the *built* environment (McDonough, 1992). Therefore, The Hannover Principles were not included in the selection.

In summary, the following NIDS are available for product development: Biomimicry, Cradle to Cradle, and Natural Capitalism. These design strategies are introduced in more detail in the following sections.

2.2 Biomimicry in sustainable product development

Biomimicry is studied and applied in a broad range of fields, including material research, product design & innovation, inventions, systems design, architecture, communication, and mechanics. Biomimicry literally means the imitation of life, combining the Greek terms 'bios', life, and 'mimikos', imitation. Benyus defines the term as "a new science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems" (1997, p.0). The core concept of Biomimicry is that nature has developed highly effective, sustainable ways of performing functions, which could benefit designers when tackling comparable challenges. According to the Biomimicry Institute, which was co-founded by Benyus, "the core idea is that nature, imaginative by necessity, has already solved many of the problems we are grappling with [...]. After 3.8 billion years of evolution, nature has learned what works and what lasts" (The Biomimicry Institute, 2010).

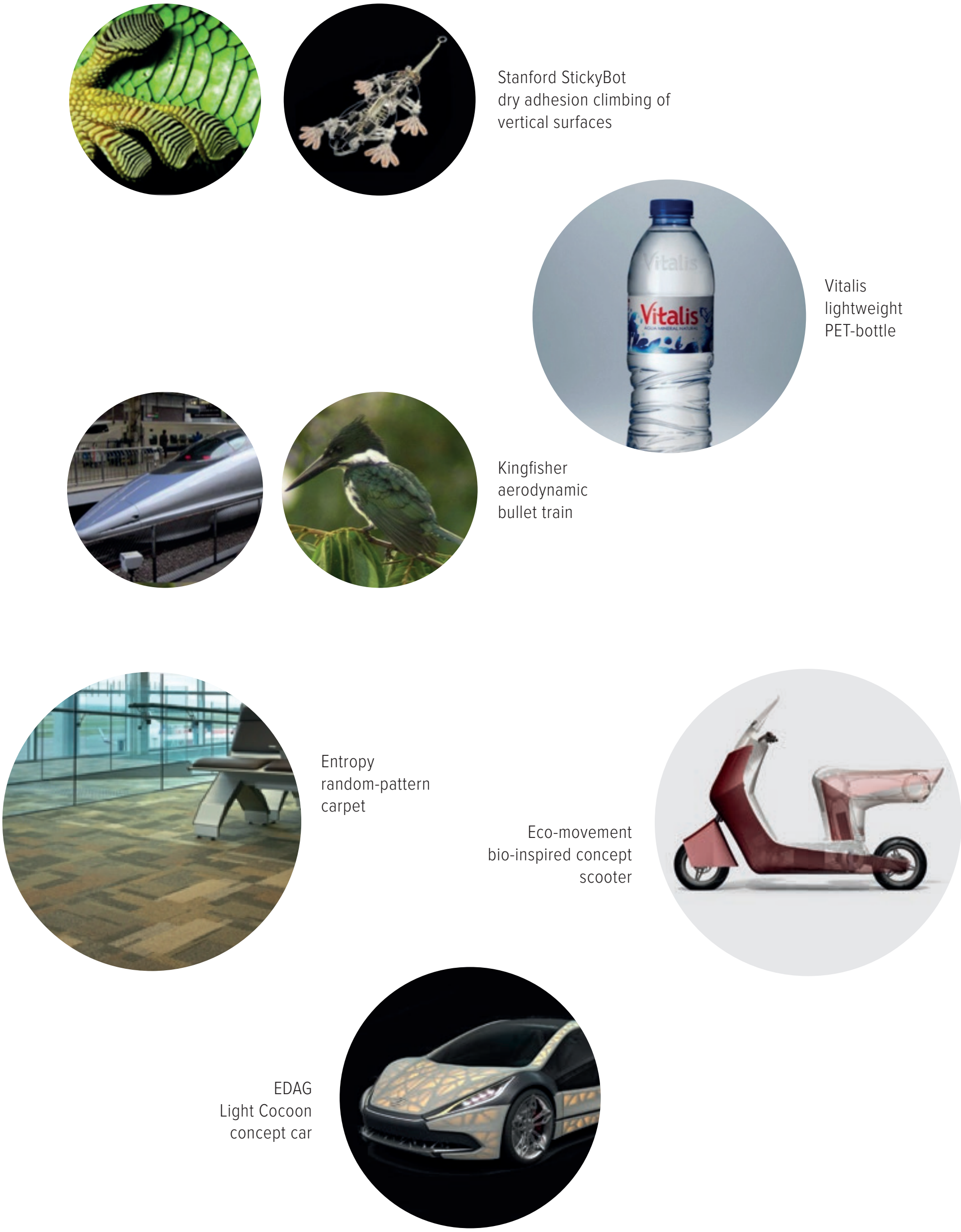


Figure 2.3: Impression of Biomimicry products

Various terms are used interchangeably in the literature for different forms of 'learning from nature', including Biomimetics, Biomimicry, Bio-inspired design, and Bionics (Bhushan, 2009, Vincent, 2009). However, when the emphasis is on finding solutions that are (environmentally) sustainable, Biomimicry is typically the term used (Kennedy et al., 2015, Reap et al., 2005, Vincent, 2009). Correspondingly, Biomimicry in this thesis refers to a design strategy aimed at generating *sustainable* solutions.

Figure 2.3 provides an impression of Biomimicry examples in product development. In terms of sustainability, Biomimicry has been applied to increase energy efficiency, reduce material use, and for the development of more sustainable product-systems. Although many designers and researchers are involved in bio-inspired design, the availability of Biomimicry methods and tools for sustainable product development is limited. Literature analysis points to 'Biomimicry 3.8', the consultancy co-founded by Janine Benyus, as the main 'provider' of a coherent set of methods and tools. New versions of their methods and tools have become available over time, the latest version being published as a 'Biomimicry resource handbook' (Baumeister et al., 2013). Table 2.1 provides an overview of the strategy's design philosophy, principles, methods and tools that were retrieved from literature. Biomimicry training courses are available to designers from Biomimicry 3.8 and their affiliates. Furthermore, a number of universities have started providing Biomimicry workshops or programs (Biomimicry 3.8, 2015, de Pauw et al., 2014, Montana-Hoyos, 2008, Santulli and Langella, 2001).

Design philosophy
Innovation inspired by nature
Life creates conditions conducive to life
Design principles
Life's principles
Methods & tools
Design spiral; which includes specific tools for analysis, ideation, and evaluation
AskNature

Table 2.1: Overview of the Biomimicry design philosophy, principles, methods and tools for sustainable product development (Baumeister et al., 2013, Benyus, 1997, Biomimicry Guild, 2007, Biomimicry Guild, 2010a)

The design philosophy behind Biomimicry can be phrased as "innovation inspired by nature". More specifically, the aim for sustainability is apparent in the aspirational goal of Biomimicry: "creating conditions conducive to life" (Benyus, 1997). This goal refers to a characteristic of organisms to function in such way that they tend to promote or assist ('conduce') their habitat. This philosophy offers a perspective towards 'achieving sustainability' in the sense that it challenges designers and engineers to create products with a beneficial impact.

Benyus (1997) emphasizes that in order to achieve environmentally sustainable solutions, designers need to integrate biological knowledge at the level of forms, processes, and systems. To implement learning from ecosystems, Biomimicry 3.8 has developed the so-called 'Life's principles' that describe generic ecosystem insights from biology (Biomimicry 3.8, 2012). These design principles, as well as the method and tools, are still evolving, and newer versions have become available throughout the PhD research. For example, Figure 2.4 illustrates the development of the Life's principles (larger versions of the illustrations are provided in Appendix 2).

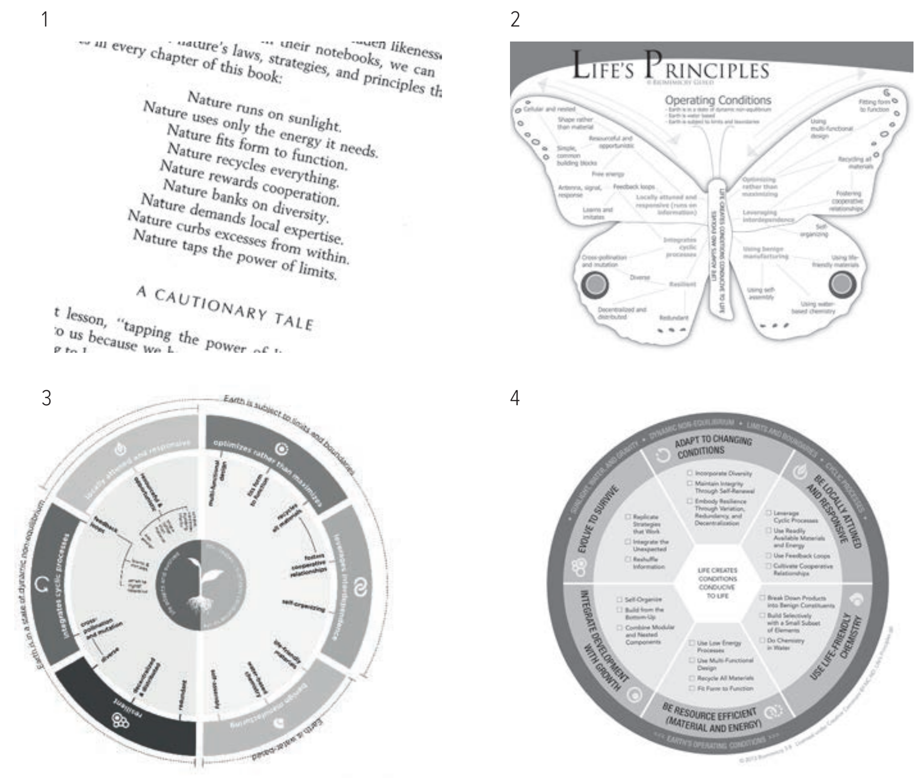


Figure 2.4: Evolution of Biomimicry Life's principles (1: Benyus 1997, 2: Biomimicry Guild 2007, 3: Biomimicry Guild 2010, 4: Baumeister et al. 2013). See Appendix 2 for larger versions.

The 'Design Spiral', shown in Figure 2.5, provides a method for applying Biomimicry in the design process. In the latest version, four different types of tools for integrating biology into design are distinguished, each for a specific purpose (Baumeister et al., 2013):
a) for scoping -(re)defining the design problem, b) for discovering - retrieving inspiration and engineering solutions from nature, c) for creating - designing and generating solutions, and d) for evaluating - assessing appropriateness and viability of a design. Specific tools are available to perform different steps from the Design Spiral, for example a set of 'scoping questions' and 'AskNature'. AskNature is an online, open-source database hosted by the Biomimicry Institute which lists organisms and their biological principles by function (The Biomimicry Institute, 2008).

In addition to the Biomimicry design strategy developed by Biomimicry 3.8 and the Biomimicry Institute, several methods and tools are being developed that can be classified as tools for Biomimetics, aimed at generating new products by 'learning from nature' without a specific aim for sustainability. Vincent, Bogatyreva et al. are developing a biomimetic engineering method, BioTRIZ (2005, 2006), and several researchers are working on methods and databases to facilitate the transfer of knowledge from the field of biology to those of design and engineering (Keshwani et al., 2013, Sarkar et al., 2008, Sartori et al., 2010, Shu et al., 2011, Stroble et al., 2009). Several of these methods and databases have been tested using design engineering assignments, but they have yet to be introduced in design engineering practice. For weight optimization, computer-aided software has been developed based on learning from nature (Mattheck and Burkhardt, 1990, SolidThinking, 2009).

Figure 2.5: Biomimicry 'challenge to biology design spiral', 2007 and 2013 version (Biomimicry Guild 2007, Baumeister et al. 2013). See Appendix 2 for larger versions of the design spirals.

Studies on the application of Biomimicry in sustainable product design are scarce. By analysing three specific products, Reap et al. (2005) illustrate that 'reductive' Biomimicry, which mimics only forms and processes, does not necessarily render more sustainable outcomes. Montana-Hoyos (2008), who developed a teaching and learning method for Design for Sustainability by combining Biomimicry with several other strategies, acknowledges the need to include the systems level of Biomimicry. Nevertheless, his findings do not provide insights into the application of methods or tools for implementing such 'system lessons' from Biomimicry. Volstad and Boks, in their study on the usefulness of Biomimicry for (sustainable) product design, explicitly limit their study to the reductive form of Biomimicry and its use "as a source of inspiration and as a toolkit for solving practical design problems" (Volstad and Boks, 2012). So far, research on the application of Biomimicry in product design has focused on the more commonly used 'biomimetic' elements of the strategy, as opposed to the Biomimicry tools and principles aimed specifically at sustainable product development.

2.3 Cradle to Cradle in sustainable product development

The term 'Cradle to Cradle' was coined by Stahel in the 1970s and popularized by McDonough and Braungart in their book on Cradle to Cradle (McDonough and Braungart, 2002, Stahel, 1994). The term Cradle to Cradle is derived from the well-known term 'Cradle to Grave', which refers to taking into account all the effects of a product during its entire life cycle, from production to disposal. According to Braungart and McDonough, the Cradle to Grave manufacturing model is responsible for creating waste and pollution. In contrast, the core concept of Cradle to Cradle is to "take nature as a model for making things" and design products that, after their useful lives, become resources for new products (McDonough and Braungart, 2002). This design strategy, which is studied and applied in product design, architecture, and material development, challenges designers to move beyond eco-efficiency towards 'eco-effectiveness' (ibid), visualised in Figure 2.7 and 2.8. Eco-effectiveness "strives to generate an entirely beneficial impact upon ecological systems" (Braungart et al., 2007, p.1343). The concept "deals directly with the issue of maintaining or upgrading resource quality and productivity through many cycles of use, rather than seeking to eliminate waste" (Braungart et al., 2007). The strategy has a clear material focus, resulting from the vision that (high quality) materials will become scarce, whereas more than sufficient solar energy income is available (Scheelhaase, 2010).

Cradle to Cradle has a clear product focus and has been applied for the design of a range of products, including office furniture, personal hygiene products, shoes, and

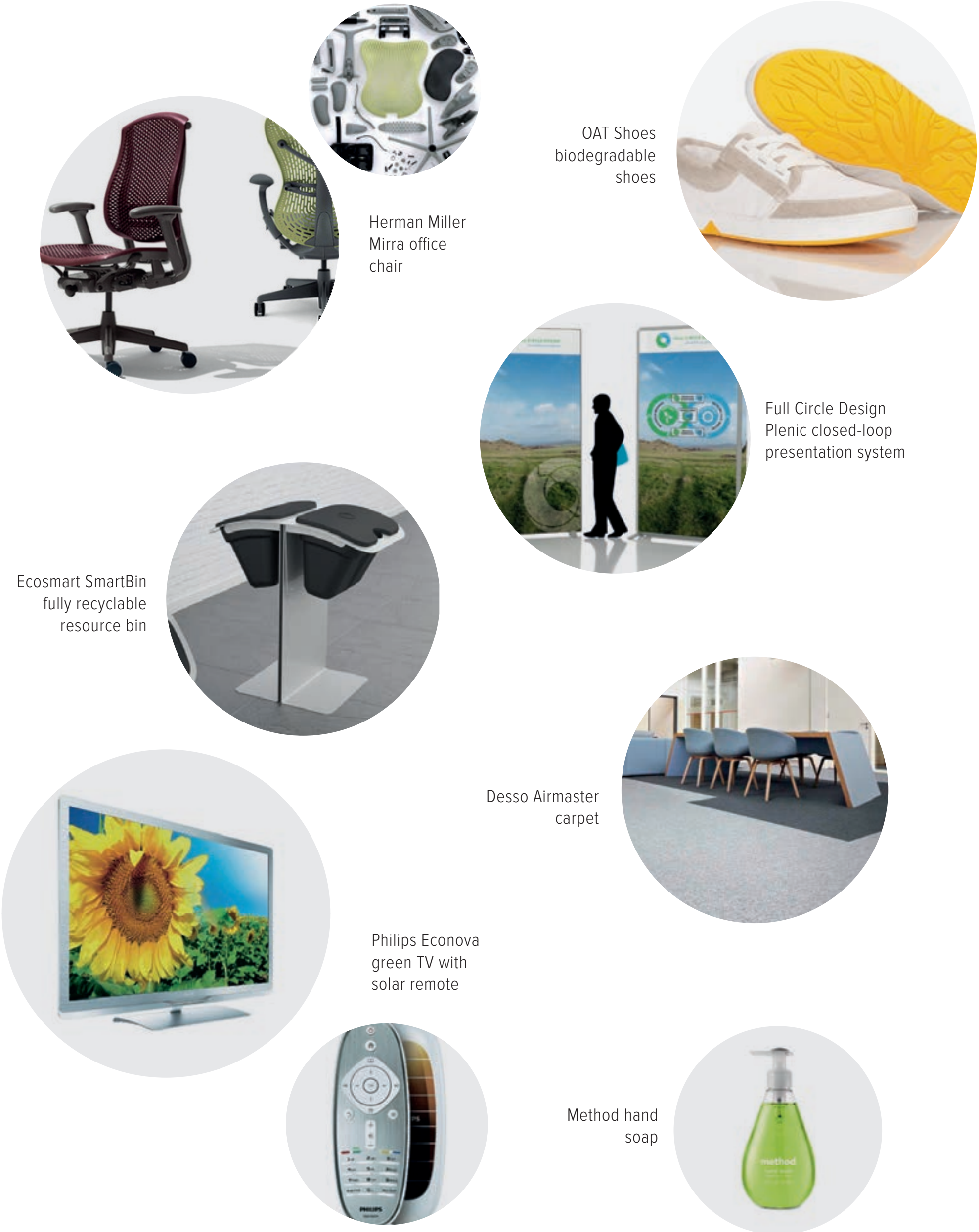


Figure 2.6: Impression of Cradle to Cradle inspired products

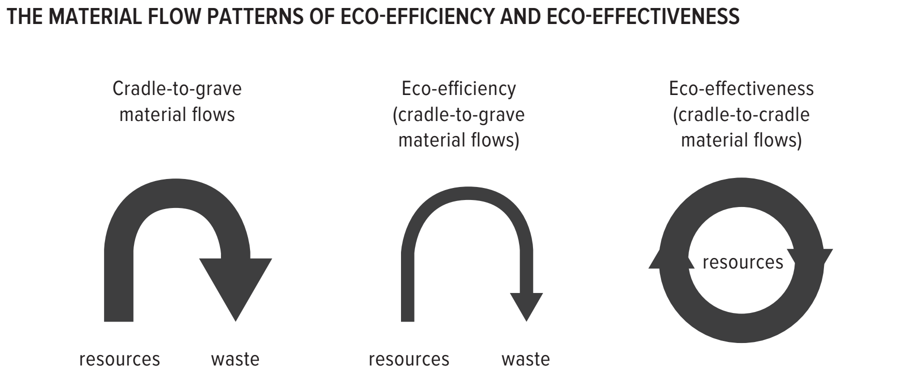


Figure 2.7: Visualisation of the differences between eco-efficiency and eco-effectiveness (redrawn from Braungart et al. 2008)

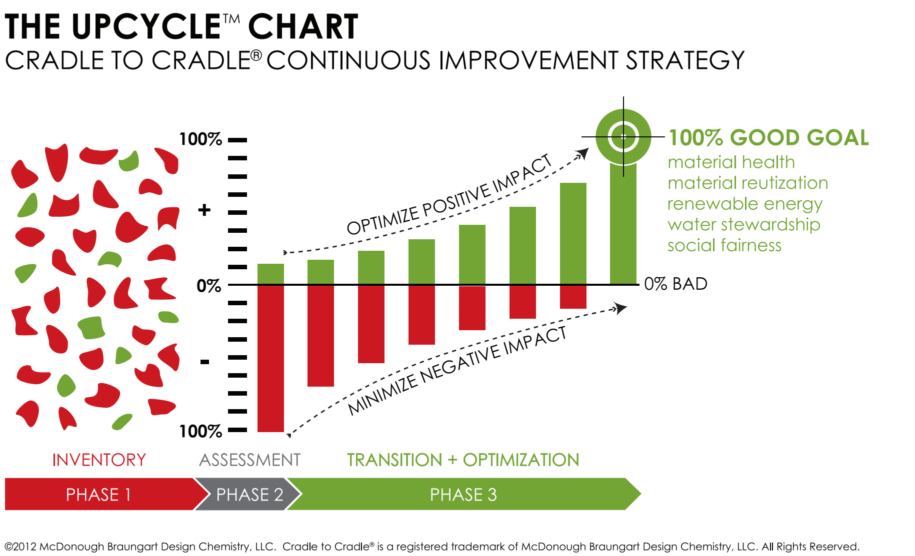


Figure 2.8: Visualisation of the eco-effectiveness approach by MBDC

home appliances, see Figure 2.6 for an impression. Table 2.2 provides an overview of the strategy's design philosophy, principles, methods and tools that were retrieved from literature. The design philosophy behind Cradle to Cradle is captured by the phrases 'doing good instead of less bad' and 'creating a beneficial footprint' (Bor et al., 2011, McDonough and Braungart, 2002), which are linked to the Cradle to Cradle concept of eco-effectiveness described in the previous section. Like Biomimicry, Cradle to Cradle challenges designers to create products with a beneficial impact, and more explicitly than Biomimicry, marks the difference between the perspectives of 'reducing unsustainability' versus 'achieving sustainability' described in Chapter 1[2].

Cradle to Cradle provides designers with three design principles for achieving eco-effectiveness, based on learning from natural systems: 1) Waste equals food - implementing continuous material cycles, 2) Use current solar income - using solar energy or tapping into passive solar processes, and 3) Celebrate diversity - tailoring designs, drawing information from local natural systems to ultimately "fit" within these systems (McDonough et al., 2003).

To implement these design principles, a number of methods and tools are available to designers, including the use of a Cradle to Cradle Roadmap, defining use in biological and technical cycles (illustrated in Figure 2.9), and design for disassembly. Cradle to Cradle Designer training courses are offered by EPEA, an agency founded by Braungart, as well as a number of universities. In their first Cradle to Cradle book, McDonough and Braungart also describe a stepwise method for the development of Cradle to Cradle products (McDonough and Braungart, 2002). However, the projects conducted by the authors seem to follow an approach that differs from this method, starting with the formulation of project specific intention statements or design principles, represented in Figure 2.8 as the "100% good goal".

In addition to the design tools, a certification program has been developed to allow companies to market their progress in applying Cradle to Cradle (C2C Products Innovation Institute, 2012). The certification criteria focus on the implementation of the strategy within an organization, but not on assessing the outcome of the design process, i.e. 'eco-effectiveness' of the design (Bor et al., 2011, Braungart, 2012). Hence, these criteria are not intended for use as design tools.

Several studies describe the theoretical and practical advantages and disadvantages of Cradle to Cradle (for example Bjørn and Hauschild, 2012, McDonough et al., 2003, Reijnders, 2008) but, as with Biomimicry, studies analysing the application of the strategy in product design are scarce. Both Rossi et al. (2006) and Lee & Bony (2009) studied the

Design philosophy	
	Doing good - instead of 'less bad'
	Creating a beneficial footprint
Design principles	
	Waste equals food
	Use current solar income
	Celebrate diversity
Methods & tools	
	Roadmap
	Material inventory
	ABC-X classification
	Define use in biological and technical cycles
	Define use period
	Add value
	Cascade use
	Design for (dis)assembly
	Use Cradle to Cradle-elements (materials, processes, ingredients)

Table 2.2: Overview of the Cradle to Cradle design philosophy, principles, and methods and tools for sustainable product development (Bjørn and Hauschild, 2013, Bor et al., 2011, EPEA, 2011, McDonough and Braungart, 2002, McDonough et al., 2003)

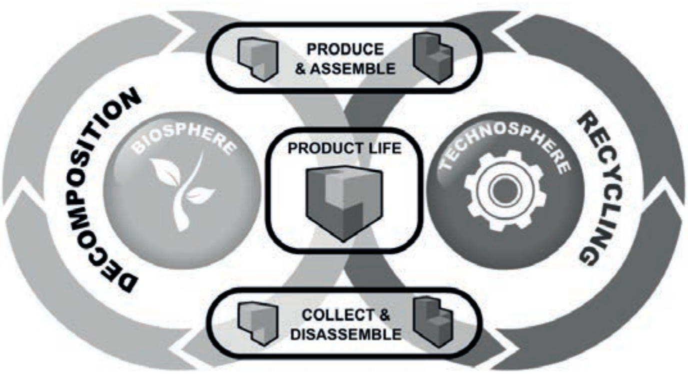


Figure 2.9: Definition of material loops in biological and technical cycles

design of the Mirra chair by office furniture manufacturer Herman-Miller, describing the design team's achievements that focused on the 'waste equals food' principle. Additionally, Bakker et al. (2009) studied the application of this design strategy based on graduation projects and literature. Although these studies shed light on the advantages and difficulties encountered in design projects, they do not clarify *how* Cradle to Cradle affects the outcome of the design process.

Figure 2.10: Hypercar by RMI

2.4 Natural Capitalism in sustainable product development

In 1999, Hawken, Lovins, and Lovins introduced Natural Capitalism, "*a road map* [...] *to solve many environmental problems at a profit, a strategy for protecting the biosphere and at the same time improving profits and competitiveness*" (Hawken et al., 1999). The strategy was termed Natural Capitalism to refer to the "natural capital" of ecosystem services, and to what capitalism might become if natural capital was valued within the economic system (Hawken et al., 1999). The basic driver for Natural Capitalism is the limited availability of natural resources: "*In the next Industrial Revolution - already under way - we will have abundant people and scarce nature, not the other way around. So it now makes sense to use nature far more productively*" (Lovins, 2001).

To achieve Natural Capitalism, the authors propose four major shifts in business practices: (1) a radical increase in the productivity of natural resources, (2) a shift to biologically inspired production models and materials, (3) a move to a "Service-and-Flow" business model, and (4) reinvesting in natural capital (Hawken et al., 1999, RMI, 2010d). In this way, the strategy seems to include Biomimicry and Cradle to Cradle. In fact, Natural Capitalism Solution, an organization founded by Hunter Lovins, directly refers to the use of Biomimicry and Cradle to Cradle, as approaches for meeting their second principle: to 'redesign as nature does' (Natural Capitalism Solutions, 2010).

Our review of Natural Capitalism from the perspective of product development yielded one product design example. The Hypercar, shown in Figure 2.10, is a concept car combining ultra-light materials, low coefficient of drag models, and electric drive architecture into one design. The project was executed by the Rocky Mountain Institute (RMI), an institute cofounded by A. Lovins and H. Lovins. With this project, RMI wanted to demonstrate that their whole-systems approach would foster greater efficiency gains than pursuing any of the design objectives individually (RMI, 2010b).

Table 2.3 lists the design philosophy, principles, methods and tools of Natural Capitalism that have been applied for product development, as retrieved from literature on the Hypercar and RMI's whole systems approach. RMI's scope seems to be limited to the first 'shift in business practice' of Natural Capitalism. In 2010, they formulated their core business as "*We create breakthrough efficiency solutions*" (RMI, 2010c). In 2013, their mission has been formulated more broadly: "to drive the efficient and restorative use of resources" (RMI, 2014). Key to their strategy is integrative design which, according to RMI, "*can often yield expanding rather than the normal diminishing returns to investments in energy efficiency, making very large (even order-of-magnitude) energy savings cost less than small or no savings*"(Lovins, 2010, p.1). To expand the adoption of their integrative design approach, RMI has developed 'factor 10 engineering principles' (10xE) that aim to "*help engineers, architects and their clients attack resource-intensive design problems, such as manufacturing processes, buildings and vehicles, using RMI's whole-system principles in order to produce fundamentally better results*" (Figure 2.11). 10xE is "*a set of ideas for shaping the design space and design approaches within it*" (RMI, 2010a). The cases described in the 10xE approach currently do not include product design.

Design philosophy

Drastically increase resource efficiency without adding cost

Design principles

'factor 10 engineering principles' (10xE)

Methods & tools

'Integrative design' or 'whole-system design'

'Introducing innovative technologies'

Table 2.3: Overview of the Natural Capitalism design philosophy, principles, and methods and tools for sustainable product development (Lovins and Cramer, 2004, Lovins et al., 2007, RMI, 2010a)

Apart from a description of the Hypercar case (Lovins and Cramer, 2004), our review of the literature yielded no other case studies where Natural Capitalism was used for sustainable product development.

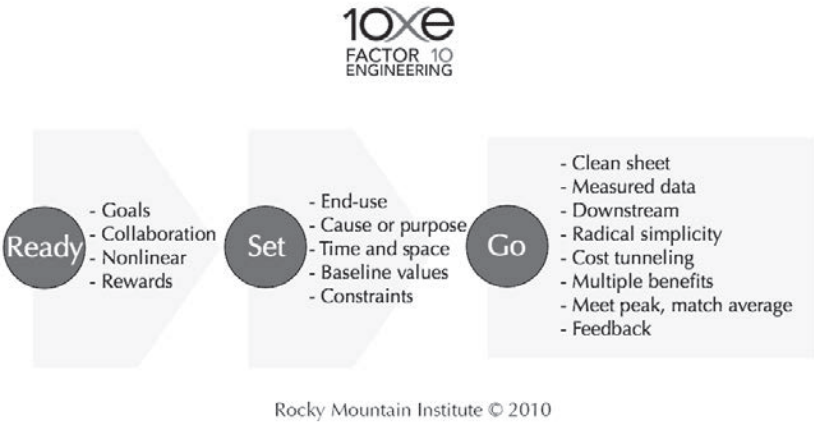


Figure 2.11: Factor Ten Engineering Principles by RMI

2.5 Conclusions and discussion

In this chapter, we introduced the term Nature-Inspired Design Strategies to describe design strategies that base a significant proportion of their theory on 'learning from nature' and regard nature as the paradigm of sustainability. To answer the first research question of this study (RQ1), we have analysed the design strategies, and described the philosophies, principles, methods, and tools that they offer designers, which allow them to integrate knowledge from the fields of biology and ecology into sustainable product development.

The analysis has led to the selection of Biomimicry and Cradle to Cradle for further study, as these two strategies are at the forefront of nature-inspired design and have already been applied in sustainable product development. In contrast, the data available on Natural Capitalism for product design is limited to one case representing one of the principles of this design strategy. As no product-design cases are currently available that capture the full spectrum of Natural Capitalism, this strategy will not be explored further within this study. By combining Biomimicry and C2C in one study, this research can provide insights that help to understand the impact of NIDS beyond that of the individual strategies.

Biomimicry and Cradle to Cradle are strategies that fit the perspective of 'achieving sustainability' described in Chapter 1. Nevertheless, there is a lack of data that shows how the application of these strategies influences the outcomes of the design process, and whether they can help designers to develop truly 'sustainable' solutions. The two strategies seem predominantly material and technology oriented. The role of consumer behaviour in addressing sustainability is either not mentioned or, as in Cradle to Cradle, not seen as a problem: "good design […] can transform the making and consumption of things into a regenerative force" (Halweil et al., 2004, p.104).

Furthermore, Biomimicry and Cradle to Cradle both focus on the ecological pillar of sustainability. No product design methods and tools seem to be available within NIDS dedicated to the impact of products on social sustainability, including themes like poverty, hunger, education, and gender equality[3]. The economic pillar is addressed indirectly, through the perspective that NIDS offer on sustainability: if products are designed from the outset that they benefit their 'ecosystem', ecological and economic objectives merge. As no design methods or tools were found that provide steps to integrate social and economic sustainability in the design process, we conclude that currently, NIDS do not offer support for designers to develop socially sustainable products or to design for economic sustainability.

Therefore, the case study research will focus on the impact of NIDS on ecological sustainability. Research into how nature can inform design for social sustainability could help create a full understanding of the potential of NIDS for sustainable design, and is therefore regarded as being of key interest for future studies.

[1] American professional organization for design - its name formerly an acronym for the American Institute of Graphic Arts.

[2] In this thesis, sustainable product design includes the concept of eco-effectiveness or ‘doing good’ (see also the Glossary). On the other hand, in Cradle to Cradle publications a more narrow interpretation is used, with the term ‘sustainability’ representing the concept of eco-efficiency, striving for ‘less bad’, whereas Cradle to Cradle is positioned as moving ‘beyond sustainability’ (e.g. McDonough and Braungart, 2002, 2013).

[3] Toxicity in relation to human health is being addressed in NIDS, but is also considered in other environmental sustainability approaches such as Ecodesign.

CHAPTER 3

Assessing the Sustainability of Nature-Inspired Design

In the previous chapter, two Nature-Inspired Design Strategies (NIDS) were selected for further study to explore how and to what extent NIDS help designers in developing 'environmentally sustainable products'. In order to do this, we assess the environmental sustainability of case-study designs explored later in this thesis (Chapter 6).

In this study, we originally set out to assess the environmental impacts of the case-study designs using an existing tool based on Life Cycle Assessment (LCA). However, as argued in this chapter, this assessment is not straightforward. Our theoretical inquiry into the objectives of nature-inspired design revealed that conventional LCA-based tools are not geared towards assessing some of the main results that NIDS strive to accomplish. Consequently, for the purposes of this study, we developed an alternative method for assessing the case study products.

The results of the inquiry are described in three parts: in section 3.1 we substantiate why common life-cycle based assessment is unsuited to assessing nature-inspired design. The findings were used to analyse and adapt the assessment framework; this is described in section 3.2. Third, in section 3.3, the adapted framework is developed into a method that can be used for assessing designs, using criteria for environmental sustainability. In section, 3.4, we reflect on the framework and criteria developed for assessing the sustainability of nature-inspired design.

Chapter 3 is based on: E PAUW, I. C., KANDACHAR, P. & KARANA, E. 2015. Assessing sustainability in nature-inspired design. International Journal of Sustainable Engineering, 8, 5-13.

3.1 The need for a different way of 'assessing sustainability'

Within current Ecodesign practice, dedicated tools based on Life Cycle Assessment (LCA) such as Eco-indicator analyses are used for assessing products on environmental sustainability. These tools enable designers to determine 'hotspots' of existing products, to choose from design alternatives, and to compare the final design with a benchmark product. However, authors in the field of Biomimicry and Cradle to Cradle have questioned the applicability of current LCA-based tools to measure some of the key qualities that these design strategies strive for (Bor et al., 2011, Reap, 2009), a discrepancy that seems to be linked to reported differences between the frameworks of eco-efficiency/ Ecodesign and Cradle to Cradle (Bakker et al. 2009, Bjørn and Hauschild 2013).

Based on literature analysis, we describe in this section how current LCA is intertwined with eco-efficiency thinking, and discuss four ways in which the assessment is linked to the perspective of 'reducing unsustainability'.

3.1.1 Comparing products guides towards impact reduction

A first link between current LCA-based assessment tools and 'reducing unsustainability' relates to the way in which these tools are applied within the design process. As Bakker et al. (2009) observed, LCA-studies typically compare solutions that offer the same functional performance within defined system boundaries. In product development, time restrictions within the design process do not allow for extensive analyses, and the effects of setting specific system boundaries are not always considered. In those cases, the assessment of existing products may lead to a 'lock-in' effect, as designers will use the outcomes of the assessment to improve product performance (within the set system boundaries), in other words to 'reduce unsustainability'.

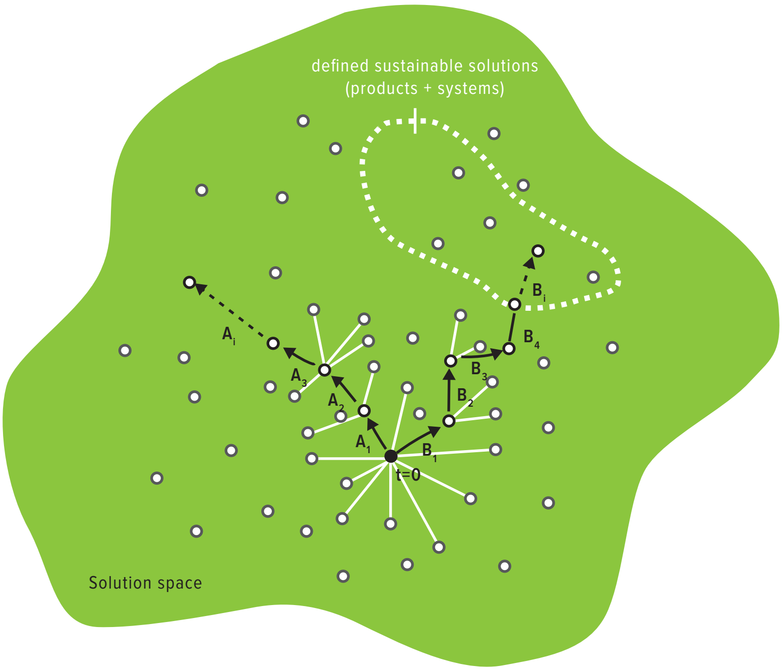
This application of LCA-based assessment tools guides the designer towards options for impact reduction rather than revealing options for capturing the *potential* performance of the products within their context of use. For instance, an assessment of existing building façade panels would inform the designer of the current environmental impacts associated with such panels. The outcomes will typically invoke measures such as selecting low-impact materials, improving production process efficiency, reducing maintenance, and possibly using recycled materials. The assessment results of this façade panel would *not* address, for example, the potential for improving air quality, for increasing biodiversity, or for generating energy, as the assessment is limited to the existing functionalities of a panel. Once a designer does incorporate such functionalities, LCA-based tools *can* be used to assess these features, but this requires expanding the functional unit of a façade panel with the extra functionalities. In the earlier example, adding the function of air cleaning to a façade panel allows the inclusion of alternative air-cleaning solutions in the benchmark-analysis. Thus, while the tools can be used to assess any design solution, their application guides towards reducing existing impacts.

3.1.2 Improving current systems versus contributing to sustainable systems

Secondly, LCA-tools assess the performance of products *within existing systems* (e.g. production and energy systems), whereas Biomimicry and Cradle to Cradle aim to develop products that contribute to an overall sustainable solution (where also production and energy systems will have changed). Both Reap (2009) and Bjorn and Hauschild (2013) illustrate that assessing performance within current systems (taking a 'snapshot'), can favour a design solution that performs well within today's world (with standard manufacturing, energy generating, and waste processing systems), whereas that same design may actually perform worse than other solutions in a future -even 'near future'- scenario with (more) sustainable systems. The assessment of products thus strongly depends on the system in which they operate. To overcome this problem, designers can expand their analysis by modelling future scenarios (see for example Vogtländer 2010) which can increase their insight into the effects of specific interventions.

However, when targeting for a sustainable solution, instead of assessing performance within an 'unsustainable' or near-future world, the matching assessment method would preferably show designers to what extent their product contributes to the achievement of a future with sustainable systems. Figure 3.1 illustrates two different routes a designer could take when developing successive versions of a product over time, within the -dynamic- solution space available for changing the design. 'Route A' represents the route of 'reducing unsustainability'. Here, the designer selects, out of all feasible alternatives considered, the one yielding the highest decrease in environmental impact as compared with the current product (at that moment). Repeating the same procedure over time determines the route taken. On a systems level this route supports the further development of the systems that currently have the lowest environmental impact. For instance, if currently waste incineration of a certain product is the 'end-of-life' scenario with the lowest environmental impact, route A may result in the development of products that are safe to incinerate and support efficient incineration systems.

In an ideal situation, designers would like to assess which design alternative contributes most to achieving a sustainable solution (within a specific context), and to develop a design strategy for achieving that aim, as represented with 'Route B'. If a sustainable solution would for instance require a fully circular flow of materials (as propagated by nature-inspired design), in the given example, route B may divert away from product incineration and instead lead to the development of a product that can be remanufactured or recycled into new products, thereby advancing cost-efficient disassembly and recycling systems. In those instances where achieving a sustainable solution requires changes in the system surrounding the product, routes A and B can head in different directions.



● = current design (at t=0)

= alternative designs considered (at t=1,2,...,i)

A_i = route chosen based on selecting the design alternative with highest impact reduction at t=1,2,...,i

B_i = route chosen based on selecting the design alternative that is expected to result in a sustainable solution at t=i

Figure 3.1: Representation of two different routes (A and B) in the development of successive design alternatives, illustrating potential differences in the outcomes, based on different ways of assessing sustainability, adapted from Reap (2009)

3.1.3 Understanding assessment indicators

The risk of routes A and B not aligning corresponds to a third aspect of LCA, concerning the understanding of the indicators that result from the assessment. LCA-based assessment tools show the quantitative impacts of certain design interventions via environmental impact indicators (or eco-indicators). These indicators reflect the aggregated environmental burden of materials and processes. By comparing the eco-indicators of design alternatives, the designer can select the alternative with the lowest environmental impact. However, the indicators do not provide insight in the underlying dynamics of the assessment system (Bakker et al. 2009), and may thus lead to optimizing to 'local minimums' (Reap 2009), i.e. sub-optimal solutions within the set system boundaries. Based on the indicators only, the designer cannot assess whether the optimal solution has been achieved. To address this issue, various design alternatives can be developed and subsequently assessed, but the indicators do not guide the development. In addition, a lack in understanding of the dynamics may also induce rebound effects. These effects occur when a reduction in a product's impact is (partially) neutralized because the product, as a result of the improvement, will be used more frequently or in larger volumes. Being unaware of where and how to contribute to sustainable solutions (shown in Figure 3.1 as the area within the dashed white line) hinders designers in 'achieving sustainability'.

3.1.4 Burdens versus beneficial impacts

The last link we discuss here, addresses the fundamentally different way in which nature-inspired design and current life cycle assessment consider the nature of impacts. LCA has been developed to assess impacts that products have on the environment, more specifically, the potentially harmful impacts, also referred to as 'burdens'. In contrast, Biomimicry and Cradle to Cradle aim to create 'beneficial impacts'. Assessment of such beneficial impacts requires inclusion of the context in which the impacts occur, because a substance that has a beneficial impact in one system may not have such benefit, or even be harmful within another system (Bjørn and Hauschild 2012).

In theory, current LCA-based assessment tools can be used for assessing nature-inspired design, by enlarging system boundaries, including context-specific data sets, including future scenarios, allowing for positive impacts, and in-depth analysis of the resulting impact scores to uncover the underlying dynamics. Apart from the complexity this assessment would bring, we are inquisitive about potentially new ways of assessment that match the design perspective of 'achieving sustainability'.

Within nature-inspired design, we have not found alternative assessment methods that address the issues raised here. For Biomimicry, no impact assessment method has been developed. Within Cradle to Cradle, a certification programme has been developed, which includes context-based assessment of environmental impacts (within companies), but is also focusing on the steps that are taken by companies towards the implementation of the Cradle to Cradle approach. Consequently, the certification levels of the standard do not represent the 'sustainability' or 'beneficiality' of a design.

3.2 Framework for assessing product sustainability

The linkage between assessment methods and design strategies in terms of the underlying perspective has triggered us to reconsider the basic framework of the assessment: what fundamental components, i.e. constituents, are required for assessing the sustainability of products? When is a solution truly sustainable or beneficial, and how can we assess progress towards achieving that goal? Building on the premise that current LCA-based evaluation tools are intertwined with the perspective of 'reducing unsustainability', we first looked at the constituents of these tools in section 3.2.1. Based on the difficulties with assessing nature-inspired design, we propose four constituents to enable assessment under the perspective of 'achieving sustainability', including two new constituents, described in section 3.2.2. Section 3.2.3 and 3.2.4 elaborate on the new constituents. In section 3.2.5, the applicability of the proposed framework is discussed for assessing nature-inspired design.

3.2.1 Current constituents for life-cycle based product assessment

The literature on LCA-based tools provides input into what can be considered as the constituents for establishing the environmental sustainability performance of products. First of all, as the term states, LCA is *a life cycle approach*, or system approach, considering the assessment of all life cycle stages of a product, from the extraction of raw materials to the 'end-of-life' of the product. Secondly, for each of the life cycle phases *all impacts* to the environment, human health, and resources that are caused by the product are taken into account (ISO 2006). A possible third constituent is described by Klöpffer (2003), who characterizes LCA as a comparative method, comparing the performance of a product with that of another product (or earlier versions of the product). It can be argued that *comparing to other products* is not specific for LCA, but should instead be regarded a feature of 'analysing' in general. However, as comparing products with the purpose of reducing impacts is the specific aim of 'reducing unsustainability' we have included this

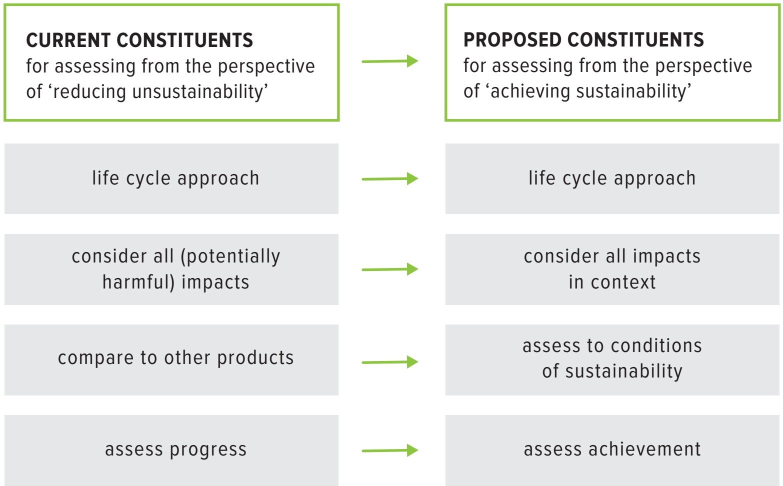


Figure 3.2: Constituents for assessing the sustainability of products for two design perspectives

as the third constituent for life-cycle based product assessment (Figure 3.2, left). The fourth constituent mentioned in Table 3.2 *assess progress* was identified in hindsight, based on the revised constituent *assess achievement*, and will be further described there.

3.2.2 Proposed constituents for assessing under the perspective of 'achieving sustainability'

To explore what possible constituents would be required for 'achieving sustainability' we considered examples of products currently on the market in light of the new perspective. Key to the new perspective is the aim to develop sustainable solutions that can provide 'beneficial impacts'. Therefore, we first considered the meaning of the term 'beneficial impact'. One could argue that *every* product on the market has beneficial impact; the value it brings to its user outweighs the effort needed to bring it on the market. However, this value concerns the primary purpose of the product, and reflects how it benefits the user of that product, not how it affects the remainder of its environment. Without this value, the product would not enter the market. We thus further specified the term, and define a product to have 'beneficial impact' when 'the impact that the product has on its environment contributes to the regeneration of that environment towards a sustainable state'[1]. To illustrate how a product could have a beneficial impact, we consider the Desso 'Airmaster' carpet tile, a product that has been developed with use of Cradle to Cradle and is acclaimed for illustrating the possible outcome of striving for eco-effectiveness.

Apart from delivering the primary functions of a carpet tile (providing users with certain aesthetics, acoustics, and tactile properties), this tile has been developed with the specific objective to capture fine dust for increasing the air quality within buildings. As 'capturing fine dust' is no regular function of a carpet tile and would improve the quality of the environment in which it is applied, this feature of the product is defined as beneficial. Whether or not the entire product can be considered as beneficial, depends on many other product characteristics. If the carpet tile would emit substances that are harmful to its users, or to factory workers, the product would not be beneficial, despite it capturing fine dust.

To be able to identify all relevant impacts, and to assess whether introducing a certain benefit does not bring adverse effects elsewhere in the system, a life cycle approach within the given context is required. We therefore conclude that the first two constituents of life-cycle based assessment tools, *a life cycle approach* and *considering all impacts*, are as important to the new perspective as they are for reducing unsustainability. However, to be able to assess the performance of products under the perspective of 'achieving sustainability', we additionally propose two constituents not included within current LCA: assessing to *conditions of sustainability* and assessing '*achievement*', the extent to which a product meets those conditions of sustainability (Figure 3.2, right). These constituents are described in the two following sections.

