BIOMIMICRY DESIGN EDUCATION ESSENTIALS

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ABSTRACT

The emerging field of biomimicry and learning to design with and for nature has expanded in recent years through a diversity of educational programs. Inspiration following natural forms may give the appearance of being sustainable, but the question remains, how sustainable is it? Misunderstanding the function of these forms may leave designers with products not as sustainable as desired. Biomimicry education addresses these issues by integrating three essential elements into their design thinking phases and by using analogical transfer while doing so. This field learns from nature as model, nature as measure, and nature as mentor, throughout the design process. Through examination, analyses and verification of students designs and reflective processes at The Hague University of Applied Sciences, this research considers natures analogies in educational factors, determining which elements are influential when incorporating biomimicry into design education.

Keywords: Design education, Bio-inspired design / biomimetics, Industrial design, Sustainability

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1 INTRODUCTION

Biomimicry addresses sustainable methodologies into design education by following three essential elements: nature as model, nature as measure, and nature as an intrinsically valuable mentor. This research examines, analyses and verifies biomimic educational processes considering its use of analogical reasoning, determining which elements are fundamental when incorporating biomimicry into design education. Since the book, Biomimicry, Innovation Inspired by Nature by Janine Benyus in 1997, the field of biomimicry has expanded rapidly across the globe and related scientific articles have increased from a handful in 2014 to over 200 in 2018. These articles, websites, educational programs and reports have watched biomimicry reach the Top 5 of emerging fields according to Forbes Magazine in 2014. In 2017, Fortune author Harnish wrote, “If you’re not incorporating the most brilliant ideas from the natural world into what you sell, you’re leaving money on the table. Biomimicry is now going mainstream”.

Biomimicry education uses contexts from Nature, learning how organisms function and how these functions can be applied within the design. While the origins of biomimicry methodology gained influence from articles as Altshuller’s analysis of function patterns in human patents in the TRIZ method (Bogatyrev, 2015) leading to the biological pattern identification in BioTriz (Vincent *et al*., 2006), this research focus is on the influence of analogies from Nature and on how students increased intrinsic value concerning Nature as a guide, may affect their ethical decision making while learning to design.

In 2019, a fourth cohort of students will graduate with a Master of Science in Biomimicry at ASU. These graduates are starting to teach these principles and write about how the biomimicry design process is achieved. Few scientific articles however delve into the effectivity of biomimicry education, making this research essential to understanding what factors increase or decrease student learning while using this methodology.

1.1 Motive for research

Design engineering programs regularly address current global challenges. Inspiration from nature may generate ideas for solutions to such challenges, but this researchers’ preliminary research showed that design teams who simply used nature’s inspiration in their designs without addressing the natural function or mechanisms, and those who did not understand why it is important to recognize the genius from Nature, left them with products not as sustainable as desired. Novice designers following form without considering function, or their inability to evaluate the designs level of sustainability, left students struggling to determine how to improve this. According to Kennedy, biomimicry addresses these issues by translating biological mechanisms into engineering concepts, learning from nature as *model* for design, as *measure* during evaluation of that design, and as guiding *mentor* (Benyus, 1997), appreciating nature’s intrinsic value throughout the design process. The heart of biomimicry is the “art of cultivating this perceptive eye … to think creatively about how to make a connection between what they [designers] saw and what application it could have” (2015). My motive is to examine and understand how analogical transfer is useful to novice designers, measuring whether students can effectively learn via these three factors (model, measure, mentor), determining how each factor is internalized for future design use.

Preliminary empirical research with Industrial Design Engineering (IDE) students at The Hague University of Applied Sciences (THUAS), showed that almost half of the responding design students had never heard of biomimicry beforehand and had never used Nature’s strategies to solve engineering challenges, nor had they an in-depth understanding of evaluating designs on sustainability. The question arose, can biomimicry offer new and compelling insights to measure and evaluate products, ultimately improving a sustainability score and how can designers benefit from learning from nature? Additional to these questions, understanding biological analogies and using these in design remains difficult. This preliminary research also showed students using these copied aspects, intentionally or unintentionally, often misinterpreted into their design, i.e. blindly copying form while leaving out process or system (e.g. using honeycomb and calling that sustainable simply by shape).

