Assessing Sustainability in Nature-Inspired Design

Author version 17/11/14

I.C. de Pauw, P. Kandachar, E. Karana

Faculty of Industrial Design Engineering, Delft University of Technology, Delft, The Netherlands

Ingrid C. de Pauw, PhD candidate, Landbergstraat 15, 2628CE Delft, the Netherlands, +31-15-2788667, fax +31-15-2781839, i.c.depauw@tudelft.nl (corresponding author)

Prabhu Kandachar, Professor, Landbergstraat 15, 2628CE Delft, the Netherlands, +31-15-2785769, fax +31-15-2781839, p.v.kandachar@tudelft.nl

Elvin Karana, Assistant Professor, Landbergstraat 15, 2628CE Delft, the Netherlands, +31-15-2785726, fax +31-15-2781839, e.karana@tudelft.nl

Assessing Sustainability in Nature-Inspired Design

In the field of sustainable product development, a new perspective for approaching sustainability has been advocated, challenging designers and engineers to aim beyond 'reducing unsustainability'. Several design strategies - including Biomimicry and Cradle to Cradle- have been suggested for developing truly sustainable, or 'beneficial', products. But do these strategies help in developing such products, and how to assess their 'sustainability'? Based on a review of the objectives in nature-inspired design, we argue that assessing environmental sustainability is not straightforward. Whereas both Biomimicry and Cradle to Cradle build on the perspective of 'achieving sustainability', current life-cycle assessment based tools are geared towards reducing current impacts. As a consequence, existing tools are insufficiently equipped for the purpose of the assessment: they do not cover some of the main results that nature-inspired design is set out to accomplish. To be able to include these results, we propose two new constituents to current life-cycle based product assessment: assessing against conditions of sustainability, and assessing 'achievement', the extent to which these conditions of sustainability have been achieved. Furthermore, the product context needs to be included for assessing beneficial impacts. This article discusses how these constituents can contribute to an assessment tool that enables designers and engineers to assess the development of environmentally sustainable solutions.

Keywords: Environmental product design, Design decision support tools, LCA methodology, Biomimicry, Cradle to Cradle

1. Introduction

The potential role of designers and engineers in addressing sustainability, and the contributions they could make in creating a sustainable world have long been recognized (Papanek 1971; Margolin 1998; Rahimifard and Clegg 2008; Manzini 2009). Part of the design community has started to integrate sustainability considerations into their work, with a focus on the environmental aspects of sustainability, aiming to reduce the impacts that products exert on the environment (Dewberry and de Barros 2009).

With the emergence of alternative design strategies such as Cradle to Cradle, a different perspective towards sustainability has been introduced, reaching beyond the aim of reducing existing impacts. These strategies may support designers and engineers in playing a more significant part in shaping the world towards a sustainable state. However, assessing to what extent the resulting products contribute to this state is no straightforward task.

The scope of this article is to investigate and address the challenges in assessing environmental sustainability for two specific Nature-Inspired Design Strategies: Biomimicry and Cradle to Cradle. We describe the new perspective towards sustainability that is embedded in Nature-Inspired Design, analyse how this perspective calls for a change in the way designers and engineers assess their products, and propose two new constituents for assessing environmental sustainability within a life-cycle based framework.

2. A changing perspective within sustainable product design

Within the field of sustainable product design, eco-efficiency is widely applied as a strategy for addressing environmental aspects. Its focus on “creating more goods and services with ever less use of resources, waste, and pollution” (Lehni 2000) resonates in the Ecodesign approaches that have been developed to facilitate product designers. For assessing progress, Life Cycle Assessment (LCA) based tools are available that allow quantitative assessment of the environmental impacts that occur throughout the life cycle of a product, thereby providing designers with the ability of making informed choices within Ecodesign.

However, different thinkers in the field have argued that eco-efficiency design has a fundamental flaw, as it is founded on the perspective of ‘reducing unsustainability’. Manzini observed that ‘re-designing what exists’ results in systems that are ‘less polluting’ than present systems, and will not help designers in discovering truly sustainable solutions (Manzini 1994). More recently, Ehrenfeld emphasized that “...reducing unsustainability, although critical, does not and will not create sustainability” (Ehrenfeld 2008, 7). To support designers in thinking beyond efficiency, they propose a shift in the aim of design from ‘reducing unsustainability’ towards ‘achieving sustainability’.