3.2.3 Assessing to conditions of sustainability

When designers aim to develop sustainable products, they will need to know what is, and what is not to be considered sustainable; a relative approach no longer suffices. In other words, they need to define or adopt conditions that describe when a product is assessed to be truly sustainable. McElroy, Jorna, and Engelen (2008) have described and illustrated a similar transformation process from the viewpoint of Corporate Social Responsibility as the development from a 'relative' towards a 'binary' approach of sustainability (Figure 3.3). The binary approach is characterized by a demarcation point determining whether a solution is or is not sustainable within the given context. "According to the binary orientation, an artefact is either wholly sustainable or not – there is no in-between. Instead, there are only higher or lower scores for sustainability performance, some of which fall on the *sustainable* side of a line, and others of which fall on the *non-sustainable* side" (McElroy, Jorna, and Engelen 2008, 6). For the assessment of products, this demarcation point can be articulated in conditions of sustainability the product has to meet. Defining such conditions of sustainability is not an easy task, as no singular, scientifically established set of conditions is available. However, looking at pioneering 'green' product examples currently on the market, several articulations of demarcation points can be distinguished, including "zero waste", "zero emissions", "safe", and "self-sufficient". Datschefski's "solar|cyclic|safe"-requirements can be considered an example of a coherent set of conditions of sustainability applicable to product design (Datschefski 1999). In addition, conditions for sustainability have already been suggested on a systems and even a global scale (Robèrt et al. 2002, Rockström et al. 2009). These conditions may inform the formulation of related conditions specific to the field of product design.

Although the idea of introducing one, universal set of sustainability criteria is tempting, 'sustainability' as a concept is being interpreted and articulated in numerous and highly diverse ways[2], and evolving with increased understanding of the ecosystems and social systems involved. What we propose here instead is the necessity of working with conditions. Current design practice that does not (explicitly) adopt *any* conditions, will not enable designers to ascertain progress towards the development of sustainable products. What specific conditions are incorporated in a design project as demarcation points for achieving sustainability will become part of an (explicitly formulated) vision on sustainability. This vision could be adopted or developed by the designer as part of the design process, or be part of a company's wider sustainability strategy.

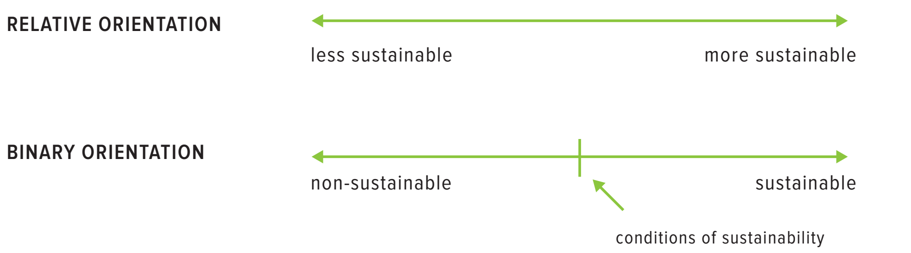


Figure 3.3: Changing goal orientation in sustainability assessment, redrawn and adapted from McElroy, Jorna, and Engelen (2008, p.7)

3.2.4 Assessing 'achievement' of sustainability

The second constituent we propose to add also addresses the shift from a relative to a binary orientation but focuses on *the extent to which sustainability is achieved*, in other words on introducing binary assessment. When the aim is to develop products that contribute to '*achieving sustainability*', instead of focusing on the *progress* made on the pathway towards sustainability, an assessment method would preferably indicate to what extent the goal is currently being met. Assessment is then based on 'achievement of target conditions', in other words: to reflect whether the full implementation beyond the required conditions for sustainability has been achieved. For instance, the conditions could require the establishment of fully circular material cycles and elimination of fossil-based energy. In that case, when considering the materialization of a product, not the reduction in use of (virgin) materials would determine what design scores best (although this would be useful to compare alternatives in today's practice), but the extent to which the design establishes such circular material cycles. Likewise, the second condition would guide designers to investigate alternatives that function without fossil-based energy. Assessing to what extent a product functions without fossil-based energy (in its use-context) renders a different outcome than assessing the reduction in energy demand.

To illustrate this difference in outcomes, an example is shown using two design alternatives for traffic signs with a traditional internal lighting system: signs using retro-reflective foil[3], and signs using LED (Figure 3.4). Both alternatives significantly increase the energy-efficiency of the traditional traffic sign, and -depending on the actual materialization- could strongly reduce the impacts related to energy consumption. To illuminate the differences, we here qualitatively assess only one impact category (energy-related impacts) in one life cycle stage (use phase), as shown in Table 3.1. The conventional assessment, based on 'assessing progress', will reflect the relative improvements in energy consumption. Both options show drastic reductions as compared with the original design, with option A. having a 10% higher score than option B. Based on additional considerations, such as economic feasibility, the designer can propose the solution (A or B) with the best combined assessment on all criteria. When instead a designer 'assesses achievement' of the conditions of sustainability, a different comparison may be made. Using the 'energy condition' that fossil-based energy should be eliminated, the traffic sign with retro-reflective foil would be assessed as 'achieving sustainability' in the use phase with respect to energy. On the other hand, the LED-illuminated sign, although significantly reducing energy demand, would only be assessed as 'achieving sustainability' when the energy used stems from a renewable resource. In other words, this binary assessment reflects the differences in measures that need to be taken for achieving a sustainable solution. In the example, this assessment may trigger the designer to compare the economic feasibility of the retro-reflective sign with an LED sign using renewable energy.

3.2.5 Implications for the product assessment framework

The new perspective towards 'achieving sustainability' that is embedded in nature-inspired design, calls for a change in the way designers assess their products. In this second part of the chapter, we proposed four basic constituents for a framework for

Figure 3.4: Three versions of traffic signs, internally lit (left), with retro-reflective coating (middle), and with LED (right). Photo's: Agmi Traffic

	Constituents for assessing the design alternatives	
Design alternatives	Assessing from the perspective of 'reducing unsustainability'	Assessing from the perspective of 'achieving sustainability'
Retro-reflective traffic sign 	Progress: 100% reduction of impacts related to energy consumption as compared with internally lit sign	Achievement: Energy condition has been met: design functions without use of fossil-based energy
LED traffic sign 	Progress: 90% reduction of impacts related to energy consumption as compared with internally lit sign	Achievement: Energy condition will be met when the required electricity is provided by renewable energy sources

Table 3.1: Differences in the assessment outcomes of two design alternatives when using different constituents for the assessment. This example illustrates the outcomes of an assessment of energy-related impacts in the use phase of a product (numbers indicative)

assessing the sustainability of products. Here, we discuss whether and how these constituents can help to address the difficulties in assessing nature-inspired design.

The two constituents introduced with LCA, *life cycle approach* and *inclusion of all impacts*, are considered equally vital constituents under the perspective of 'achieving sustainability'. The second constituent was slightly adapted, as current impact analysis does not allow the assessment of 'beneficial impacts'. By including the context of the product in the assessment, designers can be enabled to determine whether the impacts that occur throughout the life cycle of the product are beneficial or potentially harmful.

The newly proposed constituent of *assessing against conditions of sustainability* can contribute to resolving two obstacles we observed in our analysis. The conditions themselves will provide designers with insights into the factors underlying the sustainability performance of product alternatives. Knowing the core sustainability issues at play, reduces the risk of selecting sub-optimal solutions (that may render rebound effects when introduced). Secondly, the conditions can help designers to determine priorities for their new design. Thereby, this constituent -in principle- eliminates the need for a detailed analysis of existing products. Comparing the new design against other products is no longer required for assessing performance.

The constituent of *assessing achievement*, the extent to which sustainability is achieved with a product design, can enable an assessment tool to express the contribution a design can make to achieving a sustainable solution, instead of reflecting progress in the improvement of existing solutions. Informing the designer of the steps that need to be taken, as opposed to the steps already taken, may guide the designer towards achieving sustainability more effectively.

The resulting outcome differs from that of current LCA-based product assessment, but does not render 'assessing progress' as unimportant or irrelevant. Existing or new context-based tools can facilitate the designer in choosing between different routes, and in assessing possible adverse impacts that could be inflicted by intermediate solutions. However, for determining underlying dynamics, and for assessing to what extent a product is truly sustainable, a binary orientation will suffice. Although the implications of this approach need duly investigation, a binary assessment against conditions of sustainability could grant designers more time, both for adopting such conditions in their design process, and for focusing on the actual development of products and system.

For the purpose of the research project, this proposed framework with new constituents will be used for the assessment of the product designs. A first step towards this assessment is the development of a rudimentary method for assessing these designs.

3.3 Method for assessing the environmental sustainability of the case-study products

The development of a comprehensive new assessment method lies beyond the scope of this project. Nevertheless, for the purpose of assessing the case-study results, in this section we develop a basic method using a set of assessment criteria for environmental sustainability.

Building on the framework defined in the previous section, we have taken the following approach to include the four constituents in the assessment (Figure 3.5). First, inclusion of life cycle phases and relevant impact categories (constituents 1 and 2) is addressed in the inventory phase, where the different sustainability measures are categorized. The typology used to categorize the sustainability measures is described in section 3.3.1. Second, binary conditions of sustainability (constituents 3 and 4) are adopted in accordance with the perspective of 'achieving sustainability' embedded in Nature-Inspired Design Strategies (section 3.3.2). Third, the conditions are operationalised into assessment criteria to allow a binary assessment of design measures, as described in section 3.3.3. The assessment of the case-study products is described in Chapter 6.

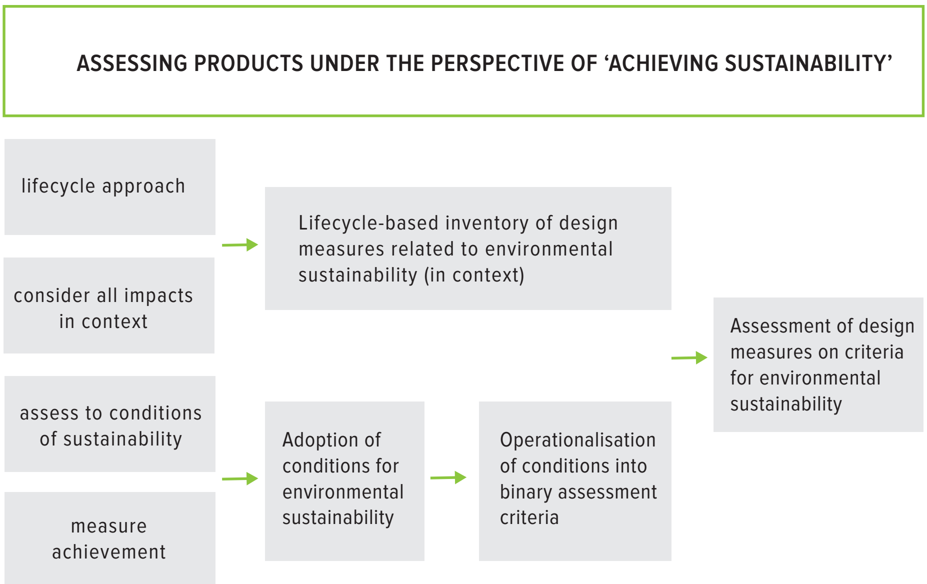


Figure 3.5: Schematic representation of the method for assessing the environmental sustainability of products

3.3.1 Inventory of design measures

For analysing the environmental sustainability measures taken by the designers, we adopted an existing typology of environmental product improvement options as developed by van Hemel, see Table 3.2 (Van Hemel, 1994, van Hemel, 1998). This typology includes the different life cycle phases of a product and allows for the inclusion of key environmental impact indicators across the life cycle: consumption of raw materials and energy, the output of waste, and the emission of substances (into air, water, and soil). Originally, this typology was developed to analyse Ecodesign practices, and several of the operational strategies are formulated with a 'reducing unsustainability' perspective. Nevertheless, this typology enables a life-cycle based analysis of the design measures taken, and is sufficiently generic to allow inclusion of the product context into the assessment. The measures taken by the designers will be analysed by reviewing each operational strategy, taking into account the possible occurrence of context-related beneficial impacts.

3.3.2 Adoption of binary conditions for environmental sustainability

The third constituent of the assessment framework requires the adoption of a set of conditions for sustainability. As described in section 3.2.3, no singular, scientifically established set of conditions is available, and coherent sets of criteria for product-systems have to be developed.

However, in Chapter 2 we already described how the perspective of 'achieving sustainability' is embedded in the design philosophy of both Biomimicry and Cradle to Cradle. This perspective resonates in the design principles that both strategies offer to guide the development of products. In Biomimicry, the Life's Principles are linked to 'creating conditions conducive to life':

> *"Life's Principles are design lessons from nature. […] Life integrates and optimises these strategies to create conditions conducive to life. […] By learning from these deep design lessons, we can […] measure our designs against these sustainable benchmarks […] using Life's Principles as our aspirational ideals" (Baumeister et al., 2013).*

In Cradle to Cradle, the use of the design principles is coupled to 'eco-effectiveness':

> *"The operating system of the natural world is an unrivalled model for human design. […] Human systems designed to operate by the same rules can approach the effectiveness of the closed-loop cycling of earth's diverse living systems in which almost no waste remains unused"(McDonough et al., 2003).*

1. Selection of low-impact materials:
    - a Clean materials
    - b Renewable materials
    - c Lower energy content materials
    - d Recycled materials

2. Reduction of materials usage:
    - a Reduction in weight
    - b Reduction in volume

3. Optimisation of production techniques:
    - a Clean production techniques
    - b Fewer production steps
    - c Lower/clean energy consumption
    - d Less production waste
    - e Few/clean production consumables

4. Optimisation of distribution system:
    - a Less/clean/reusable packaging
    - b Energy-efficient transport mode
    - c Energy-efficient logistics

5. Reduction of impact during use:
    - a Low energy consumption
    - b Clean energy source
    - c Few consumables needed
    - d Clean consumables
    - e No waste of energy/consumables

6. Optimisation of initial lifetime:
    - a High reliability and durability
    - b Easy maintenance and repair
    - c Modular/adaptable product structure
    - d Classic design
    - e Strong product-user relation

7. Optimisation of end-of-life system:
    - a Reuse of product
    - b Remanufacturing/refurbishing
    - c Recycling of materials
    - d Safe incineration (energy recovery)
    - e Safe disposal of product remains

8. New concept development:
    - a Dematerialisation
    - b Shared product use
    - c Integration of functions
    - d Functional optimisation

Table 3.2: Typology of operational Life Cycle Design Strategies in product design (van Hemel, 1998)

In their analysis of Cradle to Cradle, Van der Pluijm et.al consider the Cradle to Cradle principles as 'principles for a sustainable society' (van der Pluijm et al., 2010). The authors describe the principles as appealing and easily understood 'principles for success'.

Nevertheless, they emphasize that the purpose of the principles is to inspire and trigger creativity, and consider them insufficiently concrete and systematic to guide specific decisions. Within Biomimicry, the Life's Principles are explicitly purposed for evaluating designs, although their current formulation has a similar level of detail to that of the Cradle to Cradle principles. although the formulation of the design principles is not geared towards their use as conditions, the content of the principles may serve as a basis for 'conditions of sustainability'.

To address the fourth constituent of the framework, that of binary assessment, the design principles of both Biomimicry and Cradle to Cradle were analysed in order to determine whether they can provide 'demarcation points' for binary assessment, in other words, provide binary conditions of sustainability. A principle is suitable for binary assessment when it can be used as an *absolute* demarcation point on a binary scale, i.e. when the principle defines when to assess a product (characteristic) as either meeting that condition or not. In contrast, a *relative* condition defines whether a product (characteristic) is more or less of something. For instance, a demarcation for assessing the material H2O with the condition 'H2O needs to be frozen' provides an *absolute* demarcation point that is either met or not, whereas the condition 'reduce H2O temperature' provides a *relative* condition by which alternative samples can be ranked. All principles and sub-principles of Biomimicry and Cradle to Cradle, shown in Table 3.3, were rated either 'absolute' or 'relative'. The PhD researcher as well as three other researchers active in Nature-Inspired Design rated the principles independently. Where ratings among the four differed, the motivation for the rating was discussed to clarify differences in interpretation. Those principles for which three or all researchers agreed on the absolute nature of the principle are depicted in Table 3.3 in bold and marked with '*'.

Six of the Biomimicry principles and two of the Cradle to Cradle principles were rated as providing 'absolute' demarcation points. The two Cradle to Cradle principles are linked with four Biomimicry principles with respect to the theme they address, as indicated in Table 3.3: both 'Recycle all materials' (Biomimicry) and 'Waste equals food' (Cradle to Cradle) cover the use of raw materials and the handling of these materials after the use life of the product. Second, the Cradle to Cradle principle 'Use current solar income' overlaps with the energy part of 'Use readily available materials and energy' (Biomimicry) which refers to the use of 'freely available energy', i.e. forms of energy that rely on current sunlight (Baumeister et al., 2013, Benyus, 1997). The materials part of 'Use readily

Principles of Biomimicry	**Principles of Cradle to Cradle**
Evolve to survive	**Waste equals food***
- replicate strategies that work	
- integrate the unexpected	
- reshuffle information	
Be resource (material and energy) efficient	**Use current solar income***
- use multi-functional design	
- use low-energy processes	
- **recycle all materials***	
- fit form to function	
Adapt to changing conditions	Celebrate diversity
- incorporate diversity	
- embody resilience through variation, redundancy and decentralization	
- maintain integrity through self-renewal	
Integrate development with growth	
- **self-organize***	
- **build from the bottom-up***	
- combine modular and nested components	
Be locally attuned and responsive	
- use feedback loops	
- leverage cyclic processes	
- cultivate cooperative relationships	
- **use readily available materials and energy***	
Use life friendly chemistry	
- build selectively with a small subset of elements	
- **break down products into benign constituents***	
- **do chemistry in water***	

Table 3.3: Overview of guiding principles, which can be used to formulate conditions of sustainability. Principles that allow binary assessment are in bold and marked ‘*’, and linked to principles of the other strategy where applicable (for Biomimicry: Baumeister et al., 2013, for Cradle to Cradle: McDonough and Braungart, 2002, McDonough et al., 2003).

available materials and energy' (Biomimicry) refers to the use of locally abundant, accessible materials, showing overlap with 'Waste equals food' (Cradle to Cradle) on the availability of the raw materials. Furthermore, two Biomimicry principles 'break down products into benign constituents' and 'do chemistry in water' address toxicity and can be seen as demarcation points for assessing the absence of toxic emissions. Toxicity is not explicitly mentioned in the Cradle to Cradle principles, but 'safe' materials and products are an important characteristic under the 'Waste equals food' principle, and material safety is a major component of Cradle to Cradle certification (Cradle to Cradle Products Innovation Institute, 2012). Finally, two Biomimicry principles, 'self-organise' and 'build from the bottom up' have no direct counterpart in Cradle to Cradle. In addition, the applicability of these principles in the design process for assessing whether a product achieves sustainability is not clear in the available literature. Consequently, these last two design principles have not been included as suitable demarcation points.

The analysis of the design principles of Biomimicry and Cradle to Cradle has resulted in three groups of principles offering binary demarcation points which thereby can serve as conditions for sustainability within the current research project: 1) cycle materials (recycle all materials/waste equals food), 2) use current solar income (use readily available energy), and 3) use safe materials (break down products into benign constituents/do chemistry in water). These conditions match the topics of the nature-inspired 'cyclic|solar|safe' requirements as developed by Datschefski in design practice (Datschefski, 1999). As a consequence, a consistent set of conditions has been adopted for assessing the environmental sustainability of Nature-Inspired Design.

3.3.3 Operationalization of the binary conditions into assessment criteria

To assess the product designs against the selected conditions of environmental sustainability, these conditions need to be formulated in a manner that allows binary assessment of a product design. Therefore, the literature on existing assessment criteria and measurements related to the principles and conditions has been reviewed and used to formulate binary assessment criteria.

For condition 1) cycle materials (recycle all materials/waste equals food), three measurements are described in the literature that calculate a score based on characteristics of the input and output of materials, summarized in Figure 3.6. These measurements combine two criteria: one for input materials and one for output materials. The measurements for the material input are similar to each other and can be used to describe the first criterion: **I) input materials consist of recycled content or (rapidly) renewable content.** For the output materials, all formulations are more pragmatic than the

a) 'Nutrient (re)utilization index'(Cradle to Cradle Products Innovation Institute, 2012):

$$\frac{\left(\text{\% of the product considered recyclable or compostable}\right) \times 2 + \left(\text{\% of recycled or rapidly renewable content in the product}\right)}{(3 \times 100)}$$

In addition, criteria are formulated on whether a company has a 'nutrient management strategy' in place, and whether "the product is actively being recovered and cycled in a technical or biological metabolism" (ibid, p.50).

b) Herman Miller recyclability score, calculated per component using three criteria, the first of which defines 'full recyclability'(Rossi et al., 2006):

"Is the material a technical or biological nutrient and can it be recycled (or composted) within an existing commercial collection and recycling infrastructure? If yes, the component receives a score of 100%".

c) 'Cyclicity score'(Datschefski, 2002):

$$\frac{\left(\text{\% materials from recycled source}\right) + \left(\text{\% materials cycled at end of life}\right)}{2}$$

In this score, all organic materials are counted as being from a recycled source, as "they are made with recycled Carbon, Hydrogen and Oxygen" (ibid, p.77).

Figure 3.6: Measurements from literature for assessing the cycling of materials

'waste equals food' principle suggests, i.e. no measurement is set for the quality of the recycling process. The Cradle to Cradle certification procedure provides the following motivation:

> *"It is preferable to select materials that may be recycled into like or higher value products when possible. However it is understood that this is difficult to define as the collection infrastructure and recycling technologies are still in the early stages of development and the economic value of materials will change in the future" (Cradle to Cradle Products Innovation Institute, 2012, p.xvii).*

In other words, the responsibility of the designer is limited to designing a product of which the materials are recycled within the current recycling infrastructure. Taking this into account, the 'cyclicity score' provided by Datschefski and the Herman Miller recyclability criterion most accurately describe the principles of Biomimicry and Cradle to Cradle, as they refer to the actual cycling, and not to the capability of a product to be cycled. Consequently, the second criterion is formulated as: **II) output materials are recycled or composted.** When assessing products against this criterion, the product context will have to be included, as recycling infrastructures differ per region. Using this criterion, the design for other 'end of life' options, such as incineration with energy recovery, are not assessed as contributing to environmental sustainability.

For the second condition: use current solar income (use readily available energy) a certification criterion and score have been described, see Figure 3.7. The system boundaries used are important for determining the percentages used in the scores, but for the binary assessment, a score is not required, and the third criterion can be described as: **III) input energy originates from renewable resources based on current solar energy.**

a) Criterion for renewable energy (Cradle to Cradle Products Innovation Institute, 2012)

">100% of purchased electricity is renewably sourced or offset with renewable energy projects"

b) The requirement for 'Solar' and 'solarity score' (Datschefski, 2002):

"All materials flow and energy use is powered by photosynthesis, muscle or renewable energy"

"% kWh of energy that is solar, wind, muscle, photosynthetic, geothermal, hydro, or wave power".

Figure 3.7: Measurements from literature for assessing the use of energy

For the third condition: use safe materials (break down products into benign constituents/do chemistry in water) three different measurements were provided, see Figure 3.8. All three references address both the toxicity of substances and the exposure of those substances to humans or the environment. With the description of the first Life's principle, the example of snake venom is given to explain how toxins may be functionally required but not be harmful for the host, by being produced locally, on-demand, in small dosages and being biodegradable. The second principle seems to provide 'nature's solution' to prevent the use of toxic solvents, and as a consequence, may be considered

a) Descriptions of the Life's principles (Baumeister et al., 2013):

1) Break down products into benign constituents: Use chemistry in which decomposition results in no harmful by-products (there is no bio-accumulation of toxins).
2) Do chemistry in water: Use water as a solvent.

b) Criterion for Material Health (Cradle to Cradle Products Innovation Institute, 2012):

"All process chemicals have been assessed and none have been assessed as X".
X refers to substances that can be exposed to humans or the environment and have a "tendency to accumulate in the biosphere and lead to irreversible negative human health effects. In addition, several substances were selected due to hazardous characteristics associated with their manufacture, use, and disposal" (ibid, p.89)

c) The safety requirement and 'safety score' (Datschefski, 2002):

"The product is non-toxic in use and disposal, and its manufacture does not involve toxic releases or the disruption of ecosystems".

With releases being deliberate or accidental discharges of materials into the environment. Meeting this requirement corresponds to a safety score of 100%. To calculate relative improvements Datschefski (ibid) assesses the increase or decrease of a new products releases to the environment as compared to the releases of an equivalent product in 1990.

Figure 3.8: Measurements from literature for assessing product safety

a sub-principle of the first. In Cradle to Cradle certification, obtaining the highest level (Platinum) certification requires the elimination of all toxic substances that can be exposed to humans or the environment. Datschefski formulated a similar criterion. However, the 'safety score' that he formulated is relative, comparing release masses per product unit of the current product with one from 1990, and therefore provides no input to the binary criterion.

Based on the existing measurements, the following criterion has been formulated to address safety of materials and emissions: **IV) materials and emissions are safe to the system(s) in which they are released.** This criterion requires the inclusion of the product context into the assessment. The resulting assessment criteria are summarized in Figure 3.9.

I) Input materials consist of recycled content or (rapidly) renewable content

II) Output materials are recycled or composted

III) Input energy originates from renewable resources based on current solar energy

IV) Materials and emissions are safe to the system(s) in which they are released

Figure 3.9: Criteria for assessing the environmental sustainability of products

3.4 Discussion and conclusions

In this chapter, we described how we developed a set of criteria for assessing the contribution of NIDS to the development of sustainable products. Following on from the conclusions in Chapter 2, the study has been limited to the assessment of impacts on environmental sustainability. The theoretical inquiry into the sustainability of nature-inspired design, described in section 3.1, led to the understanding that existing assessment tools based on life cycle analysis do not cover some of the key results that NIDS strive to accomplish. Current assessment tools are geared towards measuring reductions in environmental impacts, not towards assessing to what extent products are environmentally sustainable. To enable product assessment under the perspective of 'achieving sustainability', a new framework has been proposed (section 3.2), with two new constituents for assessing environmental sustainability (Figure 3.5 p.53).

As explained in section 3.3, the development of a comprehensive new assessment method lies beyond the scope of this research. Instead, to assess the environmental sustainability of the products that are analysed in this study, a basic method was developed using four assessment criteria derived from the literature. These criteria, summarised in Figure 3.9, p.61, represent the conditions of environmental sustainability as proposed in the framework (Research Question 2), and will be used for assessing the sustainability of nature-inspired design. The criteria are based on the design principles that NIDS offer for 'achieving sustainability'. As a set, they cover key environmental impact indicators to be addressed in a life cycle analysis: input of materials and energy, the output of waste (materials), and the emission (output) of substances.

Not all nature-inspired design principles are covered by the conditions formulated for environmental sustainability. Resource efficiency, which is included in the Biomimicry Life's Principles, is a design principle not translated into a condition, as the (main) principle is not suitable for binary assessment. In nature-inspired design, efficiency may nevertheless play a crucial role, not as a target to achieve, but instead as a *means* for (physically or economically) meeting the defined conditions of environmental sustainability. For instance, one of the criteria requires that all energy inputs during the life cycle of the product be sourced from renewable resources based on current solar energy. Given a limited supply of energy (which may be limited for economic reasons), processes needed for material extraction, for production, and for use of a product, need to be sufficiently efficient. Therefore, efficiency is regarded as a means to achieve the formulated sustainability conditions, and not as a condition in itself. In addition to resource efficiency, the principles that address the interaction of a product (system) with an ecosystem that continuously adapts and evolves were not included. At this moment, 'celebrating diversity' and tapping into the dynamic nature of (eco)systems is not captured by, or coupled to a demarcation point for environmental sustainability. To address these principles, in Chapter 5 we qualitatively analyse the use of the design principles for each of the real-life cases. In Chapter 6, we use the method described in this chapter together with the assessment criteria formulated in Figure 3.9 to assess the environmental sustainability of the case-study results.

[1] Some products are specifically purposed to improve the quality of the environment, such as water purification systems. In that example, the primary function corresponds to it having a beneficial impact. These products can be considered end-of-pipe solutions, which are needed as long as other systems affect water quality.

[2] The occurrence and value of different articulations for sustainable development has been described by Mulder, Ferrer, and van Lente (2011).

[3] Traffic signs with retro-reflective coating reflect light of a car that passes, back to that car. As a result, the sign is clearly visible to the driver.

CHAPTER 4

Comparing Biomimicry and Cradle to Cradle with Ecodesign in Student Design Projects

The aim of this chapter is to reveal the effects of applying NIDS on the design process and its outcomes (Research Question 3). To elicit differences that may be specific for NIDS, two comparative case studies were conducted in which the effects from applying Biomimicry and Cradle to Cradle were analysed in comparison with effects from applying a more traditional design strategy (Ecodesign). The case studies analyse the results of student work from two courses at Delft University of Technology, in which students learn to design products using different sustainable design strategies.

Section 4.1 presents the research design. Section 4.2 describes the results of the pre-study with 6 student groups, exploring effects and characteristics by which differences between the design strategies can be compared. Section 4.3 expands on the findings with an analysis of the work of 27 student groups, to test the differences between groups that applied different design strategies. In section 4.4, we discuss how the strategies may have helped the students develop their solutions. The last section (4.5) presents our conclusions on what effects can be attributed to the application of Biomimicry and Cradle to Cradle.

Chapter 4 is based on: DE PAUW, I. C., KARANA, E. & KANDACHAR, P. V. Nature-Inspired Design Strategies In Sustainable Product Development: A Case-Study Of Student Projects. Proceedings of the 12th International Design Conference DESIGN 2012, 2012. 787-796.

DE PAUW, I., KARANA, E., KANDACHAR, P. & POPPELAARS, F. 2014. Comparing Biomimicry and Cradle to Cradle with Ecodesign: a Case Study of Student Design Projects. Journal of Cleaner Production, 78, 174-183.

4.1 Research design

Case study research was used to gain a thorough understanding of the effects resulting from the application of NIDS. For the two studies described in this chapter, a comparative set-up was chosen to highlight the findings that can be attributed to the application of Biomimicry and Cradle to Cradle[1]. The data for this study were gathered over three consecutive years from two courses on 'Sustainable Design Strategies' for final year Bachelor students and for Master students at Delft University of Technology, Faculty of Industrial Design Engineering (IDE). This research design enabled us to compare the design processes of groups working on similar assignments, but applying different design strategies: Biomimicry, Cradle to Cradle, and Ecodesign. This first section provides a brief comparison between NIDS and Ecodesign and presents the research set-up of the two studies.

4.1.1 Comparing NIDS with Ecodesign

To explore the effects specific to Biomimicry and Cradle to Cradle, we included the third design strategy taught in the courses, Ecodesign, in the research set-up as a 'baseline' strategy. In its broad interpretation, Ecodesign is understood as 'integrating environmental considerations in product design', and as such can be seen as an overarching term for all approaches concerned with environmental sustainability in design. To describe its application as a design strategy, a more strict definition is adopted in this thesis: "Ecodesign is a product development process that takes into account the complete life cycle of a product and considers environmental aspects at all stages of a process, striving for products, which make the lowest possible environmental impact throughout the product's life cycle" (Glavic and Lukman, 2007, p.1880).

Ecodesign has been described in literature for more than 35 years, with more widespread research and application in design practice emerging as of 1990-1995 (Lee-Smith and Gloster, 1975, Stevels, 2001, van Hemel and Cramer, 2002). A standard for applying this design strategy was for instance published with the UNEP Ecodesign manual (Brezet et al., 1997). Methods and tools have since been studied and developed further (see e.g. Bovea and Pérez-Belis, 2012, Byggeth and Hochschorner, 2006, Lofthouse, 2006). Ecodesign generally uses methods based on Life Cycle Assessment (LCA), such as Eco-indicator analysis (Goedkoop and Spriensma, 2001) for assessing environmental impacts that emerge throughout the life cycle of a product, in combination with guidelines or operational strategies for reducing these impacts[2].

When comparing NIDS with Ecodesign, both Biomimicry and Cradle to Cradle can be considered as relatively new design strategies that have been predominantly developed in design practice, whereas both academia and industry contributed to the development of Ecodesign. Consequently, Biomimicry and Cradle to Cradle have, so far, received less scientific debate, also compared to other approaches for sustainable design such as Product-Service Systems Design (see e.g. Mont, 2002, Tukker and Tischner, 2006, Vezzoli et al., 2015).

Similar to NIDS, Ecodesign focuses on merging environmental aspects of sustainability in the design process. However, Ecodesign is an eco-efficiency strategy with the objective of minimizing or reducing the environmental impact of products throughout their life cycle, whereas the objective of Biomimicry and Cradle to Cradle - described in Chapter 2 - is to challenge designers to develop products that benefit their environment. As a result, the strategies use different criteria and different terminology to define whether a product is successful. We therefore expect to find results that have a comparable focus on environmental sustainability and that reflect the differences between the objectives of NIDS and Ecodesign.

4.1.2 Set-up of the studies

Two studies were conducted. The first, a pre-study, explored the work of six student groups. We verified whether the student groups applied the design strategy assigned (application level), and explored which design choices they made and which sustainability aspects they took into account. Based on the results of the pre-study, a larger study was conducted with project results from 27 student groups. Application level was explicitly included, as design methodology research indicates that we should not expect full application of the methods and tools provided. The transfer of design methods and tools to design practice is acknowledged as being problematic (see for example Daalhuizen and Badke-Schaub, 2011, for a discussion). Lofthouse (2006) described a variety of factors that influenced the application of Ecodesign tools by industrial designers, which included time constraints, perceived benefits, and the form in which a tool conveys knowledge. In addition, the students involved in the case studies were novices in the use of the strategies, which may have caused some tools to be applied incorrectly. Therefore, we validated the application of the design strategies, and in the second study tested for possible significant differences in application level between the strategies.

Table 4.1 shows a schematic overview of the research set-up, which was based on the set-up of the courses (see also Appendix 3 for an excerpt of one of the course guides). Students were taught to apply one of the three design strategies: A. Biomimicry, B. Cradle to Cradle, or C. Ecodesign for designing a ‘100% sustainable’ product. The ‘100%’ target was set so that the students were sufficiently challenged to come up with a truly sustainable outcome. In 2010 and 2011, the project assignment was to design "100% sustainable cutlery and tableware" for the faculty canteen, commissioned by the fictitious caterer BiocateringNL that wanted to offer a complete catering solution. In 2012, the students were asked to design a "100% sustainable coffee machine" for groups of six people, commissioned by Redbeans, a supplier of biological coffee beans.

	Pre-study (2010)	**Main study (2011 & 2012)**	
Design assignment Design strategy	Cutlery & Tableware (6 groups)	Cutlery & Tableware (12 groups)	Coffee Machine (15 groups)
A. Biomimicry	'Biomimicry designs' (2 groups)	'Biomimicry designs' (4 groups)	'Biomimicry designs' (5 groups)
B. Cradle to Cradle	'Cradle to Cradle designs' (2 groups)	'Cradle to Cradle designs' (4 groups)	'Cradle to Cradle designs' (5 groups)
C. Ecodesign	'Ecodesigns' (2 groups)	'Ecodesigns' (4 groups)	'Ecodesigns' (5 groups)

Table 4.1: Schematic set-up of the case studies with 33 student groups

In total, 33 student groups, 154 students, participated in the courses over three consecutive academic years (2010-2012), each group included 3-6 Bachelor or Master students[3]. Most students had an IDE or other product design background. In order to have balanced groups and enable multi-disciplinary teamwork, students were assigned to groups according to their study background. Due to educational requirements, students from the Bachelor and Master programme were not combined within groups. One of the three design strategies was randomly assigned to each of the student groups.

Prior to the design assignment, the students received three half-day workshops on the design strategies, led by sustainable design experts trained in the respective strategies. Each workshop covered one strategy, providing the students with basic knowledge of the theory in the form of a lecture, followed by workshop exercises to gain experience with several strategy tools. Methods and tools were provided by the sustainable design experts.

For the design project, an external presenter, taking the guise of a fictitious representative of the company, introduced the assignment. Each group was provided with course material for the strategy they had been assigned and was encouraged to come up with a solution using that particular design strategy. The deliverables for the assignment were a group report, a presentation during which each group presented their design to their peers and jury members (lecturers and the company), and in the main study also a group poster. The students had 55 course hours to work on the design project within a period of four weeks, for group work, feedback from lecturers, and presentation.

4.2 Exploring differences: a pre-study with six student groups

As explained in the previous section, the pre-study explored the work of six student groups that each developed a concept for sustainable cutlery and tableware to be implemented at the IDE canteen. The aim of the pre-study was to: (1) determine to what extent the work of groups that apply NIDS differed from that of Ecodesign-groups; (2) explore the nature of these differences; and (3) generate tentative conclusions about the reasons NIDS may lead to different designs. Data were collected from the group reports, supported by the presentations, comments of the jury members, and the grading remarks from the lecturers.

4.2.1 Application of the design strategies

To validate whether the outcomes of the design projects could be linked to the strategies, we first analysed whether the students actually used the strategies during their design process by means of document analysis of the reports. For the pre-study, we compiled an extensive checklist containing the different steps and tools they were asked to apply, in total 20 to 21 checklist items for each strategy (Appendix 4). The researcher reviewed the contents of the student reports by analysing whether students applied each step or tool. The outcomes were graded as either a ‘yes’ (applied as instructed), ‘partly’ (some part was missing or only part of it was applied correctly), ‘incorrectly’ (the step or tool was not applied as instructed), or ‘no’ (the step or tool was not applied). Table 4.2 illustrates the grading process with an example for each grade.

Figure 4.1 summarizes the extent to which the six groups applied the assigned strategies. The groups applied more than 70% of the steps and tools from the checklist. Group 4 (Biomimicry) applied the fewest steps and tools and had the highest number of incorrectly applied items (14%), but still applied 57% of the steps and tools correctly or partly correctly. The Biomimicry groups skipped or only briefly addressed several steps that deal with translating ‘solutions in nature’ into solutions that can be used in product design; as a result, they only applied very direct analogies from biology. The C2C-groups had difficulties in developing a strategic vision and a roadmap to implement that vision. Common difficulties for the Ecodesign groups were defining the ‘functional unit’ and drawing conclusions, or setting priorities based on their analysis.

Checklist item		Grade	Researcher notes
Judging from the report, did the group...			
C2C17:	answer these tasks' questions (consumption or service, bio or tech cycle, how to cycle, how to close/ renew the loop)	**yes** - step/tool is used correctly	"questions not explicitly answered, but well described system"
BIO4:	use the worksheet 'evaluate' (using the life's principles)	**partly** - not all of the step/ tool used or not all used correctly	"the life's principle 'integrate cyclic processes' was mis-understood, problem of current system is not included here!"
BIO13:	discover 3 examples per function or life's principle	**incorrectly** - step/tool is used incorrectly	"only 5 examples in total, superficial and for search terms, not for functions or life's principles"
ECO8:	draw good conclusions based on their analysis regarding the aim for the new design	**no** - step/tool is not used	"Grader on p.7: 'I miss a clear conclusion, which of the 2 systems is better?' No aim for new design"

Table 4.2: Example of checklist items with grading 'yes', 'partly', 'incorrectly' and 'no'. Checklist items as listed in Appendix 4. BIO=Biomimicry, C2C = Cradle to Cradle, ECO = Ecodesign

4.2.2 Differences in design choices

Figure 4.2 shows the design solutions presented by the different groups. Most groups redesigned the cutlery and tableware, suggesting either reusable products combined with a deposit system to prevent theft, or disposable products, thereby eliminating the problem of theft. Looking at the results in more detail, we observed that the groups seem to have addressed the design assignment at different levels.

To explore possible differences in their design approach, the researcher first analysed the report texts for the words the groups used most frequently, to reveal different priorities in the approaches. Table 4.3 shows the 'top-10' most frequently used words for each group, based on the word frequency count of the reports, excluding 'common English words' such as 'the', 'and', 'we'. Singular and plural words are counted as one.

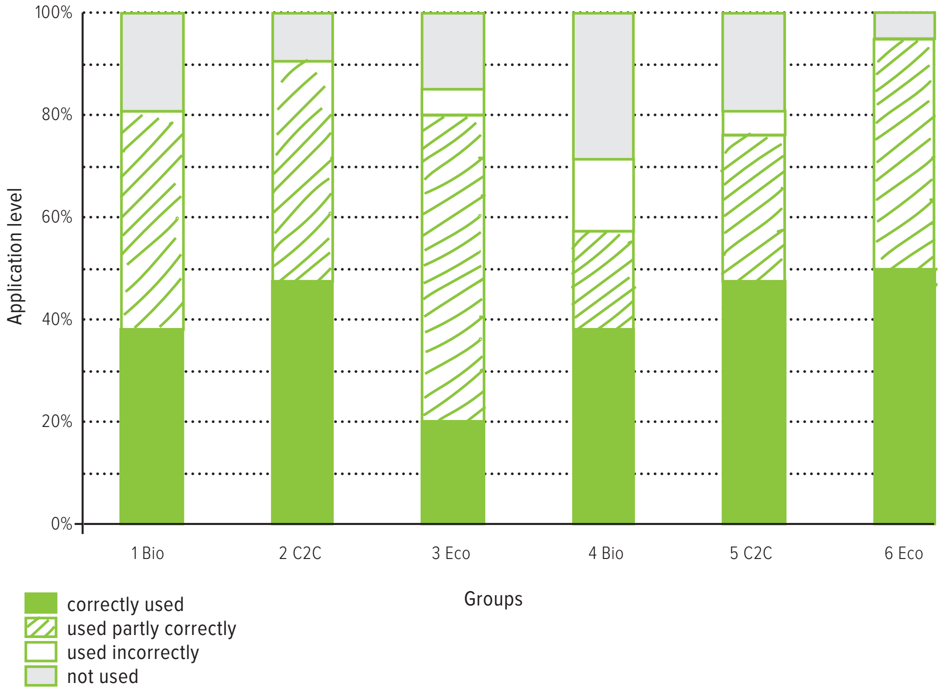


Figure 4.1: Application of the strategy, per group, based on the grading of the checklist with steps and tools. Bio= Biomimicry; C2C = Cradle to Cradle; Eco = Ecodesign

We found that only the word 'material' was frequently used by all groups. Furthermore, many of the top-10 words refer to the product(s), materials, production, or client. When looking at differences between groups using different strategies, the top-10 shows several of the words that directly relate to the strategies, being words that are mentioned in different steps and tools of a strategy. The words 'function', 'principle' and 'nature' were often used by Biomimicry groups; 'Cradle to Cradle' and 'cycle' by C2C-groups; and 'impact', 'ecodesign' and 'analysis' by Ecodesign groups. However, the analysis also showed that only the Biomimicry groups frequently used the word 'food'; and the C2C groups were the only ones that frequently applied words related to the environment in which the cutlery is used: 'canteen', 'students' and 'faculty', indicating that groups may have had a different focus depending on the design strategy they applied.

Group 1 - Biomimicry

'Spider-web' concept to prevent theft, with a large tray that has an integrated plate, cutlery fixed in place, and a deposit system.

Group 4 - Biomimicry

New food concept with edible packaging, eliminating the use of cutlery.

Group 2 - Cradle to Cradle

Closed cycle system, with design, production and recycling integrated with IDE educational system, using solar energy.

Group 5 - Cradle to Cradle

Reusable tableware and cutlery system using recycled PET, with collection-system for PET recycling.

Group 3 - Ecodesign

Design to prevent theft, using clip-on cutlery integrated plate/tray, check-in/check-out system and energy efficient washing.

Group 6 - Ecodesign

Disposable tableware and cutlery using 100% Fair-trade, biodegradable materials to be composted for food production.

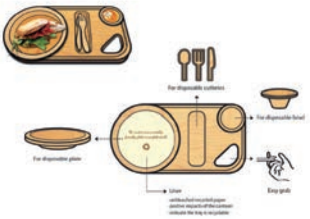


Figure 4.2: Summary of the design solutions of the six student groups, using three different design strategies to develop sustainable tableware and cutlery

No.	Group 1 Biomimicry	Group 2 C2C	Group 3 Ecodesign	Group 4 Biomimicry	Group 5 C2C	Group 6 Ecodesign
1	product	cutlery	cutlery	design	tableware	concept
2	tray	product	tableware	cutlery	material	impact
3	design	design	plate	food	canteen	sustainable
4	material	cycle	impact	nature	cup	material
5	food	material	material	sustainable	product	tray
6	cutlery	production	design	material	cradle to cradle	analysis
7	function	students	system	biomimicry	energy	tableware
8	principle	year	product	way	disposable	plate
9	nature	process	steel	process	reusable	cutlery
10	plate	faculty	Bio-catering	biocatering	system	ecodesign

Table 4.3: Top-10 most frequently used words per group, combining singular and plural words and leaving out 'common English words'. 'Cradle to Cradle' has been counted as one word.

To further analyse these differences, we categorized the design choices according to four 'solution levels' based on the 'Model of reasoning by designers' (Roozenburg and Eekels, 1995). These solution levels represent, the level of depth that the groups considered for achieving a design solution:

I. Material (the level that defines properties such as hardness, density, and viscosity).
II. Form (which, together with selection of material and production technique, defines product characteristics such as weight, stability, price).
III. Function (the level at which alternative products are considered to fulfil the current purpose, including new ways of using products).
IV. Need (the level at which alternative solutions are considered to meet the underlying needs of the user).

All groups addressed the material level (A), suggesting different materials than those currently applied, to improve the sustainability of the products. Only one group maintained stainless steel for the cutlery (Group 3 Ecodesign). Table 4.4 shows the materials the student groups selected for each of the tableware and cutlery products. Likewise, they all changed the shape of the product (level B), but most groups maintained the basic tray and cutlery shapes (Figure 4.2). The changes were introduced to improve appearance, ease of use, or stackability of the products. Three groups (1, 2, and 3) integrated the tray and plate to reduce material use and prevent theft, and therefore altered the shape of the tray/plate. Groups 1 and 3 introduced minor changes in the construction for clipping cutlery to the tray.

Group 4 (Biomimicry) introduced a new functional concept (level C): they replaced cutlery altogether by introducing edible containers and cutlery, thereby redesigning the way people eat their lunch. Group 2 (C2C) addressed the assignment up to the level of 'user needs' (D). They did not address the user need behind the primary function (having lunch), but combined the cutlery-system with the educational needs of the faculty. This group proposed having the products designed, produced, and recycled within courses at the faculty, thereby actively involving students in these processes. The purpose was to achieve added value for the customer's client (TU Delft) and at the same time establish a closed-loop recycling system. They additionally suggested that this solution would increase student awareness.

Product	Current design	Group 1 Biomimicry	Group 2 C2C	Group 3 Ecodesign	Group 4 Biomimicry	Group 5 C2C	Group 6 Ecodesign
Tray	glass fibre reinforced polyester	bioplastic or bamboo	none (product integrated)	none (product integrated)	not addressed	Seretex (recycled PET)	pressed palm leaves (pure)
Plate	ceramics / PS	none (product integrated)	PET, unfilled, amorphous	Hardwood	edible: wheat berry bread	Seretex (recycled PET)	plate liner: rec. paper or palm leaves
Cutlery	stainless steel / PS	'durable' bioplastic	PET, unfilled, amorphous	stainless steel	none (integrated/ replaced)	Seretex (recycled PET)	pressed palm leaves
Other		card & integrated print: unspecified	no print: barcode engraved	soup mug: hardwood with cutlery for grip	soup container: sweet pepper	bowl: Seretex print: unspecified	napkins: rec. paper bowl: palm leaves

Table 4.4: Types of materials selected by the student groups

4.2.3 Considerations regarding sustainability

Many of the design choices described in the previous section, relate to sustainability aspects of the tableware and cutlery system. Here, we explore the designers' considerations regarding sustainability.

