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NATURE-INSPIRED DESIGN STRATEGIES IN SUSTAINABLE PRODUCT DEVELOPMENT: A CASE-STUDY OF STUDENT PROJECTS

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1. Introduction

In the field of sustainable product design[1], several strategies can be applied to develop new products. Ecodesign is probably the most generally known and widely utilized, using a comprehensive, validated method [Brezet and Van Hemel 1997]. More recently, other design strategies have been developed and applied in practice, including Biomimicry [Benyus 2002], Cradle to Cradle[2] [McDonough and Braungart 2002], and Natural Capitalism [Hawken et al. 1999]. We have introduced the term 'Nature-Inspired Design Strategies' (NIDS) to define this new type of strategies that base a significant proportion of their theory on 'learning from nature' and regard nature as the paradigm of sustainability [De Pauw et al. 2010].

Research into the application of NIDS in product design is limited. Rossi et al. [2006] studied a Cradle to Cradle (C2C) industry case, the development of the Mirra chair by office furniture manufacturer Herman-Miller, describing the accomplishments of a dedicated Design for Environment (DfE) team that assisted the product team. Bakker et al. [2009] discuss advantages and disadvantages of applying C2C in product design, based on literature and student projects. Volstad and Boks [2008] do the same for Biomimicry, grounded on a literature review. In general, Biomimicry research related to product design is aimed at simplifying the transfer of knowledge between biology and design engineering and at identifying generic design principles from biology and ecology for instance [Vincent et al. 2006].

As knowledge on how or why NIDS help designers to develop sustainable products is lacking, we want to explore the effects of applying these strategies. Studying projects in which designers use NIDS while developing a sustainable product, may provide insight into these effects and reveal how they benefit the designer and the end result.

In this paper, we describe a first, comparative case study exploring how and why NIDS help design students to develop a specific product, based on data from a bachelor's and master's course given at the Delft University of Technology, Faculty of Industrial Design Engineering (IDE). Based on the project results of the student groups, we aim to: (1) determine to what extent the work of groups that apply NIDS differs from that of Ecodesign-groups; (2) explore the nature of these differences; and (3) generate tentative conclusions about the reasons NIDS may lead to markedly different designs.

In Section 2 we describe the case study method used. In the third section, the results are presented, reflecting on the differences between the student groups, and providing examples of how these

1 In this paper, sustainable product development is defined as design aimed at the development of products that are beneficial to people, planet and profit.

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

differences could be linked to the strategies they applied. The paper ends by discussing the nature of the differences and describing the insights obtained from the case study.

2. Method

In this study, six groups of 4-5 students worked on a sustainable product assignment, using three different strategies: two nature-inspired design strategies, (A) Cradle to Cradle and (B) Biomimicry, and a more traditional strategy, (C) Ecodesign. Figure 1 gives a schematic overview of the case study. The students were divided into three bachelor's groups (1-3) and three master's groups (4-6). All groups were given the same product assignment, but were randomly assigned a different design strategy to follow (A, B, C). The outcome was six group designs (A1-C6), two for each strategy.

