NATURE INSPIRED DESIGN: STRATEGIES TOWARDS SUSTAINABILITY

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Abstract

Current design practices focus on eco-efficiency as the main approach in the field of sustainable product development. This approach mainly aims at improving existing products and services. Environmental product performance can be greatly improved using eco-efficiency but in many cases the improvements are incremental. Furthermore, the *overall* environmental impact the product causes is often not reducing, but rising instead. Strategies based on 'learning from nature' - Biomimicry, Natural Capitalism and Cradle to Cradle- offer opportunities to design in a radically different, goal-driven manner. These strategies, which are introduced in this paper as 'nature-inspired design strategies', provide pathways and principles aimed at developing designs that are in natural balance with their environment. Common principles include the use of materials in closed loops and using solar driven energy systems. Implementing these strategies is expected to have large impacts on the business processes, on the design of products, and on the type & amount of materials used. However, clear and tested methods for designers to apply these strategies in sustainable product development are lacking.

This position paper explores and analyses nature-inspired design strategies from the perspective of sustainable product development. The main aim is to define the research work, to explore how these strategies can be applied in the design business for developing radically-sustainable products. Conclusions are drawn to facilitate the construction of the research design.

Keywords

sustainable product development, nature-inspired design strategies, biomimicry, cradle to cradle, natural capitalism.

1 Introduction

Sustainable product development is concerned with balancing economic, environmental and social aspects in the creation of products and services. In the current design practice, companies mainly focus on eco-efficiency as the strategy for sustainable product development. Eco-efficiency basically means "*creating more goods and services with ever less use of resources, waste and pollution*" (Lehni, 2000, p.1). This strategy has shown great improvements of environmental product performance but in many cases the improvement is incremental and overall environmental impact has not been reduced, but has risen instead. Causes for the rise include increasing sales volumes as a result of for instance growing population, number of households as well as increased affluence and rebound effects[1] associated with increased product-efficiency. For example, Figure 1 shows that the energy efficiency of dishwashers has gradually improved but overall energy consumption has increased drastically.

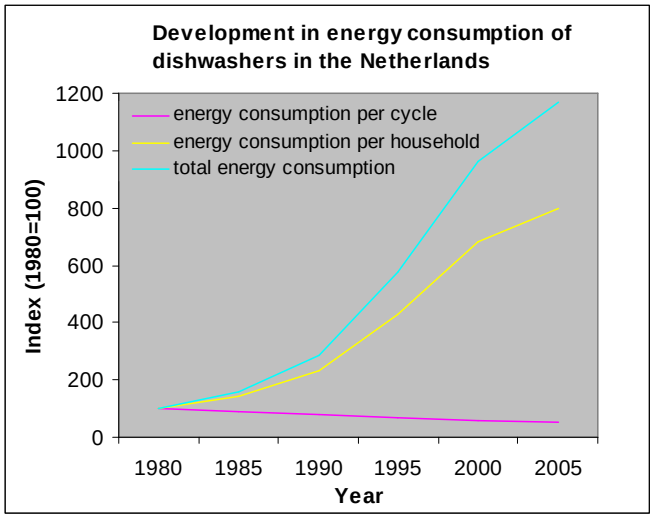

Figure 1: Development in energy consumption, based on (Elburg, 2008).

Several authors advocate 'factor-thinking', which pursues drastic efficiency improvements, to overcome rebound effects (see Crul et al., 2007, p.24 for a discussion). In contrast, others argue that the fundamental problem of eco-efficiency is that it focuses on reducing unsustainability instead of achieving sustainability (Ehrenfeld, 2008, Braungart et al., 2007,

[1] The 'rebound' or 'takeback' effect describes the phenomenon that some of the savings from energy efficiency are taken (counterbalanced) in the form of higher consumption (Herring, 1999).

Gladwin et al., 1995). As Ehrenfeld (2008, p.54) says: *"without a vision, removing what is not sustainable will not work"*. Both Ehrenfeld (2009) and Braungart (2007) go even further to state that such 'band-aid' strategies may do more harm than good.

As to which strategy to follow in order to achieve sustainability, views differ. Ehrenfeld (2008) believes a sustainable world is possible, but requires humans to change their behavior and develop sustainability as a mindset. Others such as Braungart and McDonough (McDonough and Braungart, 2002) Benyus (Benyus, 2002), Hawken, Lovins and Lovins (Hawken et al., 1999) and Robèrt (Robèrt, 2002) have developed strategies that aim to design products that are in balance with the natural world.