All groups considered the ecological aspects of their solutions, which was to be expected from the steps and tools each strategy provided. For instance, we observed that they selected specific materials and production techniques as a way of improving the sustainability performance of their products. The Ecodesign and Biomimicry groups introduced bio-based materials: bioplastic, bamboo composite, wood, edible materials, or pressed palm leaves. These materials were described as being 'low-impact' (Ecodesign term) or 'natural' (a term used by all groups). In contrast, the Cradle to Cradle (C2C) groups selected 'technical' materials (PET and recycled PET) because they can be 'recycled without loss of quality'. Furthermore, each of the groups reduced the number of different materials used; only one group (5 C2C) explicitly mentioned this reduction, stating it would facilitate recycling.

Four groups aimed to alter consumer behaviour to address environmental impact. As currently theft of tableware and cutlery is a major problem at the canteen (causing increased material use at the canteen and switching to disposables as a result) these groups all propose some type of improved collection system for their reusable products. Two of them, Group 1 (Biomimicry) and Group 3 (Ecodesign), introduced a deposit system based on fines, and furthermore tried to change behaviour by designing a product that will show if cutlery is missing. The two C2C groups proposed systems aiming at *rewarding* positive behaviour, one with a deposit system based on rewards, the other using a 'fun-interaction' return system. In contrast, the two other groups switched to a system with disposables only, eliminating the need to retrieve the products.

The Ecodesign group with a reuse system proposed an energy-efficient washing system. The Biomimicry group with a reuse system did not consider energy aspects at all, whereas the C2C-groups did not address energy *efficiency*, but introduced *renewable* energy for the production and washing of the products.

Both C2C groups actively addressed the introduction of a recycling system, either to collect and recycle products at the faculty, or to collect the products and other PET-bottles to be recycled by a specific company. The other groups mentioned recycling or composting without specifying how they would implement this system.

To a varying degree, all the groups addressed the economic implications of their choices. They were instructed to come up with a 'realistic' solution, but were not asked for detailed calculations because of the limited time available for the assignment. Most groups referred to costs briefly, in qualitative terms; only Group 2 (C2C) proposed a business model for their concept, including a cost calculation.

Two groups mentioned social considerations in their reports, during material selection; Group 1 (Biomimicry) and Group 6 (Ecodesign) explained the production processes of their materials as 'providing an honest living for local craftsmen in India' or 'providing social benefits' by being '100% fair-trade'. Group 2 (C2C) proposed a new business model which includes increasing student skills and loyalty.

4.2.4 Discussion of the pre-study

The results of the pre-study provide insights into how the NIDS included in this case study may have helped the students develop sustainable products.

First, when comparing the findings per design strategy we observed that the Cradle to Cradle (C2C) groups selected 'fully recyclable' (fossil-fuel based) plastics as viable sustainable options, whereas the other groups suggested bio-based materials. Combined with this design choice, they specifically developed a recycling system, whereas other groups only addressed the 'end of life phase' in very general terms. These results may be attributed to the specific attention C2C pays to creating 'continuous material cycles' and the distinction between 'biological' and 'technical' cycles. As a result, C2C provides designers with more freedom in selecting materials – as long as they include a high-quality recycling system within their solution. Furthermore, both C2C-groups tried to change consumer behaviour by rewarding clients who returned their cutlery and tableware, a result that seems to match the C2C objective to create positive, beneficial designs. Finally, these groups suggested the use of solar energy for producing and cleaning the cutlery and tableware, clearly linked to the C2C-principle 'use current solar income'. The C2C groups had difficulties in developing a design vision and roadmap, activities that are new to product design students and therefore may require additional training. The design solutions of the two Biomimicry groups were quite different from each other. Nevertheless, both groups considered the basic function of the products, and included 'food' as an important topic in their design process, which broadened their solution space. Both groups applied natural materials, which -because they are grown naturally- meet several Biomimicry-principles (using 'free energy', 'benign manufacturing' processes and 'recycling of all materials'). However, the Biomimicry groups did not address these in as much detail as the C2C-groups addressed the corresponding principles of their strategy. This may be due to the large number of different principles that need to be addressed in Biomimicry. Many students described this strategy as inspiring but hard to apply, indicating Biomimicry may require more time to master, or the method itself may need improvement.

Second, when comparing the NIDS groups (C2C and Biomimicry) with the Ecodesign groups, we observed two main differences: whereas none of the Ecodesign groups changed the basic concept of having cutlery and tableware (beyond improving material impact, shape and logistics), one Biomimicry group proposed a functional innovation, using no cutlery at all, by implementing edible food 'containers'; and one C2C-group addressed the assignment at the level of 'user needs', locating all design, production and recycling at the faculty, as a part of improved student education. Both C2C and Biomimicry seem to influence the design process, because they require students to address the function or need for the product, which for two of the four groups resulted in markedly different outcomes. Secondly, the absence of quantitative tools for NIDS did not hinder most groups from developing designs that were well valued by lecturers and client, although one C2C-group did include an LCA-analysis to decide whether to design a reuse or disposal system. Compared to Ecodesign groups, the NIDS-groups seem to have spent more time on finding inspiration and 'design strategies' from nature (Biomimicry), and on actively incorporating a high-quality recycling system (C2C), at the cost of having no quantified problem analysis. The nature-based design principles, although they are qualitative, seemed to challenge the students because of their absolute nature (for instance 'Use renewable energy for all processes' instead of 'Use low impact energy processes') and, as a result, helped them to develop a design strategy and concept. Although the Ecodesign groups used a quantitative tool for this purpose, the outcomes were very dependent on accurate input of data, and the analysis seemed to limit the solution space. When students compared specific design alternatives, they did appreciate having quantitative data.

4.2.5 Conclusions of the pre-study

This pre-study helped us to get a first, general overview of the possible effects of applying NIDS for sustainable product development. The insights provide input for the follow-up study. Figure 4.3 provides a summary of the conclusions we have drawn from the analysis of the pre-study. First, we conclude that the application level, the extent to which the students applied their assigned design strategy, is a relevant variable to consider, as the groups did not apply all the steps and tools provided, and the number of steps and tools that were applied differed per group. Furthermore, the findings showed us that design strategies may influence the design focus and solution level at which the students develop new designs. For two of the four groups, applying NIDS resulted in markedly different solutions. We analysed the nature of the differences and formulated the following tentative conclusion, to be tested in the follow-up study. Biomimicry and Cradle to Cradle provide methods and tools that seem to encourage students to think out-of-the-box by addressing the design assignment at the level of product function or needs. Therefore, in the follow-up study, we will analyse both the design outcomes and sustainability considerations using the four solution levels generated from the pre-study.

As to the reasons why NIDS may influence solution levels when compared to Ecodesign, the pre-study highlighted that NIDS provide qualitative nature-based design principles that are formulated in terms of absolute (instead of relative) objectives. These principles seem to challenge the students to consider different solution levels. This finding will be explored further in the follow-up study and real-life cases.

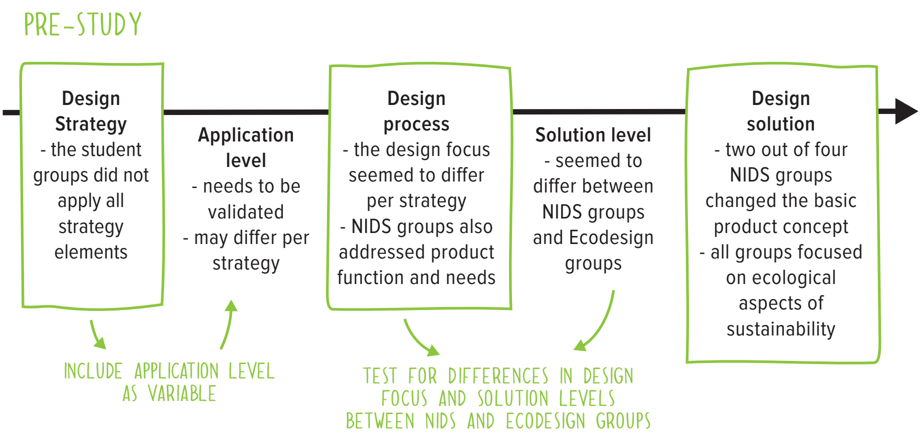


Figure 4.3: Summary of the findings from the pre-study with design students

4.3 Comparing design strategies: a follow-up study with 27 student groups

Based on the results of the pre-study, the following three objectives were formulated for the second study: (1) to analyse possible differences *in application level* between strategies, i.e. differences in the extent to which the students applied their assigned design strategy; (2) to explore whether the topics that the student groups *focus* on vary depending on the strategy applied; and (3) to explore whether groups that apply Biomimicry or Cradle to Cradle (both NIDS) interpret the assignment at different *solution levels*, and consequently design different types of solutions compared to groups that apply Ecodesign.

4.3.1 Procedure for data analysis

Application level

To analyse possible differences in application level between strategies (objective 1), we determine to what extent the student groups applied their assigned design strategy, based on document analysis of the reports. An inventory was made of the approach that the students were offered for each of the strategies. Compared to the pre-study, the checklist was simplified to 14-15 checks per design strategy, to focus on the specific steps of each design strategy. Furthermore, the list was slightly adapted to reflect minor changes in the course material. The resulting checklist is shown in Table 4.5. As in the pre-study, the reports, including the grading remarks from the coaches, were reviewed using the checklist, with each step graded either as applied 'correctly', 'partly correctly' (i.e. part of the required activity was missing or only part of the step was executed correctly), 'incorrectly' (i.e. the step was executed, but not as instructed), or as 'not applied' (see Table 4.2 for an example). To reduce the influence of the researcher, grading was performed by a second researcher, and reviewed by the primary researcher. Steps were discussed further in case a grade or the motivation for a grade was not clear to the primary researcher, and final grading was determined based on mutual agreement. An analysis of variance (one-way independent ANOVA) was executed to analyse whether overall differences in application level were statistically significant between the three strategies (using $p<.05$).

Design focus

As described in the previous section (4.2), the findings from the pre-study shed light on differences in the design focus of the student groups, i.e. in the topics that the groups focused on, such as the environmental impact of the product, its underlying function,

Biomimicry	Cradle to Cradle	Ecodesign
According to the report, did the students…		
1 explain the strategy	1 explain the strategy	1 explain the strategy
2 explain the specific method/approach	2 explain the specific method/approach	2 explain the specific method/approach
3 use the worksheet ‘evaluate’ (using the life principles)	3 make a scheme for the current life cycle	3 define the functional unit
4 select life principles	4 define the appropriate cycle	4 define and quantify all current processes
5 name the design function of the assignment	5 try to categorize all materials using the ABC-X categorization	5 calculate eco-indicator points for all phases in the product life cycle
6 use the Biomimicry Design Spiral questions for distilling the design function	6 develop a vision for the ideal Cradle to Cradle design, to be reached in 2020-2025.	6 present the results of the analysis
7 use the Design Spiral questions for translating to biology	7 develop a Cradle to Cradle roadmap for the company based on their vision	7 draw good conclusions based on their analysis regarding the aim for the new design
8 check the AskNature database	8 look for benefits/added value	8 fill in the Ecodesign strategy wheel
9 discover 3 examples per function	9 define nutrient pathways (consumption or service, bio/tech, how cycle, how close/renew loop)	9 set priorities for the new design, based on the analysis
10 describe useful natural solutions	10 design several solutions	10 design several new solutions
11 brainstorm multiple solutions emulating, not copying the solutions found in nature	11 develop these solutions based on their roadmap	11 develop a new product (or system) that has a significantly better score on some of the strategies
12 design several solutions	12 develop one into a design	12 fill in the strategy wheel for the new design (before & after)
13 develop one into a design	13 evaluate and test the new design	13 define and quantify all processes
14 use the worksheet ‘evaluate’ (for the new design)	14 use the Cradle to Cradle certification criteria for evaluation	14 calculate eco-indicator points, for all phases in the product life cycle
		15 draw conclusions based on their analysis

Table 4.5: Checklist for analysing whether student groups applied the given design strategy*

* Methods and tools were provided by the sustainable design experts. References to specific methods and tools are, for Biomimicry (Benyus, 2013, Biomimicry 3.8, 2012, reference to the earlier versions used in the course: Biomimicry Guild, 2010b, The Biomimicry Institute, 2008), for Cradle to Cradle (Bor et al., 2011, Cradle to Cradle Products Innovation Institute, 2012, EPEA, 2013), and for Ecodesign (Brezet et al., 1997, OVAM, 2010).

or the system in which it was to be used. The differences provided insights into potential effects of the different design strategies. This main study expands on these findings by exploring whether the topics that the student groups focus on vary depending on the strategy applied (objective 2). Accordingly, our question was:

> **Do the topics that the student groups focus on in their project differ per strategy, more than they differ between groups that apply the same strategy?**

Word frequencies in the student reports have been taken as a measure to determine words of interest, using coding and categorization of the results to uncover patterns (Stemler, 2001, Weber, 1990). First, an inventory was made of the top 10 of words used most frequently by each group, based on the word frequency count of the reports. In determining the top 10 frequencies, single and plural forms of words were combined. Verbs and 'common' English words were excluded from the top10 frequency list. Next, the words resulting from the inventory were categorized into topics the students focused on, using emergent coding. In this technique, the data to be coded is analysed for establishing the coding categories (i.e. the topics). Each category was subsequently defined, and all top 10 words were assigned to one of the categories based on these definitions. Following the categorization, statistical analyses of variance were performed using one-way independent ANOVA with post-hoc test (using Games-Howell Comparison) to evaluate whether the focuses of groups varied significantly across strategies.

Solution level

The third research objective addresses the type of solution that the students suggested. The corresponding question has been formulated as:

> **Do student groups that apply NIDS more often interpret the product assignment at the level of 'function' and/or 'needs', as compared to groups applying Ecodesign?**

Content analysis of the student reports was used to explore differences in the type of solutions. After the findings from the pre-study, we defined in more detail the following four 'solution levels', based on the 'Model of Reasoning by Designers' (Roozenburg and Eekels, 1995):

I. Material level: Solutions are categorized on this level when the designers applied alternative materials or energy sources to enhance product sustainability. For example, this includes the use of bio based or recycled materials, and of renewable energy sources.

II. Form level: This level applies when the physical appearance of the product was altered to improve the sustainability performance, but the function of the product stayed the same. An example is changing product shape to reduce the amount of materials used.

III. Function level: At this level, the function of the product was altered, or new functions were included to increase product sustainability. Two types of functions are considered in the analysis: product functions and system functions. Solutions with new product functions may include, for example, new ways of 'portioning and transporting food' or 'making a cup of high quality coffee', and solutions with new system functions may provide alternatives to the cleaning system or the logistic system, for instance.

IV. Needs level: Project results have been categorized at the needs level if specific needs were addressed and alternatives for fulfilling these needs were incorporated in the design to increase sustainability performance. In the student projects, the underlying need could for instance be described as 'providing the user with tasteful nutrients and a pleasant break from work'.

To detect significant differences between groups that applied either NIDS or Ecodesign, we analysed results of the content analysis using Fisher's exact test for small sample sizes. In addition, an independent t-test was performed for cross-comparing design focus with solution levels.

Exploring differences in sustainability measures

Due to the largely qualitative and conceptual nature of the student work, no quantitative analysis could be made for the impacts on sustainability. Nevertheless, for gaining qualitative insights into the possible differences between strategies, the sustainability measures were explored in more detail, based on the data available in student reports. We reviewed grading remarks on sustainability performance and looked for adverse impacts that might occur as a result of the new design; they checked apparent increases in the consumption of material and energy, the use of higher-impact materials or energy resources, and possible reductions in product lifetime or functional performance.

4.3.2 Differences in the application of the design strategies (objective 1)

Figure 4.4 summarizes the extent to which the 27 groups applied the strategies they were assigned. All groups applied more than 50% of the steps from the checklist, graded either 'correctly', 'partly correctly', or 'incorrectly'. On average, Biomimicry groups applied most of the steps (87%), Ecodesign groups 83%, and Cradle to Cradle groups 76%. However, the one-way independent ANOVA showed no statistically significant differences between the

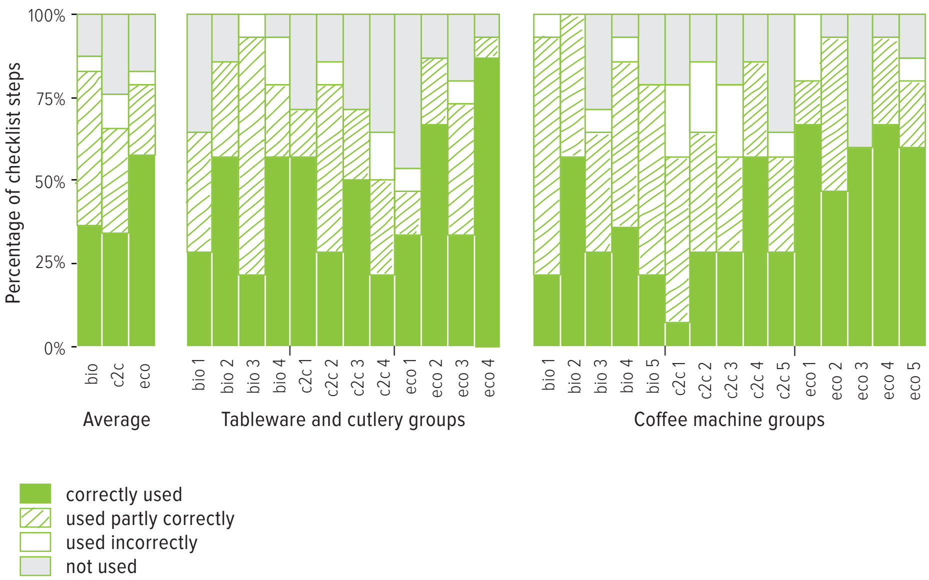


Figure 4.4: Application of the different design strategies per group, showing the level of application in four categories, based on the grading of the checklist steps. Bio= Biomimicry; c2c = Cradle to Cradle; eco = Ecodesign

groups that applied different design strategies, with $F(2, 26) = 1.66$, $p > 0.05$. As each group applied more than half of the checklist items, none of the groups has been excluded from further analysis.

The grading in Figure 4.4 shows that on average Ecodesign groups have a higher percentage of correctly applied steps (58%) than the 'NIDS groups' (35%). Results differed between groups, but several Biomimicry groups had difficulties in designing more than one solution, and several Cradle to Cradle groups showed difficulties in developing a company roadmap for meeting their vision for the ideal Cradle to Cradle design.

4.3.3 Differences in design focus (objective 2)

Table 4.6 shows the nine topics that resulted from the emergent coding of the student reports, with all top 10 words (words used most frequently by each group) categorized according to these topics. For several words, the context in which they were (predominantly) used in the report is added in Table 4.6 to clarify their meaning. Most

Topics	Topic description	Top 10 words in 2011 Tableware & cutlery	Top 10 words in 2012 Coffee machine
Comparing	Words used for comparing products and assessing differences	current, new, quantity, result, subtotal, versus	new, sarista (name of an existing coffee machine) total
Context	Words describing the context of the product	canteen, customer, situation, Sodexo (fictional client), user	break ('coffee provides a break'), people, Redbeans (fictional client)
Energy	Words related to energy and energy sources	energy, solar	battery, energy
Function	Words describing product functions, inputs and outputs	cleaning, cooling, eating, food, function, waste	bean, coffee, function, ground, heat, water
Generic	Generic words (top 10 words not categorized elsewhere)	figure, one	project, solution
Materials	Words related to material families and types	bamboo, ceramic, material, metal, PLA, plastic, PS	material, steel, zeolite
Product	Words describing products and product performance characteristics	concept, cup, cutlery, design, durable, item, plate, product, redesign, tableware, tray, weight	coffee machine, concept, cup (used as: 'per cup'), design, filter, grinder, part, product, redbeans-mini (product name), wired (product name)
Strategy	Words specific to the sustainable design strategy used (bio=Biomimicry, c2c=Cradle to Cradle, eco=Ecodesign), including 'sustainable' and 'environmental'	biomimicry (bio), cradle to cradle[w] (c2c), environmental, impact (eco), indicator (eco), life principle[w] (bio), nature (bio), strategy, sustainable.	cradle to cradle[w] (c2c), ecocost (eco), LCA (eco), nature (bio)
System	Words describing the product-system, or processes and products in that system	cycle, packaging, process, production, recycling, system, transport	cycle, process, production, system

Table 4.6: Categorization of all top 10 most frequently used words from the student reports into nine topics (presented in alphabetical order). Terms marked * are counted as one word.

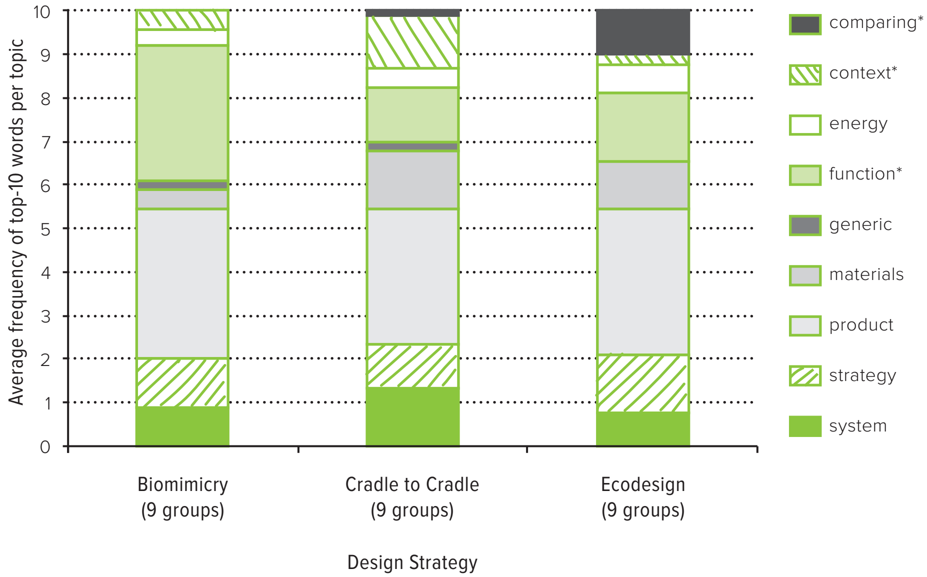


Figure 4.5: Topics addressed in student reports (years 2011 and 2012), based on the ten most frequently used words in the group reports, per design strategy. Topics marked * show significant differences between the design strategies

topics reflect upon characteristics of the solution, some on the design activities, and four words were categorized as being used predominantly in a generic meaning.

Figure 4.5 shows per strategy the average frequencies of top 10 words per topic, as used by the groups in their reports. The results confirm that the design focus in the student groups' work differed, depending on the strategy they had been assigned, for instance for the topics 'comparing', 'context', 'function', and 'materials'. The statistical analysis (ANOVA) showed a significant difference in variance across the design strategies for three topics (marked with * in Figure 4.5): for 'comparing' $F(2, 24) = 13.27$, $p < .05$; for 'context' $F(2, 24) = 5.26$, $p < .05$; and for 'function' $F(2, 24) = 7.16$, $p < .05$. For the other topics, differences were not significant ($p > .05$). These results indicate that group focus differed specifically in comparing the new product with existing ones, in regarding the functional aspects of the product, and in regarding the context in which the product is used. On average, the top 10 most frequently used words of the 'NIDS groups' referred more to function and context, whereas the 'Ecodesign groups' used more words for comparing

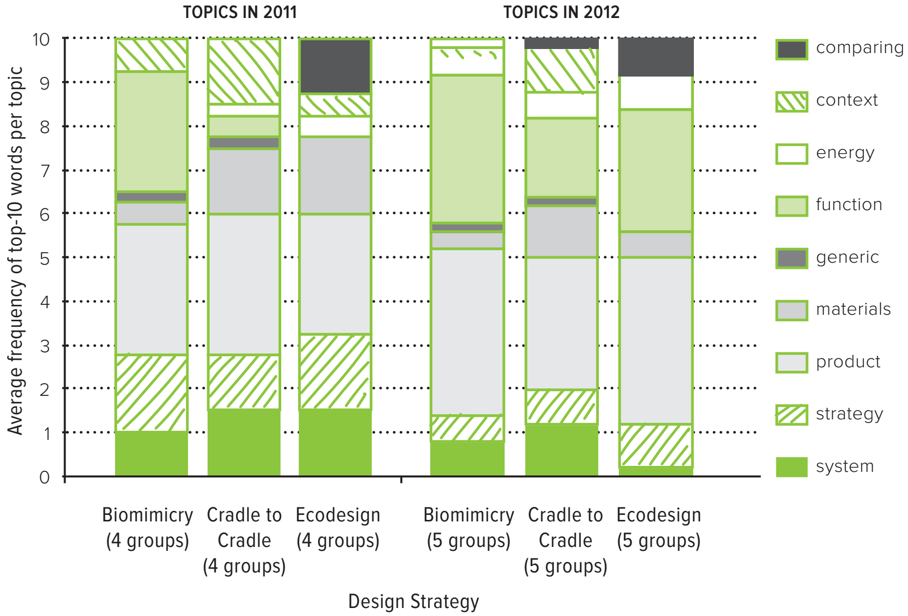


Figure 4.6: Topics addressed in student reports per year, showing frequencies per topic across the two course years, with the assignment for tableware & cutlery in 2011 on the left, and that for the coffee machine in 2012 on the right

	Design strategy									
	Biomimicry			**Cradle to Cradle**			**Ecodesign**			**Total**
Year	2011 (n=4)	2012 (n=5)	Total (n=9)	2011 (n=4)	2012 (n=5)	Total (n=9)	2011 (n=4)	2012 (n=5)	Total (n=9)	(n=27)
Solution level			%			%			%	%
Material	3	3	**6**	4	5	**9**	4	5	**9**	**24**
			67%			100%			100%	89%
Form	4	5	**9**	3	5	**8**	3	5	**8**	**25**
			100%			89%			89%	93%
Function	3	3	**6**	4	3	**7**	2	1	**3**	**16**
			67%			78%			33%	59%
Need	0	2	**2**	2	4	**6**	0	0	**0**	**8**
			22%			67%			0%	30%

Table 4.7: Occurrence of solution levels in the project designs, showing the number of groups (n), per design strategy and per year, implementing alternative design solutions at one of the four solution levels

products. The results from the post-hoc analysis (using $p<.05$) confirm that for the topic 'context' the difference is statistically significant between groups that applied Cradle to Cradle (M=1.22) and Ecodesign (M=0.22), but the difference between Biomimicry (M=0.44) and the other strategies is not significant. The focus on product 'function' is significantly different for groups that applied Biomimicry (M=3.11 versus M=1.22 for Cradle to Cradle and M=1.56 for Ecodesign); and the focus on 'comparing' is significantly different between groups using NIDS and Ecodesign (M=.00 for Biomimicry, M= .11 for Cradle to Cradle, and M=1.00 for Ecodesign).

Figure 4.6 depicts the focus of the groups per design assignment. Only qualitative interferences are made because of the smaller number of groups per year. The findings match the overall findings for the top 10 word topics 'comparing' and 'context', but not for 'function'. In 2012, more function-related words were used in the student reports for each strategy, and especially Ecodesign groups rated higher, with on average 2.8 function-related top 10 words, whereas no such words were used by Ecodesign groups in 2011. Possibly, the design of the coffee machine, with its more complicated product layout, required the students to more thoroughly analyse its functional processes. If so, the score on function-related words may not be (solely) representing the designer's consideration of alternatives for the coffee machine.

4.3.4 Differences in solution level (objective 3)

Figure 4.7 provides an impression of the designs as presented by the student groups: for sustainable tableware and cutlery (left column), and for a sustainable coffee machine (right column). To explore whether the student groups applying NIDS developed different types of solutions as compared to groups that applied Ecodesign, we analysed at which level(s) the students groups interpreted their assignment.

The 27 design solutions were assessed according to the four solution levels described in the method's section: Material, Form, Function, and Needs level. Table 4.7 shows the number of groups that implemented design solutions at the four levels, specified per design strategy and year. When a solution addressed subsequent solution levels, these were counted in each applicable level. For instance, the coffee machine design of group 'bio2' (shown in Figure 4.7), incorporates a new modular product form to reduce energy use (level II), and was designed to enhance social interaction between people (level IV).

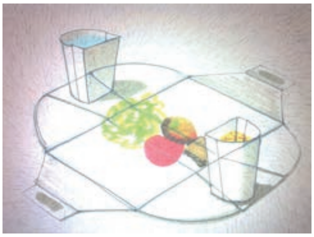
Most groups implemented solutions at the material and form level (I & II). Only three Biomimicry groups did not consider the materials of the designed solution, and two groups (one using Cradle to Cradle, one using Ecodesign) maintained the original shape

TABLEWARE & CUTLERY (2011)

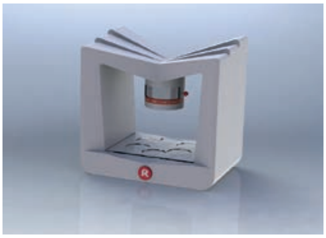
COFFEE MACHINE (2012)

Biomimicry

Meal box-system with three components: Cups-Box/Tray-Cutlery. Meal box, tray, and plate are integrated, disposable, and recyclable. Food is sold unpacked. [bio3]



The ‘Ardente’ is inspired on mammals, molars, segmentation, and capillarity. Designed to produce multiple cups at a time and makes both coffee and espresso. [bio2]



Cradle to Cradle

Cutlery and tableware are reused as raw material for 3D printed models at the faculty or for designs from the Porceleine Fles. [c2c3]

‘WiRed’ brings people together (Wi) and shows them how the Redbeans (Red) should be processed into very good coffee. [c2c5]

Ecodesign

This biodegradable set of cutlery and tray create awareness of usage thanks to small inscriptions. Overuse is discouraged by design (break off cutlery) and by cost.[eco3]

The coffee maker is mounted on the wall for the users to enjoy a ‘personal handmade’ espresso. A lever is used for manual grinding of the beans and building up pressure. [eco5]

Figure 4.7: Impression of project designs

of the tableware. Fewer groups addressed the assignment at the levels of function and need: 16 groups (59%) and 8 groups (30%) respectively.

The results confirm that when students applied NIDS, they interpreted the design assignment at the level of 'function' and 'need' more often ($p < .01$, Fisher's exact test). Overall, 19 out of 27 student groups interpreted the product assignment at the level of product function and/or needs (five groups implemented solutions at both levels). Of these groups, 16 groups applied NIDS, which amounts to 89% of the NIDS groups, and 3 groups applied Ecodesign, 33% of the Ecodesign groups.

When comparing the academic years 2011 and 2012, findings across the two assignments confirm the main result. In both years, students assigned to NIDS were dominant in providing solutions at the level of functions and needs (88% and 90% of the NIDS groups versus 50% and 20% of the Ecodesign groups respectively), with the results being more apparent in the second year.

4.3.5 Differences in sustainability measures

As presented in the previous section, NIDS groups more often incorporated alternatives for product and system functions, or fulfilled user needs in a different way. But how does this approach influence the solutions that are developed? Here, qualitative results are presented on differences in the sustainability measures taken by the designers.

Differences per solution level

At the material level (Level I) groups from all three strategies applied alternative, 'low-impact' materials to reduce the environmental impact of the product. Ecodesign groups selected recycled materials more often (5 groups), including one group that reused second-hand cutlery. The three Biomimicry groups that did not consider the materials level addressed other levels instead. One of the groups explained: "*When we started this project, we didn't expect this concept as an outcome. We expected that we would design a concrete product, such as a new set of cutlery. But after our research we realized that the challenge of becoming sustainable could be found on a much higher level.*"

At the form level (Level II), reduction of current impacts was also the motivation for most changes. Interestingly, all 2012 groups altered the design to include manual powered processes, usually for grinding the beans and also in some products for pressurizing the water, thereby reducing energy consumption (within system boundaries). Additionally, two groups of each strategy changed product shapes or introduced features to change user behaviour. Ecodesign groups focused on efficiency: reducing energy consumption (insulation of the heated water and more efficient heat exchange) or using less material per unit, whereas, compared to other groups, Biomimicry groups were more frequent in suggesting solutions to integrating products (plate and tray, or spoon and fork) or to use bulk packaging only. Cradle to Cradle groups did not attempt to increase the energy efficiency of the products, but instead focused on using other energy sources, such as waste heat and renewable energy. The two groups that did not alter product shape used polished second-hand cutlery instead (Ecodesign), or focused on the recycling of the cutlery (Cradle to Cradle).

At the function level (level III), most groups (14) designed solutions for the collection, recycling or composting of materials. For instance, one group (coded 'c2c3' in Figure 4.6) proposed that the plastic tableware be reused and, once disposed of, recycled into granules for the faculty 3D-printing machines. The reusable ceramic plates were to be recycled by a local 'Delft blue' producer, either into new plates for the canteen or into high-end ceramics.

NIDS groups offered specific recycling solutions three times more often (six groups of both strategies) than Ecodesign groups (two groups). Additionally, three Biomimicry groups designed out-of-the box products at the function level: two suggested the elimination of cutlery in favour of ready-made food, the third implemented a cold coffee extraction process to produce coffee with similar quality to espresso, to achieve a drastic reduction in energy consumption. One Ecodesign group recommended that the client install solar panels on the canteen roof, to reduce impact from the washing process of the tableware and cutlery by 29% to 40%, and additionally provide the faculty with a surplus of renewable energy.

As indicated in the previous section, only NIDS-groups addressed their assignment at the level of needs (level IV). Four groups developed solutions to improve the value of what people receive from "getting and having a coffee", and designed their product to increase the coffee drinkers' productivity and creativity, to "enhance group bonding", or to provide a more social coffee break. Four other groups, all applying Cradle to Cradle, suggested solutions to improve the quality of the users' space, by introducing plants and/or herbs into the canteen or workplace, providing reported benefits of "cleaning indoor air", "providing fresh food", up to "increasing biodiversity".

Considering the risk of shifting burdens

Based on the measures taken by the student groups, the researchers expect adverse impacts from solutions of five groups. Of two designs, the weight increased considerably (1 Biomimicry group, 1 Cradle to Cradle), two others are expected to consume more energy than the original machine (1 Biomimicry, 1 Cradle to Cradle), and one group incorrectly applied eco-indicators, resulting in the selection of a material with higher impact (1 Ecodesign group). Additionally, five groups (1 Biomimicry, 2 Cradle to Cradle, and 2 Ecodesign) implemented coffee brewing methods that can be considered to produce coffee dissimilar to espresso. Therefore, the reported decrease in energy use is coupled with a change in product quality, which was not acknowledged by the students. One other group (c2c4) was predominantly concerned with solutions that the students considered necessary to provide a beneficial work break. No adverse impacts of their design are anticipated, but the majority of sustainability issues of the design were neglected.

Focus on environmental sustainability
As described in section 4.1, the three strategies have their scope or focus on the *environmental* impacts associated with the product, as opposed to social impacts. Nevertheless, the students were asked to design a fully sustainable solution. The results indicate that indeed little to no attention was paid to social sustainability issues. The groups that did consider social structures, considered the users of their product, for instance by facilitating a 'social coffee break'. Some groups referred to the social aspects incorporated by their client (fair trade food/coffee), but did not consider these issues in the design of their product. One group referred to Corporate Social Responsibility, but only when evaluating their design.

4.4 Discussion

Based on the significant differences in the design focus, solution levels, and specific designs, that are related to the design strategies, we discuss below how the Nature-Inspired Design Strategies included in this study may have helped the students in their aim to design 'sustainable products'.

4.4.1 How design strategies can shift design focus

The differences in the design focus of groups using either Biomimicry, Cradle to Cradle, or Ecodesign, point to the influence of design strategies. Biomimicry, as taught in the course, asked the design students to translate the assignment to a functional level, in order to find useful examples in nature, thereby 'inviting' them to reconsider current product solutions. Cradle to Cradle challenged the groups to generate 'beneficial effects', which coincides with the context-specific systems focus adopted by the majority of these groups. Conversely, Ecodesign focused the groups on comparing, analysing the 'hot spots' in current products, which provided the students with the basis for reducing the product's environmental impacts.

Compared to the groups that applied Ecodesign, the stronger focus of the 'NIDS groups' on the product context (people, companies and circumstances interrelated to the product-system) signifies the influence of guiding design principles in the design process. Both Biomimicry and Cradle to Cradle have design principles and tools pointing to the value of developing solutions that are 'diverse', specifically tuned to their (local) environment (Benyus, 1997, McDonough and Braungart, 2002). Earlier case studies did not address the application of the guiding principles, which may explain why the findings were not observed prior to this research.

4.4.2 How NIDS can affect the level at which the assignment is interpreted

The results of this study indicate that Biomimicry and Cradle to Cradle help design students to consider solutions at a 'broader' level, including alternatives for fulfilling product functions, system functions, or user needs. As to how NIDS can affect the solution level, we draw on the cross-comparison of the design focus and solution levels of Study 2. On average, groups that interpreted the assignment at the level of function and/or needs, more often used 'context words' frequently in their reports ($M = .89$, $SE = .19$) than groups that did not address these levels ($M=0$), with a significant difference between the two types of groups (*t*-test, with *t*-statistic = -4.82, $p < .01$). The opposite relation was found for the frequent use of 'comparing words' (with $M = .16$ for groups that addressed the level of function and/or needs, versus $M = .88$ for groups that did not address these levels) being also significant (*t*-statistic = 2.33, $p < .05$).

All 13 groups that used context-related words frequently (8 'C2C groups', 3 'Biomimicry groups', and 2 'Ecodesign groups') addressed the project at the level of function and needs, and nine of them (5 'C2C groups', 3 'Biomimicry groups', and 1 'Ecodesign group') also proposed a context-specific solution (such as a recycling infrastructure coupled to specific local companies). Supporting integration of the product context may be a distinct feature, stimulated in nature-inspired design, for enhancing the sustainability of the system. Secondly, the reported focus of Ecodesign groups on *comparing* products may provide additional understanding into the differences in the designs. The time spent on analysing existing products at the start of a project, may have limited the time the students had available to consider more-encompassing solutions. In contrast, NIDS offered challenging 'absolute' design principles, which may have encouraged the students to widen their solution space in their effort to meet the principles. Likewise, the office chair case as described by Lee (2009) and Rossi et al. (2006) illustrates how 'absolute' limitations, posed by the Cradle to Cradle strategy, allowed more time to be spent on finding solutions within these boundary conditions.

4.4.3 Resulting differences in solution levels

More out-of-the-box designs emerged from groups that applied NIDS, with examples such as a canteen that no longer uses cutlery, or that reuses cutlery as material for 3D printing, or a coffee machine using cold-water coffee extraction. Although earlier studies offer no comparison between different strategies, the products described in these studies partly match the classification of out-of-the-box designs. The Biomimicry cases described by Reap et al. (2005) and Montana-Hoyos (2008), and the Cradle to Cradle office chair (Rossi et al., 2006) contain functional innovations. Furthermore, the Cradle to Cradle studies report a shift to close cooperation with suppliers, although only the graduation project (Bakker et al., 2009) describes the development of new system functions. Innovations in meeting user needs were not reported.

Addressing the design assignment at the level of function and needs allows for the development of more radical solutions. However, if, and to what extent NIDS tap into this potential and generate superior sustainability performance, could not be assessed from the results of the design projects. The results suggest that NIDS influence students to set more ambitious goals and objectives. The proposed functional innovations may drastically reduce the environmental impact of the designs, and the product-service-systems may have a similar effect. However, quantitative design data would be needed to perform an analysis of these solutions to determine overall impact on environmental sustainability. Such an analysis will be performed for the real-life cases. Nevertheless, the current case studies already demonstrated that groups applying NIDS, as compared to Ecodesign groups, run a higher risk of introducing adverse impacts with their solutions. Whereas the design principles of Biomimicry and Cradle to Cradle seem to offer a strategic alternative to the hot-spot analysis in Ecodesign, these principles offer no alternative for quantitative product evaluation such as available in Ecodesign.

4.5 Conclusions

In this chapter, two Nature-Inspired Design Strategies, Biomimicry and Cradle to Cradle, have been compared with Ecodesign, using results from students' work in sustainable product design, to understand the effects that NIDS have on the design process and on the design outcomes (contributing to Research Question 3). As summarized in Figure 4.8, our analysis showed significant differences in the design focus of the student groups, depending on the strategy they applied. Additionally, the main study confirms the finding from the pre-study, that NIDS help students to consider more solution levels. Whereas most groups in the main study applied different materials and changed product shapes to

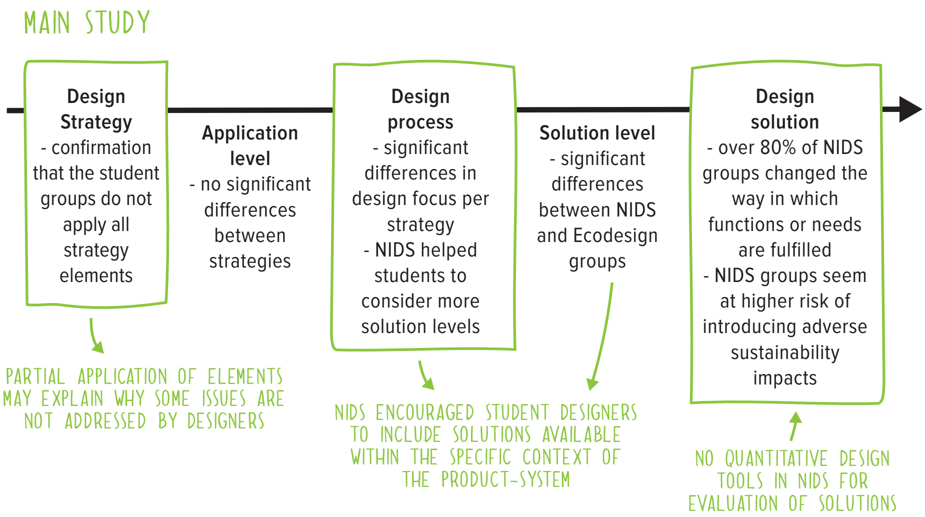


Figure 4.8: Summary of the findings from the main study with design students

improve the design, the majority of the 'NIDS groups' (over 80%) also included solutions that provide alternative and new product or system functions, or included new ways to fulfil user needs. In contrast, only one third of the groups applying Ecodesign suggested such solutions.

As to how NIDS generate these results, the comparative research revealed that NIDS encouraged the students to include solutions found within the specific *context of the product-system* (people, companies and circumstances interrelated to the product-system). In comparison, the groups using Biomimicry have taken a more functional approach, whereas Cradle to Cradle challenged the students to incorporate 'beneficial impacts' - impacts that benefit the (eco)system in which the product functions. The 'absolute' objectives embedded in the NIDS design principles may have encouraged the students to focus on finding solutions that meet these principles, and thereby widen their solution space.

In addition, we conclude that 'application level' is an important variable to consider, as the design-students did not apply all the principles, methods, and tools offered by design strategies. As reported in previous studies, the selective application of methods and tools is not unique to NIDS; it is common practice. The results confirm partial application of strategy elements for each of the design strategies, but no significant differences were found in application-level between the three strategies (section 4.3). Nevertheless, these findings improve our understanding of why some elements, though available within NIDS, have not helped designers when developing sustainable products.

We are aware that the findings of this study are to be interpreted with caution in relation to real-life design practice. The students performed the design projects for educational purposes, received workshops in each of the design strategies, and had little or no previous experience in the application of the strategies. They were assigned to a group and asked to apply a specific strategy, whereas in practice, designers adopt the strategy they see fit to a specific design challenge. Furthermore, the personal motivation of the students might influence the results. As the courses were elective, we assumed that the students were motivated to learn and apply the design strategies. This was confirmed during the coaching sessions. Finally, we recognize the limitations of this study due to the small sample size, and used statistical tests suited for this sample size to uncover significant differences between the three strategies.

Nevertheless, we have been able to show that Biomimicry and Cradle to Cradle provide design students with an approach to product design that is distinct from Ecodesign in several respects. For the cases studied, the strategies were particularly equipped to broaden the designers' solution space and to generate solutions at a function or system level. However, the studies highlighted that neither of the NIDS currently offers quantitative design tools (as Ecodesign does) for evaluating the environmental impact of the solutions across the product life cycle. This induces the risk of unforeseen impacts if the design strategies are applied in isolation.

[1] This research design shows similarities with that of quasi-experiments, as the set-up of the courses allowed some control over events: the student groups were assigned with one of three design strategies. This allowed us to compare effects between groups using different strategies. However, as described in Chapter 1, the objective of the studies is to explore the application of NIDS, and thereby gain holistic insights in how their application influenced the design process and its outcomes. No propositions have yet been developed on the manner in which the design strategies help the designers. Therefore, the aim is to identify possible relationships and processes, not to test them. Hence, a case study design was selected.

[2] The specific Ecodesign tools applied in the courses are presented in Table 4.5.

[3] With 25 students (6 groups) in the pre-study in 2010, 56 students (12 groups) in 2011 and 73 students (15 groups) in 2012. The course was set-up to include 5-6 students per group, but in total 16 students that enrolled for the courses did not start, or quit the course before the design project had started.

CHAPTER 5

Exploring Biomimicry and Cradle to Cradle in Design Practice

The comparison of Biomimicry, Cradle to Cradle, and Ecodesign described in Chapter 4, demonstrates how the application of Nature-Inspired Design Strategies (NIDS) encouraged design students to broaden their solution space and consider 'context-specific opportunities' for developing sustainable solutions. In this chapter, we build upon the findings of the student cases with the analysis of four 'real-life' cases. These cases add in-depth insights from projects in which a professional design team developed a product.

The research design is explained in section 5.1. Sections 5.2 to 5.5 describe how the application of NIDS affected the design process and the design outcomes in each of the four case studies. The cross-case analysis, presented in section 5.6, shows that several of the observed effects were replicated across cases. Section 5.7 discusses the way in which the application of NIDS may have induced these effects. In the last section, 5.8, we conclude which effects on the design process and the design outcomes can be attributed to the application of NIDS.

Chapter 5 is based on: DE PAUW, I., KARANA, E. & KANDACHAR, P. 2013. Cradle to Cradle in Product Development: A Case Study of Closed-Loop Design. In: NEE, A. Y. C., SONG, B. & ONG, S. (eds.) Re-engineering Manufacturing for Sustainability. Singapore: Springer.

5.1 Research design

Building on the findings from the student design projects, we analysed the effects of applying NIDS on the design process and design outcomes (Research Question 3) via case study research of real-life cases. We selected four cases for analysis, two Biomimicry and two Cradle to Cradle projects, allowing a comparison of findings across the cases. We answer the research question by demonstrating how the application of elements affected the design process and the outcomes of each of the four projects, with reference to 1) which specific elements of the NIDS were applied (and which not), 2) which results were achieved in terms of the design process and project outcomes, and 3) which results can be attributed to the application of NIDS. As noted in Chapter 1, the scope of this study, in terms of the product development activities, ranges from the generation of a new business idea (which product will be developed) to the final product design. After analysing the individual cases, we concluded the study by performing a cross-case analysis to provide insights into possible replication of effects across the different projects.

The remainder of this section describes the sampling procedure for the selection of the four cases, the data collection procedure, and the procedure for data analysis.

5.1.1 Selection of cases

The first step in the research design was the selection of cases to be included in our study. Figure 5.1 provides an overview of the case selection procedure. Due to the nature of case study research, cases are not selected to be representative of a wide range of cases; instead they are selected to maximize what can be learned about the research phenomenon in a realistic context, using cases that are 'likely to lead the researcher to understandings, assertions' (Stake, 1995, p.4). Consequently, case selection criteria were developed to assess the degree to which potential cases reflected the research phenomenon, and to assess whether these cases provided access to 'rich' data. Table 5.1 lists the selection criteria and includes the project characteristics used for assessing the suitability of the projects as research cases.

A shortlist of potential Biomimicry and Cradle to Cradle projects was compiled, gathered from NID websites, blogs, seminars, and training programmes. Each of the projects was assessed on the selection criteria using project data retrieved from the same sources, and supplemented with data from literature, lectures, and dedicated consultation with designers and NID experts.