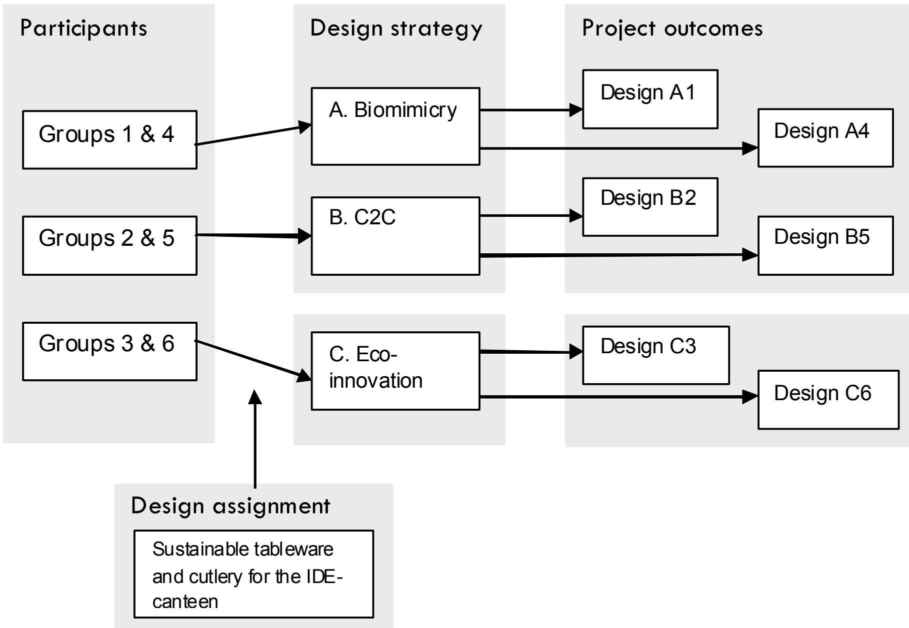


Figure 1. Schematic set-up of the case study

At the start of the course, all students filled in a questionnaire on their educational background and prior knowledge of sustainable design strategies. Most students had an IDE or other product design background. To have balanced groups and enable multi-disciplinary teamwork, we evenly divided students with non-IDE backgrounds: each bachelor group included a student from Mechanical Engineering, and one from either Architecture or Aerospace Engineering. In the master's groups we mixed students from the three different master's programmes at IDE. The majority of students indicated having some idea what the three strategies are about, only three students knew very little about any of them, whereas five students had previously applied one or two of the strategies.

To ensure that every student had basic knowledge and experience concerning the strategies, they received three half-day workshops prior to the design assignment, led by sustainable design experts trained in the respective strategies. Each workshop covered one strategy, introducing the basics and allowing students to practice the method and tools. After these workshops, each student group was asked to evaluate and compare the strategies and to critically describe why 'their' strategy could help them to develop a truly sustainable product.

The design assignment was introduced using a fictional catering company (Biocatering) specialized in biological and locally produced food and drinks. The company asked the students to come up with a 100% sustainable solution for the tableware and cutlery in the faculty canteen, using the strategy they were assigned. After four weeks, the student groups prepared a report and presented their designs to their peers and jury members (other teachers and client).

Data was retrieved from the student reports, the presentations, the grading remarks from the coaches, and questionnaires. The next section describes the main findings of the analysis.

3. Results

Six student groups each developed a concept for sustainable cutlery and tableware to be implemented at the IDE canteen. We analyzed how well they applied the strategies, what design choices they made, what sustainability aspects they took into account, and how they reflected on the strategies.

3.1 Application of strategy

To validate whether the outcomes of the assignments can be linked to the strategies, we first analyzed whether the students actually used the strategies during their design process. We reviewed the contents of the student reports using a checklist, which contains the different steps and tools they were asked to apply. For each strategy, 20 to 21 steps and tools were identified, as listed in table 1.

Table 1. Checklist for analyzing whether groups applied a given strategy

	Biomimicry		**Cradle to Cradle**		**Ecodesign**
	General:		**General:**		**General:**
1	explain strategy	1	explain strategy	1	explain strategy
2	explain method/approach	2	explain method/approach	2	explain method/approach
3	**Evaluate current product(s)**	3	**Disassemble and analyse the given product**	3	**Assignment 1 - LCA**
4	use worksheet 'evaluate'	4	make a scheme for the current life cycle: raw materials, production, use phase, end of life	4	define functional unit
5	select life principles	5	answer these tasks' questions (bio/tech/monstr?; know all materials? any heavy metals, dangerous substances?)	5	define and quantify all processes
6	**Distill**	6	try to categorize all materials using the ABC-X categorization.	6	calculate eco-indicator points for all phases in the product life cycle / use the form
7	name design function	7	develop a vision for the ideal Cradle to Cradle design, to be reached in say 2020-2025 (choose what you think is realistic).	7	present the results
8	use spiral questions	8	check use of the Desso example (guess, based on roadmap defined)	8	draw good conclusions based on your analysis regarding the aim for your new design
9	**Translate**	9	based on your vision, develop a Cradle to Cradle roadmap for the company.	9	**Assignment 2 - Ecodesign strategies**
10	use spiral questions	10	design several solutions	10	fill in the ecodesign strategy wheel
11	checked Ask Nature (guess)	11	based on roadmap	11	set priorities for the new design, based on your analysis
12	**Discover:**	12	implement short term	12	design several new solutions
13	discover 3 examples per life principle	13	develop one into a design to be presented to the jury	13	a new product (or system) that has a significant better score on some of the strategies
14	look for similarities	14	**Eco-effectiveness**	14	develop one into a design to be presented to the jury
15	describe useful natural solutions	15	answer this tasks' questions (purpose, environment, problems, added value)	15	fill in the ecodesign wheel for the new design (before&after)
16	**Emulate**	16	**Part of a continuous cycle**	16	**Evaluate your new design**
17	brainstorm multiple solutions emulating, not copying the solutions found in nature	17	answer this tasks' questions (consumption or service, bio/tech, how cycle, how close/renew loop)	17	define and quantify all processes
18	design several solutions	18	**Safe & healthy materials**	18	calculate eco-indicator points for all phases in the product life cycle / use the form
19	develop one into a design	19	answer this tasks' questions (meaning for product, risks or hazards)	19	present the results
20	**Evaluate new product(s)**	20	evaluate your new design	20	draw good conclusions based on your analysis
21	use worksheet 'evaluate' (for the new design)	21	use the Cradle-to-Cradle certification criteria		