This paper describes the positioning of a research project at Delft Technical University aiming to explore 'nature-inspired design strategies' in the field of sustainable product development. In the following section, we analyze sustainable design strategies and select those that are both nature-inspired and have been applied for sustainable product development. Then in the third section the selected strategies are described in more detail, reflecting on the available design methods and tools, and providing examples of products. The paper then goes on to analyze what knowledge is missing in order to determine the usefulness of these strategies for sustainable product development. The fifth section offers a preliminary description of the proposed research design. The paper ends with a discussion of the results and conclusions on the outcome of the analysis.

2. Nature-inspired design strategies

2.1 A new approach

The research project started with analyzing specific sustainable design strategies -Biomimicry, Cradle to Cradle, The Natural Step and Natural Capitalism- that seem to offer opportunities to design in a different, non-incremental manner. These strategies have been developed and applied in practice within a commercial business setting. They have a notable impact on the way industry and designers think and act. They have generated inspiring results and in the Netherlands Cradle-to-Cradle has enthused so many companies, designers, NGO's and (local) governments that some refer to this period as 'the third green wave' (Bakker et al., 2009).

In our first analysis we found a common characteristic among these strategies as they are based in one way or another on 'learning from nature'. This involves taking the natural world

as a lead as to how products can be designed effectively, using design principles from nature to develop sustainable solutions. Therefore we introduce the term 'Nature-inspired design strategies' as a generic term or 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.*

2.2 First selection of strategies

To determine which strategies to incorporate in the research project, an analysis was made of a comprehensive list of sustainability approaches which has been compiled in 2009 by AIGA [2] . The 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). Our main aim was to select the ones which can be labeled 'nature-inspired product design strategies'.

The following criteria have been applied as filters for the selection:

1: The strategy refers explicitly to nature.
2: The strategy uses 'nature' in the design process, that is, it explicitly refers to 'nature' as a source of inspiration, of design principles, tools and/or methods for product development.
3: The strategy has been applied for sustainable product development, which excludes strategies only used in other design fields such as architecture, graphic or fashion design.

Figure 2 lists the sustainable design approaches[3] and illustrates the selection process:

Results filter 1. Out of the 30 approaches described by AIGA, six approaches -The Hannover Principles, IDSA Eco Design Principles and Practices, The Natural Step™, Biomimicry, Natural Capitalism and Cradle to Cradle©- make reference to 'nature' or the natural world. For instance The Hannover principles have several references, such as:

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

[3] The selected strategies will be explained in the following section. More information on the other strategies can be found in Brink et al.(2009).