Views differ on which strategy designers and engineers should pursue for ‘achieving sustainability’. ‘Transformational’ strategies are proposed for bringing about social change, or for transforming behaviour and mind-sets of designers (Manzini 2009; Ehrenfeld 2001; 2008). Conversely, ‘nature-inspired’ strategies that take nature as a model for developing products and systems are suggested (Benyus 1997; McDonough and Braungart 2002). Despite the apparent differences in the suggested pathways for design practice, they promote the same change in perspective within sustainable product development.

How the aim for 'achieving sustainability' may shape the design engineering profession and the outputs of its work is largely unknown, as many of the strategies have yet to be implemented in design practice. This article addresses two of the nature-inspired design strategies, Biomimicry and Cradle to Cradle, that have already been applied in product development. Biomimicry -as described by Benyus (1997)- focuses on 'innovation inspired by nature', by taking direct inspiration from organisms, biological processes and ecosystems to develop new product shapes, manufacturing processes and product-systems. Cradle to Cradle1 is founded on three design principles that are based on learning from natural systems: 'waste equals food', 'use current solar income', and 'celebrate diversity'(McDonough and Braungart 2002; 2013).

Both strategies offer a perspective towards 'achieving sustainability' in the sense that they challenge designers and engineers to create products with a beneficial impact. The Biomimicry Institute describes this objective as "creating conditions conducive to life" (Benyus 2013), which refers to a characteristic of organisms to function in such way that they tend to promote or assist ('conduce') their habitat. In turn, Cradle to Cradle introduced the concept of 'eco-effectiveness' which 'strives to generate an entirely beneficial impact upon ecological systems' (Braungart, McDonough, and Bollinger 2007, 1343).

3. The need for a different way of assessing 'sustainability'

In our research on nature-inspired design, we encountered a challenge in assessing the 'sustainability' of project results. The current way in which the environmental impacts of products are assessed, do not seem to align with the objectives of Cradle to Cradle as well as Biomimicry. We argue here that this discrepancy between the strategies on the one hand and the assessment method on the other hand, stems from the difference in the underlying perspective on sustainability.

Within Ecodesign, dedicated LCA-based tools such as Eco-indicator analyses are applied for assessing products. They 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 Cradle to Cradle and Biomimicry strive for (Bor et al. 2011; Reap 2009; De Pauw, Karana, and Kandachar 2013), which seems to be linked to reported differences between eco-efficiency/Ecodesign and Cradle to Cradle (Bakker et al. 2009; Bjørn and Hauschild 2013).

Based on literature analysis, we describe 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'. The findings provide insight into a modified framework for environmental product assessment, based on the perspective of 'achieving sustainability'.

---

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

3.1 Comparing products may shape the design process

A first link between current LCA-based assessment tools and eco-efficiency thinking relates to the objective of product assessment within a 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 design engineer 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. For instance, adding the function of air cleaning to a façade panel allows the inclusion of alternative air-cleaning solutions in the benchmark-analysis.

3.2 Improving current systems versus contributing to sustainable systems

Secondly, LCA-tools assess the performance of products *within current production systems*, whereas Biomimicry and Cradle to Cradle aim to develop products that contribute to an overall sustainable solution (where production systems will have changed). Both Reap (2009) and Bjørn 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 and engineers can expand their analysis by modelling future scenarios (see for example Vogtländer 2010) which can increase their insight into the effects of specific interventions.

When aiming for a sustainable solution however, instead of assessing performance within an 'unsustainable' or near-future world, the matching assessment method would preferably show designers and engineers to what extent their product contributes to the achievement of a future with sustainable systems. Figure 1 illustrates two different routes a designer or engineer could take when developing successive versions a product over time, within the -dynamic- solution space available for changing the design.