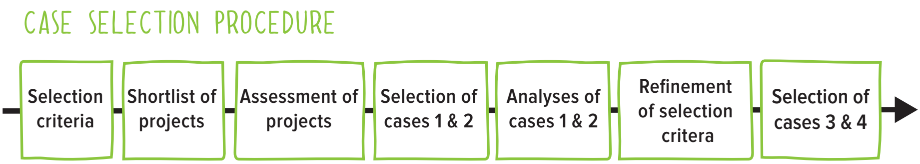


Figure 5.1: Overview of the case study selection procedure

The cases were selected in two stages: first, we selected one Biomimicry and one Cradle to Cradle project. After analysing these cases, we chose the second pair. This helped us to focus the later cases on specific findings from Cases 1 and 2. Cases 3 and 4 thus provided further insights into a specific part of the research phenomenon, replicating (part of) the case study of cases 1 and 2.

When selecting potential cases, we encountered difficulties in finding sufficient 'typical product development' projects (criterion a). Few projects matched all the case selection criteria listed in Table 5.1. Additionally, we came across several 'typical' Nature-Inspired Design projects that did not meet the second criterion (b). In these cases, the project was not aimed at the development of a product, but rather on the creation of a system, comprising multiple products or product generations and/or including new production processes. Correspondingly, the designer in these projects was part of a multidisciplinary team, and, in his/her role of designer, was not always the expert or initiator in the use of a Nature-Inspired Design Strategy.

There are several reasons that can explain the limited number of typical product development projects. First, there may simply be insufficient cases available, due to the recent origin of the design strategies. In the Netherlands, the first non-company specific training programmes for Biomimicry and Cradle to Cradle were organised in 2009-2010, which may explain why only a limited number of designers have been trained in these strategies. Alternatively, the strategies may not have attracted many designers in the first place. On the other hand, many of the projects did include designers, even though the focus was not on product development. This finding feeds into a third explanation, linking the application of NIDS to having a wider project focus than product development alone. The outcomes of the student design projects (Chapter 4) and real-life cases 1 & 2 include examples of projects that support this explanation. Based on these findings, we concluded that the application of NIDS might indeed cause designers/companies

Criteria	Most preferable characteristics
Reflection of phenomenon: designers applying NIDS when executing real-life projects aimed at the development of sustainable products	
a) NIDS are applied in the project	- clear reference to, or use of Biomimicry or Cradle to Cradle
b) the project is a formal product development assignment	- design assignments for or within companies
c) the project has a product designer involved in the project	- IDE professional or comparable (industrial designer, design engineer)
d) the project is targeted at a sustainable outcome (incl. beneficial and eco-effective)	- clear and strongly-worded sustainability target formulated in the project
e) knowledge & prior experience with NIDS are available in the project team (by the designer or other members of the project team)	- a good level of knowledge about the strategy & tools, and prior experience of applying NIDS - and/or EPEA/BiomimicryNL/3.8 are involved to provide knowledge/ expertise
Access to rich data	
f) case data are available (reports, drawings, designers' recollections of actions)	- the project is well underway, in end phase - the project was finished recently
g) the company & designer are willing to cooperate	- the company/designer is willing and positive to cooperate
h) the company/designer can be visited for the case study	- proximity of the design studio/company (visit within a day)

Table 5.1: Case study selection criteria

Acceptable characteristics	Exclusion characteristics
	- projects 'just' for certification - project only inspired by (elements of) NIDS - NIDS are used superficially
- other design assignments and projects with internal or external funding (such as company initiatives with clear chance of implementation)	- 'hobby' projects (no perspective on implementation) - submissions for competitions - consultancy projects (no development)
- professional with other background whose activities in the project closely match those of a product designer	- consultants, artists, architects, students / cases focusing on the development of buildings, materials/ingredients
- clear and substantial sustainability ambition of the designer (as stated by designer, not in design brief)	- no sustainability target, or incremental target set
- a reasonable level of knowledge (for instance 'read the book') plus prior experience, - or a good level of knowledge (training or workshops) but no prior experience	- little background knowledge on strategy
- the project was finished a while ago (designer can be interviewed) - the project is running	- the project has just started or is about to start
- the company/designer is willing to cooperate	- the company/designer or the client does not want to cooperate
- the studio/company can be reached by train/car within a day's travel	- the design studio / company is located further away

to adopt a more system-oriented approach. In selecting cases, we therefore adapted our selection procedure to such an extent that we also included projects in which the development of a product was *part* of the project, rather than prioritizing the selection of cases in which the design of the product was the major goal.

Table 5.2 lists the cases included in the study. Appendix 5 provides the full list of cases considered. The four cases have in common that the type of product being developed is non-electronic (the product contains no electronic components, and consumes no electricity in the use phase). Cases 1 and 2 are projects performed by specialised design firms, and are key examples of designer(s) applying either Cradle to Cradle or Biomimicry to develop a new product. In these cases, the designer(s) also initiated the use of the design strategy. Cases 3 and 4 are cases of projects performed at large(r) companies and are key examples of projects in which either Biomimicry or Cradle to Cradle was applied at a company level, and in which the development of the product was part of a larger innovation process.

5.1.2 Procedure for data collection

For cases 1 and 2, data was collected during three sessions held at the design offices, each session taking a different perspective on the case, as shown in Figure 5.2:
1) product-oriented (the physical end result of the project), 2) design process oriented, and 3) addressing the application of Biomimicry/Cradle to Cradle-elements (NIDS elements session).

In the first session, the researcher conducted a semi-structured interview with each of the designers. The designer was asked to describe the project outcomes with the aid of the prototype and samples. The aim of this session was to obtain knowledge on the design outcomes and, more specifically, to observe whether and how the designers mentioned

Case	Product name	Type of Product	Type of Company	NIDS applied	Strategy knowledge
1	Plenic	Presentation system	Design agency	Cradle to Cradle	Designers trained
2	Algaepack	Flower tray	Design agency	Biomimicry	Designer trained
3	Net Effect	Carpet tile	Manufacturer	Biomimicry	Designer trained plus expert support
4	SmartBin	Resource bin	Service provider	Cradle to Cradle	Development team trained plus expert support

Table 5.2: Selected cases and case characteristics (ranking in order of case study execution)

METHOD OF DATA COLLECTION CASE 1 & 2

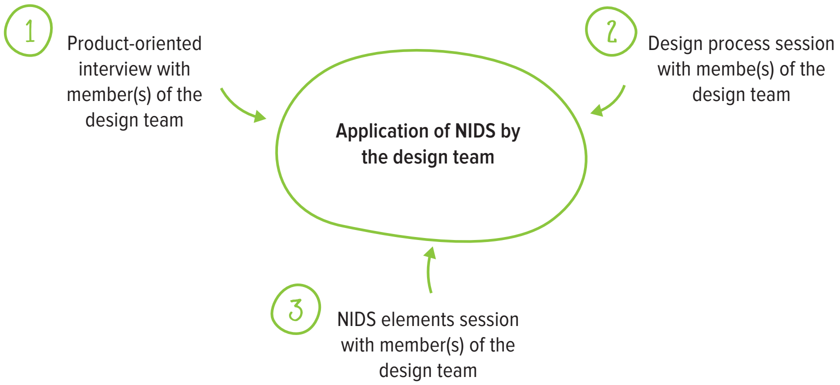


Figure 5.2: Overview of data collection method for cases 1 and 2

Figure 5.3: Example of the visualization of design process using documents, samples, and drawings

NIDS or any specific elements of the design strategy to have influenced the design. The interview questions are included in Appendix 6.

During the second meeting, the designer (in Case 1 both designers together) was first asked to visualize the design process, using project documents, samples, and drawings. The designer(s) then marked the design steps in which Biomimicry/Cradle to Cradle was applied. Figure 5.3 gives an impression of the results of one of the cases. The marked steps were discussed in detail, to gain an understanding of how the designers applied the design strategy and how it affected their design process. During the discussions, the researcher and designers together created a diagram of all major design decisions and strategy elements applied in order to reflect on the effects of applying these elements, and to incorporate direct feedback from the designers.

The final session explicitly focused on the use of strategy elements in the project, as reflected upon by the designers. Originally, the set-up was to discuss the NIDS elements used for each step of the design process. However, as session 2 took much more time than anticipated, the set-up was altered after session 2. Instead, the strategy elements considered in the study were presented to the designers in the form of a stack of cards, each card mentioning one element (see section 5.1.3 for the description of these elements). The designers were asked to divide the cards into three categories: ‘applied’, ‘known but not applied’, and ‘not known’. They could add extra cards if they felt elements they applied were missing from the cards presented to them. Furthermore, for the elements they applied, the designers marked those elements they themselves considered to be most important in the project. At least five element cards were discussed in more detail to understand how they were applied, or why they were not applied. For each case, the discussion included at least two elements marked ‘most important’; one marked ‘less important’ (why was it considered less important?), one marked ‘not applied’ (why was it not applied?), and any elements added by the interviewee. If time allowed, more elements were discussed.

All meeting sessions were recorded - both on audio and video, and the interviews were transcribed. Additionally, project results such as reports, presentations, prototypes, and samples were included in the data collection. The results of the analysis were discussed with the designers (via personal meetings, e-mail or Skype) to correct possible errors in the case descriptions, and to include possible feedback in the findings.

Based on the findings of Cases 1 and 2, the follow-up Cases 3 and 4 focussed on a specific part of the design process in which NIDS played a key role: the design activities connected to the materials design, such as material selection, application, including the design of the material cycle. The data collection procedure for Cases 3 and 4 is illustrated in Figure 5.4. In comparison to the procedure for Cases 1 and 2, three changes were made. First, the project outcomes were determined, not from an interview, but from existing data, as project information was already available from company documentation and publicly available data, such as articles, press releases, and other communications. Secondly, as both projects had a larger project team, two people were selected from each company, who could provide key information on the design of the product and the application of the design strategy in the project. The interviews with individual team members focused on the use of strategy elements for the *materials-related* design activities. As with Cases 1 and 2, the interviewees reviewed the results of the case study. In addition, the external strategy experts involved in the study were consulted to provide feedback on specific findings of the cases. Table 5.3 summarises the data collection for the four cases. The interview questions are included in Appendix 6.

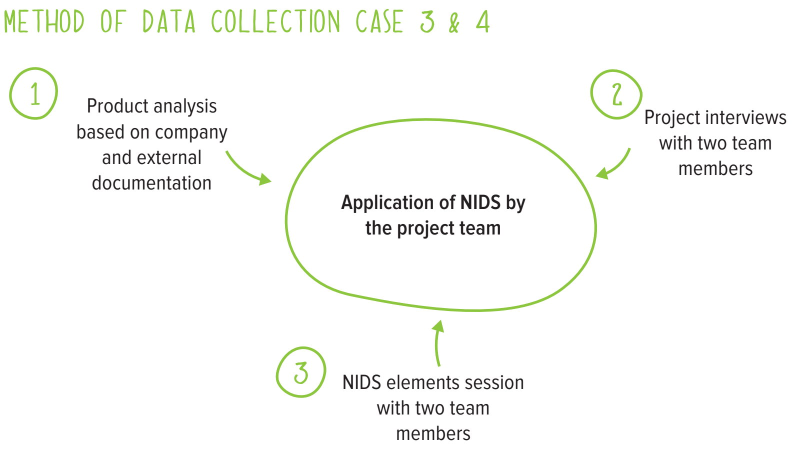


Figure 5.4: Overview of data collection method for cases 3 and 4

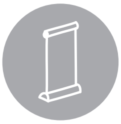
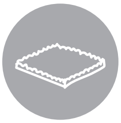
Case	Sessions
1. Plenic presentation system 	1. Product-oriented interview with designers A and B (about 2 hrs each) 2. Design process session with designers A and B (about 3 hrs) 3. NIDS elements session with designers A and B (about 1.5 hrs) - Feedback on case-study description from designers
2. Algaepack flower tray 	1. Product-oriented interview with designer (about 1.5 hrs) 2. Design process session with designer (about 1.5 hrs) 3. NIDS elements session with designer (about 25 min) - Feedback on case-study description from designers
3. Net Effect carpet tile 	1. Product analysis of company and external documentation 2. Design process session with project members A and B (about 25 min each) 3. NIDS elements session with project members A and B (about 20 and 30 min) - Feedback on case-study findings from strategy expert and on case-study description from project members
4. SmartBin resource bin 	1. Product analysis of company and external documentation 2. Design process session with project members A and B (about 35 min each) 3. NIDS elements session with project members A and B (about 35 min each) - Feedback on case-study findings from strategy expert and on case-study description from project members

Table 5.3: Summary of data collection for the four real-life cases

5.1.3 Procedure for data analysis

In multiple-case study research, each case is conducted as a separate study in which convergent evidence is sought for obtaining case-specific conclusions. The data analysis of the real-life cases addressed the application of the design strategies and the effects of applying NIDS on the design process and end result. The study of the individual cases was followed by cross-case syntheses to analyse the extent of replication logic (Yin, p.56, p.156) concerning which of the findings were replicated across the four cases.

Analysing the application of NIDS

In order to understand the extent to which Biomimicry or Cradle to Cradle were applied in the product development process, a list of the different strategy elements was compiled, consisting of expressions of the design philosophy, design principles, and methods & tools within each design strategy, expanding upon the overview presented in Chapter 2. The list was composed using different sources: the books introducing Biomimicry and Cradle to Cradle, the contents of the first European Biomimicry training with the Biomimicry Guild, and contents of the (second) Cradle to Cradle-Designer training at EPEA Hamburg. Although the training materials have not been published, the strategy elements have also been described in publications authored by strategy experts (Baumeister et al., 2013, Benyus, 1997, Biomimicry Guild, 2007, Biomimicry Guild, 2010a, Bjørn and Hauschild, 2013, Bor et al., 2011, EPEA, 2011, McDonough and Braungart, 2002, McDonough et al., 2003). Table 5.4 lists the elements included in the study[1]. For Biomimicry, two expressions were included that represent the design philosophy of the strategy: 'Innovation inspired by nature' and 'Creating conditions conducive to life'. The six main 'Life's principles' are included, and six steps for applying Biomimicry in product design, as listed in Table 5.4 (Biomimicry Guild, 2010a). For Cradle to Cradle, three expressions were included that

Elements of Biomimicry	Elements of Cradle to Cradle
Design philosophy	**Design philosophy**
Innovation inspired by nature	Doing good - instead of 'less bad'
Life creates conditions conducive to life	Creating a beneficial footprint
Design principles	Eco-effectiveness
Evolve to survive	**Design principles**
Be resource (material and energy) efficient	Waste equals food
Adapt to changing conditions	Use current solar income
Integrate development with growth	Celebrate diversity
Be locally attuned and responsive	**Methods & tools**
Use life friendly chemistry	Roadmap
Methods & tools	Material inventory
Design spiral	ABC-X classification
Evaluate your design against life's principles	Define use in biological and technical cycles
Distil the design function	Define use period
Translate to biology	Add value
Discover natural models	Cascade use
Emulate nature's strategies	Design for (dis)assembly
	Use Cradle to Cradle-elements (materials, processes, ingredients)

Table 5.4: Overview of strategy-elements considered in the case studies

represent the design philosophy: ‘Do good instead of less bad’, ‘Creating a beneficial footprint’ and ‘Eco-effectiveness’. Furthermore, the three Cradle to Cradle principles are included, as well as nine tools. The tools were selected based on the contents of the Cradle to Cradle-Designer training at EPEA Hamburg (EPEA, 2011), many of which have been described in a positioning paper co-authored by EPEA (Bor et al., 2011). The Cradle to Cradle certification criteria were not included in the list, as they are not intended as design tools (as described in Chapter 2).

Analysing the design process and end result

To analyse how, in these four cases, the application of NIDS has affected the design process and the final design, the collected data was used to generate a case-diagram (see Figures 5.6, 5.10, 5.16, 5.20 in the following sections). Each case diagram represents the design process that was followed, as described by the interviewees, and shows the relations between design steps, strategy elements, and end results. The diagrams are limited to the design activities in which strategy elements were applied. Based on the different data sources, the relations are described per element to build an understanding and to generate propositions of how the application of these elements affected the process and design.

Cross-case analysis

In section 5.6, we compare the findings across the four cases, taking into account the application level, the effects of NIDS on the design process, and the effects on the project designs. First, to allow comparison of the application level across the two different NIDS, the design strategy elements for Biomimicry and Cradle to Cradle (listed in Table 5.4) were analysed on the level of design philosophy, principles, and methods & tools. The methods and tools were subdivided into four categories, reflecting their purpose: a) analytical methods and tools, b) methods and tools for synthesis, c) methods and tools for simulation, and d) methods and tools for evaluation[2]. Second, for analysing the design processes, the findings were plotted across the different phases of the product development process and analysed for similarities and differences in the design activities specific to NIDS. Third, the designs were analysed by comparing characteristics of the designs.

5.2 Case 1: the Plenic presentation system by Full Circle Design

The company selected for this study -Full Circle Design- is a small German design firm, specializing in the development of closed-loop products. Both of the company's designers are trained in Cradle to Cradle design.

5.2.1 The design challenge

The design challenge for this project was the development of "Plenic", a presentation system for fairs and points of sale (Figure 5.5). Such systems are used to present graphic information to people, and typically consist of a frame, onto which printed textile fabric is connected with the use of keder (an elastic cord for fixing the textile onto the frame).

The goal of the project was to develop a modular presentation system that "never becomes waste". According to the designers, such systems are typically disposed of after only days of use, and contribute to the large amount of waste generated at fairs. They retrieved that, for example, the Hannover Messe, a large 5-day industrial trade fair, generated about 1225 tons of waste in 2009.

Figure 5.5: Impression of the Plenic closed-loop presentation system by Full Circle Design

5.2.2 Application of Cradle to Cradle elements

The two designers involved in the project completed two Cradle to Cradle courses, including the 2nd Cradle to Cradle-Designer training at EPEA Hamburg (which they entered after their project was well underway). They were familiar with all Cradle to Cradle-elements included in this study, but did not apply all of them in the project. Table 5.5 lists these elements. The second column shows the elements that, according to the designers, have been applied in the development process. The third column depicts the elements that have been detected in the collected case study data by the researcher.

Elements of Cradle to Cradle considered in the case study	Applied according to designers	Applied according to researcher
Philosophy		
Doing good - instead of ‘less bad’	✓	✓
Creating a beneficial footprint	✓	✓
Eco-effectiveness	x	✓*
Design principles		
Waste equals food	✓	✓
Use current solar income	x	x
Celebrate diversity	x	✓*
Methods & tools		
Roadmap	✓	✓*
Material inventory	✓	✓*
ABC-X classification	x	x
Define use in biological and technical cycles	✓	✓*
Define use period	✓	✓
Add value	✓	x*
Cascade use	✓	x*
Design for (dis)assembly	✓	✓
Use Cradle to Cradle-elements (materials, processes, ingredients)	✓	✓
Triple-top-line pyramid (added by designers)	✓	✓

Table 5.5: Overview of Cradle to Cradle-elements considered in the case study. ✓=applied, ✓*=applied partially or implicitly, x=not applied; x*=not covered as a tool in the case data; bold markings represent the elements considered to have been most important in the design project

'Doing good - instead of less bad' was marked as an important driver (by the designers), as well as the principle 'waste equals food' (both by the designers and the researcher). The tools that were marked by the designers as the most important ones were (in random order) the roadmap, material inventory, define use in bio/tech cycles and design for disassembly.

According to the designers, two Cradle to Cradle-principles, 'Use current solar income' and 'Celebrate diversity', were not considered in this project. The designers could not see a useful application opportunity for these principles within the design project. Considering the 'use of current solar income', the designers argued that there was no practical application of this principle beyond using renewable energy for all processes that require energy. Finding materials that can be fully recycled (related to the first Cradle to Cradle principle) had posed such restrictions, that the designers did not include additional constraints on their selection process regarding the energy sources used for the production. As one of the designers explained:

> *"…it's almost as difficult to find the right materials and find the right producers. […] We can't ask them the first question 'Are you using current solar income? No? Okay then, goodbye', because that's the only opportunity to go further with our project. For example, the fabric company […] I don't know if they are using this energy."*

Within Cradle to Cradle, products do not have to address all elements at once, but to progress towards a fully beneficial result, the transition to renewable energy would be part of the roadmap (Hansen, 2012). Although the designers marked this tool to be important, their roadmaps do not mention such goals. With respect to the third Cradle to Cradle principle, 'Celebrate diversity', the designers expressed difficulty in understanding how to apply it. None of the tools seems to address specifically how designers can implement this principle into their design. However, considering the context-specific solution of their product-system and the modular design, it can be argued that they in fact did include this principle to some extend (ibid), though not intentionally.

The designers performed an extensive material inventory, though not to the level (100 ppm) as described in the tool, as such data is difficult to obtain and cannot be interpreted without the help of a chemist. ABC-X analysis was also omitted, because of the financial constraints (of hiring the required expertise). On the other hand, the designers applied the 'triple-top-line' visualization triangle, a tool not used in the Cradle to Cradle-designer training, but described in the Cradle to Cradle book (McDonough and Braungart, 2002), covering ecology, equity, and economy. This tool made them aware of social aspects of

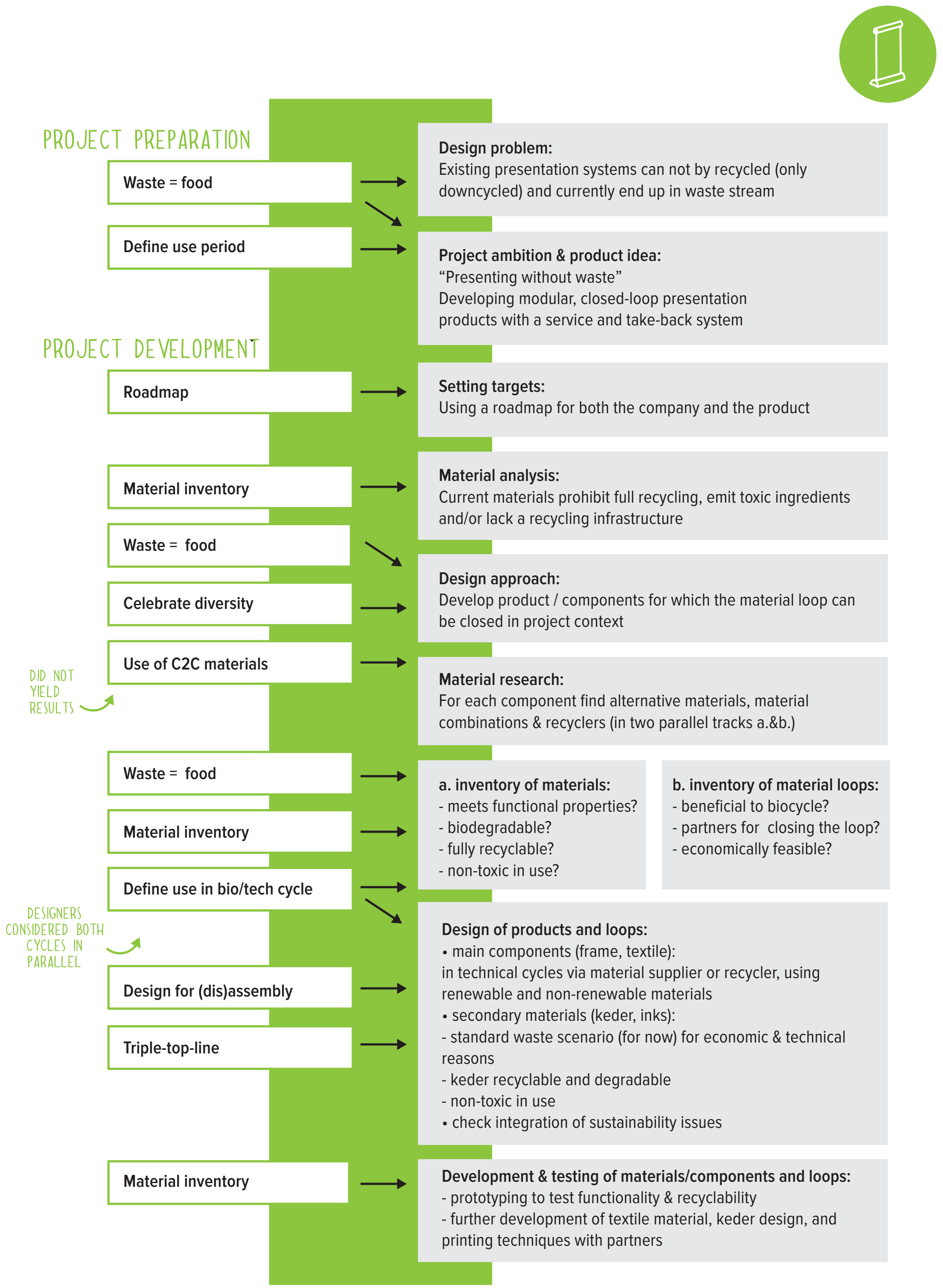


Figure 5.6: Case diagram of the design process in relation to the Cradle to Cradle-principles and tools that have been applied in the project

design, and offered an approach to include social considerations into their project. They adapted the triangle into a triple-top-line-pyramid by adding ‘design’ as the element to influence ecology, equity, and economy.

5.2.3 The effects of applying Cradle to Cradle on design process and design outcomes

From the design process that was visualized during the second case-study session, it was observed that Cradle to Cradle was blended into the design process and clearly influenced design activities and outcomes. Cradle to Cradle was not considered or applied in some design tasks, such as market analysis, sketching, and detailing of the design. The tasks in which the designers actively involved Cradle to Cradle were analysed further, based on the detailed visualizations made during the case-study session. Figure 5.6 shows a schematic summary of these design tasks in relation to the Cradle to Cradle principles and tools[3].

The Cradle to Cradle strategy was actively used in the projects’ preparation phase, which was the result of the companies’ ambition to develop products that will ‘never become waste’. Already in this phase, the designers decided to design a modular product, allowing different sizes of presentation systems to be constructed with the same frame, whereas currently, each product variant comes with a different frame. Likewise, the basic service-concept was developed in this phase, based on the Cradle to Cradle ‘define use period’ tool. The designers developed a service and take-back system, illustrated in Figure 5.7, which provides value for the customers also after the products’ first use, to enable reuse and recycling of the materials.

In the product development phase, four Cradle to Cradle tools were used. Their application seems to have triggered the designers to spend considerable time on finding suitable materials and material combinations, on developing closed-loop material systems and on establishing cooperation with value-chain partners. As compared with traditional presentation systems, the Plenic applies different materials for all product components, including the inks on the textile, as specified in Table 5.6. The designers originally intended to replace current materials with alternatives that were already developed by others using the Cradle to Cradle strategy, especially Cradle to Cradle-certified materials. However, they could not employ such materials because they were either not available (for the frame and keder), or could not be fully recycled yet (printed textile), and the textile company involved could not cooperate in the project.

The designers’ ambition to realize a closed loop system seems to have changed their material selection process. Where ‘being recyclable’ is generally seen as synonymous

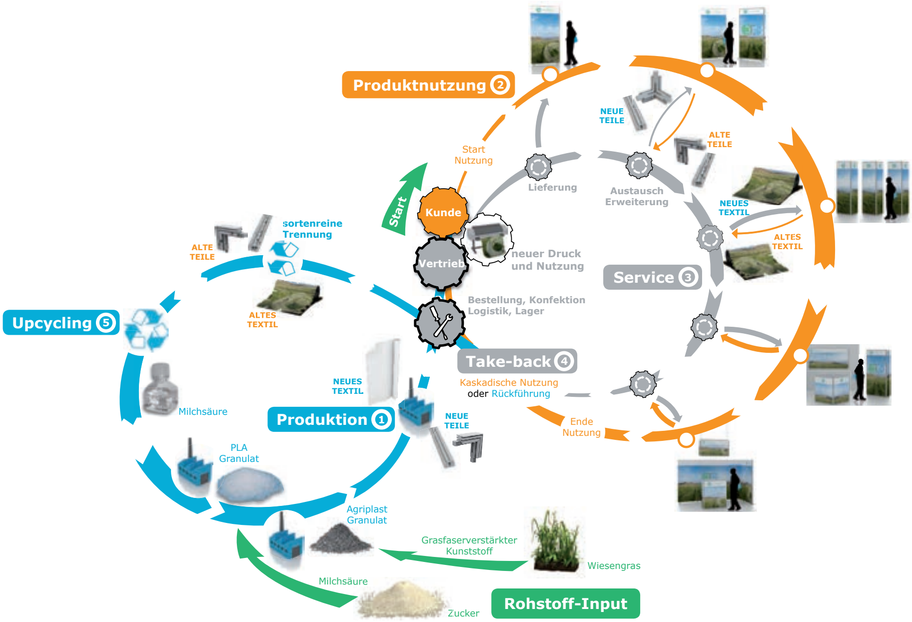


Figure 5.7: Impression of the Plenic service and take-back system by Full Circle Design

Main components	Materials applied in typical presentation systems	Material types applied in Plenic
Frame	Aluminium	Grass-fibre composite
Textile	Polyester	PLA
Inks	Solvent based or UV-curable inks	Water-based inks
Keder	PVC / Silicone	Biobased elastomer

Table 5.6: Material application in presentation systems

with being environmentally friendly, the designers went a step further, and for each component also analysed if and how it would actually *be* recycled. In one of the interviews, the designer explains:

> *"Yeah it COULD be recycled, but this is the problem, it COULD be recycled, but the question is HOW could it be recycled? [...] Everyone says 'it could be recycled' like you did. So, if I ask you how would you recycle it, in detail, do you have a clue?"*

With respect to renewable materials, the designers were not content with a material being degradable, but instead analysed whether the material would provide a benefit to the ecosystem. For instance, biodegradable PLA can be applied, but once degraded, the material does not provide ingredients valuable to the soil. This contributed to the designers' choice to apply renewable materials in a technical cycle instead.

The inks that are generally used for presentation systems, do not allow high-quality recycling of the polyester. Within the project, the designers -together with suppliers- developed an innovative new combination of textile and inks that allows full recycling of the textile after each cycle of use.

The designers did not assess the sustainability of the design. They did employ an Ecodesign checklist (Internationales Design Zentrum Berlin, 2012) during the project, because they felt the need for "having a complete picture" of sustainability issues involved.

Furthermore, they analysed external LCA-data of PLA and grass-fibre composites to check for possible environmental impacts that might influence their material selection.

In the project, the designers paid (some) attention to social aspects, using the triple-top-line visualization tool. This led them to consider and include a producer that employs handicapped people. The use of local suppliers may contribute to the strengthening of the local community, but this was not an explicit aim of the project. Other social sustainability aspects, such as social impacts associated with material extraction, or the active development of 'fair-trade' practices, were not considered. With respect to economic sustainability, the designers paid considerable attention to building a sound business-case for their product and the service system. This focus was chosen to ensure the viability of the product and to facilitate the return of the components for reuse and recycling. Equal material and production costs for the projected production volume are combined with increased modularity of the product.

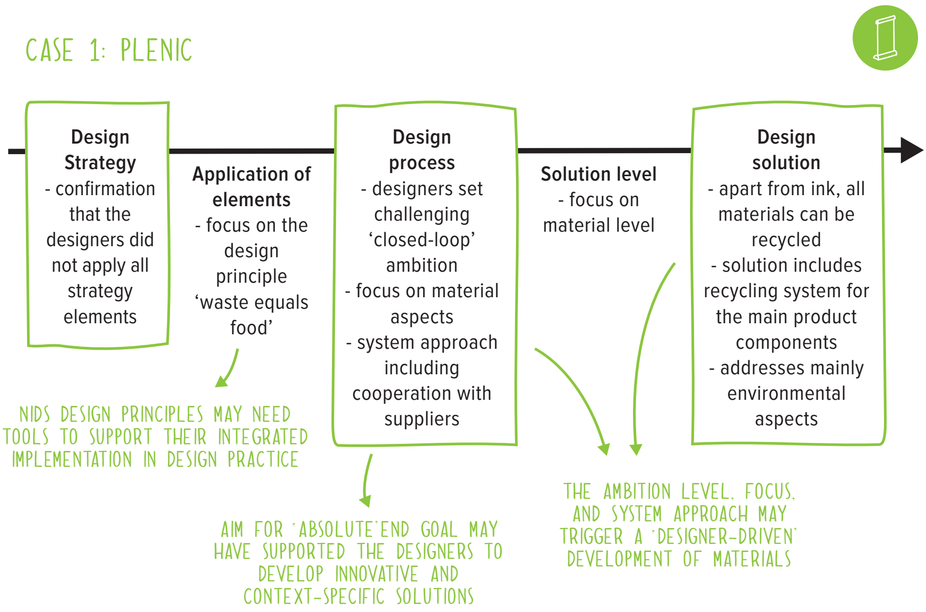


Figure 5.8: Summary of the findings from Case 1, the Plenic presentation system

5.2.4 Discussion and conclusions

Figure 5.8 summarises the findings from the Plenic presentation system case study. The analysis of the use of the design strategy showed that the designers did not apply all strategy elements. The project focused on the application of the design principle 'waste=food'. This principle, supported by the tool 'define use in biological and technical cycles', seems effective in helping designers to develop a product concept. This finding corresponds to the findings of the workshop-cases in Chapter 4. On the other hand, the designers left aside the second principle 'use current solar income' as they did not want to add further limitations to selection of materials available for designing their product. As no goals were included in the roadmap for a transition to renewable energy, environmental impacts from energy consumption may continue to exist. In our prior study in Chapter 4, the design students did include energy aspects in their design process, but the Herman-Miller case study (Rossi et al., 2006) illustrated a similar focus of the designers on the material-side of the design. Accordingly, our current findings support criticism that Cradle to Cradle may divert focus away from addressing energy aspects (Bakker et al., 2009, Bjørn and Hauschild, 2011), despite the presence of the Cradle to Cradle principle 'use current solar income' and the roadmap tool.

Furthermore, the case study showed that the designers did not explicitly aim to create beneficial social impacts, or to incorporate 'diversity' into their design. This coincides with the absence of concrete tools for these topics, hinting to the importance of tools for product designers that wish to apply Cradle to Cradle to its full potential. Further research may address the reasons why designers do not consciously include all principles of Cradle to Cradle in their projects.

Cradle to Cradle was applied from the preparation phase of the design process, resulting in a challenging ambition of a fully closed-loop system. Aiming for this absolute end goal, instead of analysing and aiming to reduce the impacts of current products, may have yielded the designers both time and creative freedom to develop innovative solutions: instead of analysing improvement options for the existing materials that could not be fully recycled, they looked for alternative, recyclable materials and analysed how they could be recycled in practice. According to the designers, the design activities performed in the project differed in many aspects from a conventional design project. The material selection process was dominant in the embodiment of the design, and their ambition to 'close the loop' led the designers engage in new material development.

The analysis of the design process furthermore revealed how the application of Cradle to Cradle activated the designers to adopt a 'systems approach', by engaging them in the actual design of 'the product loop'. The designers, though not anticipating this at the start of the project, went into cooperation with material suppliers to overcome major barriers in recycling. Consequently, apart from the ink, all materials applied in the product can be recycled. Additionally, a recycling system for the main components (the frame and textile) is included in the design solution. The designers could not 'simply' employ materials that have already been developed according to the Cradle to Cradle strategy. Their search for suitable 'Cradle to Cradle' materials proved an ineffective task, in the sense that no such materials met their requirements for closing the loop. This may change with the increasing availability of certified materials. On the other hand, the case illustrates how the fields of product and material development may converge when applying Cradle to Cradle, and thereby lead to material innovation.

Cradle to Cradle, with its three principles, in theory offers designers the possibilities to incorporate environmental, economic, as well as social benefits in the design of products. In this case, however we observed that the project focus was on the materials and environmental aspects of the design. The results indicate that new design tools, specifically aimed at incorporating renewable energy and diversity into the product development project, may help designers to integrate all three Cradle to Cradle-principles into their design process.

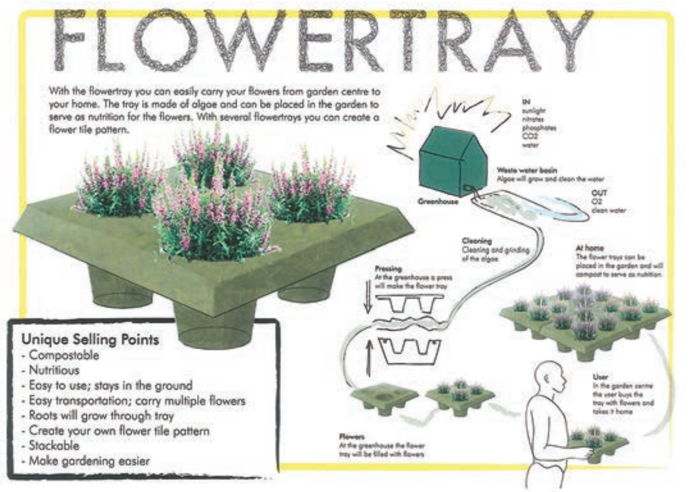


Figure 5.9: Impression of the Algaepack seeds tray and flower tray by IDEAL&CO

5.3 Case 2: the Algaepack tray by IDEAL&CO

IDEAL&CO is a small Dutch design firm specializing in sustainable product development. The designer involved in the case is specialized in applying Biomimicry.

5.3.1 The design challenge

The case project involved the development of "Algaepack", a product made out of algal material. Apart from the designer, two interns were involved in the project who worked on material analysis, concept development, shaping, and sketching of the product and product-system. The goal of the project was to develop an application "that provides value in each step of the product cycle (cultivation, manufacturing, use, and disposal)" and thereby "turn waste into a valuable material". The designer explained that algae grow on wastewater, absorbing excess nutrients from the water, and can thereby be used to clean the wastewater. Studies preceding this project had shown the opportunity of making a 'sustainable material' out of algae and for developing a useful application. The three-month project was in its final phase when the case study was conducted.

The products resulting from the project were a 'seeds tray' and 'flower tray' as illustrated in Figure 5.9. Both products enable people to plant the seeds or plants in their garden in specific patterns, by placing the tray in the soil. The tray decomposes and subsequently provides nourishment for the plants.

5.3.2 Application of Biomimicry elements

The designer trained himself in Biomimicry via self-study and through his Masters' graduation project, in which he researched the application of bio-inspired design for the development of an electric scooter. In 2010, he followed a two-day Biomimicry course from ' Biomimicry 3.8', the Biomimicry consultancy co-founded by Janine Benyus. Table 5.7 shows which strategy elements were applied in this case. Although the designer was familiar with all the Biomimicry-elements included in the study, not all were applied in the design process. The second column shows what elements were used according to the designer, and the third column marks the elements that were detected in the case study data collected by the researcher.

'Innovation inspired by nature' was marked as an important driver by the designer, an overarching element that applies to all Biomimicry projects. 'Life creates conditions conducive to life', was initially not recognized by the designer as a philosophical element of Biomimicry, and according to him, not explicitly used. Nevertheless, the case study

Elements of Biomimicry considered in the case study	**Applied according to designer**	**Applied according to researcher**
Philosophy		
Innovation inspired by nature	✓	✓
Life creates conditions conducive to life	x	✓*
Life's principles		
Evolve to survive	x	x
Be resource (material and energy) efficient	✓	✓
Adapt to changing conditions	x	x
Integrate development with growth	x	x
Be locally attuned and responsive	✓	✓
Use life friendly chemistry	✓	✓
Methods & tools		
Design spiral	x	x
Evaluate your design against life's principles	✓	✓**
Distil the design function	✓	✓
Translate to biology	✓	✓*
Discover natural models	✓	✓*
Emulate nature's strategies	✓	x
System mapping (added by designer)	✓	✓
Model system behaviour (added by designer)	✓	✓

Table 5.7: Overview of Biomimicry-elements considered in the case study. ✓=applied, ✓*=applied partially or implicitly, ✓**=applied in a modified manner, x =not applied; bold markings represent the elements considered to have been most important in the design project.

data showed a clear link between the project ambition and this element. According to Benyus, 'life creates conditions conducive to life' refers to a characteristic of organisms to function in such way that they tend to promote or assist ('conduce') their habitat. This element of providing benefit to the (eco)system was found to be an important driver for the project. For instance, when discussing the product, the designer explained:

> *"…the main point of how bio-inspired design is used in this project is that I really wanted to make a product that is a valuable part of its environment…"*

The life's principles marked as most important by the designer were 'be resource efficient' and 'be locally attuned and responsive'. Of these principles 'being locally attuned' was found to be a core principle applied throughout the project and it was also noted as 'most important' by the researcher. On the other hand, three of the six life's principles were not used in the project. The designer explained that within a project of this size -a run time of three months- integration of all principles, though important, was not feasible in the time available. He therefore focused on what he considered to be the most important principles:

> *"Yes, [integrating all life's principles] that's the goal. But I do think there's a certain hierarchy. I think the most important one is initially to make it fit in its context. That's what we've been trying to do. Throughout its life cycle."*

When discussing the application of the principles in the design process, the designer explained that he distinguished two classes of principles: on the one hand, the three life's principles that were applied in the project, and the three other "more advanced" ones that consider evolving, adapting, and growth on the other hand. More specifically, he illustrated his use of the principles within a design process:

> *"You define what you want your product to do; you define your design goals based on the fact that it should be an integrated part of the environment. From that notion, you start to look for: what is the environment and what does the environment want, what is available, so that's 'use available materials and energy' […]. And then in a later stadium […] environments will change, but then comes the adaptability [life's principle 'adapt to changing conditions'] and that's for sudden changes; more cyclic changes, that's 'leverage cyclic processes' […]. And then over a long term it will evolve. But I'm not so sure if you want your product itself directly to evolve […] you could say that the evolve mechanism should just be a part of your company. […] Innovation is the evolution of products."*

The 'Design Spiral' as proposed by Biomimicry 3.8, was not used. The designer preferred to integrate 'nature' in a design method he was already familiar with and which he indicated as being more complete, as it included things like company characteristics, the market, and trends. Nevertheless, the data suggests an overlap of the Design Spiral and the design process followed in this project. Most of the tools that were included in the study were applied in the project, although three were only applied partially or in a modified form. Furthermore, the design process was represented by the designer as being cyclical instead of linear (see Figure 5.10 in the next section), which corresponds to

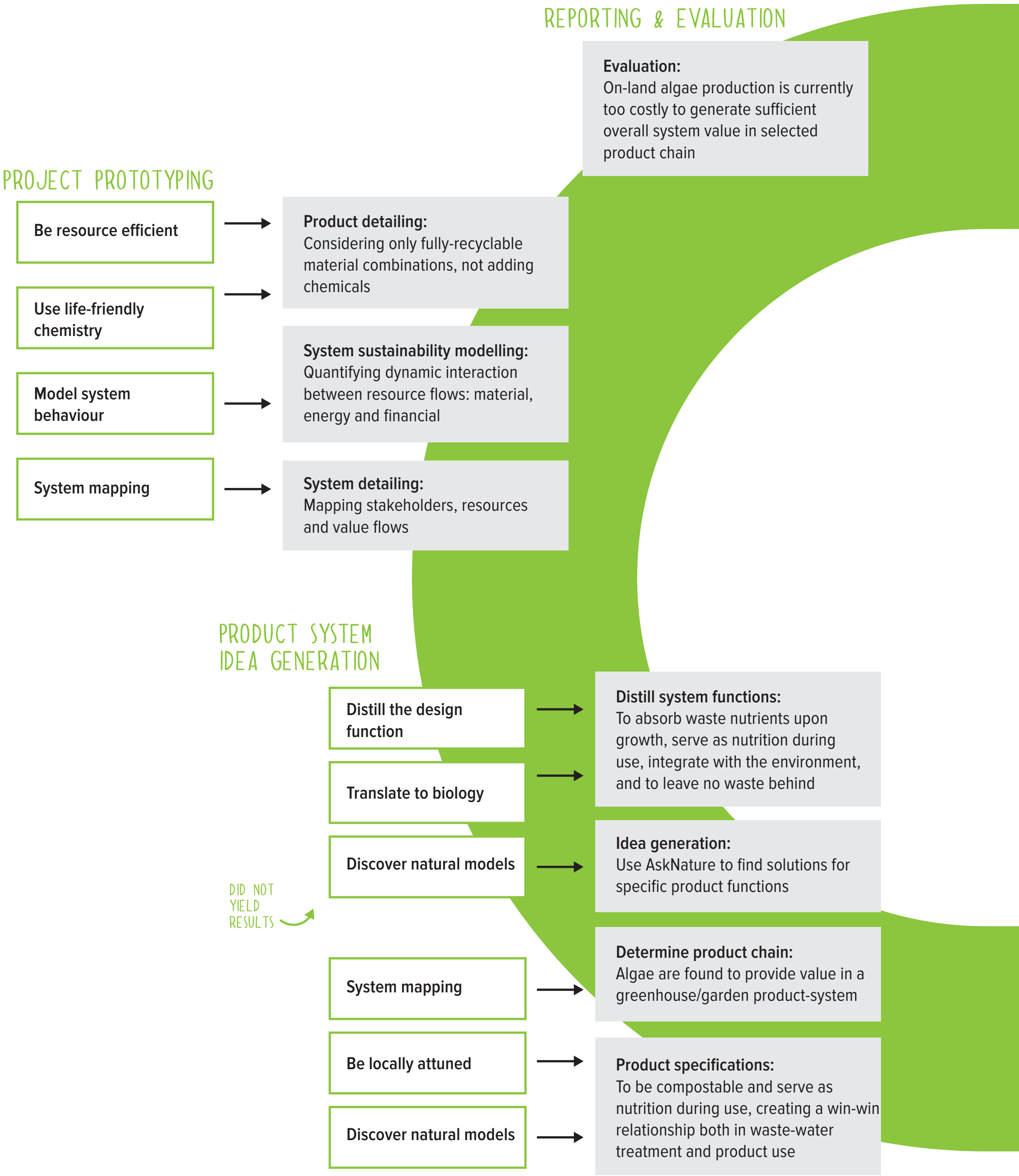


Figure 5.10: Case diagram of the design process in relation to the Biomimicry elements applied

PROJECT PREPARATION

Innovation inspired by nature → **Design challenge:** Develop a valuable product application of algae: an abundant, renewable, biodegradable waste resource

Be resource efficient → **Design challenge:** Develop a valuable product application of algae: an abundant, renewable, biodegradable waste resource

Creating conditions conducive to life → **Project ambition:** "To make a product that is a valuable part of its environment"

FAMILIARIZING

System mapping → **Material analysis:** Identify generic product cycle and environment in each step

Evaluate against LP

Be locally attuned

→ **Project goal & vision:** To develop a solution that provides value in each step of the product cycle, focussing on a location where the algae could be grown

SITUATION ANALYSIS

System mapping → **Context analysis:** Investigate for different contexts how an algae product can provide value in each life-cycle phase

Be locally attuned → **Context analysis:** Investigate for different contexts how an algae product can provide value in each life-cycle phase

Discover natural models → **Brainstorm:** Input from biologists how algae contain spores that provide valuable nutrition for growing plants the Design Spiral, as well as to generic design process models such as for instance Buijs and Valkenburg's (2005) 'Product Innovation Process'.

The designer added two tools to the list of Biomimicry elements. Of these, the tool 'system mapping' was marked as being important in the project by both designer and researcher. The designer developed this tool himself to "*really integrate some of the life's principles in your design, which I think are most important*", something he felt lacking in the existing Biomimicry-approach.

5.3.3 The effects of applying Biomimicry on the design process and outcomes

Figure 5.10 provides a schematic representation of the phases in the design process as sketched by the designer, showing the activities that involved the use of Biomimicry elements. For clarity's sake, the design phases are depicted as separate entities, but the designer indicated that the actual process was more fluid and iterative. He also explained that Biomimicry was not applied according to a strict methodology, but it was fuzzier, wherever it felt needed. The design strategy was used in all phases of the design process except for evaluation. Furthermore, no Biomimicry elements were applied in activities such as material research and shaping the design. IDEAL&CO had much freedom in determining the way in which the project was executed and they developed the project using a bio-inspired design philosophy. The project briefing made no mention of a bio-inspired approach, but the ambition to integrate the product environment in the design was already set at the start of the project and included in the project planning. The use of algae as the resource for the product had been determined in a preceding project. According to the designer, that project was also based on a 'bio-inspired notion of sustainability', but more influenced by Cradle to Cradle, a strategy he feels is closely linked to Biomimicry. The material focus of the project and the choice of materials are therefore not a result of applying Biomimicry.