For each item, we analyzed whether students applied the step or tool, grading the result 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 2 gives an example for each grade.

Table 2. Example of checklist items with grading ‘yes’, ‘partly’, ‘incorrectly’ and ‘no’

Checklist item Judging from the report, did the group...		Grade	Notes
4	use worksheet 'evaluate'	**partly** - not all of the step/tool is used or not all is used correctly	'integrate cyclic processes' misunderstood, problem of current system not included here!
8	draw good conclusions based on your analysis regarding the aim for your 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.
13	three examples per Life Principle (LP)	**incorrectly** - step/tool is used incorrectly	only 5 examples in total, superficial and for search terms, not for functions or LPs
17	answer questions (consumption or service, bio/tech, how cycle, how close/renew loop)	**yes**-step/tool is used correctly	questions not explicitly answered, but well described system

Figure 2 summarizes to what extent 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.

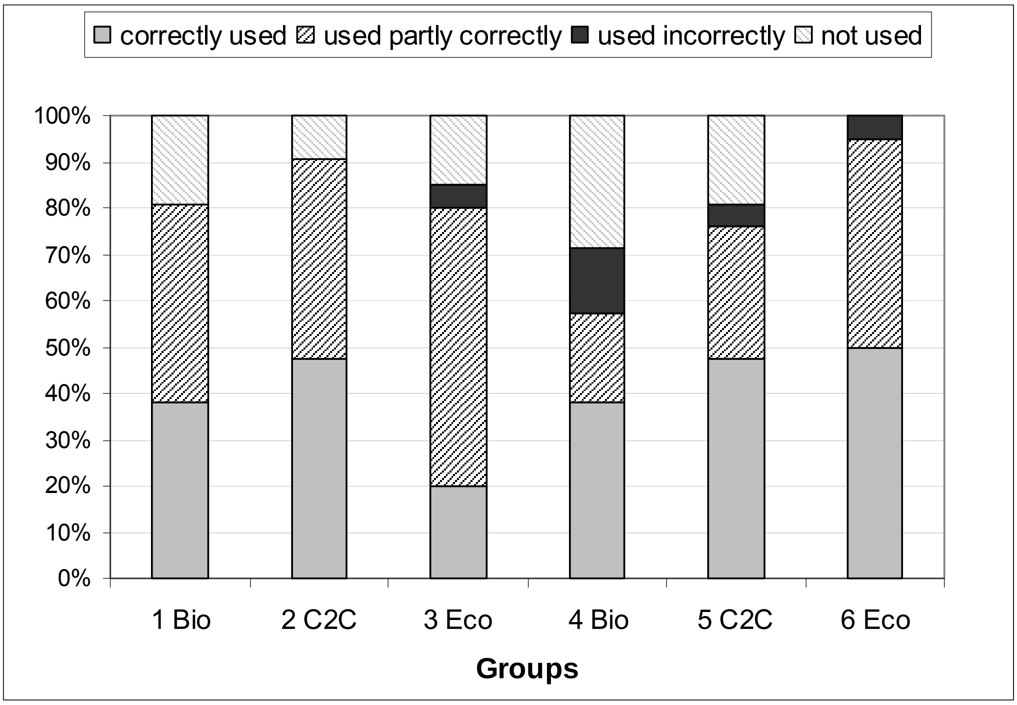


Figure 2. Application of the strategy, per group, based on the grading of the checklist with steps and tools (Bio= Biomimicry; Eco = Ecodesign; C2C = Cradle to Cradle)

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 applied only 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.