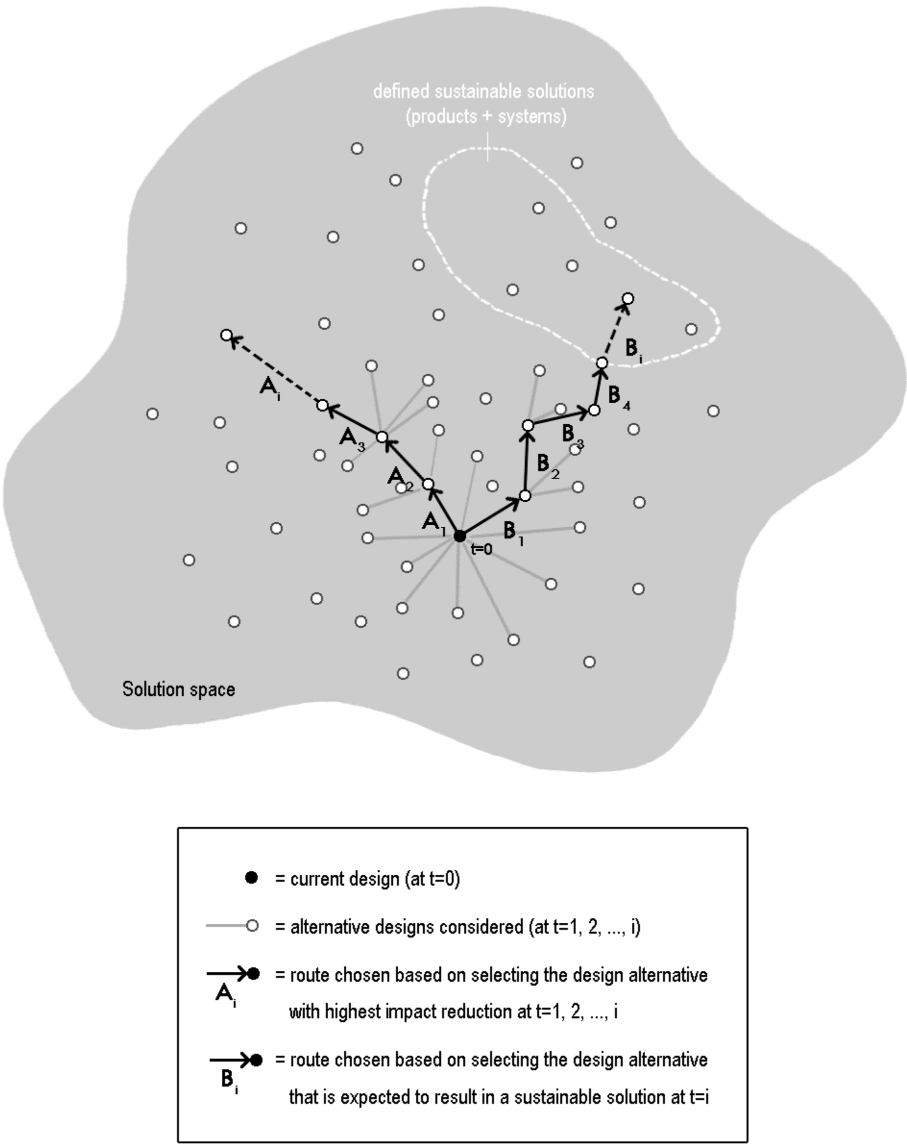

Figure 1. Representation of two different routes (A and B) in the development of successive design alternatives, illustrating potential differences in the outcomes, based on different ways of assessing sustainability, adapted from Reap (2009).

'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 and engineers 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.

3.3 Understanding assessment scores

The risk of routes A and B not aligning corresponds to a third aspect of LCA, concerning the understanding of assessment scores. LCA-based assessment tools show the quantitative impacts of certain design interventions, and thereby aid the selection between design alternatives. However, the outcomes 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 assessment scores 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 scores 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 1 as the area within the dashed white line) hinders designers and engineers in 'achieving sustainability'.

3.4 Burdens versus benefits

The last link we discuss here addresses the fundamentally different way in which nature-inspired design and current LCA 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 2013). We traced one Australian initiative for the inclusion of positive impacts within LCA-methodology (http://www.evah.com.au/eco-plan.html, accessed April 3, 2013), but their work remains to be addressed in scientific literature.

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. For one type of impact, the potential of a product is assessed (the 'material reutilization score', which allows for quantifying the recycling potential of the materials used). However, the certification levels of the standard do not represent the 'sustainability' or 'beneficiality' of a design.

4. Constituents for Assessing the 'Sustainability' of Products

The linkage between assessment methods and design strategies, in terms of the underlying perspective, has triggered us to reconsider the fundamental components, the constituents, required to assess 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 an eco-efficiency approach, we start with describing the constituents of these tools.

4.1 Current constituents for assessing sustainability

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, 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 as the third constituent (figure 2, left).