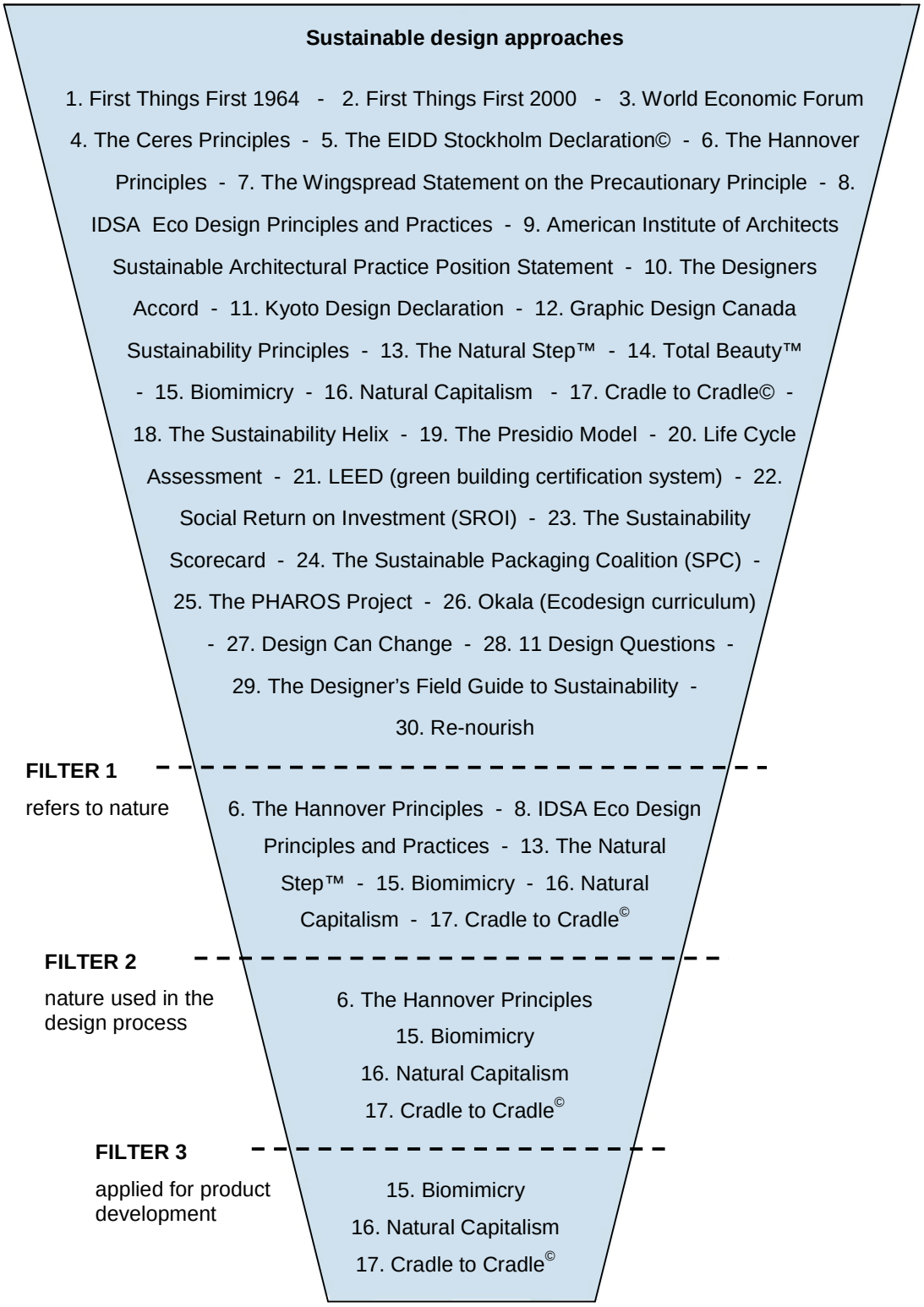

Figure 2: analysis of sustainability approaches, based on Brink (et al., 2009).

"*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*".

Results filter 2. Looking at how 'nature' is used in the six approaches, two different ways can be distinguished:
(a) those coupling nature directly to the design process, and
(b) those that relate more indirectly to the design process.
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. The description of Biomimicry refers very directly to nature: "*In her 1997 book 'Biomimicry: Innovation inspired by Nature', Janine Benyus invites people to reframe their thinking about innovation and argues that people should look at nature as a model, mentor, and measure".* In Natural Capitalism, the direct link can be seen in one of the 'shifts' which the original thinkers suggest must be made in business practices. This is summed up as "*Ecological redesign (turning to nature as a model)*". And finally, the Cradle to Cradle strategy *further develops the concept of eco-effectiveness, which "seeks to design systems that emulate the healthy abundance of nature"* (Brink et al., 2009).
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 crucial services. Society's systematic destruction of the biosphere threatens nature's health and its capacity to sustain human society".* In The Natural Step (TNS) the name of the strategy refers explicitly to nature, and 'nature' is used to determine what is called the 'system conditions' and 'principles of sustainability'. TNS focuses on what should not be done to nature in order to achieve a sustainable society: "*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) biosphere threatens nature's health and its capacity to sustain human society"* (Brink et al., 2009).

Results filter 3. The last criterion for the selection addresses the applicability of the approaches for sustainable product development. The approaches which have already been applied in this field have been selected. Both the Hannover Principles and Cradle to Cradle

have been developed by McDonough and Braungart. Of the two, Cradle to Cradle (C2C) has specifically been 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 is not to be included in the current research as a separate strategy.

To sum up, the following nature-inspired design strategies have been selected for the current research project: Biomimicry, Natural Capitalism and Cradle to Cradle.

3 Biomimicry, Natural Capitalism and C2C as Nature Inspired Design Strategies

The aim of this section is to give an overview of the selected strategies and the ways in which they have already been applied for sustainable product development. These strategies are certainly not limited to this specific field of design but in the context of the research project they are explored here with a focus on product development.

3.1 Biomimicry

3.1.1 What is Biomimicry?

Biomimicry literally means the imitation of life. The combination of the Greek roots 'bios', life, and 'mimikos', imitation, gives rise to the term.

According to the Biomimicry Institute: "*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 more our world functions like the natural world, the more likely we are to endure*" (Biomimicry-Institute, 2010).

From bio-robotics to material science, the mimicry of life is providing novel insights into engineering problems (Reap et al., 2005). Benyus, who is responsible for developing the name biomimicry, 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…*" (Benyus, 2002, p.0).