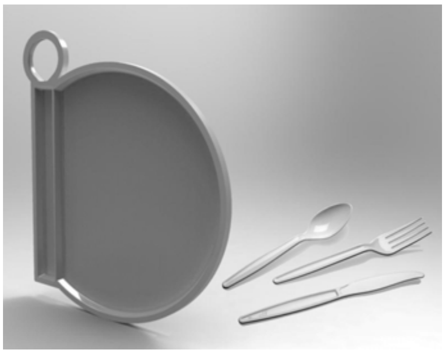
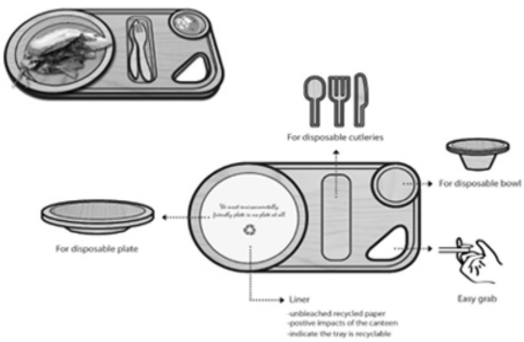
<table>
<tr>
<td>Group 1 / Biomimicry
‘Spider-web’ concept to prevent stealing, with a large tray that has an integrated plate, cutlery fixed in place, and a deposit system.
</td>
<td>Group 4 / Biomimicry
New food concept with edible packaging, eliminating the use of cutlery.
</td>
</tr>
<tr>
<td>Group 2 / Cradle to Cradle
Closed cycle system, with design, production and recycling integrated with IDE educational system, using solar energy.
</td>
<td>Group 5 / Cradle to Cradle
Reusable tableware and cutlery system using recycled PET, with collecting-system for PET recycling.
</td>
</tr>
<tr>
<td>Group 3 / Ecodesign
Design to prevent stealing, using clip-on cutlery, integrated plate/tray, check-in/check-out system and energy efficient washing.
</td>
<td>Group 6 / Ecodesign
Disposable tableware and cutlery system using 100% Fair-trade, biodegradable materials to be composted for food production.

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Figure 3. Summary of the design solutions of the six student groups, using three different design strategies to develop sustainable tableware and cutlery

3.2 Design choices

Figure 3 shows a summary of 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 stealing, or disposable products, thereby eliminating the problem of theft. Looking at the results in more detail, we observe that the groups seem to have addressed the design assignment at different levels.

To explore possible differences in their design approach, we first analyzed the report texts for the words the groups used most frequently, which may reveal different priorities in the approaches. Table 3 shows the 'top-10' most frequently used words for each group; 'common English words' such as 'the', 'and', 'we' etc. are left out, and singular and plural words have been counted together.

Table 3. Top-10 most frequently used words per group, combining singular and plural words and leaving out 'common English words'

Group 1 / Bio	Group 2 / C2C	Group 3 / Eco	Group 4 /Bio	Group 5 / C2C	Group 6 / Eco
words	words	words	words	words	words
product	cutlery	cutlery	design	tableware	concept
tray	product	tableware	cutlery	material	impact
design	design	plate	food	canteen	sustainable
material	cycle	impact	nature	cup	material
food	material	material	sustainable	product	tray
cutlery	production	design	material	cradle to cradle	analysis
function	students	system	biomimicry	energy	tableware
principle	year	product	way	disposable	plate
nature	process	steel	process	reusable	cutlery
plate	faculty	Bio-catering	biocatering	system	ecodesign

'Cradle to Cradle' has been counted as one word. Shaded cells have been selected for further discussion.

We found that only the word 'material' was frequently used by all groups. As expected, several of the top-10-words 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. But the analysis furthermore shows 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'.

To further analyze these differences, we categorized the design choices based on the level of 'depth' that the groups considered for achieving a design solution, at four levels:

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

These levels are based on the 'Model of reasoning by designers' [Roozenburg and Eekels 1995].

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 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 (see figure 3). 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 on the tray.