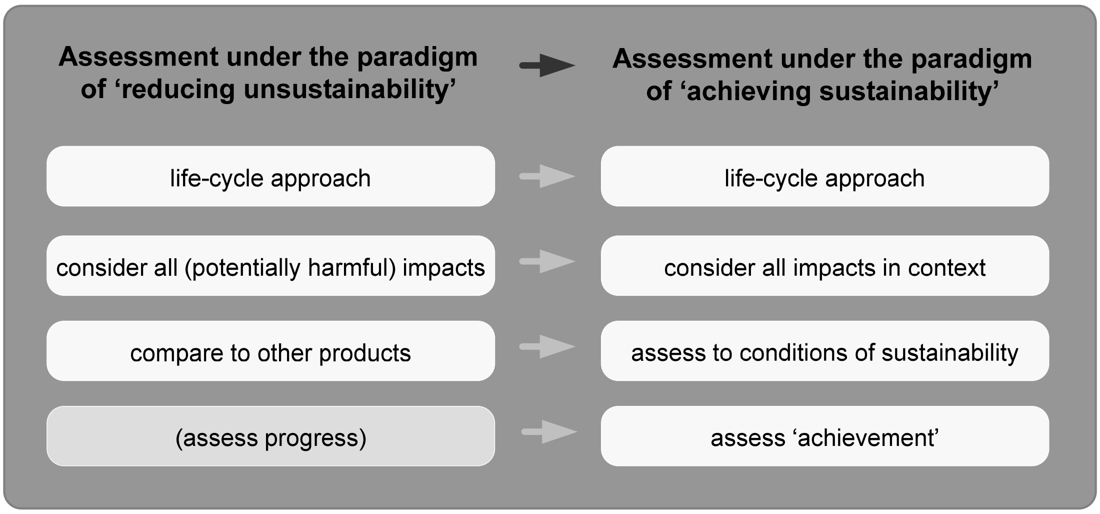

Figure 2. Constituents for assessing the sustainability of products under two design perspectives.

4.2 Constituents 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. First, we addressed the meaning of the term 'beneficial impact', as pursued by especially Cradle to Cradle. One can 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 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[2]. 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 LCA 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 against *conditions of sustainability* and assessing '*achievement'*, the extent to which a product meets those conditions of sustainability (figure 2, right).

4.2.1 Assessing against Conditions of Sustainability

When designers and engineers 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). The binary

---

2 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.

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).

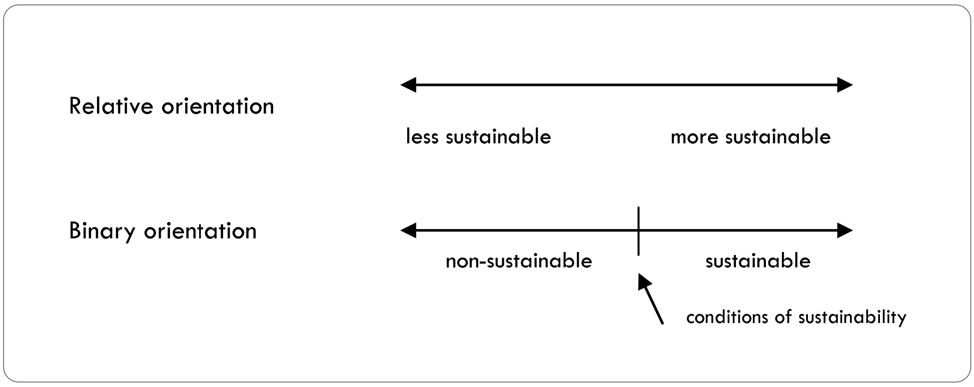

Figure 3. Changing goal orientation in sustainability assessment, adapted from McElroy, Jorna, and Engelen (2008, 7).

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 and engineering.

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[3], 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 engineering practice that does not (explicitly) adopt *any* conditions will not enable designers and engineers 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.

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

4.2.2 Assessing 'achievement': the extent to which sustainability is achieved

The second constituent we propose to add also addresses the shift from a relative to a binary orientation but focuses on *the extent to whichsustainability 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 *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 and engineers 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, we consider two design alternatives for traffic signs with a traditional internal lighting system: signs using retro-reflective foil[4], and signs using LED (figure 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 1.

Figure 4. Three versions of traffic signs, internally lit (left), with retro-reflective coating (middle), and with LED (right). Photo's: Agmi Traffic.

4 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.

Table 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).