The field of Biomimicry encompasses a broad range of strategies and approaches, and several research groups and institutes are specialized in this area, each with a different approach and using different terms such as biomimetics, bionics and bio-inspired design (Vincent, 2009, Bhushan, 2009). Biomimicry is studied and applied in a broad range of fields including material research, product design & innovation, inventions, systems design,

architecture, communication and mechanics. One of the best known product examples of biomimicry is Velcro, invented by de Mestral.

As the 'design languages' in biology and engineering differ greatly, several researchers are working on methods and databases to facilitate the transfer of knowledge from biology to design and engineering (Sarkar et al., 2008, Stroble et al., 2009). For instance AskNature is an online, open-source database of the Biomimicry Institute which lists organisms and their biological principles by function (The-Biomimicry-Institute, 2008).

Apart from such databases with specific solutions from nature, research is being carried out on identifying more general design principles from the field of biology and ecology (Bowyer et al., 2003, Winters, 2009, Reap et al., 2005). The University of Bath developed BioTRIZ and the Biomimicry Institute has developed 'Life's principles' (figure 3).

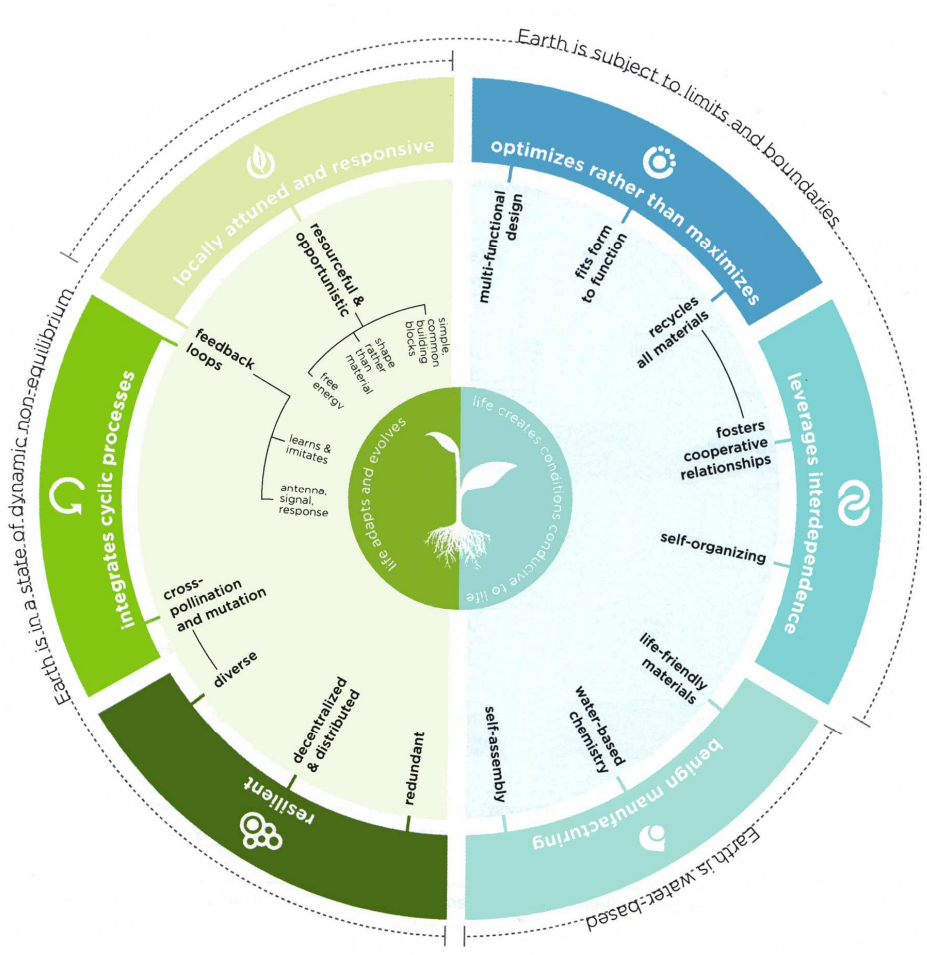

Figure 3: Biomimicry Life's principles circle. © 2010 Biomimicry Guild

3.1.2 Biomimicry in the design process

Biomimicry can be applied in several steps of a design process. The Biomimicry Institute gives the following options for integrating biology into design (BiomimicryGuild, 2010):

- In scoping: (re)defining the design problem.
- In idea-generation: retrieving inspiration and engineering solutions from nature.
- In engineering and evaluation: guidelines and (sustainability) criteria for product engineering.

Their 'Design Spiral', shown in figure 4, gives a method for applying Biomimicry in the design process.