1.2 Goal for this research

Development of an applicable model to enhance abilities of in-depth recognition of biological analogies as well as the effectivity of analogical transfer used in biomimicry education, gives a unique focus to this research, demonstrating first how analogies are relevant within biomimicry and secondly how analogical thinking is relevant to designers, beyond the biomimicry examples.

Kennedy (2015) describes the similarity between Design Thinking and Biomimicry Thinking in the core phases of 'defining the problem, explore, create and evaluate (or redefine)'. Biomimicry adds the component of looking to learn from nature throughout each of these phases to correlate how specific aspects inherently improve the sustainability of the product (Baumeister, 2014). Finding the correlation between the two design thinking processes, and introducing biomimicry instruction into existing Design Engineering curriculum at The Hague University, aims to demonstrate this relevancy and resolve sustainability concerns mentioned above. Casakin and Goldschmidt (1999) established that the use of visual analogies improved the quality of novice designers significantly. Consequently, students who are 'novice designers' have been known to "put more effort on the functionality of design" (Chai *et al*., 2014), making this participant group ideal to work with during comparison of the functional aspect of the design need to the functional strategy found in Nature. A comparison between novice and experienced designers may be included in future phases of this research.

2 MAIN RESEARCH QUESTION

Research question: What course characteristics are needed to aid in the application and comprehension of biomimetic models from nature to support sustainably designed products and services?

Sub-question: Do students face problems (Swaroop *et al*., 2016) when learning to recognize value in natural analogies when designing following biomimicry principles? And if so, how can we measure this?

3 THEORETICAL FRAMEWORK

3.1 Teaching Biomimicry

Swaroop *et al*. (2016) stated, design students "consistently fell prey to a common set of mistakes" while incorporating natural forms into designs. Functional and form analogies from nature is the heart of biomimicry according to Shu (2010). Researchers described the importance of understanding biological systems during sustainable innovation in design engineering (Kennedy *et al*., 2015). Vosniadou (1988), specifies the importance of general analogies to "scientific discovery and creativity", and Dahl and Moreau (2002) describe the importance of analogies, but maintain these are difficult to reproduce into translatable [measurable] engineering. Mead & Jeanrenaud (2016) explain the need to explore the misunderstandings of biomimicry [education] and the misuse of form in *The elephant in the room: biomimetics and sustainability?*

3.2 Educational intervention

In *Integrating Biomimicry into Higher Education*, Urmann (2016) explains the view of the Biomimicry Education Network which describes biomimicry as a field that is "influencing how we solve problems and design our world", and "revolutionizing education – offering teachers a way to engage students of all ages with biology, STEM subjects, creative problem-solving, and systems thinking".

Urmann continues that biomimicry education can provide:

- A direct renewal and review of our own education through seamless integration in current methods.
- A compelling way to learn design.
- An interdisciplinary platform connecting subjects to the real world beyond classroom walls.
- A tool enhancing creativity and problem-solving skills through design and project-based activities.
- A unique and powerful way to think and learn about sustainability.

This research aims to follow these principles in the case studies used for observation and analysis.

University biomimicry assignments are repeatable building blocks which support one another. Key assignments used for these case studies at The Hague University are:

- Design challenges, *Biology-to-Design*: participants look to nature to discover relevant forms, functions, structures or patterns that are key to solving a human challenge, or, *Challenge-to-Biology*: participants address a challenge, then scope/discover/create and evaluate as in any design thinking process, continually adding lessons and laws (see 2&3) from nature (Biomimicry3.8, 2015).
- *iSites* use visual communication techniques recording data concerning organisms in their operating conditions, noting contexts, form, function, eventually completed with researched facts. The focus is on recognition of specific aspects useful for learning from nature to design without using "heat, beat and treat" methods (Baumeister, 2014).
- *Life's Principles* "represent… overarching patterns found" within 3.8billion years of Life's evolved set of strategies (Biomimicry3.8, 2013). Life's Principles provide tools, guidelines and design evaluation requirements according to main principles found in Nature and Life Sciences.

Cobb states in *Design Experiments in Educational Research*, that "design experiments ideally result in greater understanding of … learning …" (2003). Our sub-projects are "pragmatic as well as theoretical" and focus on both "one-on-one (teacher-experimenter-student) design experiments" as well as "classroom experiments where the researcher is responsible for instruction" (2003).