	Constituents for assessing the design alternatives	
Design alternatives:	'Assessing progress'	'Assessing achievement'
A. Retro-reflective traffic sign	100% reduction of impacts related to energy consumption as compared with internally lit sign	Energy condition has been met; design functions without use of fossil-based energy
B. LED traffic sign	90% reduction of impacts related to energy consumption as compared with internally lit sign	Energy condition will be met on the condition that the required electricity is provided by renewable energy sources

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. 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.

5. Discussion

The new perspective towards 'achieving sustainability' that is embedded in Nature-Inspired Design, calls for a change in the way designers and engineers assess their products. Here we discuss whether and how the constituents for assessing environmental sustainability that are proposed in this article, could help address the difficulties in assessing nature-inspired design.

The life-cycle approach and inclusion of all impacts, as introduced with LCA, are considered equally vital constituents under the perspective of 'achieving sustainability'. However, current impact analysis does not allow the assessment of 'beneficial impacts'. By including the *context* of the product in the assessment, designers and engineers 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 and engineers insight 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 and engineers 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 such an approach need duly investigation, a binary assessment against conditions of sustainability could grant designers and engineers more time, both for adopting such conditions in their design process, and for focusing on the actual development of products and systems.

The constituents we tentatively propose here stem from our research on nature-inspired design strategies, in an analysis limited to the assessment of environmental sustainability. Nevertheless, these constituents may be more generally applicable. For one, they are not inextricably linked to the strategies that started our inquiry, and could equally apply to addressing social impacts. On the other hand, research on alternative design strategies for 'achieving sustainability' may bring different constituents, or require a modification in their formulation. The findings presented here require critical reflection and consecutive further development into an assessment tool.

6. Conclusions

Following our inquiry into the assessment of nature-inspired design, we have proposed two new constituents for assessing environmental sustainability (figure 2). In addition to the conventional *life-cycle approach* and *inclusion of all relevant impacts*, these are: *assessing products to conditions of sustainability*, and introducing a *binary assessment on 'achievement'*, the extent to which a product achieves those conditions of sustainability. We have argued that these constituents can contribute to solving the obstacles, described in this article, that designers and engineers face when they want to assess the results of nature-inspired design.

In future studies, we will verify the use of the constituents within nature-inspired design, on both a strategy level and a project level. The first level entails the analysis of whether and how Biomimicry and Cradle to Cradle aid the designer in developing solutions that contribute to 'achieving sustainability'. On a project level, we plan to analyse the applicability of the constituents for assessing products that have been developed using nature-inspired design. The results of this research can inform the development of LCA-based product assessment tools that, instead of measuring improvements over today's solutions, assesses a products' contribution to achieving a sustainable future.

Acknowledgements

We would like to thank the designers and researchers in the field of sustainable product design and engineering who helped us in shaping our inquiry, as well as the reviewers whose comments and suggestions have improved and clarified this manuscript.

References

Bakker, C. A., R. Wever, Ch. Teoh, and S. De Clercq. 2009. "Designing Cradle-to-Cradle Products: A Reality Check." International Journal of Sustainable Engineering no. 3 (1): 2 - 8. doi: 10.1080/19397030903395166. http://www.informaworld.com/10.1080/19397030903395166.

Benyus, J. 1997. Biomimicry: Innovation Inspired by Nature. New York: William Morrow & Co.

Benyus, Janine M. 2013. "A Biomimicry Primer." In Resource Handbook. Missoula: Biomimicry 3.8.

Bjørn, Anders, and Michael Z. Hauschild. 2013. "Absolute Versus Relative Environmental Sustainability." Journal of Industrial Ecology no. 17 (2): 321-332. doi: 10.1111/j.1530-9290.2012.00520.x. http://dx.doi.org/10.1111/j.1530-9290.2012.00520.x.

Bor, Anne-Marie, Katja Hansen, Mark Goedkoop, Alain Rivière, Carmen Alvarado, and Walter van den Wittenboer. 2011. Usability of Life Cycle Assessment for Cradle to Cradle Purposes. Utrecht: NL Agency.

Braungart, Michael, William McDonough, and Andrew Bollinger. 2007. "Cradle-to-Cradle Design: Creating Healthy Emissions - a Strategy for Eco-Effective Product and System Design." Journal of Cleaner Production no. 15 (13-14): 1337-1348. http://www.sciencedirect.com/science/article/B6VFX-4M9H3JT-8/2/19cec3273735d06aec0829cc84c19b0b.