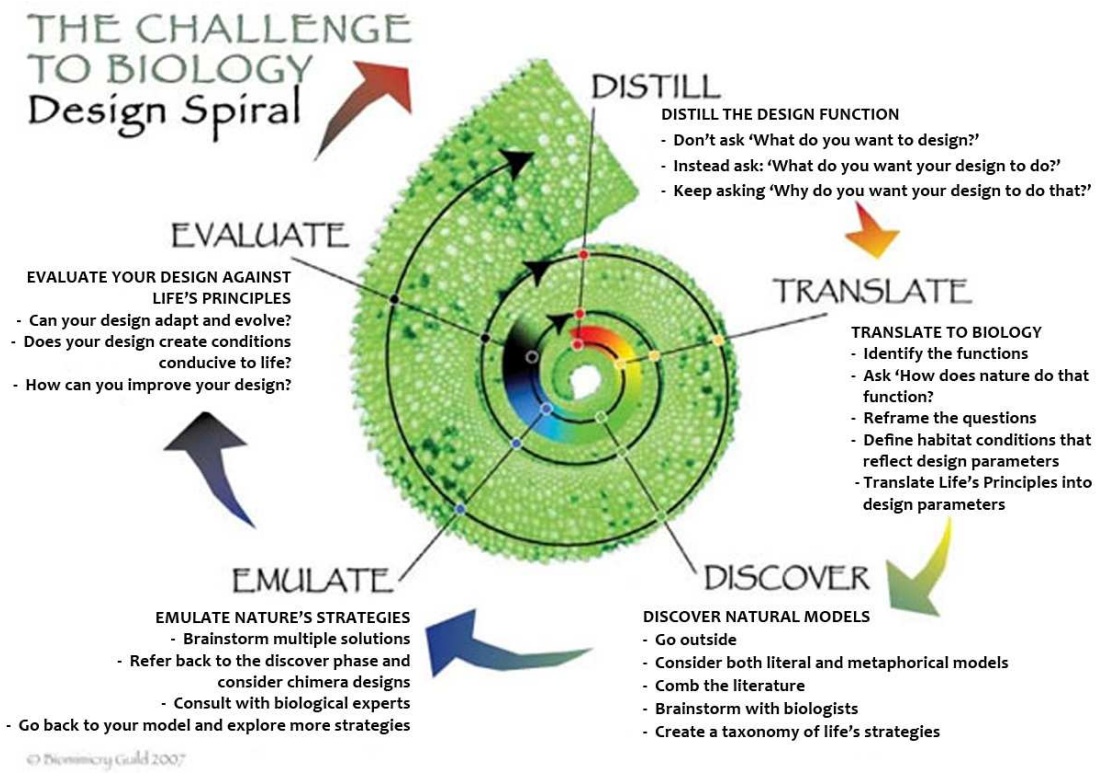

Figure 4: Biomimicry design spiral. © 2007 Biomimicry Guild.

The Biomimicry Guild (the commercial biomimicry consultancy) organizes workshops for designers and in 2010 gave their first European workshop. Several universities have started experimenting with workshops (Santulli and Langella, 2001) and students have graduated on Bio-inspired design projects (Mul, 2009).

An example of a company that applies biomimicry in their product development process is Interface Flor. They have developed several products using this strategy. A relatively simple example is their non-directional carpet tile 'Spring Leaf'™ inspired by the 'organized chaos' of the forest floor, which resulted in *faster installation and significantly less cutting waste*[4]. Another biomimicry-product is their TacTiles®, a carpet tile installation system inspired by many examples of adhesion without glue in nature, which has eliminated the need for glue (Interface, 2008).

3.2 Natural Capitalism

3.2.1 What is Natural Capitalism?

In 1999, Lovins, Lovins and Hawken introduced 'a road map for Natural Capitalism' to *solve many environmental problems at a profit*, a strategy for protecting the biosphere and at the same time improving profits and competitiveness. The strategy is named Natural Capitalism *because that is what capitalism might become if its largest category of capital - the "natural capital" of ecosystem services - were properly valued* (Hawken et al., 1999).

The basic driver for Natural Capitalism is that *"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, four major shifts in business practices are proposed:

- Radically increase the productivity of natural resources.
- Shift to biologically inspired production models and materials
- Move to a "Service-and-Flow" business model
- Reinvest in natural capital.

(Hawken et al., 1999, Rocky-Mountain-Institute, 2010b).

The strategy seems to include Biomimicry and Cradle to Cradle in their approach. 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' (NaturalCapitalismSolutions, 2010).