Table 4. Types of materials selected by the student groups

Product	Current design	Group 1 Biomimicry	Group 2 C2C	Group 3 Ecodesign	Group 4 Biomimicry	Group 5 C2C	Group 6 Ecodesign
Tray	glass fiber 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

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.

3.3 Considerations regarding sustainability

Many of the design choices described above relate to sustainability aspects of the tableware and cutlery system. Earlier analysis of NIDS showed that these strategies focus on environmental sustainability, address economic feasibility, but refer less to social sustainability [Pauw et.al. 2010].
All groups considered ecological aspects of their solutions, which was to be expected from the steps and tools each strategy provided. For instance, we observed they selected specific materials and production techniques as a way to improve 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) mentioned this reduction, stating it would facilitate recycling.
Four groups aimed to alter consumer behaviour to address environmental impacts. As theft of tableware and cutlery is currently a big problem at the canteen (causing increased material use at the canteen and switching to disposables as a result) they 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 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 at a specific company. The other groups mentioned recycling or composting without specifying how to implement this system.
All groups addressed economic implications of their choices, to varying degrees. 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 'allowing 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.

3.4 Student evaluation of strategies

The students were asked to briefly evaluate the three strategies via a questionnaire, as a means to provide additional insights on whether and why NIDS may help designers in developing sustainable products. Most students indicated they would use the strategies (or parts thereof) again, many want to apply all strategies or combine them. Cradle to Cradle was generally well valued, and for instance described as 'useful', 'beautiful', and 'inspiring'; students mentioned various tools and aspects as useful, whereas some students from *other* strategies evaluated C2C as 'hard to realize'. Biomimicry was considered as 'inspiring' and 'leaving room for creativity' but often 'hard to apply' for different reasons, most of them concerning the method currently available. Nevertheless, only two students that applied Biomimicry did not state they would use it again in future projects. For comparison, Ecodesign was most valued for 'giving insights in numbers'.

4. Discussion

The results provide insights in how the Nature-Inspired Design Strategies (NIDS) included in this case study may have helped the students to develop sustainable products. 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 return 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 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 caused by 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.
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 on 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 well-valued by teachers 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, seem 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 help them to develop a design strategy and concept. Although the Ecodesign groups used a quantitative tool for this purpose, the outcomes are very dependent on accurate input of data, and the analysis seems to limit the solution space. When students compare specific design alternatives, they do appreciate having quantitative data.

This case study additionally showed us that the strategies may help designers in presenting their work to clients. During the course, the students were specifically asked to include information on their strategy and design process during their presentations. This seems to have helped them to explain the results of their work to the client. In our next study, we want to see whether students will integrate elements from the strategies in their presentations even if they are not required to do so. Furthermore, we will ask both teacher and client to grade the products developed by each group, as a means to address possible effects on the overall quality of the designs.

5. Conclusions

The aim of this case study was to explore the effects of applying Nature-Inspired Design Strategies (NIDS) when design students perform a sustainable product development assignment, and to generate tentative conclusions on the reasons NIDS may affect the outcomes. We conclude that NIDS influence the type of design activities performed by the students, resulting in several different product characteristics. For two out of four groups, applying NIDS resulted in markedly different solutions. We analyzed the nature of the differences and formulated the following tentative conclusions. 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 on the level of product function or needs. Furthermore, the nature-based design principles help students to develop a design strategy and concept. The principles, although qualitative, seem to challenge the students because of their absolute (instead of relative) nature. Finally, the use of examples from nature -that are easy to grasp- seems to help them to effectively present the design solutions to their client.

We conducted this study with six student groups. When forming the groups, we could mix students from different educational backgrounds, but were unable to assign bachelor and master students to the same group or consider prior knowledge level. In addition, the personal motivation of the students might influence the results. As the courses were elective, we assume students were motivated to learn and apply the strategies. This was confirmed during the coaching sessions.

This case study helped us to get a first, general overview about the possible effects of applying NIDS for sustainable product development. NIDS are promising strategies that seem to inspire and assist design students in this type of projects. We aim to expand our findings in larger studies, to validate the outcomes of this first exploration. Additionally we will study key cases where professional designers apply NIDS in their work, to explore whether comparable and additional effects can be found in the design practice, to assess the impact of these effect on the design and thereby gain in-depth understanding of how NIDS help designers in their product development projects.

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