In the first design phases, the project was highly influenced by the life's principle 'be locally attuned and responsive' and the 'system mapping' tool that the designer developed for integrating the principle in the design process. In system mapping, the life cycle of the product is visualised, with an inventory of the product environment for each step of the cycle (see Figure 5.11). Given the knowledge that the algae can clean wastewater, the designer analysed and visited various locations, interviewing experts at sites where algae production algae could provide value. A result of applying this tool was the setup of a brainstorm session with experts from each part of the value chain, including biologists. The biologists provided the team with information about how algae can provide value in the use phase, steering the project to a system in which applications could be developed for gardening.

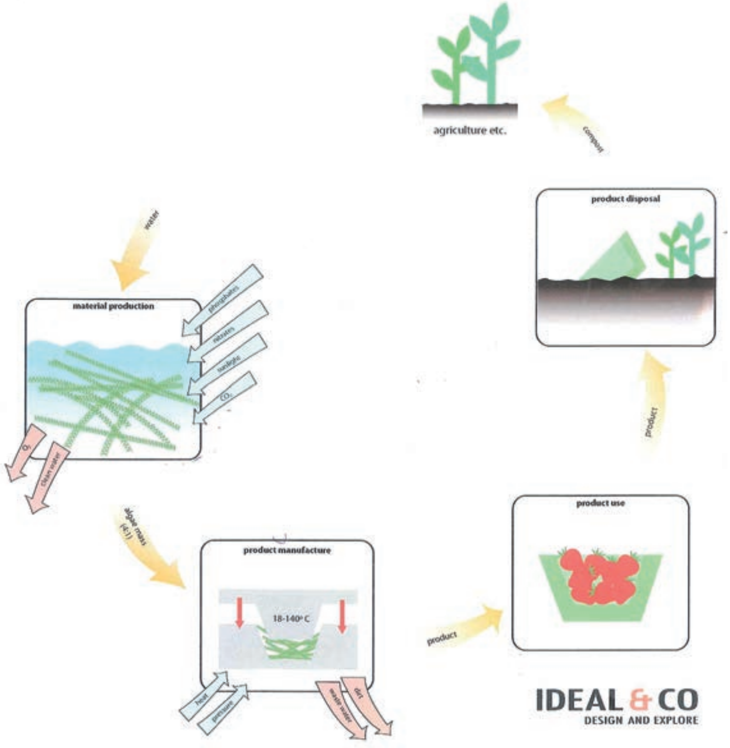


Figure 5.11: First system map, illustrating the product cycle for an application of algae material

In the ‘product-system idea generation phase’, three Biomimicry tools were used. Their application helped to develop the system further and determine the system functions, but did not yield solutions for the system functions under consideration. When discussing the use of the AskNature-database, the designer explained:

> *“I think it’s just that the product just needs to be very simple, and that only leaves us with a few opportunities for these specific examples to be integrated. I know there are very simple specific solutions you can find in nature, like the shape to increase stiffness and that kind of stuff. But most of them you already know, or were just not relevant for this product…”*

Additionally, the use of a natural material in a ‘bio-cycle’ already made the system meet several of the life’s principles. Nevertheless, these principles did influence product detailing, either explicitly or not. For instance, on the use of ‘life-friendly chemistry’, the designer explained:

> *"Well, we didn't choose for integrating algae with epoxy for example, which could have been a way to go; those are options that you don't even consider anymore."*

The designers' ambition to create value in each phase seems to have influenced many decisions, not only for what purpose the product was to be applied (provide user value) but also where to source the material, where to produce it (in the greenhouse) and how to discard of it (integrated in the use of the product). As a result, the material replaces other resources in different phases of the product cycle, as specified in Table 5.8.

The resulting solution is highly innovative, and requires the development of growing infrastructure, material, and product production, as well as market development. A major project barrier was the lack of data, for example on the growth patterns of the type of Algae being applied, which was needed to model the system and thereby determine its feasibility.

The project did not include a conventional sustainability analysis. The designer did set-up a dynamic model to determine 'system sustainability', quantifying the environmental and system's financial inputs and outputs. Although he considered the product would bring environmental *benefit*, based on his analysis, he also concluded that the product-system did not provide a sustainable solution in the Netherlands. The designer strived to build a sound business-case for the product-system by adding value in each phase of the product cycle. However, the current solution is expected to generate insufficient value to

Product cycle phase	Materials applied in typical system	Function of algae
Growth	Either diverse (wastewater treatment unit at greenhouse) or none (causing loss of water quality)	Removing/recollecting nutrients from waste-water (caused by an over concentration of nutrients due to flushing of greenhouse soil).
Production	Polystyrene (plant pot tray)	Replacing fossil fuel based plastic by bio-based material.
Use	Fertilizer	Providing nutrients (phosphor, nitrate, trace-elements) to an ecosystem that requires those for plant growth.
Disposal	PS recycling or incineration	Decomposing into soil (combined with use phase).

Table 5.8: Resource replacement throughout the product cycle

be economically sustainable. Given the required developments of the infrastructure, the project was not continued in its current form. The designer did not take social aspects of the design into account. Given the nature of the project, we anticipate no adverse social impacts; the use of local suppliers may contribute to the strengthening of the local community, but this was not a project aim. Other social sustainability aspects, such as social impacts associated with material extraction, or the active development of 'fair-trade' practices, were not considered.

5.3.4 Discussion and conclusions Case 2

Figure 5.12 summarises the findings from the Algaepack flower tray case study. As in the earlier cases, the analysis showed that not all strategy tools were applied. The project focused on the principle 'Be locally attuned'. This principle, supported by the 'system mapping' tool, seemed effective in helping the designers develop a product system. The resulting context-specific approach corresponds to our findings noted in Chapter 4.

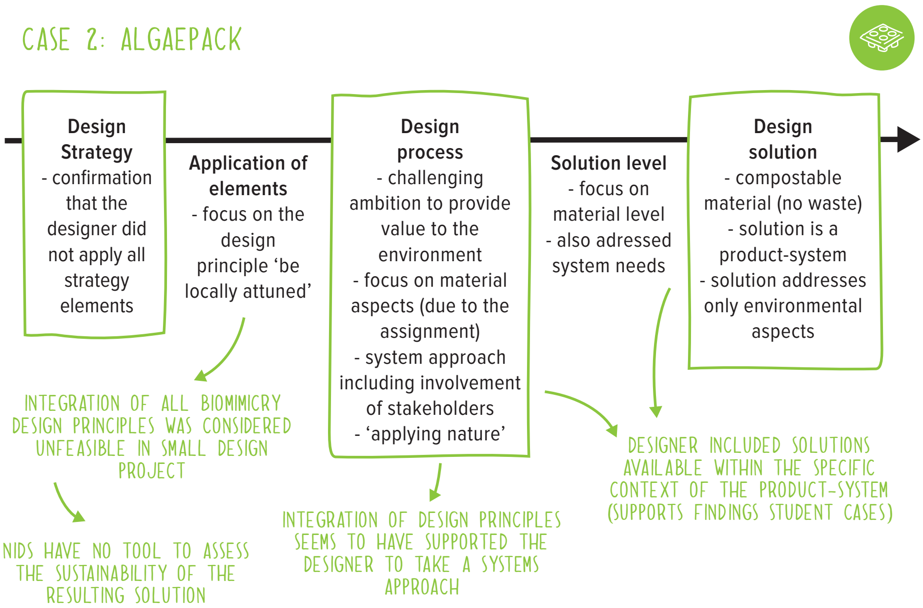


Figure 5.12: Summary of the findings from Case 2, the Algaepack flower tray

The results illustrate how the application of all six life's principles seems unfeasible within relatively small product development projects, due to the required resources. In this particular case, the designer left out half of the life's principles due to time constraints. This finding is particularly relevant, as Biomimicry offers no tool to calculate or systematically assess the sustainability of a product or system, and thereby assess the possible effects of omitting certain life's principles. Therefore, this strategy does not aid the designer in mitigating the risk of introducing environmental impacts into its solutions. The life's principles used in the project clearly steered the solution-space and selection of ideas and concepts. Applying Biomimicry tools on a system-level allowed the designer to identify and analyse the product system and generate the requirements.

The Biomimicry tool 'Discover natural models' for finding inspiration from specific organisms did not yield results. However, as the project involved the application of a natural material and several biological processes, nature seems to have been directly integrated, thereby reducing the need to look at nature for inspiration and the emulation of solutions.

Applying Biomimicry in the design process resulted in a systems-approach and in the involvement of potential stakeholders in the early phase of the design process. Furthermore, the project had a strong material focus, but this focus resulted from the nature of the assignment, and was not initiated by applying Biomimicry. The design strategy was applied from the preparation phase of the project resulting in a challenging ambition of creating a product that provided value to its environment. Even though the project was relatively small, the context-dependent ambition led the designer to look more deeply into the characteristics of the material, and to include the context in which the product was cultivated, produced, used, and discarded. The Biomimicry design philosophy, principles, and tools in this project clearly aided the designer in achieving this result.

The case at IDEAL&CO shows how the application of Biomimicry activated the designer to adopt a 'systems approach', by closely linking the product to its environment throughout the different life cycle phases. System development was dominant throughout the design process, and this resulted in an innovative product-system. Apart from the manufacturing phase, the product was designed to generate value at each product stage. Furthermore, the product was made from renewable resources that can be composted (no waste generated). The direct use of 'nature' by applying a natural material and biological processes, instead of being inspired by, and then emulating the natural world, offers designers an 'easy' way of meeting several life's principles, an approach not specifically included within Biomimicry. Nevertheless, this approach helped to develop a solution that produces no waste, and offers context-specific environmental benefits, within a relatively small-sized development project.

In this case, we observed that the designer focused more on the life's principles than the Design spiral and tools, and that he additionally developed his own 'system mapping tool' for integrating some of the life's principles in the design process. The results indicate that a focus on the use of life's principles within the design process, and guidance for their integration within resource-constrained design projects, may help designers to more effectively integrate the eco-systems' level of Biomimicry.

The case study shows that the designer did not aim to create beneficial social impacts. This coincides with the absence of principles and tools for social sustainability, which indicates a major limitation of this design strategy with respect to sustainable product development. Biomimicry, as observed in this study, can complement other design strategies for environmental sustainability, providing knowledge of how the natural world creates 'products' that benefit their ecosystem. For assessing overall environmental impact, other strategies and tools are required.

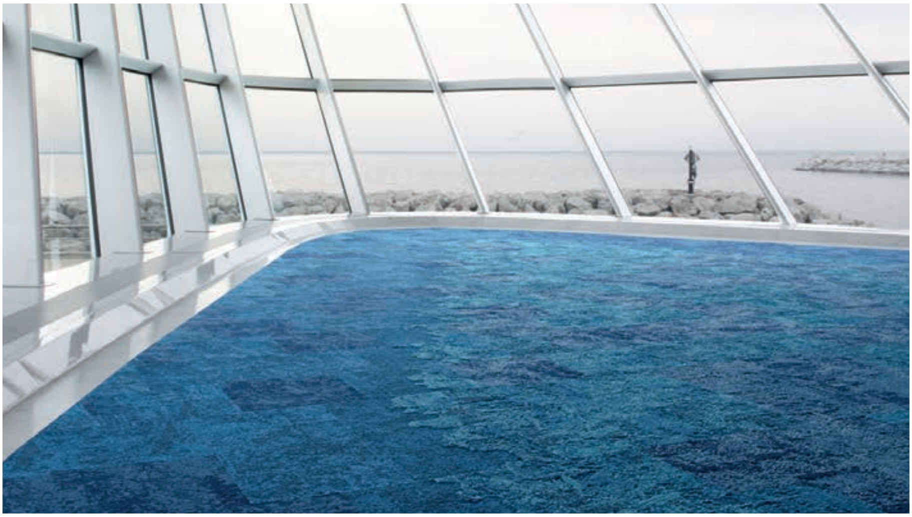


Figure 5.13: impression of Interface Net Effect carpet tiles, designed by David Oakey

Figure 5.14: impression of the Net-Works project by Interface

5.4 Case 3: Net Effect and Net-Works by Interface

Interface is a global carpet tile manufacturer, market leader in modular carpet, with over 3000 employees and 5 manufacturing facilities worldwide[4]. The company is well-known for its 'Mission Zero', developed by Interface's founder Ray Anderson, to "eliminate any negative impact our company may have on the environment by the year 2020" (Anderson and White, 2011).

5.4.1 The design challenge

The case studied is a combination of two linked projects, both conducted at Interface: 'Net Effect' and 'Net-Works'. Net Effect is the design of Interface's 2013 global carpet tile collection, which introduced yarn from Net Works, a co-innovation project for sourcing nylon by collecting discarded fishing nets from oceans and beaches.

The Net Effect was designed by Interface's lead designer and his team. The product is the result of a series of nature-inspired development projects. Compared with conventional carpet tiles, this Interface tile has three distinguishing features: the use of random patterns, application of 100% recycled yarn, and 'TacTiles' - small 'stickers' to connect the tiles.

The Net-Works project contributes to Interface's ambition to create a 'restorative' loop. According to Interface "Net-Works is the first step in creating a truly restorative loop in carpet tile production, cleaning up oceans and beaches whilst also creating financial opportunities for some of the poorest people in the world." The project was launched in 2012 in the Danajon Bank area of the Philippines, starting in 5 villages, and has since expanded to 15. As of 2013, the collected nets are shipped to Aquafil, one of Interface's yarn suppliers, providing a (currently small) new stream of waste material for their production of 100% recycled nylon.

Interface regularly initiates projects that contribute to fulfilling their sustainability mission. The Net-Works project leader explains how the two case projects matched:

> *"We [Interface] saw a chance to design a new way of sourcing fishing nets for Aquafil [one of the material suppliers] and, in doing so, create an inclusive business model that would benefit vulnerable coastal communities. Then we found out that Oakey [lead designer] was designing a collection inspired by Sylvia [Sylvia Earle, oceanographer] and the oceans. It all came together!"*

> *"It may seem a little crazy that a commercial carpet tile company has ended up working with the fishing community on a remote, double-barrier reef. But*

> *that's the beauty of seeing design as more than just product. Co-innovating with experts from lots of different disciplines has been brilliant; together we've re-imagined what the value chain could look like" (Arratia, 2013).*

5.4.2 Application of Biomimicry elements

At Interface, the influence of Biomimicry reaches beyond its application in product development projects. Janine Benyus was one of a team of environmental experts that advised Interface on their corporate sustainability mission. Biomimicry, as well as the Natural Step, were central to the formulation of the '7 fronts', illustrated in Figure 5.15, on which the company wants to achieve sustainability (Harel, 2013). The designer of the Net Effect can be considered an expert in Biomimicry, both in training and experience. In his projects, he regularly involved biology experts from 'Biomimicry 3.8'. The Net-Works project leader received no specific training in Biomimicry, but has a background in ecology.

Figure 5.15: The '7 fronts of sustainability' by Interface

The case study results show that Biomimicry was applied explicitly for the development of Net Effect, together with 'Biophilia', a concept suggesting innate emotional affiliation of human beings to other living organisms[5] (Kellert and Wilson, 1995). In the Net-Works project however, the team did not use Biomimicry explicitly. When asked, the project leader explained:

> *"it was never [Biomimicry], you know, although it.. I guess it just shows that for us, thinking about taking waste and turning it into something else, is just how we, you know, how we think about, how we run business."*

The role of Biomimicry in the Net-Works project can therefore 'only' be attributed to the ambition level resulting from the mission and the 'sustainability fronts' of Interface, parts of which have been explicitly linked to Biomimicry or to 'learning from nature'.

Table 5.9 illustrates the application of Biomimicry for the development of the carpet tile. The designer was familiar with all the Biomimicry-elements included in the study, but not all of them were applied in the design process. The second column shows the elements that were used, as marked by the designer, and the third column the elements that were detected in the collected case study data by the researcher.

'Innovation inspired by nature' was characterised by the designer as "*the start of the whole thing*". On the other hand, the aspirational goal to 'create conditions conducive to life', was not explicitly used in the development of the tile. Interestingly, the element of 'conducing' *was* observed in the Net-Works project. The project leader described the project as "*an expression of what it would mean to be restorative*", and providing benefits to the ecological and social systems were key project ambitions. However, within the project itself, the team did not use Biomimicry but instead applied 'inclusive business development' combined with systems thinking.

In the development of the carpet tile, five of the six life's principles were used. Only one, 'evolve to survive', was not used in the project. The designer considered that this principle reflected innovation processes in general, and was not specific to a Biomimicry approach[6]. The principle 'be resource efficient' was considered of key interest. Within his projects, the designer focuses on 'closing of the material loop' and involving the supply chain to contribute to this ambition. 'Integrating development with growth' was described by the designer as the one that inspires future developments: "*this one here is when I dream of what carpet-tile could look like*", referring to tiles that would 'build from the bottom up'. For the principle 'be locally attuned and responsive', only the first part is reflected in the case study data. The tile-concept facilitates custom-made ('attuned') solutions for clients, but this was not explicitly linked to the use of Biomimicry by the designer. The use of

Elements of Biomimicry considered in the case study	Applied according to designer	Applied according to researcher
Philosophy		
Innovation inspired by nature	✓	✓
Life creates conditions conducive to life	x	x
Life's principles		
Evolve to survive	x	x
Be resource (material and energy) efficient	✓	✓
Adapt to changing conditions	✓	✓
Integrate development with growth	✓	✓*
Be locally attuned and responsive	✓	✓*
Use life friendly chemistry	✓	✓
Methods & tools		
Design spiral	x	x
Evaluate your design against life's principles	x	✓**
Distil the design function	x	x
Translate to biology	x	✓
Discover natural models	✓	✓
Emulate nature's strategies	✓	✓
Sharing/dispersing Biomimicry (added by designer)	✓	✓

Table 5.9: Overview of Biomimicry-elements considered in the case study. ✓=applied, ✓*=applied partially or implicitly, ✓**=applied in a modified manner, x=not applied; bold highlighting represents the elements considered to have been most important in the design project.

'readily available materials' played an important role with the application of 100% waste resources for the yarn, and for the further development of the resource loop via the Net-Works initiative. Both projects focused on the yarn used for the carpet face fibres, and did not consider the composition of the backing material. The last principle, 'use life friendly chemistry', was marked as being relatively less important, as the designer has less influence of affecting the chemistry used, and instead relies on expertise from within Interface.

The 'Design Spiral' method was not used. Nevertheless, according to the case study data, most of the tools included in the method were applied in the project. Whereas the designer did not recognise 'evaluate your design against life's principles' and 'translate to biology' as tools for his design process, the data indicate that their application played an important role, combined with the tools ‘discover natural models’ and ‘emulating nature’s strategies’. The designer explained:

> *“…one of the fundamentals was: How would nature design a carpet-tile? So you got the principles, and we would go down principles of how WE did it. And then they [the Biomimicry consultants] took us outside to look at carpet. Well, carpet is leaves and it’s grass and it’s, you know […] What are the differences? And if they’re so, so big, it’s unbelievable. You know, we’re controlling, we’re making things, uniformity, cutting, assembling, put it all back, and then HERE [in nature] it’s random, organised chaos, similar but different colours, it goes from a product to a floor and then decays and it becomes waste. If you go through the whole system, and then say okay, how can I get mine to do it?”*
>
> *“So, that’s what we have to do, so, can we change that process in any way, of any of these principles to help; and the first one we thought about was diversity”.*

The tool ‘distil the design function’ was not recognized by the designer, nor was it found in the case study data. The expert from Biomimicry 3.8 nevertheless explained how, in the early development phases, the different functions of carpet tiles were formulated and studied.

The last tool in Table 5.9, Sharing/dispersing Biomimicry, was added by the designer to the tools included in the case study, to share, or disperse, knowledge about ecosystems (contributing to the sixth ‘front’ of Interface, see Figure 5.15).

5.4.3 The effects of applying Biomimicry on design process and design outcomes

Figure 5.16 shows a schematic representation of the phases in the design process of the carpet tile that involved the use of Biomimicry elements. At Interface, the effects of applying Biomimicry may be more indirect and widespread when compared to other cases, as a result of the inclusion of several nature-inspired principles in the ‘7 fronts’ of the company strategy. The mission and ambitions affect both product and process development.

The development of the carpet tiles can be characterized as evolutionary. Each year, Interface introduces new collections that offer new aesthetic designs, implements new technological solutions in manufacturing, as well as process innovations that have been developed by Interface and their suppliers. The use of the Net-Works material in the Net Effect is an example of how these process developments have been introduced, providing

COMPANY MISSION & AMBITIONS

- Innovation inspired by nature
- Be resource efficient
- Use life-friendly chemistry
- Be locally attuned

Sustainability mission:
“eliminate any negative impact our company may have on the environment by the year 2020”

Sustainability ambitions:
“7 fronts to sustainability”
including closing the loop, eliminating waste, and using renewable energy

CARPET TILE DEVELOPMENT

- Translate to biology
- Discover natural models
- Evaluate against life’s principles
- Emulate nature’s strategies
- Adapt to changing conditions
- Emulate nature’s strategies

DID NOT YIELD RESULTS

- Use life-friendly chemistry
- Be resource efficient
- Discover natural models
- Emulate nature’s strategies
- Sharing Biomimicry
- Be locally attuned
- Be resource efficient
- Evaluateagainst LP

Design challenge:
How would nature design carpet?

Design principles:
General life principles connected to specific solutions in nature

Continuous project ambition:
Developing carpet-tiles, including the systems design, according to the principles found in nature

Development of ‘random’ design (Entropy, 2000):
Providing new aesthetics and reducing waste during manufacturing & installation

Development of TacTile (2006):
Replacing glue for installation, reducing environmental impact of product and facilitating recycling

Increasing recycled content:
Continuous increase by selecting different yarns and implementing technological developments at Interface on the backing material

Theme for the Net Effect (2012):
Development by going outside, photographing & reading, resulting in the ocean as the theme for the new collection

a. inspiration:
colours, patterns, textures

b. information:
gaining knowlegde, developing message, linking to Net-Works project

Material selection:
Use of 100% recycled nylon for yarn production, including introduction of waste stream from ‘restorative’ Net-Works project

Evaluation:
Did we do better than last year?

Figure 5.16: Case diagram of the design process in relation to the Biomimicry elements applied in the project

synergy between the design, the communication of a relevant ecosystem problem, and the efforts of Interface to address those problems.

The formulation of the design problem ‘How would nature design a carpet?’ is directly linked to the use of Biomimicry, and has resulted in principles driving the design process. Examples of principles found in “nature’s carpets” are the application of ‘diversity’ in patterns, colours and textures, using ‘life-friendly chemistry’ by finding an alternative to gluing the tiles, and ‘being resource efficient’. Based on these principles, the designer has developed several patented technological innovations that affected the design of the carpet-tile and the carpet-tile system, and has reduced its environmental impact.

The first result of the use of Biomimicry at Interface was the introduction of ‘random’ tiles, a design concept reflecting the diversity of patterns and colours of a forest ‘floor’, marking a change to the earlier uniform, directional patterned tiles. This design led to several user and company benefits: the non-directional patterns allow tiles to be placed in any orientation, reducing waste and installation time, whereas the application of similar instead of identical colours allows the combination of tiles from different dye lots, thereby providing flexibility in production as well as allowing the replacement of individual tiles in an installed carpet.

Furthermore, the influence of Biomimicry is clearly visible in the design of the tile collections. In the Net Effect, ‘the Ocean’ inspired the colour schemes, patterns, textures, as well as the message. Its application thus involved more than incorporating environmental sustainability. According to the designer, people buy a product not because of its environmental merits, but because of its quality, “*I think my job is now, you know, really to make beauty from waste*”.

However, the application of Biomimicry did not always yield results. When the design team tried to develop an alternative for gluing the tiles to the floor, mimicking the working principles of a Gecko (that can stick to the wall without using ‘glue’) proved technically unfeasible. The designer learned that differences in scale between the solution in nature and the required solution are important to consider:

> *“So we were looking at […] Gecko paws, and, we could never make it work. But even when I look back at what we tried to do, in nature that design was very, very small, you know, it’s a small animal climbing up the wall, and I’m trying to make carpet tiles with the same design process stay on the floor. And then we kept working with it, and then eventually we thought about gravity. And then we developed the TacTile to bring them [the tiles] together”.*

TacTiles are small 'stickers' that connect the corners of the carpet tiles, thereby removing the need to glue the tiles to the floor. According to the designer, this solution was no Biomimetic innovation:

> *"In my house I was trying to use carpet tiles […]. We have wooden floors and I tried it with tape, trying to pull it down, we were trying to put frames around the carpet tile to hold it together. And then we started to think about, you know, all kinds of things, and then we said; if we can hold all the tiles together […], gravity will.. and that's how that came."*

Interestingly, the Gecko was still used to communicate the solution: as having provided an initial source of inspiration to the design team and as a metaphor for the 'glue-free' solution that was developed (Interface, 2013b).

When compared to traditional carpet tiles, the Net Effect applies similar materials. However, the material loops differ considerably, as specified in Table 5.10. By choosing the 'best available' materials, with each collection, the designer tries to increase the amount of recycled content used:

> *"And my principle is: every year, I have to measure myself, or what we do. Did we do better than last year? Growing towards sustainability. That means: moving away from virgin material. How much.. and we measure this each year. And so we know that we* ARE *actually making a difference".*

With respect to closing the loop, the designer especially influenced the application of recycled nylon, selecting yarns that contained recycled resources. He has a long-standing relation with the current supplier, Aquafil, which in turn, was inspired by Ray Anderson and his mission, and developed nylon from 100% waste resources, using depolymerisation to develop high quality yarns. The waste nylon includes old carpet fluff recovered by Interface, industrial fishing nets, and, as of 2013, fishing nets originating from the Net-Works project.

Interface uses LCA to determine hotspots for their product and process development, and EPDs (Environmental Product Declarations) for providing their clients with information on environmental performance. For example, the LCA-data in Figure 5.17 illustrates why Interface focuses on reducing the impact from raw materials, and specifically on the impacts of the use of yarn. The designer uses these results from Interface to inform the design process, but he does not apply LCA-based tools within the design process.

With respect to social sustainability, the designer addressed the users' well-being. The use of natural elements in the design of the Net Effect carpet collection was specifically aimed

Carpet tiles	**Conventional**	**Net Effect**		
Components	Materials	Materials applied	Material origin	Material destination
Face fibre (13-19 wt%)	**Polyamide - virgin resources**	Polyamide - 100% recycled input (Econyl) for 5 out of 6 Net Effect products, and at least 87.5% recycled input for the other Net Effect product	100% recycled, of which 50% post-consumer waste, including nylon from: - ReEntry - Industrial fishing nets - Introduction Net-works material	ReEntry2.0 program (since 1995 this program has processed 191,000 tons of carpets from various manufacturers, which amounts to, on average, 10% of Interface's European production volume per year)
Backing (80-86 wt%)	**Bitumen backing with limestone filler - virgin, may contain recycled content including limestone filler**	Graphlex: Bitumen backing compound with limestone filler (containing recycled materials), glass-fleece reinforcement and polypropylene covering fleece	54% recycled content on average - recycled limestone - limited content from ReEntry program	Suitable for ReEntry
Pigments & additives	**Data unavailable**	Not specified	Not specified	Not specified
Adhesive system	**Polymer dispersion adhesive**	Tiles suitable for installation with TacTiles (PET, with compounded natural rubber)	Virgin	Suitable for PET-recycling

Table 5.10: Material application in carpet tiles; data from Interviews and documentation (Aquafil, 2012, Interface, 2013a)

at providing increased well-being (linked to the use of Biophilia), but the designer did not consider social aspects across the life cycle of the product. In turn, the Net-Works project specifically aimed at generating positive social and environmental impacts. However, the project activities in Net-Works were not the result of applying a Biomimicry design strategy. In the design of Net Effect, economic sustainability was addressed indirectly. The designer strived to develop a collection that would be highly appreciated by customers, thereby ensuring a sound business case. In turn, the Net-Works project had a specific

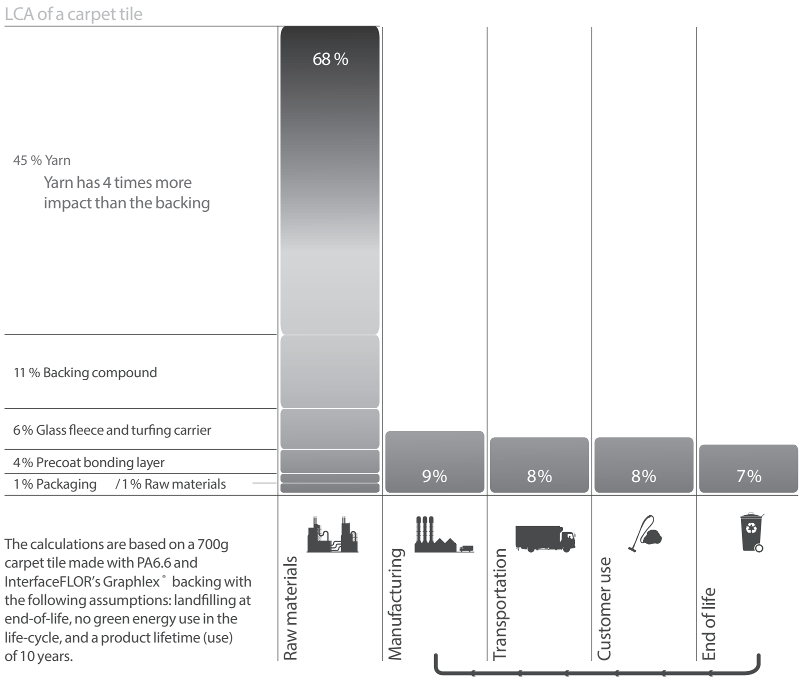


Figure 5.17: LCA outputs from Interface, based on GABI 4 database, with GHG emissions, embodied energy and toxicity each account for 1/3 to the overall index (Arratia 2011, InterfaceFLOR 2012)

focus on ensuring economic sustainability, improving the welfare of specific groups of low-income people, however, as already mentioned, these results are not attributed to the use of Biomimicry.

5.4.4 Discussion and conclusions Case 3

Figure 5.18 summarises the findings from the Net Effect and Net-Works carpet tile case study. At Interface, principles based on 'learning from nature' are included in the company strategy. Consequently, these principles may affect both process and product development projects, also without the use of a strategy such as Biomimicry. This third real-life case both illustrates the potential influence of including nature-inspired principles in a company's strategy, and demonstrates how Biomimicry can be applied at a form, process, and systems level. As this study examined the application of Biomimicry in a specific case, no general conclusions can be drawn on the influence of these

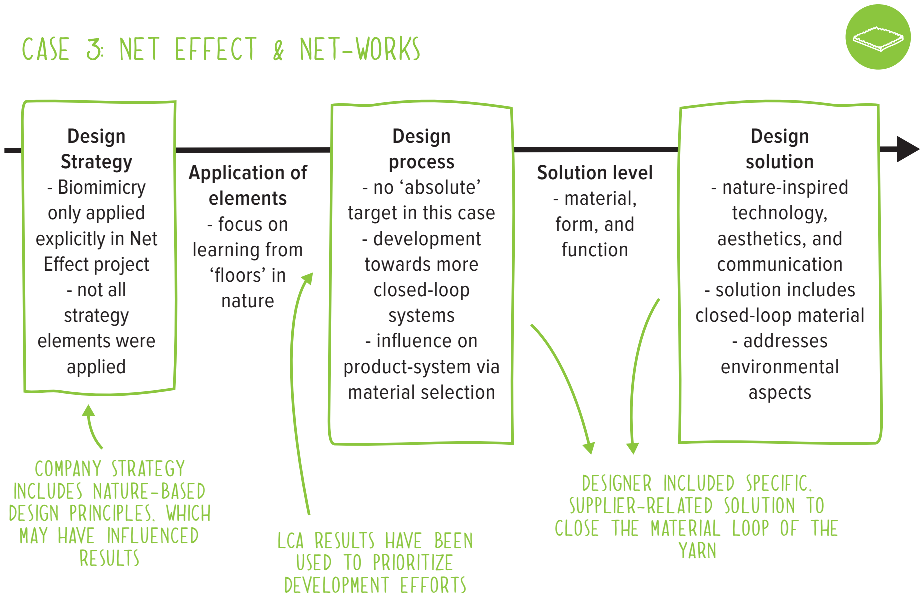


Figure 5.18: Summary of the findings from Case 3, the Net Effect & Net-Works carpet tile

principles as such. Nevertheless, the Net-Works project illustrates how a project, in which Biomimicry was not explicitly applied, can incorporate many Biomimicry principles, aiming to turn waste into a valuable product and at the same time having a restorative effect on ecosystems.

In turn, the Net Effect carpet-tile design process was marked by the explicit application of Biomimicry. The design strategy was used for developing technical solutions, for designing new collections inspired by nature, and for communicating the results to the client. The carpet tile, as developed by Interface's lead designer, shows an 'evolutionary' process in which product and process innovations have been introduced gradually, together with new colour schemes, patterns, and textures. The application of Biomimicry principles activated the designer to adopt a 'systems approach', especially for the material loop. The findings indicate that the application of Biomimicry tools helped the designer to develop new concepts and designs, and thereby to address the environmental pillar of sustainability. In the design phase, natural themes were used to develop the collections, to communicate the design, as well as to convey ecosystem knowledge to clients. Furthermore, the Net Effect collection introduced and communicated the outcomes of the Net-Works project.

The designer considers material selection to play an important part in the design process, a way by which designers can influence the product system and that can actively support suppliers to develop the required system improvements. Nevertheless, the influence of the designer is limited, as he strongly depends on technological innovations at Interface and their partners, for instance on innovations to enable recycling of the tile backing.

The technical innovations focused on the development towards a closed loop system, by using available waste material and by recycling materials. The case study data points to an effective application of the Biomimicry 'life's principles' by the designer, taking into account that in the first years of application, Biomimicry experts supported the team to master the methods and tools. By studying the principles and functions of natural 'floors', the designer and his team gained inspiration as well as knowledge of specific solutions which they then applied in their products.

With respect to the ambition level, no quantitative or 'absolute' environmental targets were set within the design process. Instead, the designer aims to improve performance on one or more of the principles with each collection. The designer performed no quantitative assessment of sustainability performance of his designs. However, Interface performs Life Cycle Assessments for assessing environmental performance, and its results have been used to prioritize efforts towards reducing impacts from the yarn. These findings indicate that the Biomimicry approach, as used in this case, did not trigger the design team to set 'Mission Zero' or 'restorative' targets. Tools to specifically support designers in targeting and developing solutions that will 'conduce' the (eco)system in which they function, may help to further shift the designers' focus towards creating the conditions that Biomimicry strives for. In that sense, the Net-Works project highlights the potential impact of setting restorative targets.

Corresponding to earlier findings, this study shows that the designer did not aim to address social sustainability across the product life cycle. This result coincides with the apparent absence of principles and tools for social sustainability, underpinning what may be a limitation of Biomimicry with respect to sustainable product development. When asking the designer about his opinion on the use of Biomimicry for social sustainability, he answered: "that would be very interesting to ask a biologist […] how does that work in nature?"

5.5 Case 4: the SmartBin-system by EcoSmart

EcoSmart is a Dutch waste management company, employing 180 people, and works for offices, schools, institutions, and local governments. EcoSmart is a daughter company of Van Gansewinkel, a waste collection and recycling company that has adopted the Cradle to Cradle philosophy for their corporate strategy. The company motto, in Dutch ‘”Afval bestaat niet”, literally translated as “Waste does not exist”[7], marks the influence of Cradle to Cradle, and illustrates their transition from a waste management to a resource management company.

In connection to the Van Gansewinkel motto, the ambition of EcoSmart is to create ‘waste free’ environments for their clients. Five employees of EcoSmart have been trained in Cradle to Cradle via company-training programmes at EPEA Hamburg.

5.5.1 The design challenge

The case project involved the development of the SmartBin2.0 (Figure 5.19), a ‘means for resource collection’ for offices and similar buildings, that facilitates users to collect their waste in separate streams, which in turn enables improved recycling of the materials. This project is one of about fifteen projects where EcoSmart has started to implement the Cradle to Cradle-design philosophy, linking to other Van Gansewinkel projects, such as the development of Cradle to Cradle-certified office paper. The SmartBin replaces regular office waste bins and paper collection crates.

Figure 5.19: Impression of the EcoSmart SmartBin2.0

In this project, the SmartBin was redesigned according to the Cradle to Cradle design philosophy and Cradle to Cradle certified at the 'Silver' level. The SmartBin is one of the company's main products for collecting separate waste streams and was therefore selected as a showcase of a Cradle to Cradle product. The turnaround time of the design and certification process was about two years.

5.5.2 Application of Cradle to Cradle elements

Cradle to Cradle is explicitly used within EcoSmart. The strategy matches the company's vision on utilising the value of materials that are currently wasted, and helps them to communicate their philosophy to clients. A team of six people at EcoSmart were involved in the development of the SmartBin2.0, four of whom were trained in the Cradle to Cradle strategy. An external industrial designer, not trained in Cradle to Cradle, designed the new metal frame; EcoSmart gave him the specifications that resulted from applying Cradle to Cradle.

For the case study, the researcher interviewed two trained members of the design team: the project leader and the project member assigned with the development of the plastic parts. Both were familiar with most Cradle to Cradle-elements included in this study. Only the tool 'cascade use' was noted as unknown by both. Table 5.11 lists the elements, showing which were applied in the development process, according to the designers (second column), and as detected in the collected case study data by the researcher (third column).

With respect to the philosophical element 'Doing good - instead of less bad', the interviewees had different opinions: one regarded this principle to have been highly important, the other doubted whether the project actually reflected 'doing good'; using waste as a resource can be viewed both as doing good, or as reducing current waste streams. The second element, 'Creating a beneficial footprint' was not considered in the project, and one interviewee indicated being unfamiliar with both this concept as well as with 'eco-effectiveness'. When the researcher asked what EcoSmart would consider to be the 'ideal collection product', he explained (translated from Dutch):

> *"…then you very quickly return to certification towards 'gold', because then that's the optimal collection product […] Look, such certification is quite, indeed very challenging. Quite a lot is being asked for."*

On the other hand, the Cradle to Cradle expert involved in the project explained that the current product already provides a service that contributes to eco-effective resource management. In other words, the concept "did not need to be rethought before it could

Elements of Cradle to Cradle considered in the case study	Applied according to interviewees	Applied according to researcher
Design philosophy		
Doing good - instead of 'less bad'	?-✓	✓*
Creating a beneficial footprint	X	x
Eco-effectiveness	X	✓*
Design principles		
Waste equals food	✓	✓
Use current solar income	✓	x*
Celebrate diversity	✓	x*
Methods & tools		
Roadmap	✓	✓*
Material inventory	✓-✓	✓
ABC-X classification	✓	✓
Define use in biological and technical cycles	x-✓	✓
Define use period	x-✓	✓*
Add value	x	✓*
Cascade use	x	x
Design for (dis)assembly	✓-✓	✓
Use Cradle to Cradle-elements (materials, processes, ingredients)	x-✓	✓*
Certification (added by interviewee)	✓	✓*

Table 5.11: Overview of Cradle to Cradle-elements considered in the case study. ✓=applied, x=not applied, ✓*=applied partially or implicitly, x*=not applied as intended according to the case data; bold markings represent the elements considered to have been most important in the design project.

be optimised", and thereby fitted the ambition of doing good/being eco-effective[8]. The project itself focused on optimising the product design towards meeting the Cradle to Cradle-principles.

The principle 'waste equals food' was marked as the most important principle by both the two interviewees and the researcher. The two other Cradle to Cradle-principles, 'Use current solar income' and 'Celebrate diversity', were marked by the interviewees as being applied but of less importance. According to the researcher, 'Use current solar income' played a role in the certification of the product. The company made an inventory of the energy consumption and sources currently used by the manufacturers, and needed to develop a renewable energy strategy. However, no impact was observed from this principle on the design process or design of the product.

> *"…because you can say that you have to ensure that production is based on solar energy within three years, but you know that with the current [production volume], this is not possible, perhaps if I order 100,000 [products], but with this product it cannot be done. You also have to be realistic, feasible, and we are a major client of those companies, but we do not have this type of [production] company ourselves. If so, then we could say that we would organise that company according to Cradle to Cradle".*

The application of the third Cradle to Cradle principle, 'Celebrate diversity', was considered difficult, also within the specific project. Both interviewees showed different interpretations as to what is meant by its implementation: either the inclusion of different types of users in the product development process (i.e. user-centred design), or the consideration of different materials for the product. The case study data showed no focus on developing a solution that was attuned to, or 'celebrated', the specific place or context of the product.

The tools that were marked as being most important were 'ABC-X' by both interviewees and the researcher, and 'design for disassembly' by one interviewee and the researcher.

In addition, one of the interviewees considered 'material inventory' as most important, and both interviewees considered material inventory and ABC-X to be closely linked or even integrated tools.

Although the interviewees marked the tool 'Add value' as being not applied, the case study showed how the product (frame) was redesigned, to improve appearance and material quality. This was a deliberate choice, which added to the market value of the product, and was considered as an implicit use of the tool.

Certification was not included as a Cradle to Cradle design tool in the research (see section 5.1.3). Nevertheless, one of the interviewees indicated that the certification had affected the design process, which was confirmed by the case study data. Consequently, certification was added to this case as a design tool. Furthermore, both interviewees considered that cooperation with their main suppliers played a key role in the project. This finding has been included in the analysis as being a result of (rather than a tool for) applying Cradle to Cradle.

5.5.3 The effects of applying Cradle to Cradle on design process and design outcomes

Figure 5.20 shows in which stages of the development process the different Cradle to Cradle elements were applied. The Cradle to Cradle strategy played a key role in formulating the ambition and targets of EcoSmart. According to both interviewees, Cradle to Cradle appealed to the company as it reflects and 'confirms' the mission that EcoSmart had already developed. For the development of the SmartBin2.0, EcoSmart set out to develop a 'Cradle to Cradle-product' and decided to have the product certified. They aimed for a high certification level ('silver'), to be able to market the product as being Cradle to Cradle, and the design challenge reflects the application of the 'waste=food' principle.

In the product development phase, most Cradle to Cradle tools were used. The case study results show that the Cradle to Cradle-methods and tools triggered the development team to spend considerable time finding and analysing suitable materials. Certification required the identification of the plastic ingredients down to parts-per-million, and the materials used were tested for harmful content and emissions. At the time, no Cradle to Cradle-certified plastics were available for this application. EPEA supported EcoSmart by performing the ABC-X analysis, coordinating the certification process, and clarifying the process to suppliers. For defining the content of the materials and for finding suitable recycled materials, EcoSmart organised 'pressure cooker' sessions. In these sessions, the company worked together with both the suppliers of the frame and plastic bins, some of the suppliers' suppliers, Van Gansewinkel, and EPEA. The interviewees considered working together with these value chain partners as an important, positive experience, and something markedly different from traditional projects (translated from Dutch):

> *"Previously, you would go to a supplier that could deliver a product, and now you go to a supplier that can contribute to the philosophy of your company and product […] And that supplier therefore looks at you very differently, too. You are not a customer, but you are a partner."*

> *"When I was in Hamburg [Cradle to Cradle training] we also discussed this a lot, in the sense of, you have to, you should not see it as a BURDEN […]. But you should indeed as supplier think, 'What's in it for me?' […] if everyone sees that […] then you will also get, that you want to invest that energy.*

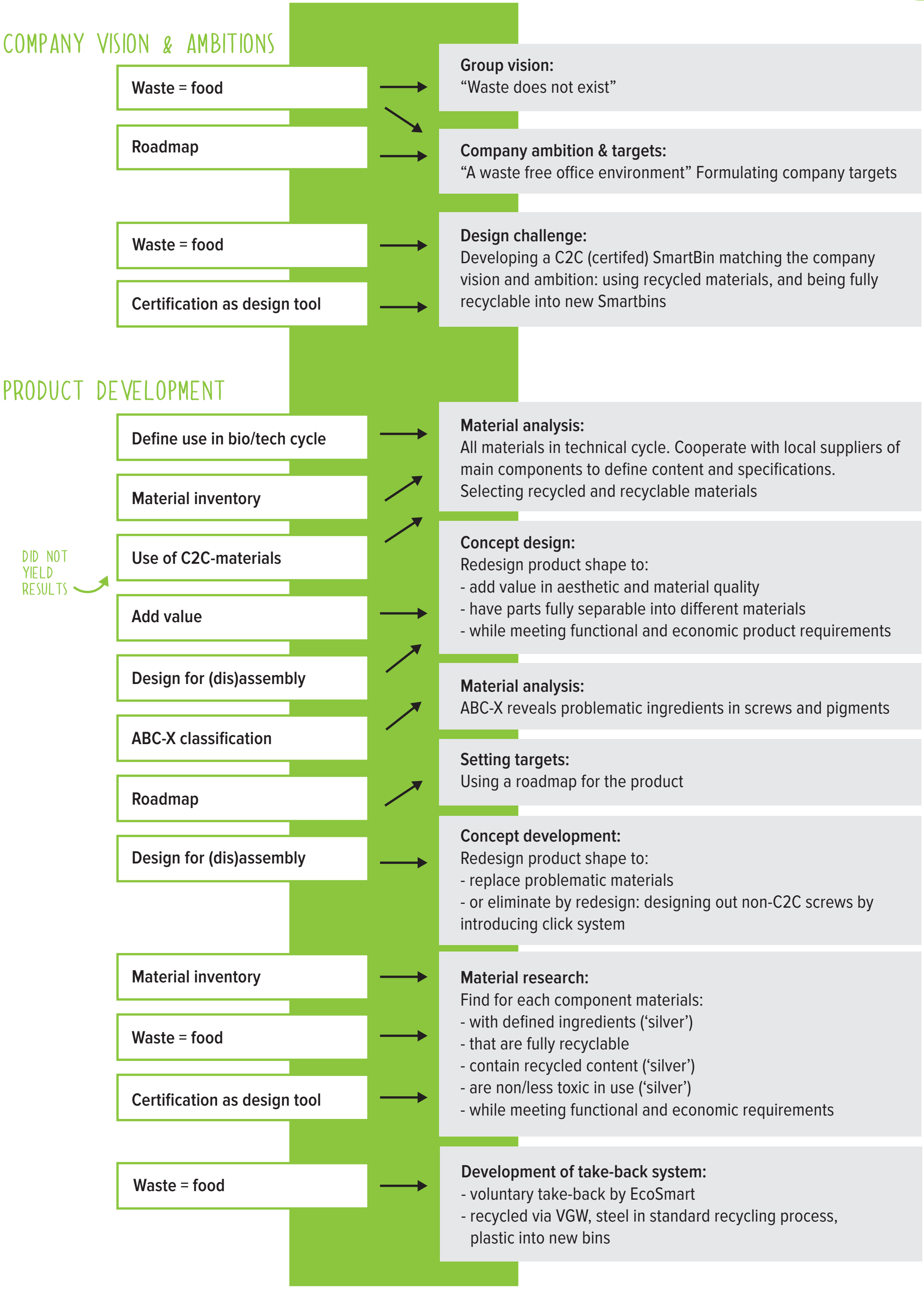


Figure 5.20: Case diagram of the design process in relation to the Cradle to Cradle elements applied

Illustrating the response of one of their suppliers:

> *"… they were thinking of their OWN product, something that they could BETTER market […] could supply to customers which have very heavy demands. And this would have been impossible before, so they were very much into this cooperation."*

The tool 'define use in technical or biological cycles' was not seen as important, simply because all parts of the product were determined as fitting the technical cycle. Nevertheless, this decision may have supported the continued use of the current fossil-based resources; using renewable materials was not considered.