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[4] For more information on these products, see for instance:
http://www.interfaceglobal.com/Sustainability/Sustainability-in-Action/Biomimicry.aspx

3.2.2 Product development and Natural Capitalism

Several organizations base their work on the principles of Natural Capitalism, including the Rocky Mountain Institute (RMI), which was cofounded by A. Lovins and H. Lovins.
RMI focuses on three areas: the built environment, energy and mobility. The latter is most linked to product development. RMI's main focus seems to be on their first principle: "We create breakthrough efficiency solutions…" (RockyMountainInstitute, 2010). An example of their work in this field is the Hypercar®, a design concept combining ultra-light materials, low coefficient of drag models, and electric drive architecture into one design[5].

RMI wanted to demonstrate their whole-systems approach would foster greater efficiency gains than pursuing any of the design objectives individually (Rocky-Mountain-Institute, 2010a). According to Lovins (2001) it can be a car with comparable performance as a large American-style suburban 'assault vehicle' (six adults plus cargo), weighs only 700 kilos, with a fuel consumption of 2 liter per 100 kilometer and emits *nothing but hot drinking water* (Lovins, 2001).

Specific information on *how* to apply Natural Capitalism for product development seems to be limited. The literature studied more often refers to production issues, such as closed-loop manufacturing.

3.3 Cradle to Cradle

3.3.1 What is Cradle to Cradle?

Cradle-to-Cradle is a phrase invented by Stahel in the 1970s and popularized by McDonough and Braungart in 2002 in their book of the same name. It is an alternative for the well known phrase 'Cradle-to-Grave', which refers to taking into account all effects of a product during its entire lifecycle from production to disposal.
The Cradle to Cradle strategy (C2C) *takes the natural world as a model for making things*, and aims to 'remake' products so that after their useful lives, they will provide useful 'food' for new products (McDonough and Braungart, 2002). Braungart and McDonough *challenge the belief that human industry must damage the world*. According to them, this Cradle to Grave manufacturing model results in great amounts of waste and pollution. Instead, their

[5] More information on the Hypercar: http://move.rmi.org/markets-in-motion/case-studies/automotive/hypercar.html.

central strategy is to be 'eco-effective' instead of eco-efficient. 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 was*te (Braungart et al., 2007). The strategy has a clear material focus, resulting from their long term vision that (high quality) materials will become scarce, whereas more than sufficient solar energy income is available (Scheelhaase, 2010).

Cradle to Cradle identifies *three key tenets in the intelligence of natural systems that can inform human design*:

- Waste equals food; using closed-loop material systems.
- Use current solar income; C2C systems could directly collect solar energy or tap into passive solar processes
- Celebrate diversity; tailoring designs, drawing information from local natural systems and ultimately "fit" within these systems.

(McDonough et al., 2003).

3.3.2 Cradle to Cradle Product development

In Cradle to Cradle: Remaking the way we make things (McDonough and Braungart, 2002) a stepwise approach is described for the development of Cradle-to-Cradle products. Also a certification procedure has been developed for assessing products, which uses criteria addressing material, energy, water and social issues (McDonough Braungart Design Chemistry, 2010). In the case-studies conducted by Braungard and McDonough, a partly different approach seems to be followed, starting with the formulation of design principles that define the foreseen -ultimate- end-result.

In the field of product development, many examples of Cradle to Cradle products are available. Application areas include office furniture, personal hygiene products, shoes, sanitary products and home appliances. A well known example is the Mirra office chair of Herman Miller[6]. According to the authors, the use of the C2C process created a number of design changes, including selecting completely new materials (75% green chemistry composition), increased use of recyclable parts (83% in weight), increasing recycled content (42% pre- and postconsumer waste), eliminating all PVC and design for rapid disassembly (93% readily disassembled) (Rossi et al., 2006).

[6] See http://www.hermanmiller.com/Products/Mirra-Chairs for more information on this product.

Bakker et al. (2009) evaluated the applicability of the C2C concept in *day-to-day product development* based on literature and student design projects for several multinationals.

3.4 Summary of strategies

Nature-inspired design strategies have some common characteristics when viewed from the perspective of sustainable product development:

- They are goal-driven, aiming for a sustainable end-result inspired by natural systems.
- Each strategy incorporates principles aimed at the realization of closed-loop material systems and the use of solar or 'freely' available energy systems.
- The design process is oriented to improving product systems.
- The strategies focus on environmental sustainability, address economical feasibility and refer less to social sustainability.

Table 1 summarizes the different strategies on key characteristics.