Datschefski, Edwin. 1999. "Cyclic, Solar, Safe-Biodesign's Solution Requirements for Sustainability." The Journal of Sustainable Product Design: 42.

De Pauw, Ingrid, Elvin Karana, and Prabhu Kandachar. 2013. Cradle to Cradle in Product Development: A Case Study of Closed-Loop Design. In Re-engineering Manufacturing for Sustainability. Heidelberg: Springer.

Dewberry, E. L., and M. Monteiro de Barros. 2009. "Exploring the Need for More Radical Sustainable Innovation: What Does It Look Like and Why?" International Journal of Sustainable Engineering no. 2 (1): 28 - 39. doi: 10.1080/19397030802643518. http://www.informaworld.com/10.1080/19397030802643518.

Ehrenfeld, J. 2008. Sustainability by Design: A Subversive Strategy for Transforming Our Consumer Culture. New Haven: Yale University Press.

Ehrenfeld, J. 2001. Designing 'Sustainable' Product/Service Systems. Paper read at Environmentally Conscious Design and Inverse Manufacturing, 2001. Proceedings EcoDesign 2001: Second International Symposium on, 2001.

ISO. 2006. Iso14040. Environmental Management — Life Cycle Assessment — Principles and Framework. Switserland.

Klöpffer, Walter. 2003. "Life-Cycle Based Methods for Sustainable Product Development." International Journal of Life Cycle Assessment no. 8 (3): 157-159. doi: 10.1007/bf02978462. http://dx.doi.org/10.1007/BF02978462.

Lehni, M. 2000. Eco-Efficiency: Creating More Value with Less Impact. Conches-Geneva: WBCSD.

Manzini, Ezio. 1994. "Design, Environment and Social Quality: From "Existenzminimum" to "Quality Maximum"." Design Issues no. 10 (1): 37-43. doi: 10.2307/1511653. http://www.jstor.org/stable/1511653.

Manzini, Ezio. 2009. "New Design Knowledge." Design Studies no. 30 (1): 4-12. http://www.sciencedirect.com/science/article/B6V2K-4V053FX-1/2/8b1600b96e2951d85f868dbd4f5aab5d.

Margolin, Victor. 1998. "Design for a Sustainable World." Design Issues no. 14 (2): 83-92.

McDonough, W, and M Braungart. 2002. Cradle to Cradle: Remaking the Way We Make Things. New York: North Point Press.

McDonough, William, and Michael Braungart. 2013. The Upcycle: Beyond Sustainability--Designing for Abundance. New York: North Point Press.

McElroy, Mark W., Rene J. Jorna, and Jo van Engelen. 2008. "Sustainability Quotients and the Social Footprint." Corporate Social Responsibility and Environmental Management no. 15 (4): 223-234. http://dx.doi.org/10.1002/csr.164.

Mulder, Karel, Didac Ferrer, and Harro van Lente. 2011. What Is Sustainable Technology?: Perceptions, Paradoxes and Possibilities. Sheffield, England: Greenleaf Publishing.

Papanek, V. 1971. Design for the Real World: Human Ecology and Social Change. New York: Pantheon Books.

Rahimifard, Shahin, and Allen J Clegg. 2008. "The Role of the Engineering Community in Sustainable Development." International Journal of Sustainable Engineering no. 1 (1): 1-2.

Reap, John J. 2009. Holistic Biomimicry: A Biologically Inspired Approach to Environmentally Benign Engineering, Georgia Institute of Technology, Atlanta.

Robèrt, K. H., B. Schmidt-Bleek, J. Aloisi de Larderel, G. Basile, J. L. Jansen, R. Kuehr, P. Price Thomas, M. Suzuki, P. Hawken, and M. Wackernagel. 2002. "Strategic Sustainable Development -- Selection, Design and Synergies of Applied Tools." Journal of Cleaner Production no. 10 (3): 197-214. http://www.sciencedirect.com/science/article/B6VFX-44KVV9J-1/2/43d73f21a10006d2265f9f8e9ee502ce.

Rockström, Johan, Will Steffen, Kevin Noone, Åsa Persson, F Stuart Chapin, Eric F Lambin, Timothy M Lenton, Marten Scheffer, Carl Folke, Hans Joachim Schellnhuber, and more. 2009. "A Safe Operating Space for Humanity." Nature no. 461: 472-475.

Vogtländer, Joost Geert. 2010. A Practical Guide to Lca for Students, Designers and Business Managers, Sustainable Design Series. Delft: VSSD.