The design of the polypropylene bins remained unaltered so as to be able to use the existing moulds. However, the material loop of the plastic bins has changed, as specified in Table 5.12. The bins are now manufactured using 100% post-consumer recycled polypropylene. This material is delivered to EcoSmart's supplier by one of the Van Gansewinkel companies, thereby supporting the company's transition to a resource supplier. As illustrated in Figure 5.21, the coated steel tube frame was replaced by coated steel plate. Other materials were considered, to eliminate the use of a powder coating, but no affordable alternative was available. Instead, EcoSmart determined, together with the supplier, the colour containing the least harmful pigments -white- which was consequently applied to the new design. For recycling of the steel parts, EcoSmart depends on the standard recycling infrastructure.

Apart from the material-related design activities, the team addressed the disassembly of the product and developed a take-back system, taking measures for storing recollected bins to be recycled. The application of Cradle to Cradle influenced important decisions in this part of the design process. The screws used in the original design, did not meet the Cradle to Cradle-criteria. EcoSmart discussed options for developing 'Cradle to Cradle-screws' with a supplier, but regarded changes unfeasible due to the limited number of parts required (translated from Dutch):

> *"…we had these screws, which were on the model; they were.., they are not Cradle to Cradle at all. So, then we went to a supplier, saying we wanted them to be Cradle to Cradle. He was delighted, until he learned how many we needed [laughing]."*

> *"We were really stuck, like, yes, should you then move to plastic screws? Well, then you also have to deal with quality demands. Stainless steel, yes, but that is yet another type of metal, so then you have mixed material streams"*

Resource bin	**SmartBin1**	**SmartBin2.0**		
Main components	Materials	Materials applied	Material origin	Material destination
Bins	Virgin PP, with additives such as colorants, catalysts, UV stabilizers, antioxidants	100% post-consumer recycled PP, with similar additives, but less-toxic pigments	Specific waste stream, with FDA assessment for contact with food	New bins or comparable application
Frame	Coated steel, with 34% recycled content (industry standard)	Coated steel, with 34% recycled content (industry standard)	Standard supply, local manufacturing	Standard steel recycling process
Powder coating	Diverse, including ‘X’-rated substances	White paint, less-toxic pigments	Standard supply	Waste in steel recycling
Wheels/ sliders	PA, galvanised steel	Wheels eliminated, sliding on frame	n.a.	n.a.
Fasteners	Galvanised steel screws	Screws eliminated, click system in frame	n.a.	n.a.
Plastic bags	Virgin HDPE/LDPE	Similar (future development)	Standard supply	Standard process (incineration)

Table 5.12: Material application in the SmartBin, data from Interviews, EcoSmart, and Certification standard (steel recycling)

Figure 5.21: EcoSmart Smartbin1 (left) and Smartbin2.0 (right)

Instead, the team developed a click system to assemble the product. This design thus removed the need for using screws, and according to EcoSmart turned out to reduce the time needed for (dis)assembly:

> *"And then you first think: I need a screw that meets these [requirements], but more importantly: what do you need that screw for? And THAT thought, I think, we would never have had, if you did not look at a part like that in such a way".*

> *"The time we need to assemble the bin at the customer, that decreased enormously, and we did not anticipate that; in fact we also did not even consider it, but that was a result of eliminating the screws".*

Furthermore, the team decided to eliminate the wheels by designing a frame that could glide on the floor, which provided good functionality and improved the product appearance.

For measuring performance on environmental and social issues, EcoSmart used the Cradle to Cradle certification criteria (Cradle to Cradle Products Innovation Cradle to Cradle Products Innovation Institute, 2012)[9]. The product succeeded in meeting the criteria linked to the Cradle to Cradle 'silver' label. No LCA-based sustainability analysis was conducted.

Improving social sustainability was not a part of the design brief. Cradle to Cradle certification does include social fairness criteria, for instance by asking for a company inventory and development plan for social issues related to the facility or facilities where final product is manufactured. The switch to a local manufacturer may have affected social performance, but this selection was initiated in order to collect the required company data. The performance of the original manufacturer was not known.

With respect to economic sustainability, the team paid considerable attention to maintaining the business-case for the SmartBin, including the take-back system, to ensure the viability of the product. When compared with the original product, the new design and the certification label introduced additional costs, but also provided added value. As a result, the product quality and market value increased with 30%. Financial considerations also affected design decisions, for instance on material selection and the design of the take-back system that currently consists of physical arrangements for taking back the products. Options such as leasing and buying back SmartBins were not introduced, although the company aims to address the optimisation of the take-back system in coming years.

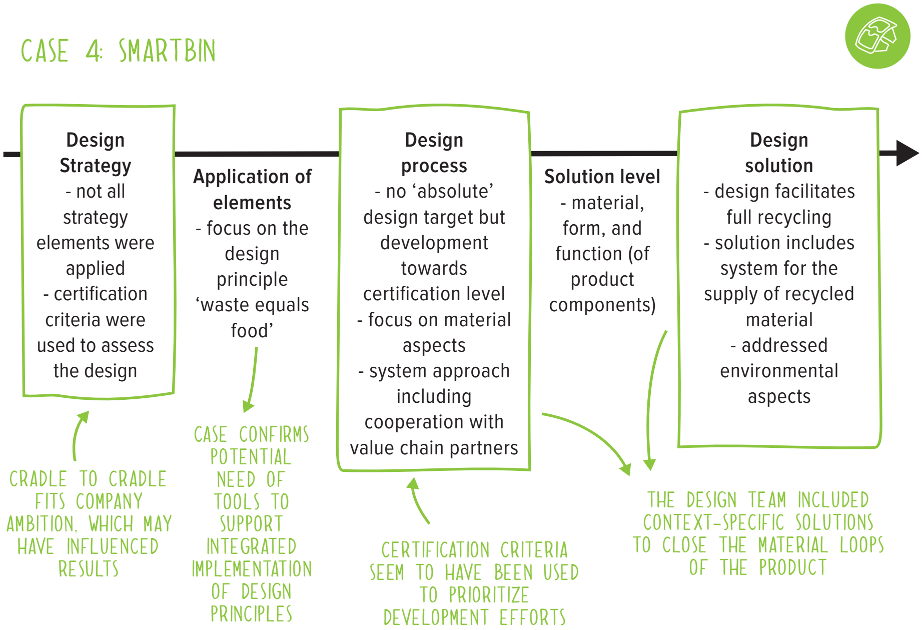


Figure 5.22: Summary of the findings from Case 4, the SmartBin 2.0 resource bin

5.5.4 Discussion & conclusions Case 4

Figure 5.22 summarises the findings from the SmartBin resource bin case study. Building on the Cradle to Cradle related company ambition to create a waste-free environment, the project targeted the development of a 'Cradle to Cradle product', to be certified at a high level. This gave the team the budget and design freedom to apply Cradle to Cradle as they saw fit, and for instance to have a full ABC-X analysis performed.

As described in Chapter 2, the the Cradle to Cradle certification procedure has been developed to monitor organisational progress and is not intended as a design tool. Nevertheless, the aim for certification in this case provided the development team with clear product assessment criteria. In that sense, certification *was* used as a tool within the design process. The case study results suggest that its application as a design tool may have influenced the design approach. The effect that was observed relates to the difference in the objectives of the Cradle to Cradle design approach and the certification process. The aim for certification coincided with, and seems to have triggered a development approach that was focused on optimising the design of the SmartBin to meet the certification criteria, and not on developing a product that creates a 'beneficial footprint'. This could explain why the designers considered 'eco-effectiveness' or 'creating a beneficial footprint' not to be part of the project. On the other hand, the original SmartBin already introduced added value over traditional solutions, by providing a means to collect waste in five separate flows within a compact, modular design. The basic concept thus supports eco-effective material management, which offers an alternative explanation for the focus on optimisation. This basic concept was introduced in the first SmartBin, without applying Cradle to Cradle product design. Further research is needed to uncover the role of certification on the design of products for which the potential eco-effectiveness has not yet been established.

The first Cradle to Cradle-principle 'waste equals food' was well reflected in the case study data. Material analysis and selection played an important role in the project, focusing on achieving a 'waste-free' design. This principle, supported by several design tools, seems effective for developing this type of product design, which corresponds to our findings in our studies with student projects (Chapter 4).

To collect the required knowledge and to find suitable materials, the team went into close cooperation with value chain partners. Cooperation proved fruitful with the suppliers of the main components and with Van Gansewinkel for the supply of recycled plastic. For smaller components, the team could not get the much larger companies involved in supplying data or changing their products. However, the development team introduced an effective design alternative: several of the smaller components that could not be adapted were eliminated by changing the product design. This approach turned out to provide suitable solutions, and the change from screws to a click system provided an additional system benefit to the company: reduced assembly times. EcoSmart could not apply this design approach for all components. For instance, replacing the coated steel by another material without coating proved too expensive. Instead, the team selected the finishing with 'the least harmful' impact, an approach that is similar to that of Ecodesign.

The second and third Cradle to Cradle principles did not affect the design of the product. In the design project, EcoSmart could not influence the application of 'current solar income' for the production processes. The third principle, 'celebrate diversity', proved difficult to grasp and apply to the design of the SmartBin. As observed in the previous Cradle to Cradle-case, the absence of design tools for integrating these Cradle to Cradle-principles into product design may have contributed to this result. As argued by Bjørn and Hauschild (2012), without implementation of the second Cradle to Cradle-principle, a design fit for 'waste equals food', may result in trade-off effects that increase the current environmental impact of the product, due to the use of fossil-fuel energy.

The design of the SmartBin2.0 illustrates how the Cradle to Cradle strategy can support the realisation of an overarching company mission. It furthermore shows an example of how a development team applied Cradle to Cradle in cooperation with strategy experts, and by including certification in the development process. The application of Cradle to Cradle activated the design team to develop a product fit for recycling according to the ‘waste equals food’ principle. Both the selection of traceable and recyclable materials, as well as changing the design to facilitate full recycling contributed to this result. This case illustrates how the development team used Cradle to Cradle to redesign a product by taking an in-depth approach on a relatively limited number of topics.

The Cradle to Cradle-standards provided the team with targets they could include in the design process, and therefore facilitated assessment of the results. Nevertheless, the current assessment does not reflect performance throughout the products life cycle, nor the ‘beneficiality’ of the design. The Cradle to Cradle ‘Silver’ standard was met, but a quantitative analysis of the product is needed to uncover possible unintended adverse effects.

5.6 Cross-case analysis

Based on the results of the four cases, in this section we provide a cross-case analysis of the findings, by analysing whether findings were replicated across the different cases, taking into account differences in the application level of the Nature-Inspired Design Strategies, the effects on the design process, and the outcome of the projects.

5.6.1 Application of the strategies

Table 5.13 shows the different design strategy elements for Biomimicry and Cradle to Cradle at the level of design philosophy, principles, and methods & tools. The last level has been subdivided into four categories reflecting the purpose of the methods & tools, as described in section 5.1.3. Table 5.14 shows the application of the strategy elements across the four cases.

In all cases, the development team integrated strategy elements within their own design method; the overall design method as offered in the Biomimicry Design Spiral was not applied. Nevertheless, most elements -not all- were integrated in the design process for each of the projects. The designers and teams each have their own ‘way’ of applying strategy elements. Every case included elements that were applied partially, differently than ‘instructed’, or, in some case, applied implicitly. These results were found for both

Design strategy elements	Elements of Biomimicry	Elements of Cradle to Cradle
Design philosophy elements	Innovation inspired by nature	Doing good - instead of 'less bad'
	Life creates conditions conducive to life	Creating a beneficial footprint
	Sharing Biomimicry	Eco-effectiveness
Design principles	Evolve to survive	Waste equals food*
	Be resource (material and energy) efficient	Use current solar income
	Adapt to changing conditions	Celebrate diversity
	Integrate development with growth	
	Be locally attuned and responsive*	
	Use life friendly chemistry	
Analytical methods and tools	Design spiral	Roadmap
	Evaluate your design against life's principles	Material inventory
	Distil the design function	ABC-X classification
	System mapping	Define use in biological and technical cycles
		Define use period
Methods and tools for synthesis	Translate to biology	Add value
	Discover natural models / AskNature	Cascade use
	Emulate nature's strategies	Design for (dis)assembly
		Use Cradle to Cradle-elements (materials, processes, ingredients)
		Triple-top-line pyramid
Methods and tools for simulation	Model system behaviour	(no tools available)
Methods and tools for evaluation	(Evaluate your design against life's principles, already listed under analytical methods and tools)	Cradle to Cradle Certification

Table 5.13: Overview of strategy-elements applied in the cases. Elements in italics have been added by the designers. Elements in grey were included in the research but were not applied by the design teams, elements marked* were regarded as most important across the Biomimicry or Cradle to Cradle cases. Categories of methods and tools after the basic design cycle (Roozenburg and Eekels, 1995, van Boeijen et al., 2013).

Strategy elements considered in the case studies	Case 1 Plenic presentation system (Cradle to Cradle)	Case 2 Algaepack flower tray (Biomimicry)	Case 3 Net Effect carpet tile (Biomimicry)	Case 4 SmartBin 2.0 resource bin (Cradle to Cradle)
Design philosophy elements	●●◉	●◉	●○	◉◉○
Design principles	●◉○	●●●○○○	●●●◉◉○	●○○
Methods and tools:				
- analytical	●●●○	●◉Δ○	◉○○	●●●◉
- for synthesis	●●●Δ○○	◉◉○	●●●Δ	●◉◉◉○
- for simulation		Δ		
- for evaluation	☐			Δ

Table 5.14: Application of strategy elements across cases. Application of strategy elements by the design teams= applied ◉= applied partially, differently, or implicitly ○=not applied Δ=applied new strategy method/tool ☐=applied other method/tool.

the design principles and the tools. In addition, in each case, methods or tools were added, building on the knowledge generated by the design strategy.

Tools were added for different design purposes, as described in the individual cases. Two were developed for simulating and evaluating solutions, purposes for which both Biomimicry and Cradle to Cradle currently offer no quantitative tools[10] . In the Algaepack case of IDEAL&CO, the designer applied system modelling to simulate system behaviour. In the other cases, only generic design techniques, such as drawing and prototyping, were employed to simulate product performance. To evaluate their design, Ecosmart (Case 4) used the Cradle to Cradle-certification criteria. In contrast, Full Circle Design (Case 1) applied an Ecodesign tool for evaluating the design. Interface (Case 3) uses life cycle analysis to evaluate environmental performance, but this tool was not employed in the design process.

5.6.2 Effects of NIDS on the design process

The case studies have provided insights into the effects that the application of Biomimicry and Cradle to Cradle can have on the design process. The researcher compared the use of NIDS-elements across the different phases of the product development process, illustrated in Figure 5.23, which shows similar results for the four cases. In all cases, most NIDS elements were applied in the strict development phase, predominantly in product design, but also for activities that can be grouped under production development. Furthermore, NIDS elements were also embedded in the product policy and were applied when determining the product development assignment in each of the companies.

Table 5.15 summarises the similarities and differences in process characteristics described for each of the cases. A first similarity among the four cases is the ambitious vision on sustainability of the four companies, in line with the NIDS design philosophies.

Second, elements of NIDS, especially the design principles, affected the product policy and the development of new business ideas in each of the cases. In most cases, formulation of the product policy was part of another company process, and not developed within the product development process. Nevertheless, NIDS affected the formulation of the design challenges. In Case 1, the Plenic presentation system, the project goal was to develop a presentation system that “never becomes waste”, an effect attributed to the Cradle to Cradle design principle ‘Waste equals food’ within the design philosophy of ‘Doing good - instead of less bad’. In Case 2, the Algaepack flower tray, the project ambition was “to make a product that is a valuable part of its environment”, which is related to the Biomimicry design philosophy of ‘Creating conditions conducive to life’. The design challenge in Case 3, the Net Effect carpet tile, was also based on the design principles, although with a slightly different take: the challenge was directly linked to learning from nature, by posing the question: ‘How would nature design carpets?’ Based on that question, all principles were taken as drivers for product development. For Case 4, the design challenge for the SmartBin resource bin was again centred on the Cradle to Cradle principle ‘Waste equals food’; to develop a certified SmartBin that matches the group vision “Waste does not exist”.

Third, a system approach was taken in each of the cases, and the strict development phase of the cases was characterised by a strong focus on designing the materials loop, both by considering the design of the product and the design of the system. In the two Cradle to Cradle cases, the tools ‘material inventory’, ‘define use in biological and technical cycles’, and ‘design for disassembly’ were used for developing a product design suited to (re) cycling materials. In the Biomimicry cases, the design principles helped the designers by providing conditions, but no specific tools (that provide ways to meet the conditions) were

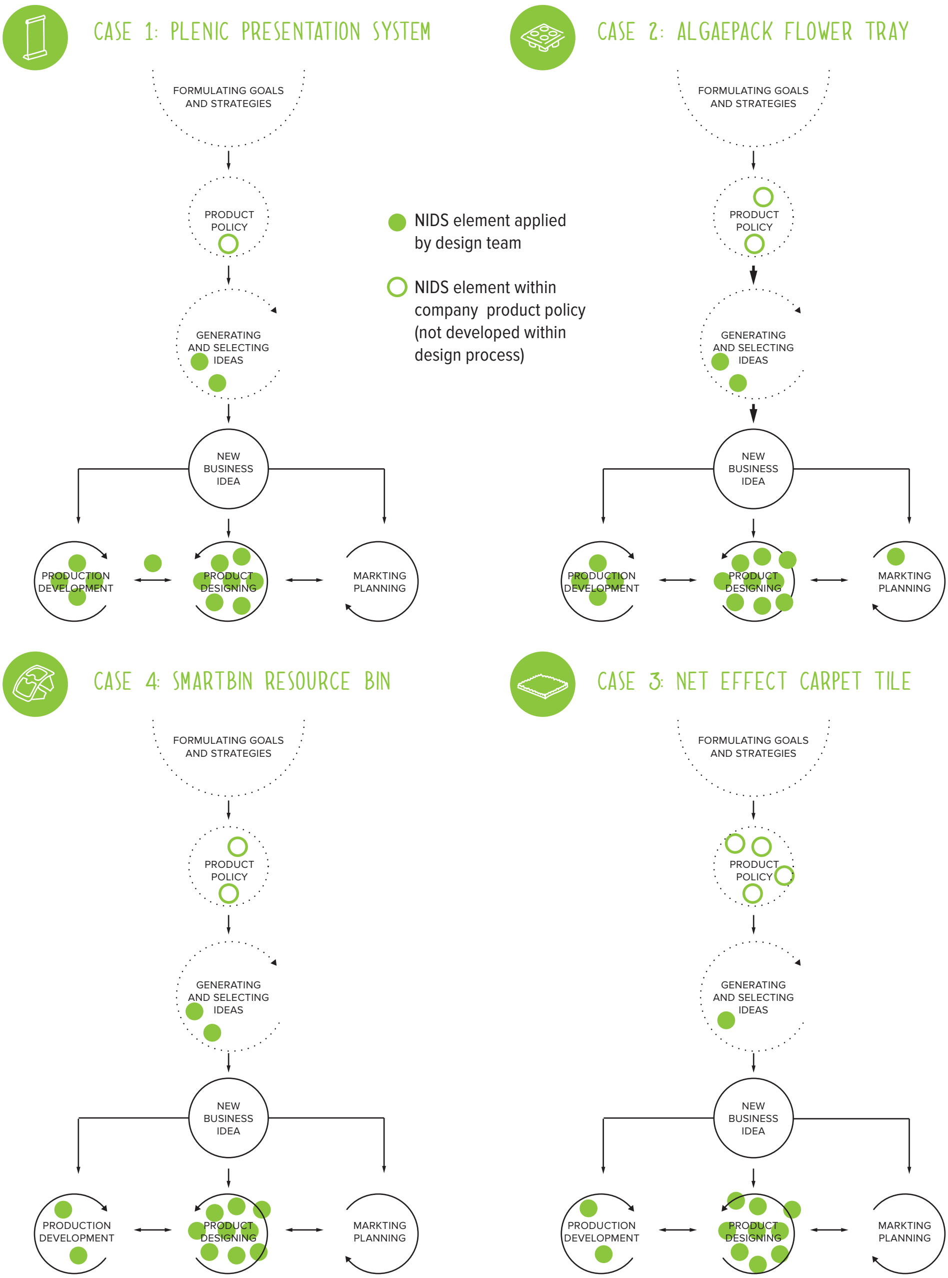


Figure 5.23: Comparison of the application of nature-inspired design strategies in the cases along the product development process for the four cases (model after Figure 1.4)

	Different for Biomimicry (Bio) cases	Similar for each design strategy	Different for Cradle to Cradle (C2C) cases
Different for small design teams	**Unique to Case 2** **Bio - Small design team** - aim for beneficial impacts	**Similar for Cases 1 & 2** **Small design teams** - formulation of 'absolute' project ambitions - development of new materials - absence of an analysis of the existing product - absence of assessment of project results	**Unique to Case 1** **C2C - Small design team**
Similar for each type of team	**Similar for Cases 2 & 3** **Bio** - absence of assessment of project results (by designer)	**Similar across Cases 1, 2, 3 & 4** **NIDS** - support of an ambitious company vision - influence of NIDS on product policy and generation of product idea - system approach with focus on designing for 'closing' the materials loop - minor attention for 'using renewable energy' - minimal attention for social sustainability	**Similar for Cases 1 & 4** **C2C** - focus on material-related aspects in entire design process - application of Design for Disassembly - absence of an explicit focus on 'celebrating diversity'
Different for large(r) project teams	**Unique to Case 3** **Bio - Large(r) project team** - use of the strategy for aesthetics and communication - no inclusion of the products' 'end of use' in the design process	**Similar for Cases 3 & 4** **Large(r) project teams** - formulation of 'relative' project targets	**Unique to Case 4** **C2C - Large(r) project team** - formal assessment of project results

Table 5.15: Comparison of qualitative characteristics of the NIDS design process across the four cases.
Text in grey refers to issues that were not included

applied to that purpose. In Case 2, the Algaepack flower tray, the consultation of biologists did help the designer establish how the product could be beneficial within the system.

The comparative study of student design projects (Chapter 4) revealed that NIDS encouraged students to include solutions found within the specific context of the product-system (people, companies and circumstances interrelated to the product-system). Also in the real-life cases, NIDS guided the designers towards context specific solutions to develop material loops. In Case 1, the Plenic presentation system, the designers analysed how each of the products' components was to be used again and by which companies, and consequently came up with localised solutions for the recycling of materials. Also in Case 2, the Algaepack flower tray, the designer studied specific solutions for the material loop, and 'being locally attuned' was considered a condition for being able to add value throughout the loop. As in Case 1, the designer of Case 3, the Net Effect carpet tile, involved suppliers when designing the resource loop. Here, the product itself can be locally attuned to the place where it is being used, but the production and recycling system were not localised. As the company has a worldwide network of clients and suppliers, there seems to be less incentive to 'cycle' locally. Instead, they cooperated with a supplier that developed a recycling process matching the companies' objectives of closing the loop. In Case 4, the SmartBin, the principle of celebrating diversity was not applied, at least not with a clear link to the design principles. Still, as in the other cases, in this case the team also worked closely with suppliers on 'closing' the material loop.

Apart from characteristics that the cases shared, the four cases also shared topics that were barely addressed in the design process. 'Renewable energy' was one of these topics: the Cradle to Cradle principle related to energy was not applied by the design teams, and in the Biomimicry cases, the designers also did not focus on energy related aspects. Figure 5.20 illustrates potential explanations that were examined of why some principles affected the design process and outcomes, and others not. Comparison of the findings of the different cases shows that principles that were considered as most important -some even influencing the project ambition- were applied, even when no NIDS tools were available for their implementation. The designer of Case 2, the Algaepack tray, added an external tool to be able to integrate the principles. Furthermore, principles that can be implemented by influencing the design of the product -thus being within the scope of the traditional design process- were applied in all cases, whereas principles such as 'use current solar income' that were considered to be outside the scope of influence of designers, were not applied. Principles that designers could apply 'indirectly' -by selecting different materials, processes, or companies- were applied when prioritised, and not applied or applied indirectly when no priority was given to the principle. The principle for which specific tools are available -Waste equals food- was applied in both Cradle to Cradle cases.

Furthermore, NIDS did not help designers include the social impacts of their design. Social impacts either only received minor attention, or were included on the basis of another design approach (non-NID). This result is not surprising, as NIDS do not focus on social sustainability (Chapter 2) and lack specific design tools to integrate this pillar of sustainability.

Similarly, no specific design tools are currently available within NIDS to implement economic considerations. Only in Case 2 did the designer consider the economics of the solution throughout the products' use cycle, which may have been the results of the system perspective resulting from the application of NIDS.

5.6.3 Effects of NIDS on the design outcomes

In each of the cases, the effects of NIDS on the design process are clearly reflected in the results. The qualitative comparison of the designs, summarised in Table 5.16, shows that for all four cases, the material loop is part of the solution. For several main materials, this solution includes a closed loop or continuous loop[11]. In Case 1, the textile will be recycled to a similar quality material; in Case 2, the material will compost in the soil, releasing nutrients; the face fibre of the carpet tile of Case 3 is made of 100% recycled nylon; and the plastics of the SmartBin (Case 4) are made from 100% post-consumer recycled content. In terms of effects, the application of NIDS resulted in two types of material selection. The (smaller) design firms selected *different* materials to ensure that full recycling of materials was established, including renewable materials. Instead, the two larger companies employed materials similar to those they were accustomed to, and focused on the maximisation of recycled content. Components that contained toxic materials were either eliminated, or replaced by less-toxic alternatives where feasible.

Furthermore, all products have a modular design (the product can be applied in different configurations). Modular design fits with the design principles of diversity and being locally attuned. However, the results across cases show no replication that modular design is an effect of the application of NIDS. Only for the Plenic presentation system (Case 1), was the modularity linked to the application of Cradle to Cradle, providing a solution to lengthen the product life cycle as part of economic requirements for the design. For the plant tray (Case 2), no link was established in the data between the modularity and the application of Biomimicry. For the carpet tile (Case 3) and the SmartBin (Case 4) modularity was already core to the product concept, and had been achieved before the companies applied nature-inspired design.

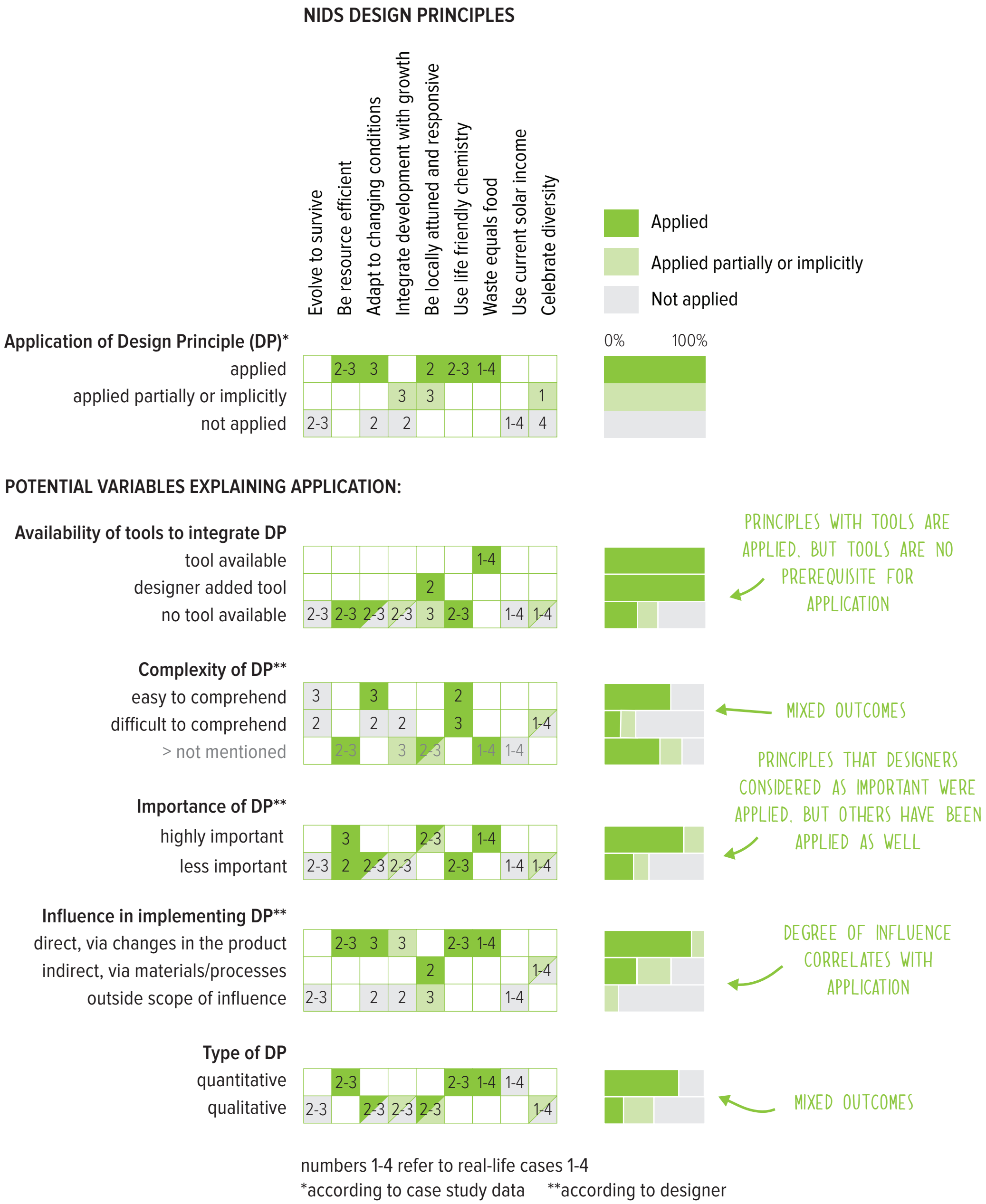


Figure 5.24: Exploration of the effect of potential variables on the application of NIDS design principles

	Different for Biomimicry (Bio) cases	Similar for each design strategy	Different for Cradle to Cradle (C2C) cases
Different for small design teams	**Unique to Case 2** **Bio - Small design team** - use of renewable, compostable materials - lack of economic feasibility due to current lack of infrastructure	**Similar for Cases 1 & 2** **Small design teams** - selection of different materials as compared with existing designs - highly context-specific solution	**Unique to Case 1** **C2C - Small design team** - use of both renewable and fossil-based materials (no use of recycled content for first product cycle)
Similar for each type of team	**Similar for Cases 2 & 3** **Bio**	**Similar for Cases 1, 2, 3 & 4** **NIDS** - design solution for the material loop - realisation of material loops, with either fully recycled or renewable content for some of the products' materials - modular design	**Similar for Cases 1 & 4** **C2C** - realisation of a >90% recyclable product - design of a take-back system
Different for large(r) project teams	**Unique to Case 3** **Bio - Large(r) project team** - nature-inspired aesthetics	**Similar for Cases 3 & 4** **Large(r) project teams** - use of fossil-based materials - use of 100% recycled content for part of the materials - elimination of 'problematic' small components (functional innovation) (no change in main materials) (less context-specific solution)	**Unique to Case 4** **C2C - Large(r) project team**

Table 5.16: Comparison of the designs across the four cases.

Text in grey refers to issues that were not included

Figure 5.25: Impression of the product designs of the four cases

5.7 Discussion

When considering how the application of NIDS affects the design process and the end results, this study shows that application-level is an important variable to consider. The cases show that the project teams had their 'own way' of applying the principles, methods and tools provided by either Biomimicry or Cradle to Cradle. Why designers deviate from the suggested design strategy may be explained by their prior expertise with other, more generic design strategies. For instance, one of the designers (of Case 2, the Algaepack flower tray) explained that the design method he was accustomed to was more complete than the method offered for -in this case- Biomimicry. He therefore applied the design method he was used to, and integrated into this method the NIDS elements as he saw fit. In Case 1 (the Plenic presentation system), the designers took the same approach. For Cases 3 and 4 (the Net Effect carpet tile and SmartBin resource bin), insufficient data were available to confirm replication. Hence, this factor can explain why principles and tools were applied in a different way, but does not provide an understanding of why several of the principles and tools were ‘simply’ not applied. As reported in Chapter 4 (section 4.1.2), various studies on the transfer of design methods and tools to design practice give reasons why methods and tools are not used as suggested, including time constraints and a (lack of) perceived benefits, appeal, and usability of tools. When asked why a specific principle or tool was not applied, the interviewees themselves provided overlapping explanations: either they did not know of a specific tool, felt the principle or tool was too complex or restrictive to develop a solution in the time available, or did not see the tool as relevant or fitting for the task at hand. In addition, the designers did not seem concerned whether or not they applied all tools or even all design principles, and they usually did not reflect on their application of the strategy. Also in the student projects (Chapter 4), not all tools were applied, but no further conclusions can be drawn from the comparison, as the students were not asked why they refrained from using specific tools in that study. In conclusion, partial application of methods and tools is not unique to NIDS but should be considered when interpreting the outcomes of the cases.

In all cases, the integration of NIDS affected the design process: according to the interviewees, they performed design tasks outside their usual scope, especially tasks considering the material cycle. The design principles played an important part in the process – in as much as they were applied. The Cradle to Cradle principle ‘waste equals food’ and Biomimicry sub-principle ‘recycle all materials’ seem to have helped designers to get involved in the design of the ‘material loop’ and -together with suppliers- tackle some barriers in ‘closing’ this loop. As in Chapter 4, context-specific solutions were included as a strategy: working with dedicated suppliers that were willing to apply or test new materials, and by selecting materials for which a generic or dedicated recycling infrastructure is available. In contrast, consumption of energy, both direct and indirect, received little attention, despite the related Cradle to Cradle principle ‘use current solar income’ and Biomimicry sub-principle ‘use readily available materials and energy’[12]. The products in each of the four cases do not consume energy during use, which may explain the (perceived) lack of importance of this topic. For these types of products, energy consumption is more related to production processes, the design of which falls outside the traditional responsibility of the designer. Nevertheless, the same can be argued for the design of the material cycles. However, for implementing the ‘closed loop’ principles, tools were available to the designers (in Case 1, the Plenic presentation system and Case 4, the SmartBin resource bin) or added by the designer (in Case 2, the Algaepack flower tray). The availability of related tools seems to have been an important factor in facilitating the application of design principles. The criticism in the literature that Cradle to Cradle may divert focus away from addressing energy aspects (Bakker et al., 2009, Bjørn and Hauschild, 2011), can thus be narrowed down to a problem in the application of the design principle that should be addressing these aspects. Inversely, the lack of principles or tools for integrating social sustainability through NIDS was clearly reflected in the design processes.

The design outcomes reflect the attention that was given in the design process to the material cycle. In each of the cases a system design was developed with a material loop solution and application of fully recycled or renewable content for one or more of the main materials. The two teams at small companies developed different loops than those at the large companies. The large companies did not change the type of materials used. This may reflect the vested interests that the companies have in manufacturing equipment or moulds, whereas the small design firms were 'free' to select suppliers. In the student projects (Chapter 4), groups that applied Biomimicry or Cradle to Cradle included innovations that provide alternative fulfilment of functions or needs; the real-life cases do not replicate this finding. The difference in design context is large: design students being motivated to develop 'fully sustainable solutions' versus design teams that develop products within a specific business setting. Nevertheless, the design teams of the larger companies included functional innovations on a part level to solve bottlenecks in the application of nature-inspired design principles.

5.8 Conclusions

The in-depth analysis of the four company cases has enabled us to explore the effects of applying NIDS in real-life design projects aimed at developing sustainable products (Research Question 3). These cases illustrated how designers have their 'own way' of applying NIDS; the designers included many NIDS principles and tools but excluded others as they saw fit. Consequently, the effects on the design process and products can only be linked to the specific strategy elements that were applied.

The design principles that were included in the projects clearly affected the outcomes of the design process. The cases show how their application activated the designers to adopt a 'systems approach'. They engaged them in designing parts of the 'material loop', a finding that was replicated in all four cases. Ambitious targets were set to 'design out waste' or to integrate principles from nature. The application of the design principles and tools led the designers to focus on the material cycle and to overcome barriers in the recycling of the product. These results were achieved by cooperating with suppliers, by selecting different materials or even by developing new material combinations, and in some cases by implementing functional innovations that eliminated materials that hindered closed loop or continuous loop cycling of the product. Whereas the products of all cases have a modular design, this result could only be attributed to the application of NIDS in one case.

The application of NIDS did not affect design activities aimed at simulating or evaluating design outcomes, and did not help the designers integrate social and economic sustainability in the design process. These findings match the current lack of tools within Biomimicry and Cradle to Cradle for modelling designs, for quantitative assessment of environmental impacts across the products' life cycle, and for integrating social and economic sustainability.

The real-life cases share several characteristics that facilitated replication of findings. At the same time, shared characteristics can point to intervening variables not included in the current study. The cross-case analysis pointed out two shared characteristics that were not part of the case study selection criteria; in each of the cases, NIDS supported the ambitious visions of the companies on sustainability, and each product contained elements of modular design (without a replicable link to the application of NIDS). Further research is needed to uncover how these characteristics may have influenced the findings.

[1] Many of these elements are also included in the checklist used in the Workshop study (Chapter 4). However, the Workshop checklist is not based on the sources mentioned here, but on the study material provided to the students.

[2] Categories of methods and tools after the basic design cycle (Roozenburg and Eekels 1995, van Boeijen, [1] Daalhuizen et al. 2013), see Glossary for explanation of terms.

[3] Design activities in which no Cradle to Cradle tools were applied, such as sketching of the new frame, are not included in Figure 5.6.

[4] Interface, Mission Zero, Net Effect, Net-Works, and TacTiles are registered trademarks.

[5] In this case study, the scope is the application of Biomimicry.

[6] 'Evolve to survive' has been added in the 2011 version of the Life's Principles.

[7] Van Gansewinkel translates this motto as 'Waste no more'.

[8] Personal communication with K. Hansen, EPEA, Hamburg, 23-03-2013.

[9] The SmartBin was certified using an earlier version of the certification criteria.

[10] Simulating in design is the drawing and modelling of ideas to be able to estimate and define the expected properties of the design, and evaluation consists of evaluating the design against the design criteria to support decision making while designing (see also Glossary).

[11] See glossary for the difference between closed loop and continuous loop.

[12] In the book Biomimicry: Innovation inspired by nature, the related principles are formulated as 'Nature recycles everything' and 'Nature runs on sunlight' (Benyus, 1997).

CHAPTER 6

The Environmental Sustainability of Nature-Inspired Designs

Chapters 4 and 5 described the effects of applying Biomimicry and Cradle to Cradle in 33 student and 4 professional design projects. The insights on how NIDS affect the design process have already given rise to potential explanations of how these strategies may help or hinder designers with sustainable product development. However, we still have to analyse the effects of applying NIDS on the sustainability of the designs (Research Question 4) to understand to what extent the designers have succeeded in 'achieving sustainability'. Accordingly, this chapter assesses the designs from the real-life cases using the conditions for sustainable product development introduced in Chapter 3.

The method used for evaluating the designs is described in the first section (6.1). In section 6.2, an inventory is made of the design measures taken in the four real-life cases from the perspective of their impact on environmental sustainability. Based on this inventory, in section 6.3, the designs are then assessed against the adopted criteria for environmental sustainability. Section 6.4 discusses the results in view of the effects that the application of NIDS had on the design outcomes. The last section (6.5) concludes to what extent the application of NIDS has resulted in meeting the adopted criteria of environmental sustainability, i.e. in 'achieving environmental sustainability' for the real-life cases.

6.1 Method for evaluating the environmental sustainability of the real-life cases

To understand whether Nature-Inspired Design Strategies (NIDS) help designers in developing sustainable products, and to what extent, the results from the real-life cases were assessed using the framework for product assessment described earlier in this thesis. As described in Chapter 3, this framework is different from existing life-cycle based product assessment, and aims at assessing to what extent a design contributes to 'achieving sustainability'. The assessment thus reflects the extent to which the product (bene)fits a sustainable environment, which does not necessarily correspond to its current performance within today's (unsustainable) systems. As designers cannot change today's systems[1] within a design project, the achievement of fully sustainable product-systems is neither anticipated nor claimed by NIDS proponents. However, what is aspired, are designs that fit within a sustainable system and that, through their design, target a change in both products and systems directed towards reaching a fully beneficial end result.

Figure 6.1 summarises the criteria adopted in Chapter 3. Consequently, the basic assessment conducted in this chapter is used to determine whether and to what extent the designs from the real-life cases succeed in meeting one or more criteria for environmental sustainability, based on the data available from the case studies. To address the transition from today's product-systems to a future product-system that meets the criteria for environmental sustainability, the relative improvements in the design and the (potential) impact of the design on current production systems are also discussed.

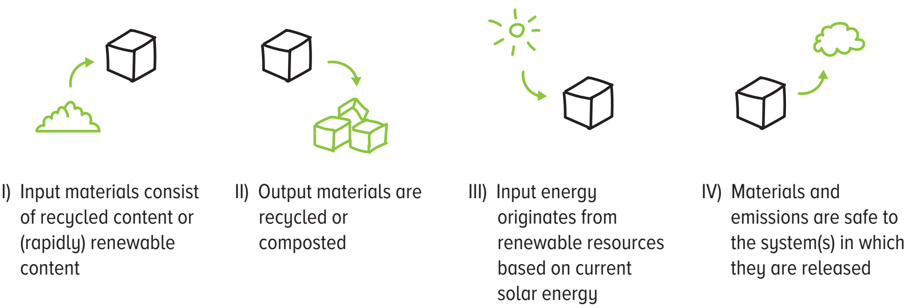


Figure 6.1: Criteria for assessing the environmental sustainability of products

6.1.1 Inventory of design measures

As described in Chapter 3, first an inventory was made of the design measures taken in each of the four real-life cases using the typology of life cycle design strategies by Van Hemel and Cramer (2002):

1. Selection of low-impact materials
2. Reduction of materials usage
3. Optimisation of production techniques
4. Optimisation of distribution system
5. Reduction of impact during use
6. Optimisation of initial lifetime
7. Optimisation of end-of-life system
8. New concept development.

Where possible, the design measures have been quantified. When describing 'relative' design measures, i.e. measures that describe an improvement, the design is compared to either the company's preceding product, or a conventional, functionally similar, product in the market (as described in Chapter 5). The list of design measures was compiled by the researcher from the case study data, and checked by the company interviewees for correctness.

For the inventory, system boundaries were chosen as illustrated in Figure 6.2. Following the framework, the inventory includes the processes needed to make, use, and recycle the product, it's components and materials, but do not include today's processes to make, use, and recycle production machines, transport equipment etc. Furthermore, the inventory was made based on the data available, and limited to include processes that were addressed in the design project. For instance, in the case of Interface, where transport systems and distances were not addressed in the case, transport is not included in the inventory. Processes and products that were not included in the project are assumed to fail the criteria of environmental sustainability.

6.1.2 Product assessment

Products that consist of multiple components and materials were assessed at the component-level. Figure 6.3 illustrates how the assessment score of a product is represented. The primary assessment has three possible outcomes: either 'red' for failing a criterion, 'yellow' for meeting a criterion, or 'green' for generating a beneficial impact. In addition, the inventory data are used to make a rudimentary assessment of the degree to which harmful impacts have been reduced when compared to a preceding (or conventional) design, which provides an indication whether and to what extent

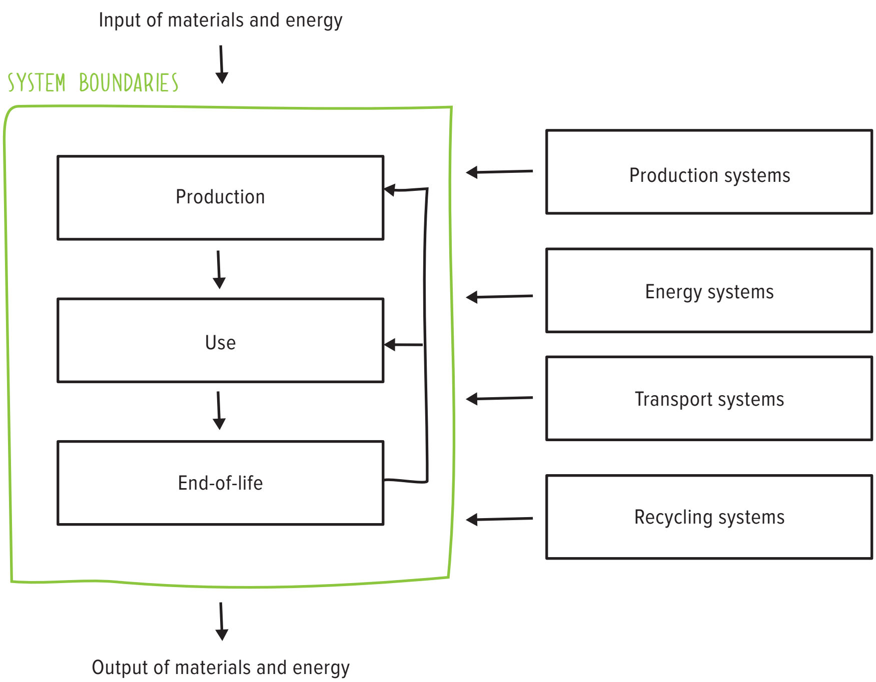


Figure 6.2: System boundaries for the product assessment

NIDS may help designers reduce environmental impacts (as advocated by Eco design strategies). This rudimentary assessment is based on the criteria and system boundaries described in the previous section.

6.2 Inventory of design measures of the real-life cases

This section describes the results of the inventory of the design measures related to environmental sustainability for each of the four real-life cases. Table 6.1 summarises per case the design measures, categorised according to the eight life cycle design strategies. The following sub-sections elaborate on the findings.

6.2.1 Case 1: Plenic presentation system

As described in Chapter 5, Case 1 involved the development of "Plenic", a presentation system for fairs and points of sale. The inventory of design measures in Table 6.1 shows that the Plenic case focused on three life cycle design strategies: 1. 'Selection of low-impact materials' by using renewable materials and avoiding the use of toxic materials, 6. Optimisation of initial lifetime' by reuse of components, and 7. 'Optimisation of end-of-life system' by recycling materials. Three strategies were not followed: 'Reduction of material usage' (no. 2) was not addressed, as the goal of Cradle to Cradle is not to reduce the use of materials but to recycle all materials used. In principle, this approach could result in recyclable products with increased weight. However, the designers considered product weight because the user has to carry the product, and the weight was kept comparable to that of existing presentation systems. Strategy 3 'Optimisation of the production processes' was not considered as a design strategy as the production techniques were directly coupled to the materials. Production techniques seem comparable to those currently used. Part of the energy from production originates from solar energy. A change of the basic concept -Strategy 8 'New concept development'- was (deliberately) not included. The designers wanted to maintain the current primary function of the product because they aim for high market acceptance. Making a radical change in the design of the current concept was deemed unrealistic for maintaining acceptance.