Characteristics	Biomimicry	Natural Capitalism	Cradle to Cradle
Basic thought	- Nature has solved many problems similar to the ones designers face. - The more the human world functions like the natural world, the more likely humans are to endure.	- Natural capital should be valued. - Use profits from drastic improvement in efficiency to invest in natural capital.	- Industry does not have to harm nature per definition, look at nature. - Aim for *good* design, not 'less bad'.
Main focus	Innovation 'inspired by nature'.	Drastic eco-efficiency.	Closing the material cycle with 'upcycling' and use of non-toxic materials.
Sustainability focus	Environmental focus.	Environmental and economical focus. Book addresses social aspects.	Environmental and economical focus. Social aspects included in certification criteria.
Applications in sustainable product development	Carpet, train, fluid-mixer, cars, electronics. Broad in innovation (solution-driven) .	Car.	Office furniture, personal hygiene products, shoes, sanitary products, home appliances.
Differences	Extensive list of principles, with most direct link to natural examples.	Aims for drastic efficiency as a first step, refers to other strategies for shift to biologically inspired products.	Rejects aim for sustainability and efficiency (for reasons of insufficiency and ineffectiveness). Link to nature abstracted and simplified in set of design principles.

Table 1: comparison of nature-inspired design strategies.

4 An analysis of nature-inspired design strategies for sustainable product development

Applying nature-inspired design strategies in (sustainable) product development is expected to have a large impact on the business processes, on the design of products, the type and amount of materials used and on the way materials are applied. However, these strategies have to be applied in a way that fits resource (especially time)-constrained, problem-driven commercial design challenges. The aim of this section is to analyze what knowledge is needed to determine the usability and even the usefulness of nature-inspired design strategies for sustainable product development.

To be able to determine the effectiveness of a strategy, the following information is required

- What is the strategy (theory/hypothesis, principles)?
- Is the strategy applicable in the field of study (here sustainable product development)?
- Is it clear how to apply the strategy (has it been operationalized into a methods and tools)?
- Are there case studies using this strategy (describing the process, the tools used, and the results)?
- Have the case studies been analyzed?
- Has the strategy been compared to a base-strategy (to determine added value).

Information on these topics should preferably be objective, consistent, systematic and general.

From the data collected so far, it is clear only part of the required information is available. Table 2 reviews the three strategies on the above criteria. This overview is not complete but serves as a starting point for the research.

From the analysis it can be concluded that the strategies are well-described and are already being applied in practice with the goal to develop sustainable products and systems. For Biomimicry and Cradle to Cradle, methods and tools are described, though not elaborately as with for instance Design for Sustainability (Crul and Diehl, 2007). Several case-studies have been described and analyzed. However, observing the results from the preliminary research, it seems that no clearly described and tested method is available on how to apply the strategies and their design principles in problem-driven, commercial product development projects to support the development of sustainable products.

It should be noted that most of the publications on the research topic are of recent origin, so the research field is still in its nascent stage.

Information	Biomimicry	Natural Capitalism	Cradle to Cradle
Has the Strategy been described?	Yes, book and many scientific publications.	Yes, book and scientific publications.	Yes, book and scientific publications.
Are methods, tools etc. offered for sustainable product development?	Yes, the Biomimicry Institute's Design spiral, including tools for scoping & creating, guidelines and evaluating.	No generic methods, tools etc. for product development found so far, process for development of the Hypercar has been described.	Yes, the Cradle to Cradle five steps to eco-effectiveness. Also approaches described in case studies, including the formulation of a vision of the ideal end-target in the form of design principles.
Has the strategy been widely applied in sustainable product development?	On a limited scale in diverse applications. More applications can be found in inventions and in reductive design (usually solution and non-sustainable driven).	On a small scale in product development. More applications can be found in architecture.	On a larger scale in diverse, mostly simple product applications.
Is information on case-studies available?	Yes, in books, scientific publications and the popular press, graduation thesis. Mostly qualitative, using examples from nature and practice.	Limited. Possibly information from other application fields are suitable (quantitative case-studies in architecture available).	Yes, scientific publications and the popular press, graduation theses. Mostly qualitative, but also quantitative case-studies.
Has the strategy been evaluated, tested or compared for use in sustainable product development?	Limited. Evaluations and discussions in Biomimicry groups, graduation reports, qualitative analysis for industrial design.	Not found so far.	Limited. Qualitative information in scientific publications, the popular press and discussion groups.

Table 2: overview of knowledge gap regarding nature-inspired design strategies for sustainable product development.
Green, yellow and red colors of cells refer to respectively 'good', 'limited' and 'non' availability of information.

5 Research design

This section describes the objective of the research project and how this objective has been translated into research questions.

5.1 Research objective and focus

The aim of the project is to explore whether nature-inspired design strategies can be applied by designers, active in the business of sustainable product development, for developing radically sustainable products. The term 'radical' is used here to emphasize that the project is targeted at a non-incremental, goal-driven or *'eco-effective'* approach to sustainable design, and not at the incremental *eco-efficiency* approach which in the current design practice is often also labeled sustainable product development. Determining the right term for this target and operationalizing the objective will be part of the project.
As this field of research is relatively new and available knowledge regarding the objective is limited, the nature of the research will be exploratory, intended to generate insights into the applicability of nature-inspired design strategies.

The research will start with a focus on exploring the use of the strategies for developing 'simple' products, or for fulfilling 'simple' functions. The 'simple' refers to having one clear function, limited amounts of components, materials and production techniques. For instance, -randomly chosen- examples are coffee cups, hand soap dispensers, shoe-laces, street benches, staplers etc. The motivation for choosing this focus is that simple products offer good opportunities to fathom the core of the research objective:

- Current case-studies indicate the implications of applying the strategies already become apparent during the development of simple products.
- The sustainable impact of simple products can be substantial, especially as many of this type of products are mass-produced and generate considerable amounts of waste.
- Simple products allow easier access to information required for the analysis (the amount of information required is less).
- All strategies seem applicable for this type of products.

5.2 Research questions

Following the research objective, the main research question of the project is:

How can nature-inspired design strategies support designers, active in the field of sustainable product development, in the development of radically sustainable products?

To answer this main question, several sub-questions can be formulated:

1: What is radically-sustainable product development?
2: What features of nature-inspired design strategies seem useful for sustainable product development?
3. Are (the selected features of) nature-inspired design strategies useful for developing radically sustainable products?
4. In what way can nature-inspired strategies be incorporated in the product development process?

6 Discussion

Nature-inspired design strategies seem to offer good potential for sustainable product development. The 'founders' of these strategies each developed a new vision on sustainable design, which is using nature as the lead for sustainability. The paradigm shift involved -moving from 'reducing unsustainability' to 'working towards sustainability'- is one which seems to appeal to designers active in (sustainable) product development.

The big question of course is whether these strategies offer a solution for the problems encountered with current approach of eco-efficient design. So far, there is no evidence that applying nature-inspired design strategies can actually result in the development of products that are in balance with the natural world. Generally speaking, working towards a goal -a vision of a sustainable future- does not ensure that that goal will be reached. However, following a goal-driven strategy does seem a step forward compared to current strategies that work on improving the performance of existing products.

Being inspired by nature requires understanding how nature 'works'. Although many researchers have explored specific and general design principles in nature, our understanding of what makes nature sustainable could very well be too limited to be of practical value in sustainable design. On the other hand, the knowledge that *has* been published so far does provide insights that seem to back-up existing sustainability principles and adds principles that are novel to sustainable product development.

Nature-inspired design strategies touch only very briefly upon social sustainability. The design principles of the strategies focus on the environmental and economical aspects of sustainability. No 'inspiration from nature' seems to be available for addressing the social impact of products. When exploring the effectiveness of the strategies, the research should therefore either limit its focus to the environmental and economical pillars of sustainability, or,

it should include the impact of applying the strategies on relevant aspects of social sustainability. Research into how nature can inform design for social sustainability could be of interest for future research.

Nature-inspired strategies seem predominantly material and technology oriented. The role of consumer behavior 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). However, several design principles in Biomimicry do relate to the way people use products and interact with the product-system. This topic might be explored further.

No publications have been found describing a method for developing products based on Natural Capitalism. The strategy has been applied, but it is unclear how results were achieved. If no additional information can be retrieved, this poses a serious problem to explore this strategy. For Biomimicry and Cradle-to-Cradle, methods and tools have been described. However, existing case-studies are expected to reveal what *actual* methods and tools have been applied in practice. A careful translation of the strategies into working methods and tools is required in this research project.

7 Conclusions

Newly emerging sustainable design strategies can help companies and designers to pursue the development of products that contribute to a sustainable world. This paper has 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.

The analysis has resulted in the selection of Biomimicry, Natural Capitalism and Cradle to Cradle as nature-inspired design strategies that can be applied for sustainable product development. Although promising and inspiring, the strategies seem not yet to offer a clear and tested approach on how to apply the strategies and their design principles in product development projects to support the development of sustainable products.

The current research project aims to explore whether these strategies can be applied by designers, active in the business of sustainable product development, for developing radically sustainable products.

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