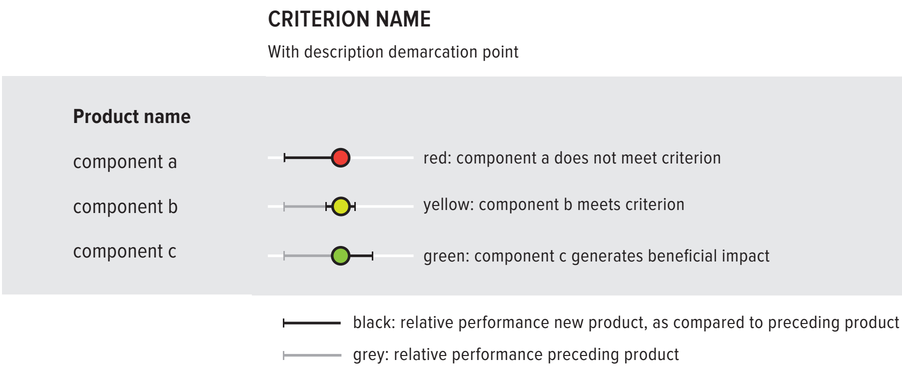


Figure 6.3: Example of the graphical representation of assessment scores

Case 1: Plenic presentation system	Case 2: Algaepack flower tray
1. Selection of low-impact materials: - 80% renewable materials (textile, keder, frame-fibre), 20% fossil-fuel based (frame-polymer); reduced amount of toxic ingredients for printing, with non-toxic solvent; textile still contains flame-retardants; the inks contain toxic ingredients.	**1. Selection of low-impact materials:** - 100% renewable, abundant, 'waste' material. Starch additive also renewable.
2. Reduction of materials usage: - no change in product weight (see 6 for frame).	**2. Reduction of materials usage:** - no data available on product weight; increased weight could cause increased impact from the material and during transport.
3. Optimisation of production techniques: - optimisation was not considered; the textile still requires chemical optical brightening; - supplier of the frame produces more solar energy than they consume.	**3. Optimisation of production techniques:** - optimisation was not considered; although a high amount of energy is needed for drying the algae, (direct) solar energy is to be utilised. The required surface is scarce/expensive at greenhouses. Energy for forming the tray is estimated to be fossil fuel based.
4. Optimisation of distribution system: - energy efficiency of distribution was not considered; instead a local production and recycling network (Western Europe) is being created for all components; packaging will be recycled together with textile.	**4. Optimisation of distribution system:** - energy efficiency of distribution was not considered; instead a highly local production and logistic system (province level) is being created; no data is available on packaging.
5. Reduction of impact during use: - product does not consume energy or materials during use.	**5. Reduction of impact during use:** - product provides nutrients that are required (beneficial) in the local ecosystem - product does not consume energy or materials during use.
6. Optimisation of initial lifetime: - use period of the frame increased from days (duration of an exhibition) to 2-5 years due to modular design and ease of repair; reuse or recycling of components via take-back system.	**6. Optimisation of initial lifetime:** - use period of the tray is unaltered.
7. Optimisation of end-of-life system: - full recycling of the textile (back to feedstock); frame recyclable into new frames four times (material can thus be used 8-20 years for this application); keder is recyclable, but at the time of study not foreseen to be recycled due to economic constraints; inks are treated as waste materials.	**7. Optimisation of end-of-life system:** - product is fully composted.
8. New concept development: - not considered.	**8. New concept development:** - project was aimed at new concept development, both material and sustainability driven; integration of functions has been applied to generate environmental benefit by moving nutrients (phosphates, nitrates) from waste-water to soil.

Table 6.1: Qualitative inventory of design measures related to environmental impacts

Case 3: Net Effect carpet tile

1. Selection of low-impact materials:

- improved performance from the use of recycled materials: 100% recycled PA6 for face fibre, reducing impact of the fibre by 68%[2]; 54% recycled materials in the backing system.
- ecosystem benefits generated from the use of discarded fishing nets as input material for face fibre.

2. Reduction of materials usage:

- tile weight similar to other carpet tiles; the collection includes a version that is microtufted, reducing the amount of face fibre used 'up to 50%'
- the TacTiles reduce the amount of adhesives by more than 95%.

3. Optimisation of production techniques:

- optimisation of the production techniques was not considered by the designer (but is considered by Interface as part of the '7 fronts').

4. Optimisation of distribution system:

- similar to 3.

5. Reduction of impact during use:

- the use of random tiles reduces waste from installation from 3-6% to 1-2%, and reduces material usage by allowing for individual tile replacement (dye-lot independent design)
- the use of TacTiles reduces emissions of VOC from glue by more than 95% , facilitates recycling, and improves the quality of the recyclate (glue residues).

6. Optimisation of initial lifetime:

- the use period of the tile is unaltered.

7. Optimisation of end-of-life system:

- the end-of-life system was not considered by the designer; the product can be processed via the ReEntry program, which recovers part of the nylon for closed loop recycling, and processes the backing material into filler for new backings.

8. New concept development:

- not considered in this case.

Case 4: SmartBin resource bin

1. Selection of low-impact materials:

- bins from 100% recycled PP, reduced amount of toxic ingredients by change in colour and exclusion of galvanized screws; plate steel 'sliding' frame instead of steel tube frame with wheels; the powder coating still contains toxic pigments, though less than the original design.

2. Reduction of materials usage:

- product weight increased from 4.4 to 8.7 kg; this will increase impacts from steel production and coating (larger surface area). No increase is anticipated for the transport of the frame as distances were reduced (see 4).

3. Optimisation of production techniques:

- optimisation was not included; the main production processes remain unaltered.

4. Optimisation of distribution system:

- energy efficiency of distribution was not considered; however, the production of the frame was transferred to a local manufacturer; packaging was not altered.

5. Reduction of impact during use:

- no changes were made to the number of waste fractions, the use of waste bags and maintenance
- the product is not hazardous to the users, assessed materials do not contain any carcinogenic, mutagenic, or reproductively toxic (CMR) chemicals (no comparative data available).

6. Optimisation of initial lifetime:

- the use period of the SmartBin is unaltered.

7. Optimisation of end-of-life system:

- full recycling of the plastic bins into new bins (mechanical recycling); frame recyclable via standard steel recycling infrastructure; improved disassembly; pigments are treated as waste materials.

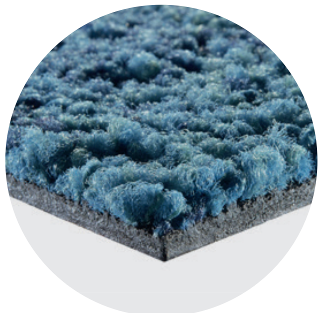
8. New concept development:

- no new ways of collecting ' discarded resources' were considered.

6.2.2 Case 2: Algaepack flower tray

For the “Algaepack”, a flowertray made out of algae material, the design measures focused on five life cycle design strategies: 1. ‘Selection of low-impact materials’ by using the algae material, 4. ‘Optimisation of distribution system’ by using highly localised production, 5. ‘Reduction of impact during use’ by improving soil condition, 7. ‘Optimisation of end-of-life system’ by composting of material, and 8. ‘New Concept Development’ by developing a product that during material cultivation purifies wastewater. Three strategies were not followed (2, 3, and 6). ‘Reduction of material usage’ (no. 2) was not addressed as creating a fully (biologically) closed material cycle prevailed over the reduction of materials used. We anticipate some adverse effects if the product weight would be higher than that of a conventional tray. Strategy 3 ‘Optimisation of the production processes’ was not considered as the production technique is directly coupled to the material. Compared to vacuum moulding, the foreseen production process will require considerably more energy. However, using (direct) solar energy is foreseen for the drying, but not for forming the trays.

6.2.3 Case 3: Net Effect carpet tile



The inventory shows the design measures for the carpet tile focused on five life cycle design strategies: 1. ‘Selection of low-impact materials’ by using recycled content, 2 ‘Reduction of materials usage’ by using TacTiles, 5 ‘Reduction of impact during use’ resulting from the application of random tiles and TacTiles, and that 7 ‘Optimisation of end-of-life system’ is addressed by Interface through recycling of material. As described in Chapter 5, a small percentage of the face fibre stems from recycled polyamide sourced from discarded fishing nets that Interface collects in the Net-Works project. Currently, only small material volumes of nets have been removed, however the project aims to reclaim 2,400 kg of nets per village per year. The size of the resulting ecosystem benefits could not be assessed, but a small beneficial impact can be attributed to the tile. Strategies 3, 4 and 7 were not part of the design process, but addressed in separate Interface projects (not related to the use of Biomimicry as a design strategy). Strategy 8 ‘New Concept Development’ was not part of the design brief. The designer does envision new concepts, but these will require innovative technological developments.

6.2.4 Case 4: SmartBin resource bin

The inventory in Table 3 indicates the design measures for the Smartbin focused on three life cycle design strategies: 1. Selection of low-impact materials' by applying recycled materials and reducing toxicity, 4. Optimisation of distribution system' by reducing transport distances, and 7. 'Optimisation of end-of-life system' by recycling of materials. Five strategies were not followed. 'Reduction of material usage' (no. 2) was not addressed, following the premise of Cradle to Cradle not to focus on reducing, but instead on aiming for full recycling. We anticipate this will cause adverse environmental impacts, as the product weight has almost doubled. Strategy 3 'Optimisation of the production processes' was not included as a design measure. The Cradle to Cradle certification did require a full *inventory* of the production processes used, but the processes were not optimised. Whereas the design team addressed the application of materials without harmful substances (included here under Strategy 1), they did not aim to reduce other impacts during the use phase, included in Strategy 5. This result coincides with the scope of the Cradle to Cradle certification, which considers materials and energy only up to the point where the product leaves the production facility (Cradle to Cradle Products Innovation Cradle to Cradle Products Innovation Institute, 2012). For example, the use of the waste bags was not included in the design process. Instead, the waste bag is considered as a separate product that the company plans to optimise in future. Finally, a change of the initial lifetime or basic product concept -Strategies 6 and 8- were not part of the design brief, and therefore not included.

6.3 Assessment of the environmental sustainability of the real-life cases

Based on the inventory of design measures, the researcher assessed all product components against the adopted criteria for environmental sustainability as described in section 6.1. Here, the results of the assessment are presented as well as the contribution of the designs to the transition towards sustainable product-systems.

Figure 6.4 shows the assessment of the four real-life cases on environmental sustainability. As shown in the figure, assessment scores range from 'failing to meet a criterion' to

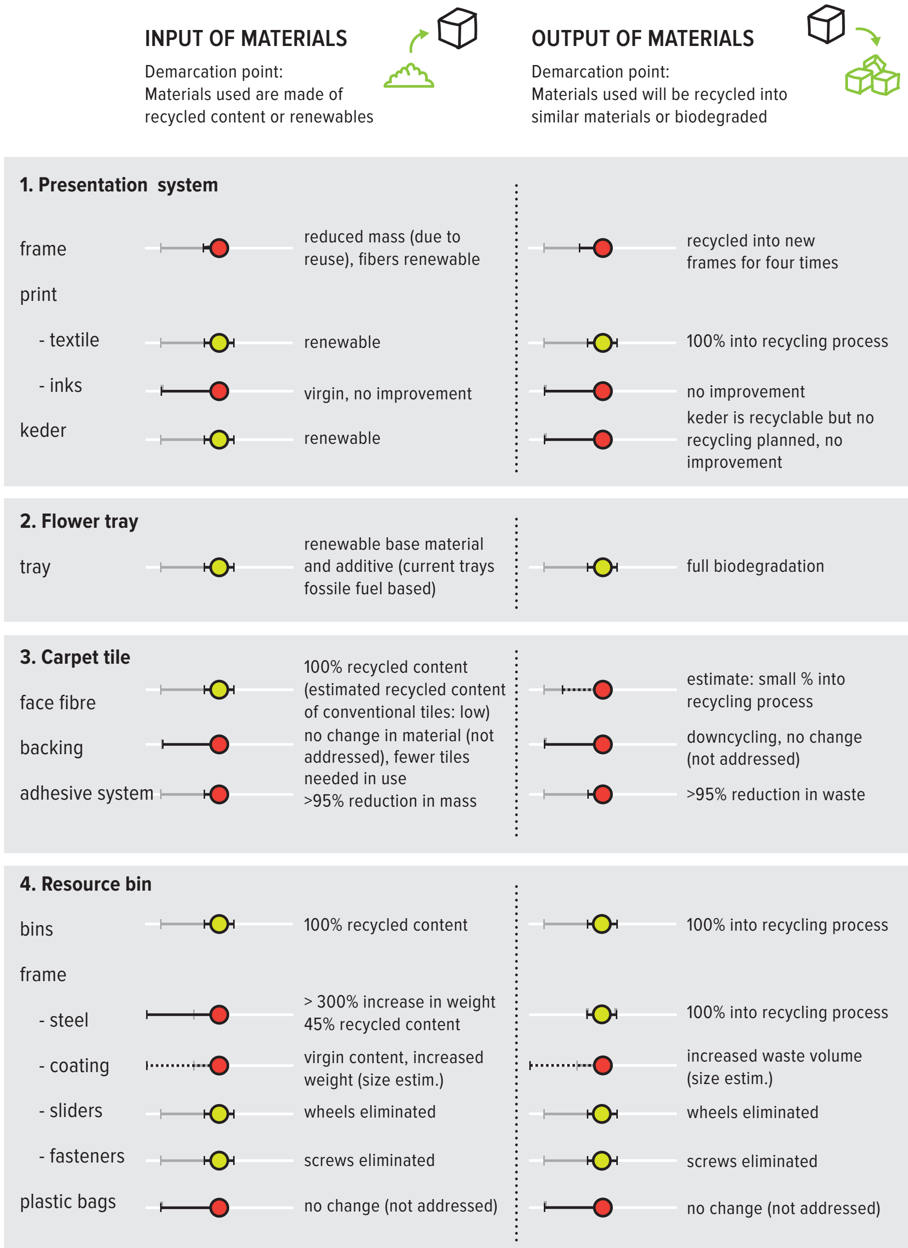


Figure 6.4: Assessment scores of the real-life case products on the criteria of environmental sustainability

INPUT OF ENERGY

Demarcation point:
Energy used from renewable resources

SAFETY

Demarcation point:
Materials used will have no harmful effects to the system(s) in which the product operates

1. Presentation system	Input of energy	Safety
frame	solar energy, net-supply of energy	estimate: base materials safe, impacts from production (red. estim.)
print		
- textile	no data available	textile brightened; contains flame-retardants (red. estim.)
- inks	no data available	water-based & reduction in toxic ingredients (red. estim.)
keder	no data available	replaces material with plasticisers (red. estim.)

2. Flower tray	Input of energy	Safety
tray	fossil fuel based energy for forming, solar energy for drying (red. estim.)	beneficial effects (nutrients) to ecosystem (size estim.)

3. Carpet tile	Input of energy	Safety
face fibre	renewable (no change)	small part restorative, base material non-toxic
backing	estimate: no change	estimate: no change
adhesive system	estimate: >95% reduction in fossil energy	>95% reduction in VOC, estimated as safe for ecosystem

4. Resource bin	Input of energy	Safety
bins	no change	no change, base material non-toxic
frame		
- steel	estimate: increase	no data available
- coating	estimate: increase	more but less harmful pigments (red. estimated)
- sliders	wheels eliminated	wheels eliminated
- fasteners	screws eliminated	screws eliminated
plastic bags	no change (not addressed)	no change (not addressed)

relative performance new product
relative performance new product, estimate
relative performance preceding product

new product component fails criterion
new product component meets criterion
new product component generates beneficial impact

'generating beneficial impacts'. None of the products meet all four criteria so not one fully fits an environmentally sustainable system. In the real-life cases included in this study, 10 of the 14 components met one or more of the assessment criteria (in total 23 yellow or green scores). The *beneficial* results that Nature-Inspired Design strives for have been established to some extent: in three of the four cases, a (small) beneficial impact has been observed on one of the four assessment criteria. None of the original products that the designs were compared with was assessed to generate a beneficial impact, and only 2 of the 14 components met one of the criteria (the original products in Case 3, the Net Effect carpet tile and Case 4, the SmartBin resource bin).

For 7 of the 14 components, relative improvements were achieved on one or more criteria, ranging from incremental (2-4%) to drastic (factor 20 improvement). In contrast, 2 components showed setbacks in performance. In Case 4, the SmartBin resource bin, the weight of the frame increased by more than 300%, which results in increased use of virgin resources for steel production and coating, including resources coupled to the use of non-renewable energy for production.

In each of the real-life cases, different or adapted production and recycling systems were selected to meet the project ambitions, and the design teams were closely involved with suppliers to implement innovative solutions. For some cases, the result can be seen to facilitate the transition to sustainable product-systems as described in section 6.1, in line with the perspective of 'achieving sustainability'. In Case 1, the Plenic presentation system, one supplier currently introduces the material innovation that was developed into the market, thereby facilitating the broader application of printed textiles of which the textile can be fully recycled. Furthermore, the recycling of the frames and textile may aid the success of the state-of-the art recycling technologies used, but the anticipated volumes, and thus the impact, are estimated to be small. For Case 2, the Algaepack flower tray, the product-system will not be developed further due to its unsatisfactory economic feasibility. In the third case, the Net Effect carpet tile, the tile production and installation system as well as the gluing system were altered. These innovations were implemented within Interface, and marketed as competitive solutions. They currently have no further impact outside the Interface supply chain. The introduction of nylon via Net-Works is anticipated to have beneficial impacts beyond the Interface supply chain, but this impact is not attributed to the application of Nature-Inspired Design Strategies (see section 5.4). In Case 4, the SmartBin resource bin, the supplier of the plastic bin has gained experience in producing products from 100% recycled content, and has shown interest in employing these solutions in other applications.

6.4 Discussion

To evaluate whether and to what extent Nature-Inspired Design Strategies (NIDS) helped or hindered the designers in developing sustainable products, the assessment results are discussed in view of the effects that NIDS have had on the designs (described in Chapter 5).

The assessment shows that 21 of 23 positive scores for meeting criteria for environmental sustainability were achieved as a result of the new designs. Meeting these criteria was therefore regarded as being established within the design process. When linking the assessment scores with the design outcomes described in Chapter 5, five design solutions were found to be implemented across different real-life cases that contributed to meeting criteria: a) changing materials from fossil-based to renewable, and from not (fully) recyclable to either fully recyclable or compostable (in Case 1, the Plenic presentation system and Case 2, the Algaepack flower tray), b) changing the material origin from virgin to recycled content (in Case 3, the Net Effect carpet tile and Case 4, the SmartBin resource bin), c) designing recycling and reuse systems (Cases 1, 2, 4), d) changing from toxic to non-toxic or beneficial additives and processes (Cases 1, 2, 3, 4) and e) eliminating parts that do not meet the criteria, via design changes (Cases 3, 4). Of the beneficial impacts, only one (Case 2) can be attributed to the application of NIDS. For the presentation system and carpet tile (Cases 1 and 3), the beneficial impacts were welcomed by the designers, but their occurrence was related to measures taken by others and cannot be coupled to the application of NIDS.

In addition to meeting the assessment criteria, relative improvements were generated from the design process that can be attributed to the application of NIDS. In line with the design solutions described above, reasons for having a relative improvement include: changing part of the components' materials (not all, due to economic or technical constraints), using materials that contain less than 100% recycled content (such as steel), reducing toxicity of additives, and implementing design changes that reduce or minimise impacts rather than eliminate impacts (for instance the TacTiles in Case 3). In Chapters 4 and 5, the risk of introducing unforeseen increasing impacts was coupled to the absence of quantitative evaluation tools for NIDS. Though rudimentary, the assessment framework used in this thesis does indicate these impacts occurring in one of the cases (Case 4, SmartBin).

The assessment scores show great variation between the evaluated product components: in each of the cases, at least one component meets 2 to 4 of the criteria, whereas in three cases the product contains components that meet none of the criteria. As described in Chapter 5, some components were ‘simply’ not included in the design project, such as the backing of the carpet tiles and the plastic bags in the waste bins, explaining why the criteria were not met. However, for the components that were addressed, the scores indicate that the criteria can be difficult to attain. For instance, the designers of the presentation system (Case 1) did try to find alternative inks, and for the SmartBin (Case 4), the team did consider the impact of the coating. However, no suitable alternatives were available on the market. The scope of the task, in these cases the need to develop new inks and coatings, was beyond the expertise of the designers and beyond the project budget.

Furthermore, the assessment scores show variation between the four different criteria: only 4 of 14 components met criterion 3 -Input of energy-, whereas for the other criteria, 6 to 7 of the 14 components met the respective criterion. The variation between criteria links to the findings reported in Chapter 5, that the design teams focussed on closing the materials loops. Consumption of energy, direct and indirect, received little attention, despite the related C2C principle ‘use current solar income’ and Biomimicry sub-principle ‘use readily available materials and energy’. The impact of this design focus is thus clearly reflected in the assessment scores.

Beyond the system boundaries of the assessment, the design projects have resulted in the application of production and recycling systems that facilitate closed-loop recycling. The impact their application may have on the production and recycling infrastructure is anticipated as being in line with the perspective of ‘achieving sustainability’, but is small in volume. Influencing the energy processes of suppliers (to operate with renewable energy sources) or transport processes was either seen as unfeasible or outside the scope of the design project.

6.5 Conclusions

To understand the effects of applying NIDS on the sustainability of the designs (Research Question 4), the results of the real-life cases were assessed using the criteria for environmental sustainability. The assessment of the designs from the real-life cases, as described in this chapter, shows that NIDS can help designers to succeed in meeting specific sustainability criteria and in achieving beneficial impacts. By doing so, the designers achieved more than a reduction in environmental impacts for specific product components. However, these results were obtained only partially; for part of the components and for part of the criteria, as is shown in Figure 6.4. On a product level, none of the case study projects succeeded in meeting all criteria. The assessment scores reflect the ambitious targets that were set by the designers, described in Chapter 5, that also addressed specific conditions of environmental sustainability. With respect to achieving *beneficial* impacts (green scores), the results can be attributed to the application of NIDS for one of the real-life cases only. For *meeting* criteria (yellow scores), the results can be attributed to specific design solutions for each of the real-life cases. The criteria for ‘input of material’, ‘output of material’, and ‘safety’, were met more frequently than the criterion ‘input of energy’. Finally, relative improvements were obtained by applying solutions similar to those used for meeting criteria, but in these instances, the solutions were only partially implemented.

As explained in Chapter 3, the assessment method used in this evaluation is a first version, based on the adapted framework for assessing environmental sustainability as developed in this thesis. Consequently, the assessment results only provide a basic impression of the environmental performance of the products. A more detailed analysis, including for instance data on production and transport processes, could highlight new life cycle impacts that have not been included in the current assessment. Nevertheless, the results indicate that, in principle, NIDS are capable of helping designers to ‘achieve’ one or more criteria for environmental sustainability, especially with respect to establishing material loops.

From the current study, no conclusions can be drawn as to whether NIDS can help designers meet all the criteria for environmental sustainability in one design. Although NIDS offer a philosophy and design principles to develop products that fully fit within a sustainable system, the designers seem to have favoured specific principles over others, and the resulting solutions never fulfilled all criteria. In addition, this partial application of NIDS poses the risk of developing products that have increased environmental impacts within today’s systems. The results of the assessment stress the importance of overarching tools like the Cradle to Cradle roadmap and evaluation tools to ensure the effective implementation of NIDS. By offering suitable design tools for implementing each of the design principles, and a tool for evaluating the overall environmental sustainability, designers can work towards the design of products that meet *each* of the criteria. On the other hand, this study has illustrated the complexity and scope needed for the development of a design that fully fits within a sustainable system, which may prove to be beyond the restrictions that many designers face in everyday practice.

[1] Such as production, energy, and waste processing systems (see also section 3.1.2).

[2] Based on LCA-results of CO2-emissions for a standard Interface carpet tile of 712g/m^2, when replacing virgin PA6 with 100% recycled PA6 (Interface CO2 Calculator, http://www.interfaceflor. co.uk/web/in/sustainability/CO2_calculator). Other references for Case 3 data from Interface (Arratia, 2009, 2011, Interface, 2013a).

CHAPTER 7

Conclusions & Recommendations

In this thesis, we explored the application of two Nature-Inspired Design Strategies (NIDS), Biomimicry and Cradle to Cradle, within the field of sustainable product design. Both design strategies are currently used in design practice and are taught in institutions of higher education. However, little empirical knowledge is available on how these strategies are applied and how they actually support product designers in the development of sustainable products. Accordingly, we started this investigation with the main research question:

How do Nature-Inspired Design Strategies help designers in developing 'sustainable products'?

In this chapter, we present the main conclusions of the study (section 7.1) that answer our central research question. Section 7.2 provides recommendations for future research and for the further development of NIDS; in section 7.3, we make recommendations for those practising and teaching sustainable product design.

7.1 How do Nature-Inspired Design Strategies help designers in developing 'sustainable products'?

To answer this research question, we explored the application of NIDS by reviewing the available literature and using a multiple case study approach. Our findings demonstrate how NIDS have helped designers at different conceptual levels and in different phases of the design process. In addition, the analysis has provided insights into the limitations of NIDS, reflecting how their application did *not* help designers in the development of sustainable products. The following conclusions capture the understanding of NIDS that we were able to generate from this study.

Addressing (environmental) sustainability by 'learning from nature'
Numerous strategies are available to help product designers integrate sustainability into the design process. Among these, we identified a distinct class of strategies which we designated as Nature-Inspired Design Strategies (NIDS); strategies that *base a significant proportion of their theory on 'learning from nature' and regard nature as the paradigm of sustainability* (Chapter 2). Biomimicry and Cradle to Cradle, the two NIDS included in this study, offer product designers a design philosophy, principles, and tools, to implement this learning from nature in their design process. NIDS acknowledge the need to address sustainability at a systems level, and convey ecosystem knowledge in the form of 'design principles'; in Biomimicry these are referred to as 'Life's Principles' and in Cradle to Cradle, as 'guiding principles' (Baumeister et al., 2013, McDonough and Braungart, 2002). The empirical findings confirm the importance of the design principles within NIDS for addressing (environmental) sustainability at a systems level.

Biomimicry and Cradle to Cradle share many characteristics in terms of design philosophy, design principles, and focus, as also reflected in the outcomes of their application (Chapter 4 and 5). Nevertheless, the two design strategies are quite different in terms of methods and tools. Biomimicry provided the designers more support for addressing product form and product function, and frequently guided them towards the application of renewable, compostable materials. In comparison, designers applying Cradle to Cradle mostly selected 'technical materials' and incorporated a solution for the recycling of these materials at a high quality level (i.e. allowing reuse within the same, or a similar application).

Aim for 'achieving sustainability'
NIDS offer designers a different view on sustainability when compared with more established eco-efficiency approaches: the designers are challenged to work with the perspective of 'achieving sustainability' instead of 'reducing unsustainability' (Chapter 1

and 3). This perspective is embedded in the NIDS design philosophy. Both Biomimicry and Cradle to Cradle offer the vision that products, like their natural counterparts, can be designed to fit within and even benefit the 'ecosystems' in which they operate. Where the aim of eco-efficiency is to create "more goods and services with ever less use of resources, waste, and pollution" (WBCSD, 2000, p.1) and thus to reduce environmental impacts and resource intensity, the aim of NIDS is to achieve beneficial impacts and cyclic resource flows (see Figure 7.1). Consequently, NIDS hold the premise that designers can develop solutions that contribute to achieving sustainability.

Figure 7.1: Visualisation of the differences in the primary objectives of eco-efficiency strategies and nature-inspired design strategies (NIDS) in terms of resource flows (based on Braungart et al., 2008)

Our findings did not show whether working towards achieving environmental sustainability was more effective than reducing current impacts. The differences between the two approaches are rooted in the different perspectives towards sustainability, and conclusions on their effectiveness would require analysis of the long-term implications of applying both approaches. The findings of this study indicate that the perspective embedded in NIDS offers advantages to the design process that can help to overcome some of the barriers in the transition to a sustainable society. First, the case study results show that NIDS can influence the designers' ambition with regard to environmental sustainability (Chapter 4 and 5). In each of the four real-life cases, the application of NIDS was reflected in ambitious project goals to 'design out waste' (Cradle to Cradle) or to integrate principles from nature (Biomimicry). Second, the NIDS design philosophy and principles seem to support the transition from 'thinking in sustainability trade-offs' towards 'thinking in conditions for sustainability' within which a designer wants to develop a solution. As to how NIDS contribute to this transition, this study generated the proposition that the absolute, or binary, nature of some of the design principles triggers designers to aim for ‘achieving sustainability’ instead of ‘reducing unsustainability’. This effect was especially observed for the design principle ‘Waste equals food’, which inspired designers to aim for the development of fully circular material cycles. The high ambition that is enclosed within most of the NIDS principles seemed to stimulate the designers rather than put them off, which may be linked to the designers’ expertise of generating solutions within constraints.

Developing ‘sustainable products’

In terms of environmental sustainability, the assessment of the products from the real-life cases (Chapter 6) revealed different types of outcomes. First, designers were able to meet specific conditions of sustainability for several product components, thereby demonstrating that the application of NIDS can contribute to the perspective of ‘achieving sustainability’. However, these results were only partial: specific criteria were met for specific components; no product met all criteria. Second, the designers incorporated relative improvements in 50% of the product components, ranging in size from incremental (2-4%) to drastic (factor 20). These results demonstrate how the application of NIDS also generated results that fit the perspective of ‘reducing unsustainability’, a result we also observed in the student design projects. Third, the achievement of *beneficial* impacts as advocated by NIDS was observed in a limited number of the cases included in this study, both for the real-life and the student design cases. However, in the real-life cases, these beneficial impacts could only be attributed to the application of NIDS in one of the four cases: the Algaepack flower tray of Case 2. For the Plenic presentation system and Net Effect carpet tile designs (Case 1 and 3), the beneficial impacts were welcomed by the designers, but their occurrence was related to measures taken by others (Chapter 5). Consequently, our findings demonstrate that NIDS can help designers to ‘achieve’ one or more criteria for environmental sustainability, but we were not able to establish whether NIDS are capable of helping designers develop fully beneficial products.

Expanding the solution space - design of the material loop

Learning from nature helped designers to think and act ‘out-of-the-box’. More specifically, the student design projects showed that NIDS helped to broaden the solution space of the student groups (Chapter 4). In parallel, the real-life cases showed how the design teams, in addition to designing the product, also designed the ‘product or material loop’, thereby establishing a solution for the cycling of resources (Chapter 5); the designers determined how the product, or its materials, are to be handled after the use-period of the product. Furthermore, the designs of the product loops were context-specific, meaning that the designers developed non-generic solutions that were deemed feasible within the specific context of the product, company, or use-scenario; a solution strategy also observed in the student design projects (Chapter 4). The designers either selected materials for which a high quality level recycling system was already in place, cooperated with other companies to develop and introduce new materials and material cycles, or -if the material used in a component could not be influenced- introduced functional innovations to replace that component. By doing so, the designers were able to tackle barriers for 'closing the loop'. These findings have led to the proposition that NIDS help designers to tackle environmental hurdles by expanding the solution space towards the system surrounding the product, especially by designing the material loop.

Designing this loop and developing materials alongside the design of products has profound impacts on the design process and on the information requirements of designers. On the other hand, the need for material data is not new to the field of (sustainable) product development. Sustainability aspects of materials are increasingly being addressed in research and materials databases (e.g. Ashby et al., 2015, Hornbuckle, 2010, Karana et al., 2015b, Vezzoli, 2014). Furthermore, the integration of product design and material development is also pursued for gaining technological and economic advantages (e.g. Karana et al., 2015a, Köhler, 2013, Nathan et al., 2012, Tempelman and Adamovic, 2015). In addition, nature-inspired design is being applied in the field of material science; the combination of physical and environmental properties found in biological materials can inspire the development of technical materials and material production processes such as additive manufacturing, that mimic or incorporate these qualities (see e.g. Boyer, 2013, Darensbourg, 2007, Vincent, 2014). The resulting materials and processes, in turn, can benefit designers in the development of 'sustainable products'.

Although the primary focus of this study was to explore those elements of NIDS that helped (i.e. were useful or necessary for) designers, our study highlighted several obstacles that designers currently face when applying NIDS for the development of sustainable products.

Selective application of design principles and tools

Whereas both Biomimicry and Cradle to Cradle state the importance of including all design principles within the design process, this study shows how designers -being constrained in time and budget- focused on a reduced number of principles; especially those related to the use of renewable energy were ill-addressed. Designers selected the principles and tools they considered useful. The cross-case analysis of the real-life cases (Chapter 5) showed that when a design principle was given priority by the design team (for example via the ambition statement) that the principle was always applied, irrespective of the availability or absence of NIDS tools to integrate the principle. In addition, the designers applied the principles that could be addressed by influencing the design of the product, whereas they did not apply principles such as 'use current solar income' that they considered to be outside the scope of their influence. This finding leads to the proposition that designers implement specific principles, only if they are seen as a design priority and /or when their implementation influences the design of the product -thus being within the scope of the traditional design process. Further research is needed to determine whether these variables are independent or interdependent (i.e. that designers tend to prioritize principles that can be addressed with measures that fit their usual scope of work). The selective application of design principles induces the risk that the positive impact of meeting one design principle will be at the expense of negative impacts caused by not addressing another design principle, thereby negating the core objective of NIDS.

Evaluating the overall environmental impacts of solutions

In the cases studied, NIDS did not help the designers to consider potentially adverse environmental impacts of their designs. In several of the student cases and one of the real-life cases, we anticipated the occurrence of these adverse impacts (Chapter 4 and 5). The assessment of the real-life case (Chapter 6) confirmed the occurrence of additional impacts: although the design allows full recycling of the main materials, the new product requires more virgin resources than the preceding design.

Being able to assess these effects is especially important as this study shows that designers did not implement all the design principles offered. However, Biomimicry and Cradle to Cradle currently offer no quantitative tools for evaluating the overall environmental impacts of solutions that could highlight adverse effects. In principle, designers can use life-cycle based assessment tools to evaluate the environmental impacts of the designs, but, as described in Chapter 3, these tools do not assess some of the key results that NIDS strive to accomplish. In this thesis, we present an adapted framework for assessing the environmental sustainability of products which can form the basis for a new assessment method that fits the perspective of 'achieving sustainability'.

Addressing social and economic sustainability

The application of NIDS did not help the designers address social and economic sustainability in the design process (Chapter 4 and 5). The current lack of dedicated design tools within Biomimicry and Cradle to Cradle for integrating social and economic sustainability explain these findings (Chapter 2). For integrating economic aspects, the designers employed generic design skills (product level), and in one case used a system-modelling tool to capture financial system-dynamics (product-system level). Social sustainability received relatively little attention in the cases studied, or was included on the basis of another design approach (Chapter 4 and 5).

Both social and economic considerations are gaining increasing interest from Biomimicry and Cradle to Cradle experts and researchers. For instance, the Arizona State University dedicated their 2010 'Frontiers in Life Sciences' conference to the topic of Social Biomimicry, Biomimicry 3.8 recently announced their "first public workshop on the 'social' applications of biomimicry", and the Cradle to Cradle Certification process includes criteria for 'Social Fairness' that apply to practices at production facilities (Biomimicry 3.8, 2014, Cradle to Cradle Products Innovation Institute, 2012, Holbrook et al., 2010). Furthermore, NIDS can be applied for the development of products that are dedicated to solving or mitigating social sustainability issues, and thereby contribute to social sustainability. The economic pillar of sustainability is specifically being addressed by the 'Circular Economy' movement (e.g. Ellen MacArthur Foundation and McKinsey, 2012). Different business models and additional options for the economic cycling of resources are being proposed and analysed to support the introduction of 'circular' designs (ibid, Bakker and den Hollander, 2014, Bocken et al., 2015). These developments may be translated into NIDS methods and tools, but for now, designers and educators should recognise that the focus of NIDS is limited to integrating environmental sustainability.

7.2 Recommendations for future research and development

As described in this thesis, NIDS can be considered as relatively new design strategies, and their principles, methods and tools have evolved over the course of this project to better support designers (Chapter 2). As a contribution to the further development of NIDS, our findings provide specific options to support designers that want to develop sustainable products. Furthermore, we have identified several aspects of NIDS worthwhile investigating, that could not be addressed within the scope of this PhD-study. This section provides an overview of the recommendations for future research and development of NIDS.

The application of NIDS in different contexts
The case study projects included in the current study shared several characteristics that facilitated replication of findings. However, as discussed in Chapter 5, shared characteristics may point to intervening variables that can influence the effects of applying NIDS. For instance, in each of the cases, ambitious goals were set in terms of environmental sustainability that supported the company visions on sustainability[1].

Analysis of additional cases, especially projects that are not supported by ambitious sustainability visions, can advance our understanding of the benefits and limitations of NIDS and may confirm or contradict the findings of this study. Furthermore, none of the products of the real-life cases consumed energy. Inclusion of company projects in which electronic products are developed can show whether the NIDS principles that address use of energy are indeed applied when the products themselves consume energy during operation. In addition, cases are available from related disciplines such as architecture, for which dedicated NIDS-approaches have been developed (e.g. Braungart and Mulhall, 2010, Kadri, 2012). The analysis and evaluation of these cases and approaches will deepen our understanding of the value of NIDS for design practice.

The nature of beneficial impacts

The aim to generate beneficial (environmental) impacts through design is key to NIDS. However, no prior research was found that considers the nature of these impacts and how to design them, apart from a critical reflection by Reijnders (2008) stressing that 'biological nutrients' are not intrinsically beneficial to ecosystems. Beneficial impacts can only be established via a context-specific approach, as impacts that benefit one context may be harmful in another (section 3.1). Insights from ecology on the nature of context-specific, diverse solutions may provide a starting point for understanding the phenomenon of beneficial impacts (e.g. Maier, 2012, Vet, 2008). Future research that integrates knowledge from biology and ecology into the field of product design may provide insights that form the basis of specific methods and tools for including beneficial impacts. This research can complement existing research into the transfer of knowledge between the fields of design and biology. In future research, we recommend including the factor 'time', as its role is hardly addressed within Biomimicry and Cradle to Cradle. On the one hand, learning from nature allows designers to 'leap forward' by implementing existing ecosystem knowledge; on the other, nature also takes its time when 'producing' designs with beneficial impacts, for instance the growth of trees, whereas in our society time is a scarce resource and companies generally like to sell their products throughout the year. Conscious inclusion of time as an enabler, already applied in products such as washing machines, toilet reservoirs, and rechargeable batteries, can provide designers with an additional solution strategy.

Facilitating a designerly way of thinking and working

Apart from the differences in content between NIDS and Ecodesign analysed in this thesis, we noted a difference in 'design style' between the two types of strategies. The design philosophy, principles, methods and tools of Biomimicry and Cradle to Cradle share characteristics that seem to fit *the way designers think and work* (see e.g. Cross, 2006, Roozenburg and Eekels, 1995). Shared characteristics include the positive, goal-driven approach, the use of visual communication (graphics, video presentations), and the use of nature-based examples and analogies in the case of NIDS. We recommend that developers of design strategies, methods, and tools, account for the designers' way of working, their needs and requirements in terms of methodological support, to make sure NIDS are used to their full potential. To illustrate, designers can use nature-based examples for different purposes throughout the design process. Design literature has identified purposes such as providing inspiration, providing solution strategies, and deepening the designers' understanding of the issues at hand (Buijs et al., 2009, Herring et al., 2009, Lofthouse, 2006). This knowledge can help to develop methods and tools for sustainable design that support specific design needs.

Assessing the environmental sustainability of designs

In this study, a rudimentary method was developed for assessing environmental sustainability in a framework that fits the NIDS' design philosophy. The results can be used for the development of an LCA-based product assessment tool that, instead of measuring improvements over today's solutions, assesses a products' contribution to achieving a sustainable future. This method could provide a quantitative assessment tool, currently absent in NIDS, that captures the benefits that NIDS strive to accomplish. When integrated into the evaluation phase of the design process, this assessment method can help designers to consider all of the conditions for environmental sustainability.

Integrating NIDS design principles

We conclude in this study that NIDS currently do not sufficiently support designers to integrate all design principles in their product development project. Providing a sequence or hierarchy in the principles, especially the many Life's Principles in Biomimicry, may help designers to limit or prioritise a manageable number of principles. However, considering the case study findings and the recommendation on designers' needs, it may be more effective to develop specific tools that show designers how to include each of the principles, including examples of how these principles are included in nature and in manufactured designs. The tool 'design in biological and technical cycles' can serve as an example of how a tool has helped designers to include the 'waste equals food' design principle. In addition, only very few studies have explored the use of ecosystem knowledge in the field of design (e.g. Pedersen Zari, 2014, Reap, 2009). Further research is needed to develop scientific support for ecosystem principles, which will, in turn, increase our understanding of these principles.

Learning from best-practices

As described in this thesis, designers had their own way of applying NIDS. Apart from the risks that were identified in this study from the partial application of NIDS, designers were also seen to add practices, methods and tools to overcome the limitations they faced when applying NIDS. For example, we noted several cases where designers applied natural elements in their designs in the form of renewable materials or plants, as a way to meet design principles and achieve beneficial impacts. Within the Biomimicry design method, this approach is described as bio-utilisation and is not considered part of Biomimicry, as it deals with using nature directly instead of learning from nature. Nevertheless, considering the difficulties we observed of creating sustainable solutions, the application and integration of nature itself seems a solution strategy that fits the objectives of NIDS. Cradle to Cradle already includes tools for the design of 'biological cycles', so Biomimicry, as a design strategy, may benefit from this approach in the form of a method, tool, examples, or other, showing designers how to integrate renewable materials in a way that fits the Biomimicry philosophy and principles.

Based on our finding that designers add solution-strategies when applying NIDS, in 2012 a project was started as a spin-off of this PhD-research, to further analyse design practices at ten Dutch companies applying Biomimicry and/or Cradle to Cradle approaches, especially practices that helped them to overcome difficulties in the application of NIDS (Tempelman et al., forthcoming). Based on the research findings, specific methods and tools have been developed for integrating these practices into product development (Tempelman et al., 2015).

NIDS and designing for social sustainability

'Learning from nature' can provide opposing solution strategies when considering social practices; for instance, nature provides many examples of both symbiosis (linking to cooperation) and of parasitism (linking to exploitation) as successful 'social design strategies'. Nevertheless, learning from these social strategies may provide insights that build our understanding of the conditions that generate practices needed to achieve social sustainability. In addition, research into the social part of 'achieving sustainability' can help create a full understanding of the potential of NIDS for sustainable design, and is therefore regarded as being of key interest for future studies.

Comparing NIDS with design strategies for sustainable product-service-systems (PSS)

As described throughout this thesis, designers who apply NIDS address environmental sustainability at a systems level. In addition to our comparison of NIDS with the Ecodesign strategy described in Chapter 4, a comparison of NIDS with PSS design strategies will deepen our insights into their specific contribution. To date, the diffusion of PSS is still limited and empirical data is scarce (Beuren et al., 2013, Vezzoli et al., 2015), but methods, tools, and cases are available for making a comparison. Many of the barriers companies face when implementing NIDS and PSS are related, and as Vezzoli et al. (2015) noted, an exploration of potential synergies may enhance the implementation of system-level solutions.

7.3 Recommendations for design practice

In this study, we explore how Biomimicry and Cradle to Cradle have helped designers in sustainable product development, and provide theoretical propositions for the way in which NIDS contribute to the results. The findings give rise to several recommendations for designers who aim to develop sustainable products. In addition, these recommendations may be valuable for lecturers, as they highlight the qualities and limitations of NIDS. They are based on the experiences of the designers interviewed during the course of this research, who so generously shared their best practices, and on the earlier work of researchers studying Biomimicry and Cradle to Cradle. We want to emphasise that our findings are the result of an exploratory case-based research, and that NIDS will not necessarily deliver similar results when applied in a different context.

This section presents six recommendations which represent what the author considers the most valuable insights for those practicing and teaching nature-inspired design.

Apply the design philosophy of NIDS

First and foremost, this study illustrates how NIDS consider sustainability as a state that can be achieved, instead of something impossible to fully reach. Even more so, both Biomimicry and Cradle to Cradle build on the premise that products can be designed to *benefit* the (eco)systems in which they are used. In this way, design will be able to contribute to a world in which products enhance sustainability instead of having a harmful impact. It is this perspective towards sustainability which differentiates NIDS from Ecodesign strategies that aim for eco-efficiency. Based on what we have learnt from the cases included in this project, we recommend that designers integrate this perspective in their projects, to capture the full potential of what NIDS have to offer. With this perspective embedded in the project ambitions, it will be easier to design a product that aims to meet the inspiring design principles of NIDS. A consequence of pursuing this strategy is that the project will be at risk of going beyond the 'usual' scope of product design assignments. This development fits what has been described by Gardien et al. (2014) as the design competences needed for the 'Transformation Economy'.

The cases included in this study show that applying the design philosophy of NIDS can help designers to tackle barriers needed to meet criteria of environmental sustainability. If, on the other hand, the designers' ambition is to reduce the environmental impact of a product, and to integrate the design principles as much as possible within the constraints of the project, we anticipate they are bound to be pursuing eco-efficiency using NID-tools. This is a perfectly acceptable approach, but in that case, the application of Ecodesign might be more effective, as Ecodesign methodology is geared towards eco-efficiency and is currently much further developed than NIDS, and hence considered 'easier' to apply.

Define sustainability

NIDS hold the perspective that designs can contribute to sustainability. To be able to verify a product's contribution, it will be necessary to make explicit what is meant by 'sustainable': when do these designs benefit people, planet, and profit? We recommend designers to define or adopt a consistent set of criteria that describe when a product can be considered truly sustainable (see Chapter 3). NIDS provide design principles that capture several demarcation points for achieving environmental sustainability. These were used in this thesis to define four conditions of environmental sustainability. However, no conditions are provided for social sustainability. The Cradle to Cradle principle 'Celebrate diversity' may be an inspiration to think of ways to include social factors, but offers no demarcation of the solution space.

Embrace the inspiration captured in the design principles

In this study, the Biomimicry and Cradle to Cradle design principles were used to define conditions of environmental sustainability for assessing the case-study designs. Within NIDS however, their purpose is quite different; not analytic but generative, to provide inspiration for designers to achieve beneficial designs. In the cases included in this study, the design principles, or even following the generic principle of 'learning from the principles of nature', clearly guided the designers in their decision-making process. For instance, the principle 'waste equals food' coined by McDonough and Braungart (2002), formulated by Benyus as 'nature recycles everything' (1997), clearly expresses how designers can implement ecosystem knowledge for dealing with nature's resources.

Make a roadmap

This study has provided an understanding of the difficulties designers face when aiming to realise a beneficial design. Developing a product that benefits people, planet, and profit, requires designers to change both the product design as well as the processes in the product-system, which will inevitably take time, very probably more time than available in most product-design projects. To create a fully beneficial outcome, both the

Biomimicry and Cradle to Cradle strategy call for the integration of all of their design principles, although they do acknowledge that not all of them can be achieved at once. However, the cases included in this study highlighted that designers tend to focus on meeting specific principles, considering other principles to be ‘out of their scope’. From our analysis of NIDS, we identified one tool aimed at developing a company strategy beyond single design projects, the Cradle to Cradle roadmap tool. This strategic tool seems to have more potential than was shown in the cases included in this study. The application of this tool can help designers to envision and plot the ultimate sustainable product[2] and then back-cast a pathway towards achieving that goal. In line with the Cradle to Cradle philosophy, this ‘100% good goal’ is to be expressed in terms of beneficial outputs, using “positive, proactive terms” (McDonough and Braungart, 2002, p.162). In the well-known Cradle to Cradle (architecture) example of the Ford Rouge factory, the aspired result was captured in the statement “a factory site where Ford employees’ children could safely play” (ibid). The roadmap tool can help to keep the long-term goal in mind and to plot a strategy that includes all the design principles over time.

Explore solutions in the specific context of the product-system

Both Biomimicry and Cradle to Cradle offer design principles that embrace context-specific, diverse solutions: ‘Be locally attuned and responsive’ (Biomimicry) and ‘Celebrate diversity’ (Cradle to Cradle). These principles reflect that, in biological systems, diversity is a measure for success. However, it may be difficult for designers to aspire to diversity for its own sake, especially as most designers have been taught the advantages of mass production and economy of scale. The cases included in this study show how diversity was applied as a strategy to achieve beneficial impacts and to meet other design principles, which explained why it could make good (business) sense to incorporate diversity. As discussed in Chapter 3, beneficial effects are local by definition: an impact can be positive in one location or timescale, but harmful in another, depending on the local context. Therefore, the quest for beneficial impacts is a local one. Furthermore, a context-specific approach is sensible when trying to close resource cycles. Designers can make use of existing high-quality recycling infrastructures, such as the glass-recycling system in the Netherlands, but as many resource streams currently lack such an infrastructure, establishing resource cycles often requires the implementation of new recycling systems. The designers included in this study searched for and implemented context-specific solutions by applying specific ‘waste’ resource streams and by cooperating with companies that could already cycle the resources into the same or a similar quality product.

We acknowledge that the implications of this approach can be considerable. Compared with design projects where companies prefer to have solutions that are independent of specific customers, suppliers, or other stakeholders, NIDS can trigger the development of solutions where the unique qualities of partners offer added value. One way of reducing the risk of becoming too dependent on specific partners, as applied by one of the case-study companies, was to integrate a context-specific solution with one of their supply-chain partners up to a restricted percentage of their product portfolio.

Assess for unintended consequences
NIDS offer designers a qualitative strategy for product development. This approach is explicitly propagated in Cradle to Cradle, when explaining the concept of eco-effectiveness as being about 'doing the right things, before starting to do things right'. Consequently, following the (Cradle to Cradle) design principles - implementing resource cycles, use of renewable energy, and celebrating diversity - is given priority over reducing material and energy intensity[3]. However, as long as the principles have not been fully implemented, any increase in material and energy consumption will cause additional environmental effects. This study shows that full implementation of design principles is not to be expected within a single design development project. We therefore recommend that designers apply NIDS in combination with a tool for assessing the impacts of their designs across the products' life cycle. Existing LCA-based tools can be used to compare the (harmful) environmental impacts of a design with that of a previous model or a competing product. Alternatively, designers can use the (rudimentary) assessment method developed in this thesis to assess a design against criteria of environmental sustainability, to highlight both harmful and beneficial impacts. In addition, when considering Cradle to Cradle Certification, designers can assess their design against the Cradle to Cradle certification criteria, while being aware that these criteria do not cover the full life cycle of a product (Chapter 2).

Biomimicry and Cradle to Cradle add to the palette of design strategies available to designers. We hope these recommendations will help designers and educators to distinguish NIDS from other strategies for sustainable product design, and that they will support them to get the most out of NIDS in design practice.

1 In the student cases these ambitious goals and visions were given.

2 In Cradle to Cradle terminology framed as the '100% good for people, planet and profits', see also Figure 2.7.

3 In the latest versions of the Biomimicry Life's principles, resource efficiency is included alongside the other principles.

WRAPPING UP

In this thesis, I have explored the value of Nature-Inspired Design Strategies (NIDS) for sustainable product development by analysing the work of both professional and student designers. The results demonstrate how learning from nature can provide inspiration, valuable insights, and key ecosystem knowledge. Applying NIDS helped designers to tackle barriers in the cycling of resources, by designing both the product and the material cycle. In addition, the study revealed how design may play a role in generating beneficial environmental impacts, with products that contribute to the ecosystems of which they are part. On the other hand, this project also highlights the disadvantages and limitations of the current strategies. Designing products as intelligent as the Blowball still seems an aspirational goal rather than an easily attainable objective. Nevertheless, NIDS offer designers a design philosophy, design tools, and a wealth of knowledge, to help them pursue this goal.

APPENDICES

Appendix 1: Glossary

This Glossary contains the key terms used in this thesis and their definitions.

Analysis (as a design activity)	The analysis of product values, needs, and functions in relation to the design goal or design problem, yielding design criteria (based on van Boeijen et al., 2013).
Beneficial impact	Impact of a product on its environment that contributes to the regeneration of that environment towards a sustainable state (Chapter 3).
Closed loop/ Continuous loop	The term closed-loop refers to a resource cycle in which technical materials, or “technical nutrients”, continuously circulate as pure and valuable materials for industry (McDonough and Braungart, 2002). In later documentation, EPEA uses the term ‘continuous metabolism’ instead, to emphasise that in the technical cycle, materials do not necessarily have to be used again by the same company, and for the same purpose. The point is to cycle technical nutrients while retaining their high quality (ibid, p.110).
Context	People, companies and circumstances interrelated to the product-system (Chapter 4).
Cradle to Cradle principles	Design principles within Cradle to Cradle capturing generic ecosystem insights from biology, see also Chapter 2.
Designer / Product designer	In this thesis, a product designer is defined as a qualified person who executes product design and product development activities (Chapter 1). Novice designers (i.e. students) who are being trained to become product designers are also included in the study. In this thesis, we will use the term designers to refer to the target group described here.
Design Strategy	A strategy providing a general plan of action for a design project towards achieving a particular goal (based on Cross, 2000).
Ecodesign	A product development process that takes into account the complete life cycle of a product and considers environmental aspects at all stages of a process, striving for products, which make the lowest possible environmental impact throughout the product’s life cycle (Glavic and Lukman, 2007, p.1880).
Eco-effectiveness	Concept striving to generate an entirely beneficial impact upon ecological systems. After Braungart et al. (2007, p.1343). Eco-effectiveness “deals directly with the issue of maintaining or upgrading resource quality and productivity through many cycles of use, rather than seeking to eliminate waste” (ibid., p.1338).

Eco-efficiency
Strategy aiming to “creating more goods and services with ever less use of resources, waste, and pollution” (WBCSD 2000, p.1)

Evaluation
(as a design activity)
Evaluating the design against the design criteria to support decision making while designing (based on van Boeijen et al., 2013).

Life Cycle Assessment (LCA)
A structured, comprehensive, and internationally standardized method that quantifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any goods or services (‘products’) (ILCD, 2010).

LCA-based assessment tools
Product assessment tools based on Life Cycle Assessment (LCA) dedicated towards application within product development, such as Eco-indicator analysis (Chapter 3).

These tools are typically applied to determine ‘hotspots’ of existing products, to choose from design alternatives, and to compare the final design with a benchmark product.

Life’s principles
Design principles within Biomimicry, capturing generic ecosystem insights from biology, see also Chapter 2.

Nature-Inspired Design Strategies (NIDS)
Design strategies that base a significant proportion of their theory on ‘learning from nature’ and regard nature as the paradigm of sustainability (Chapter 2).

Products
Goods, services, and product-service systems that are developed by product designers (Chapter 1).

Product design & Product development
Both terms are used interchangeably throughout this thesis as those activities within the product innovation process in which product designers are involved (Chapter 1).

In their strict meaning, product development includes all activities involved from generating an idea for a new business activity, up to the development of the product design, production plan, and marking plan, whereas product design (activity) is that part of the product development process where a new business idea is transformed into a detailed product design (Roozenburg and Eekels, 1995), see also Figure 1.4.

Recycling
The reprocessing of discarded (waste) products into new materials (based on Allaby and Park, 2013, Åström, 1997).
To establish closed-loop cycles, ‘high quality’ or ‘primary’ recycling is needed, where the recycled materials have properties equivalent to those of the original material.

Simulating (as a design activity)	The drawing and modelling of ideas to be able to estimate and define the expected properties of the design (based on van Boeijen et al., 2013).
Solution level	The level of depth that a designer/design group considers for achieving a design solution, using four distinct levels based on the 'Model of reasoning by designers' (Roozenburg and Eekels, 1995): A. Material level (the level that defines properties such as hardness, density, and viscosity). B. Form level (which, together with selection of material and production technique, defines product characteristics such as weight, stability, price). C. Function level (the level at which alternative products are considered to fulfil the current purpose, including new ways of using products). D. Need level (the level at which alternative solutions are considered to meet the underlying needs of the user). See section 4.3.1 for further details.
Sustainable	Sustainability is a complex and ill-defined concept. Many definitions and descriptions are provided in the literature for the term sustainable (e.g. Faber et al., 2005, Grober, 2007, Toman, 2006). The definition adopted in this thesis is taken from the Oxford dictionary of environment & conservation: Capable of being sustained or continued over the long term, without adverse effects (Allaby and Park, 2013).
Sustainable development	Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: - the concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and - the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs (WCED, 1987).
Sustainable product design	Design aimed at the development of products that are beneficial to people, planet and profit (Chapter 1). Also known as Design for Sustainability or Sustainable product development.
'Sustainable product'	A product that is beneficial to people, planet, and profit - within the social, ecological and economic system in which it operates.
Synthesis (as a design activity)	The generation of possible solutions in the form of ideas and designs (based on van Boeijen et al., 2013).

Appendix 2: Evolution of Biomimicry Life's principles and Design Spiral

This appendix contains enlarged versions of the images from Figures 2.4 and 2.5.

1: Life's Principles as formulated in Benyus, 1997

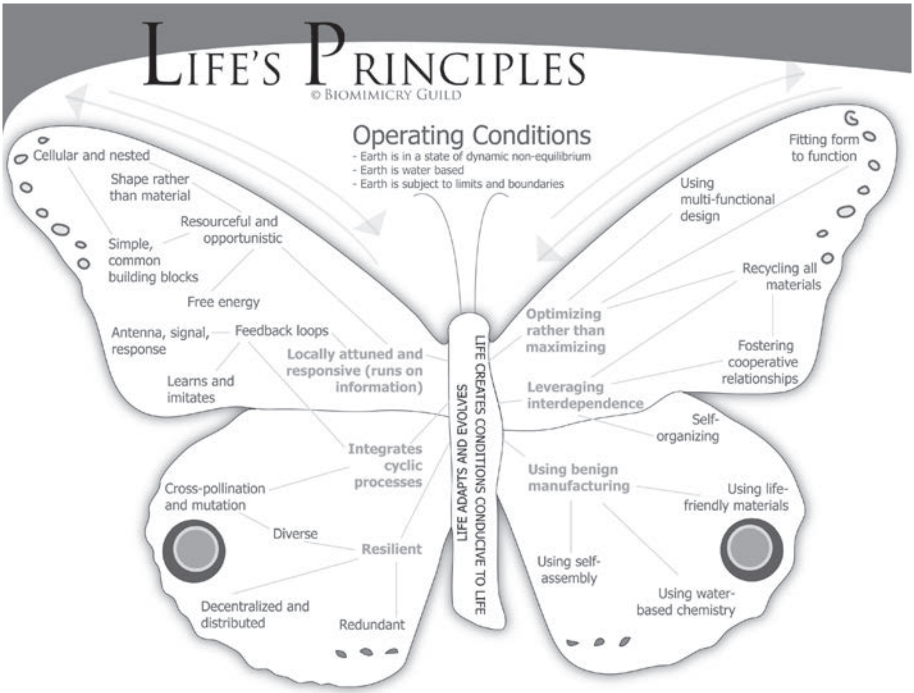
in every chapter of this book: nature's laws, strategies, and principles ... their notebooks, we can ... likenesses

Nature runs on sunlight.
Nature uses only the energy it needs.
Nature fits form to function.
Nature recycles everything.
Nature rewards cooperation.
Nature banks on diversity.
Nature demands local expertise.
Nature curbs excesses from within.
Nature taps the power of limits.

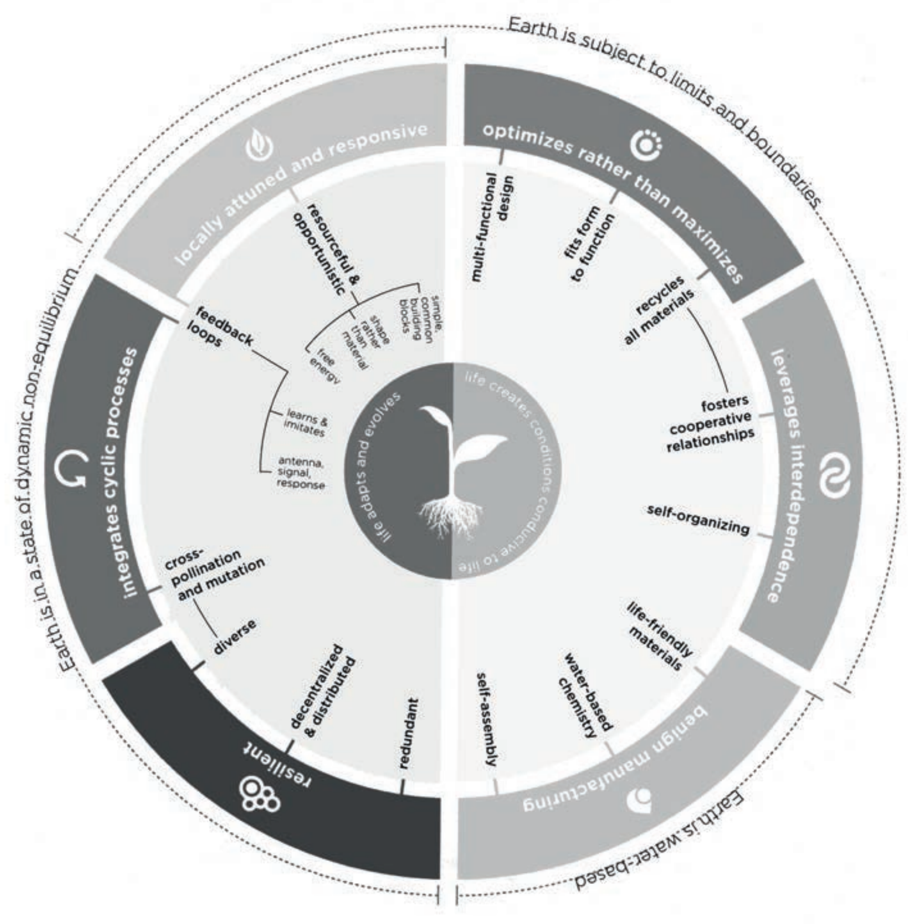
A CAUTIONARY TALE

t lesson, "tapping the power of l...
o us because we h...

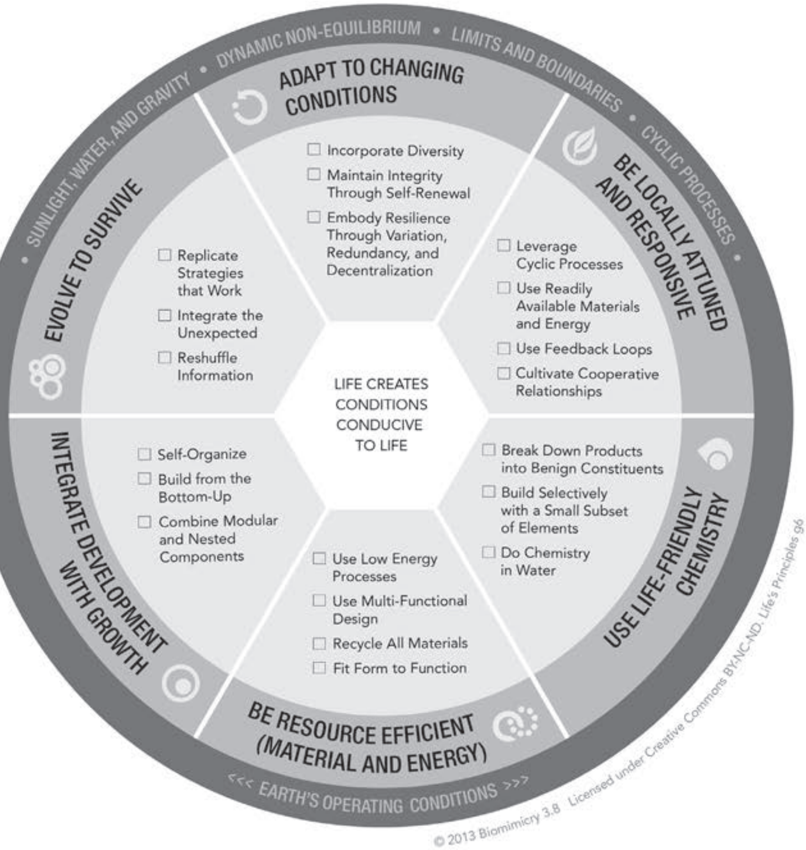
2: Life's Principles as depicted by the Biomimicry Guild, 2007



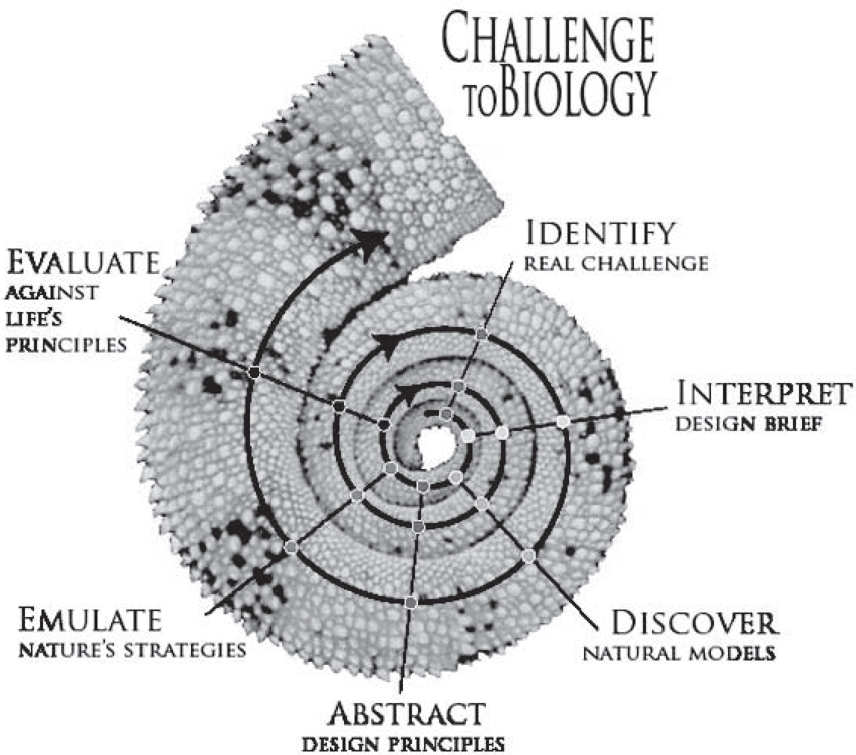
3: Life's Principles as depicted by the Biomimicry Guild, 2010



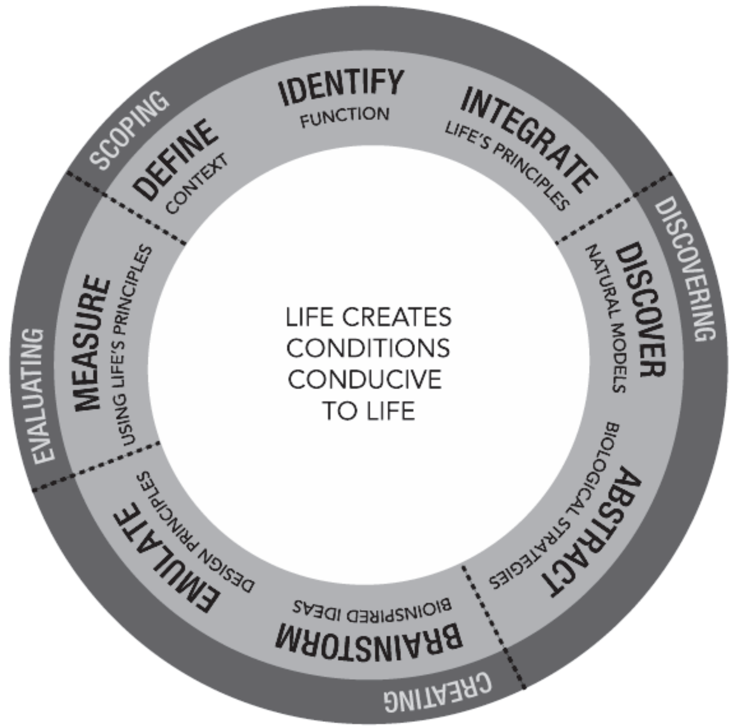
4: Life's Principles as depicted by Biomimicry 3.8 in Baumeister et al. 2013



The Design Spiral as depicted by the Biomimicry Guild, 2007



The Design Spiral as depicted by Biomimicry 3.8 in Baumeister, Tocke et al. 2013



APPENDIX 3: Excerpt from Course guide Sustainable Design Strategies

This appendix contains an excerpt from one of the course guides of the Sustainable Design Strategies courses (see Chapter 4).

introduction

Ask yourself: what is the ultimate green product? Then develop it, using state of the art design strategies such as Cradle to Cradle, Biomimicry or Eco-innovation.

Designers can use different strategies to develop sustainable products, but creating a truly beneficial product is quite a challenge.

In this course you get the chance to explore in deep a particular sustainability strategy and to apply it for a radically-sustainable assignment.

The objective is to learn about these sustainability strategies, experience applying one and together evaluate their effectiveness.

learning goals

After this course you can:

- Describe the sustainable design strategies explained in the course
- Apply (one of) these strategies to the design of a 'radically' sustainable product
- Explain how these strategies interrelate
- Reflect critically on the value of these strategies (opportunities and limitations experienced) for industrial designers/engineers, and understand the difference between core concepts: efficient vs. effective, cradle-to-grave vs. cradle-to-cradle, reductionistic vs. holistic.

education method

This course is teamwork. In three intensive workshops you'll explore the sustainable design strategies in detail. Next, your team will use one of the strategies to design a truly green product. In a final plenary workshop all teams present and discuss their results.

contents

1. SDS Workshop Eco-innovation
2. SDS Workshop Cradle to Cradle
3. SDS Workshop Biomimicry
4. Design-dream-product
5. Presentation of designs

deliverables

The deliverables of this course are assignments, a report, A3-poster and Powerpoint presentation.

contents report

The report should contain clear descriptions, drawings and illustrations of how your group went through the design process:

- Project planning
- Product analysis & data collection
- Sketches & concept development
- Design detailing
- Evaluation.

In each section, underpin your design decisions by showing what alternatives you considered and how you came to your decision. Make sure to draw clear conclusions at the end of each section, and devote some time at the end of the report to a critical reflection of what you learned from this course.

assessment criteria

The assignments are obligatory and are graded either 'passed' or 'failed'. The report and your presentation of the results will be graded with a combined mark, based on the following criteria:

- Understanding, curiosity and creativity: show a thorough understanding of the product assignment (problem description) and the sustainability strategy used. Show how you applied the assigned strategy and show several realistic, creative solutions for the design problem.
- Accurateness: have clear descriptions of choices made and of the process followed, clear calculations (if applicable), unambiguous statements, well-argued interpretations and conclusions (scientific rigour).
- Group process (individual contributions, teamwork, active presence during course, etc).
- Independent: showing initiative and commitment, able to perform self-planned process & collecting relevant data.
- Overall quality and clarity of the reporting (reporting technique).
- The quality of the Powerpoint presentation (structure, clarity and quality of the data presented).
- Make sure the report, presentation and poster meet high-quality standards. They (both) should be understandable for an external, educated audience! Some of the jury members have not heard or read about your work before watching your presentation or reading your report.

APPENDIX 4: Pre-study checklist of design strategy steps and tools

Checklist for analysing whether student groups applied a given design strategy (section 4.2). Methods and tools were provided by the sustainable design experts involved in the courses. Checklist items in *italics* refer to overall steps, with the consecutive (non-italic) items providing the specific design activities. References to methods and tools are, for Biomimicry (Benyus, 2013, Biomimicry 3.8, 2012, reference to the earlier versions used in the course: Biomimicry Guild, 2010b, The Biomimicry Institute, 2008), for Cradle to Cradle (Bor et al., 2011, Cradle to Cradle Products Innovation Institute, 2012, EPEA, 2013), and for Ecodesign (Brezet et al., 1997, OVAM, 2010).

Biomimicry		**Cradle to Cradle**		**Ecodesign**	
According to the report, did the students...					
1	explain the strategy	1	explain the strategy	1	explain the strategy
2	explain the specific method/approach	2	explain the specific method/ approach	2	explain the specific method/ approach
3	*perform the step Evaluate*	3	*perform the task disassemble and analyse the given product*	3	*perform assignment 1 - LCA*
4	use the worksheet 'evaluate' (using the life principles)	4	make a scheme for the current life cycle	4	define the functional unit
5	select life's principles	5	answer these tasks' questions (bio/tech/monstrous, all materials, heavy metals, dangerous substances)	5	define and quantify all current processes
6	*perform the step Distil*	6	try to categorize all materials using the ABC-X categorization	6	calculate eco-indicator points for all phases in the product life cycle
7	name the design function of the assignment	7	develop a vision for the ideal Cradle to Cradle design, to be reached in 2020-2025	7	present the results of the analysis
8	use the Biomimicry Design Spiral questions for distilling the design function	8	study the Desso example (guess, based on the defined roadmap)	8	draw good conclusions based on the analysis regarding the aim for the new design

Biomimicry		Cradle to Cradle		Ecodesign	
9	*perform the step Translate*	9	develop a Cradle to Cradle roadmap for the company based on their vision	9	*perform assignment 2 - Ecodesign strategies*
10	use the Design Spiral questions for translating to biology	10	design several solutions	10	fill in the Ecodesign strategy wheel
11	check the AskNature database (guess)	11	that are based on the roadmap	11	set priorities for the new design, based on the analysis
12	*perform the step Discover*	12	implement the short-term steps	12	design several new solutions
13	discover 3 examples per function or life's principle	13	develop one into a design	13	develop a new product (or system) that has a significantly better score on some of the strategies
14	look for similarities	14	*perform the task eco-effectiveness*	14	develop one into a design
15	describe useful natural solutions	15	answer these tasks' questions (purpose, environment, problems, added value)	15	fill in the strategy wheel for the new design (before & after)
16	*perform the step Emulate*	16	*perform the task Part of a continuous cycle*	16	*perform the assignment Evaluate your new design*
17	brainstorm multiple solutions emulating, not copying the solutions found in nature	17	answer these tasks' questions (consumption or service, bio or tech cycle, how to cycle, how to close/renew the loop)	17	define and quantify all processes
18	design several solutions	18	*perform the task Safe & healthy materials*	18	calculate eco-indicator points, for all phases in the product life cycle
19	develop one into a design	19	answer these tasks' questions (meaning for product, risks or hazards)	19	present the results of the evaluation
20	*perform the step Evaluate*	20	*perform the task Evaluate the new design*	20	draw conclusions based on the analysis
21	use the worksheet 'evaluate' (for the new design)	21	use the Cradle to Cradle certification criteria for evaluation		

APPENDIX 5: Full list of real-life cases considered for the study

List of considered real-life cases: Company - Product(s)

Ahrend - Chair 2020 (and other desks & chairs)

Auping - Bed Essential, Mattress Vivo

AVEDA - Packaging

Bas Sanders - Drilling machine - Bone bike

Desso - Airmaster carpet tiles

E.J. Mul - Bio-inspired scooter graduation project

Ecosmart/VGW - Smartbin

Festo - Nano Force gripper

Flectofin - Sun shielding

Full Circle Design - Plenic' presentation system

Haynest - Packaging

Hema - Maternity products graduation project Anna Noyons

Herman Miller - office chair (Celle/ Mirra) - Flo Monitor Arm

IDEAL&CO - Algaepack

Interface - Entropy, TacTile, Net-Works, Net Effect

Khattak - 'Cradle to Cradle' coffee cup

Kranium design - Bicycle helmet

Laarman - Bone chair

Logoplaste - Vitalis water bottle

List of considered real-life cases: Company - Product(s)

Mercedes - Concept car

OAT - Shoes

Océ - Ecotoner bottle

Orangebox - Office furniture

Pax - Impeller

PCV - Dispenser

Pezy - Water bottle

Philips - Econova, Vacuum cleaner

Puma - InCycle

Quinny - Stroller

Ro&Ad - Couch

Stabilo - Pen

TUD - ‘Cradle to Cradle’ Picnic experience - graduation project Sven van Klaarbergen

Turnkey - Buggy

Van der Lande - Conveyor belt

Van der Veer - Bicycle saddle

Van Houtum - Dispenser

Well - Chair

Not listed here are additional Biomimicry and Cradle to Cradle inspired projects primarily dealing with material development, such as Cradle to Cradle Office paper (VGW/Océ), Toilet paper (Van Houtum), Tiles (Mosa), shampoo’s and fabrics, and companies located outside Europe, such as Steelcase and Herman Miller.

APPENDIX 6: Interview questions real-life cases

Project: Nature-inspired design strategies Ingrid de Pauw

Case study interviews for Cases 1 and 2: Session 1 - the 'product' view

Before starting

> repeat goal (short), explain programme and goal of this session

> explain that I want to uncover as much as I can :) so I will therefore ask challenging questions; not to question their work but to trigger the discussion

> ask designer to have near the product (physical or graphical and/or text-based)

> install camera and voicerecorder, check that they function

> check time

> inform that they can ask clarification any time, please ask if term or whatever is unclear to them.

Questions:

A - Background & examples

1 - can you shortly describe your background and what do you do (profession); [check education & experience]

2 [if not mentioned ask] can you shortly describe how your work is related to a) product development/ innovation b) sustainability

3 - can you give examples of the type of other projects you have been working on and the type of products you have developed?

4 - can you shortly describe the company you work for [check: what it does, what kind of projects, clients, products]?

check time, voice & video

B - The product

Interviewee describes product, based on results on the table or elsewhere, in whatever form they prefer.

Note what they use in presenting

5 - Imagine you have been asked to contribute to a TV item on the successes of Biomimicry/C2C, 'what concise and media friendly answer could you give to the following question:

'What are the unique qualities of [product name] and how have they been achieved?

6 - Can you describe your role in the project?

7 - Ok, let's get to the core: Can you describe to me the solution you have developed?

Check any Biomimicry/C2C-elements mentioned

8 - For each result, ask how they achieved it, why is it as it is, what is special about the decision, why not different (name alternative), what difficulties were overcome?

Again, check any Biomimicry/C2C-elements mentioned

9 - if possible, check analysis boxes (can be done afterwards)

10 - What was not achieved?

11 - (if so) What prevented its achievement?

12 - What are you most proud of?

13 - If that had to do with Biomimicry/C2C, ask for details.

14 - What to your opinion was disappointing?

15 - If that had to do with Biomimicry/C2C, ask: How it was disappointing?

16 - How did you define the project/assignment? and did you formulate requirements? any data are available that I can see?

17 - How have you defined/described the end result, what measurable data are available?

18 - How did you evaluate the results, what measurable data are available?

Case study interviews for Cases 1 and 2: Session 2 - the 'process' view

Before starting

> put down all drawing materials

> install voicerecorder, and have camera ready, check that they function!

> check time

> explain programme and goal

> repeat that I want to uncover as much as I can :) so I will therefore ask challenging questions; not to question their work but to trigger the discussion

> inform that they can ask clarification any time, please ask if term or whatever is unclear to them.

Questions:

A - Introduction to strategy

1 - how did you come in contact with Biomimicry/C2C?

2 - how have you started applying it?

3 - are more people you work with active with Biomimicry/C2C? [check function]

4 - can you give examples of other Biomimicry/C2C-projects you and others in your company have been working on?

5 - how did you learn to use Biomimicry/C2C? [check: just doing, reading book, documentary, Biomimicry/C2C-designer training, Biomimicry/C2C-.......training, other: ....

check time, voice & video

B - The process

6 - This session, I would like to understand as much as possible from how you implemented C2C in your design process. As you have been working on it for a long time, I want to ask you -as a first task- to visualize on this paper your design process; in any way you like. Purpose is to try and reconstruct both your image on the design process.

7 - Check for specific elements: project definition/brief, specifications, analysis, ideation, concept development, detailing/embodiment design, prototyping, evaluation.

8 - If some seem missing, ask whether they did such a thing (but not steer): did you have something of a ...

if process is drawn, follow each step/phase

[added during interview] mark steps/phases where Biomimicry/C2C was applied - picture

9 - Can you describe in short, what you did here?

10 - Did you apply Biomimicry/C2C here?

11a - If not: to next step

11b - If so: let them write down keyword + short sentence what they used and how.

12 - At end (if time left): for each phase where Biomimicry/C2C was NOT used > check why not: no tools available? or not considered?

then for each step more in depth

13 - Write dow step on large paper + Get relevant element cards, put on paper

14 - Ask them to tell how they applied the element (check if is as understood) + to describe the effects of using it: what results did it bring, what important ideas/insights generated, what decisions were taken (or not)

15 - Visualize them on card + ask for follow-up effects etc. up to measurable results.

16 - Was it only Biomimicry/C2C that provided this effect/result?

17 - Ask relevant falsifying questions (> question list)

repeat for each step

18 - Make links between different elements

check time, voice & video

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Case study interviews for Cases 1 and 2: Session 3 - the NIDS elements session

[set-up changed during first interview: added sorting of element cards, questions per element instead of per effect]

Before starting

> put down all materials

> install voicerecorder, and have camera ready, check that they function!

> check time

> explain programme and goal

> repeat that I want to uncover as much as I can :) so I will therefore ask challenging questions; not to question their work but to trigger the discussion

> inform that they can ask clarification any time, please ask if term or whatever is unclear to them.

Questions:

1 - show all element cards to designer(s), and have them sort them in 3 categories: used / know it, but not used / don't know this one

2 - ask them to sort the category 'used' into 3 piles: most important - important - less important

mark cards & write down/record motivations of the designers during sorting

discuss relevant element cards: at least one per category most important/less important/not used/added (if any)

3 - If applied: ask how element was applied (check if is as understood) + to describe the effects of using it: what results did it bring, what important ideas/insights generated, what decisions were taken (or not)

4 - If not applied: ask why not: unknown? not considered? not regarded relevant?

5 - Was it only Biomimicry/C2C that provided this effect/result?

if time available: ask relevant 'falsifying' questions (> question list: energy, transport)

Case study sessions for Cases 3 and 4

Before starting

> put down all drawing materials

> explain programme and goal

> explain that I want to uncover as much as I can :) so I will therefore ask 'challenging' questions; not to question the work but to trigger the discussion

> install voicerecorder, and have camera ready, check that they function!

> check time

> inform that interviewee can ask clarification any time, please ask if term or whatever is unclear to them.

Questions:

background

1 - Can you summarize in about a minute the solution you have developed?

2 - Can you briefly describe your role in the project, and how many people from Interface/Ecosmart were involved in the project?

on Biomimicry/C2C in the project

3 - Imagine you have been asked to contribute to a TV item on the successes of Biomimicry/C2C, 'what concise and media friendly answer could you give to the following question:

'What are the unique qualities of [project name] and how have they been achieved?

4 - Can you describe where Biomimicry/C2C played a role in this particular project?

5 - how did you learn to use Biomimicry/C2C? [check: just doing, reading book, documentary, designer training,.......training, other: ....]

element cards sorting

6 - As a quick tool for understanding which elements of Biomimicry/C2C have been applied in the project, I have made a set of cards showing different aspects of Biomimicry/C2C and specific biomimicry/C2C tools, which I would like you to browse through. Maybe they are not all familiar to you, that is ok, so I would like to ask you to sort them in 3 categories, depending on whether or not you know them and applied them in this project: used - know it, but not used - don't know this one [show all element cards to designer, and have him sort them]

7 - Ok, thank you. So these elements you applied. Could you please sort these [category 'used'] in 3 piles: most important - important - less important

8 - Can you indicate which ones were involved when choosing materials & 'designing' the material cycle?

mark cards & write down/record motivations of the designers during sorting

discuss relevant element cards: at least one per category materials/most important/less important/not used/ added (if any)

9 - If applied: ask how element was applied (check if is as understood) + to describe the effects of using it: what results did it bring, what important ideas/insights generated, what decisions were taken (or not)

10 - If not applied: ask why not: unknown? not considered? not regarded relevant?

11 - Was it only Biomimicry/C2C that provided this effect/result?

if time available: ask relevant 'falsifying' questions (> question list: energy, transport)

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SAMENVATTING

Productontwerpers kunnen verschillende strategieën, methoden, en tools toepassen voor duurzame productontwikkeling. Natuur-geïnspireerde ontwerpstrategieën (naar de Engelse term afgekort tot NIDS) onderscheiden zich van andere duurzaamheidsstrategieën door kennis en inspiratie uit 'de natuur' als leidraad te gebruiken voor duurzaam ontwerpen. Biomimicry en Cradle to Cradle, twee NIDS, worden momenteel al toegepast in de ontwerppraktijk en zijn opgenomen in curricula van het hoger onderwijs. Tot nog toe is echter weinig onderzoek verricht naar de toepassing van NIDS en naar de wijze waarop deze strategieën ontwerpers helpen in duurzame productontwikkeling. Daardoor ontbreekt de empirische onderbouwing van de toepasbaarheid, verdiensten, en beperkingen van deze strategieën. Een eerste stap richting effectieve toepassing van NIDS voor duurzame productontwikkeling is het verkennen en begrijpen van de huidige natuur geïnspireerde ontwerppraktijk. De hoofdonderzoeksvraag in dit proefschrift is daarom:

> **Hoe helpen Natuur-geïnspireerde ontwerpstrategieën (NIDS) ontwerpers in het ontwikkelen van 'duurzame producten'?**

Om deze onderzoeksvraag te beantwoorden is een case-studie aanpak gebruikt waarbij meerdere NIDS-projecten zijn geanalyseerd, met als doel duidelijk te maken hoe de toepassing van de ontwerpstrategieën het ontwerpproces en de uitkomsten daarvan beïnvloedt. Ten eerste is een vergelijkende studie verricht met ontwerpprojecten van studenten, waarin is verkend welke effecten kunnen worden toegeschreven aan de toepassing van NIDS. De resultaten daarvan zijn gebruikt in een vervolgstudie met vier praktijkprojecten. Via analyse van diepte-interviews en projectgegevens heeft deze tweede studie geleid tot een diepgaander inzicht van de effecten van de toepassing van NIDS.

De drie eerste hoofdstukken van dit proefschrift beschrijven het onderzoek dat aan de case-studies is voorafgegaan. In **Hoofdstuk 1** beschrijven we de bredere context van duurzaam ontwerp denken waarbinnen NIDS zich hebben ontwikkeld. We beargumenteren dat NIDS een veranderend perspectief op het doel van duurzaam ontwerpen ondersteunen dat is te omschrijven als de overstap van het 'verminderen van onduurzaamheid' naar het 'bereiken van duurzaamheid'. Zowel Biomimicry als Cradle to Cradle bouwt voort op dit principe van 'duurzaamheid bereiken' en de strategieën hebben belangrijke eigenschappen met elkaar gemeen. In **Hoofdstuk 2** definiëren we Natuur-geïnspireerde ontwerpstrategieën (NIDS) als ontwerpstrategieën die "een belangrijk deel van hun theorie baseren op 'leren van de natuur' en die de natuur beschouwen als het paradigma van duurzaamheid". Vanuit deze definitie analyseren we welke strategieën als NIDS geclassificeerd kunnen worden, en wat deze strategieën te bieden hebben voor productontwikkeling. Deze analyse heeft geleid tot de selectie van Biomimicry en Cradle to Cradle als de ontwerpstrategieën die geschikt zijn voor het beoogde case-studie onderzoek.

Om te kunnen beoordelen hoe NIDS ontwerpers helpen om 'duurzame producten' te ontwikkelen, evalueren we de duurzaamheid van de case studie producten. Zoals we in **Hoofdstuk 3** beschrijven, zijn huidige, op levenscyclusanalyse gebaseerde, beoordelings-methoden echter niet toegerust om enkele belangrijke resultaten die NIDS nastreven te beoordelen. Daarom hebben we ten behoeve van het onderzoek een aangepaste methode ontwikkeld, beschreven in Hoofdstuk 3, die evalueert in hoeverre producten passen in een duurzame omgeving (of deze zelfs versterken), met behulp van beoordelingscriteria voor (ecologische) duurzaamheid.

In **Hoofdstuk 4** beschrijven we bevindingen van de case-studies van de ontwerpprojecten met studenten. We hebben Biomimicry en Cradle to Cradle vergeleken met een meer gevestigde ontwerpstrategie (Ecodesign) en verschillen naar boven gehaald die toegeschreven kunnen worden aan de toepassing van NIDS. De resultaten van deze case-studies laten zien hoe de toepassing van verschillende ontwerpstrategieën samenvalt met verschillen in a) the ontwerpfocus van de studentengroepen, b) het niveau waarop de ontwerpopdracht werd geïnterpreteerd, en c) de daaruit resulterende oplossingsniveaus. NIDS hielpen de ontwerpstudenten om hun oplossingsruimte te verbreden en oplossingen mee te nemen die productfuncties, systeemfuncties, of gebruikers-behoeften op een andere wijze vervullen. De analyse werpt licht op twee kenmerkende eigenschappen van NIDS die hebben bijgedragen aan deze bevindingen. Zowel Biomimicry als Cradle to Cradle biedt ontwerpers uitdagende 'absolute' ontwerpprincipes om het ontwerpproces te sturen, en beide strategieën lokken de integratie van context-specifieke oplossingen uit die voorbij het productontwerp reiken, zoals oplossingen waarbij ook een recycling-infrastructuur met specifieke, lokale bedrijven is ontwikkeld. Daarnaast heeft deze studie laten zien dat studentengroepen niet alle onderdelen toepassen die de ontwerpstrategieën bieden, wat kan leiden tot een gedeeltelijke implementatie van de ontwerpfilosofie waarop de strategieën zijn gebaseerd. Voor de studie naar NIDS is deze bevinding extra relevant omdat, in tegenstelling tot Ecodesign, binnen Biomimicry en Cradle to Cradle geen kwantitatieve tools beschikbaar zijn om de milieueffecten van de ontwerpoplossingen te beoordelen.

Hoofdstuk 5 presenteert de resultaten van de case-studies van de praktijkprojecten. Deze cases bevestigen dat de mate waarin ontwerpstrategieën worden toegepast een belangrijke variabele is: ontwerpers hebben zo hun 'eigen' manier van toepassen van NIDS-ontwerpprincipes, -methoden, en tools, en gebruiken ook niet alle elementen die een strategie biedt. De ontwerpprincipes die wel werden toegepast zette de ontwerpers ertoe aan om ambitieuze doelen te stellen en een 'systeemaanpak' te hanteren. In elk van de vier cases, hebben de ontwerpers/ontwerpteams ook delen van de 'materiaalcyclus' ontwikkeld. Deze resultaten werden bereikt door samenwerking met toeleveranciers, door andere materialen te selecteren of zelfs nieuwe materiaalcombinaties te ontwikkelen, en in sommige gevallen door functionele innovaties toe te passen om materialen te vervangen die potentieel schadelijke ingrediënten bevatten of waarvoor geen materiaalcyclus kon worden gerealiseerd.

In **Hoofdstuk 6**, evalueren we de uitkomsten van de praktijkprojecten aan de hand van de in Hoofdstuk 3 ontwikkelde beoordelingsmethode met -criteria voor (ecologische) duurzaamheid. De beoordeling wijst uit dat NIDS ontwerpers heeft geholpen om op componentniveau aan bepaalde duurzaamheidscriteria te voldoen en, in beperkte mate, een positief milieueffect te realiseren. Daarmee hebben de ontwerpers voor specifieke componenten meer bereikt dan het verminderen van negatieve milieueffecten. Deze resultaten laten zien dat NIDS, in principe, in staat zijn om ontwerpers te helpen op een of meer ecologische criteria duurzaamheid te 'bereiken', vooral de realisatie van materiaalkringlopen. Echter, op productniveau is geen van de projecten erin geslaagd om aan alle criteria te voldoen; de ontwerpers hebben zich gericht op bepaalde principes ten koste van andere. Het risico daarvan is dat er enerzijds doorbraken worden gerealiseerd op specifieke thema's zoals materiaalhergebruik, terwijl anderzijds mogelijk extra milieueffecten optreden binnen het systeem waarin de producten worden geproduceerd, gebruikt, en herverwerkt.

Hoofdstuk 7 presenteert de hoofdconclusies van het onderzoek. Deze conclusies verschaffen inzicht in de toepassing van NIDS voor duurzame productontwikkeling. Samengevat zijn de volgende conclusies getrokken:

- Natuur-geïnspireerde ontwerpstrategieën bieden een ontwerpfilosofie ten aanzien van duurzame productontwikkeling die het 'bereiken van duurzaamheid' nastreeft als ontwerpperspectief. Dit perspectief daagt ontwerpers uit om producten te ontwikkelen die, net als in de natuur, passen binnen het 'ecosysteem' waar ze deel van uitmaken en dit systeem zelfs versterken.
- Om deze ontwerpfilosofie te integreren in productontwikkeling, bieden Biomimicry en Cradle to Cradle ontwerpprincipes en methodes die ecosysteemkennis toepasbaar maken binnen het ontwerpproces. Ons onderzoek geeft aan hoe de principes ontwerpers hebben geholpen hun ambitieniveau vast te stellen en het ontwerpproces te sturen.
- De studies uit dit onderzoek laten zien dat NIDS de ontwerpers heeft geholpen om oplossingen te ontwikkelen die meer omvatten dan het ontwerp van het product (het artefact), en dat daarbij hindernissen om ecologische duurzaamheid te kunnen bereiken zijn overwonnen, vooral voor wat betreft het realiseren van materiaalkringlopen.
- NIDS bieden echter geen tools om ontwerpers te wijzen op mogelijke nadelige effecten van hun ontwerp die gedurende de productlevenscyclus kunnen optreden. Het onderzoek heeft uitgewezen dat gedeeltelijke toepassing van NIDS door ontwerpers kan leiden tot dergelijke effecten.

Dit promotieonderzoek verschaft inzicht in de manier waarop NIDS het ontwerpproces en de uitkomsten daarvan kunnen beïnvloeden. De daaruit afgeleide proposities bieden startpunten voor vervolgonderzoek. Daarnaast hebben de bevindingen geleid tot aanbevelingen voor het ontwikkelen van NIDS-tools die huidige problemen in de toepassing van deze strategieën kunnen wegnemen. Het proefschrift sluit af met aanbevelingen van de onderzoeker aan ontwerpers die NIDS in de praktijk brengen, en aan onderwijzers die de komende generatie ontwerpers aanmoedigen om te leren van, en geïnspireerd te raken door de natuur.

PUBLICATIONS

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- DE PAUW, I. C., KANDACHAR, P. & KARANA, E. 2015. Assessing sustainability in nature-inspired design. International Journal of Sustainable Engineering, 8, 5-13.
- TEMPELMAN, E., DE PAUW, I., VAN DER GRINTEN, B., MUL, E.-J. & GREVERS, K. forthcoming. Biomimicry and Cradle to Cradle in product design: an analysis of current design practice. Journal of Design Research.

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It all started with a simple email; 'was I interested in a PhD position that had become vacant', Conny wrote, 'maybe something for you?' Being a partner in a design studio, busy meeting project deadlines and bringing in new innovation projects, starting a PhD was not something I had considered doing at that moment. But, of course I was quite curious to find out why the position might be something for me, so I opened the attached project description. And, there it was, in writing: the ultimate design research project, exploring new design strategies that had emerged for sustainable product design, including Biomimicry and Cradle to Cradle.

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ABOUT THE AUTHOR

Ingrid de Pauw was born on the 26th of February 1970 in Amsterdam. She studied Industrial Design Engineering at the Delft University of Technology specializing in environmental product development, and graduated (cum laude) in 1994. She has been working as a product designer for 15 years, on diverse product development and strategic projects in the field of sustainable design. In 2004, she co-founded design bureau IDEAL&CO in which she is currently partner. Projects she worked on include an award-winning wooden guardrail barrier for highways.

In 2010, she returned to Delft as PhD candidate to study the application of Nature-Inspired Design Strategies in product development. During her doctoral research she initiated a 3-year spin-off project on Nature-Inspired Design with the Delft University of Technology and ten industry partners, which was funded by RVO.nl. Furthermore, she has been giving lectures at Bachelor and Masters level on sustainable design strategies and presented her research at a number of international conferences. She currently works at IDEAL&CO on national and European projects supporting companies in the transition towards sustainable and circular business, and continues to teach sustainable design strategies.

This book is about Nature-Inspired Design Strategies; strategies that use 'nature' as a source of knowledge and inspiration for sustainable product development. Biomimicry and Cradle to Cradle, two Nature-Inspired Design Strategies, have already been implemented in product design practice and in curricula of higher education. But how are these strategies applied, and how do they help designers in developing 'sustainable products'?

Based on case-study research of multiple design projects, this study shows how the design philosophy, principles, methods, and tools of Biomimicry and Cradle to Cradle have inspired and guided product designers in their work. The findings demonstrate the value, as well as the current limitations, of Nature-Inspired Design Strategies. The insights and recommendations provided in this book are valuable for researchers, designers, and educators with an interest in Nature-Inspired Design, and help to clearly position Nature-Inspired Design in sustainable design practice.