Intermediate results advise following research sub-projects, aiding a "rapid pay-off". Blessing and Chakrabarti (2009) agree, research on Biomimicry Engineering should use two essential, guiding methodologies: Active Learning and Inquiry-based research, integrated into a Design Research Methodology (DRM). These methodologies fit within the framework of current IDE methods and this research plan.

3.3 Analogical reasoning

Kolodner (2003) describes design-based learning environments with analogical thinking as those which promote retention of content and skills through iterations. Practicing these skills help students to remember a concept, help to apply that concept, and help recognition of the need to solve real-life challenges. Kennedy stated, "The best ideas are often borrowed" (2017). Nature as model *promotes learning* from the best adapted models that inspire innovative solutions to human challenges (technological, design, social) for long-term survival. Considering 3.8 billion years of evolution acknowledges that these tested solutions work. Nature as measure asks, "are our designs as good at these functions as the organism we modelled them after?" (Kennedy, 2017). Life's Principles weigh decisions before, during and after the design process and Benyus states, Nature as mentor, *recognizes* nature as a source for ideas instead of a source for raw materials (womenofgreencom, 2018).

3.4 Design Based Learning (DBL)

Students identify what to learn, engage in investigative activities on what they've identified, apply this to achieve their design goal following up with reflection on the design process - all essential for analogical reasoning (Kolodner *et al.*, 2003). This 'Learning by Design™' (2003) process is the framework of biomimicry case-studies. Kolodner further describes transfer of knowledge, as "a kind of analogical leap between two usually-separate contexts". The biomimic example Ornilux Birdsafe glass, makes this 'leaps' between the Orb Weaver Spiders web to windows that birds can see and thus do not fly into (Orniluxcom, 2018).

DBL Assignments use relevant scientific knowledge and skills and are practical and reflected upon so students may internalize in a way that allows for a variety of learning styles. Three main processes are needed: **"**(1) recalling (identifying) something relevant from memory, (2) deciding on its applicability, and (3) applying what has been recalled" (2003)**.** The link between biomimicry and analogical transfer is made here. A successful DBL case "provides students a need to learn, a reason for remaining engaged, a venue for application and practice, a venue for failing softly and needing to explain, and a venue where reflection on and articulation of what they are learning and iteration towards better understanding are natural" (Kolodner, 2003). During this process, students also collaborate in small groups, uncover trends, communicate, and reflect continuously.

4 METHODS

To answer the question on the course characteristics aiding biomimicry in design, we looked to essential biomimicry education elements: learn from Nature as Model, Nature as Measure and Nature

as Mentor, as Kennedy (2015) describes. Using these three main elements we looked to the successes and problems that students face with their first attempt to understand and apply these analogies from Nature to support sustainably designed products and services.
Forty one of the 57 Industrial Design Engineering (IDE) students from The Hague University, participated in this research in three workshops using biomimicry during the Design Exploration course in 2017. Workshops were prepared, recorded and observed by the research lecturer. Case study observations and recordings of the three workshops aimed to gain initial insights into determining to what extent the chosen didactical methods increase or decrease student recognition of nature's analogies while learning biomimicry design. During the second step, student portfolio reflections containing keywords mentioning functions and value statements from these workshops were analyzed on their ability to recognize and relate biological functions to their design function needs, their ability to measure the design sustainability using Life and Science "Laws of Nature" (called Life's Principles) and their recognition of Nature as being a valuable resource (see dependent variables). During the portfolio analysis, new keywords were added to the summative content sheet to draw initial conclusions. Goal of this analysis was "to provide knowledge and understanding of the phenomenon under study" (Downe-Wamboldt, 1992). One portfolio page per student, per week with students' reflection on the workshops were used for this analysis. According to Bloom's Taxonomy (1956), reflections, or self-reports of awareness and understanding are effectively used to demonstrate competencies. Finally, 1:1 interviews with 11 of the participating students verified or disproved conclusions already made on the effectivity of learned knowledge, retrieval and application of biomimicry principles.

4.1 Variables

During biomimicry thinking phases, students define context, identify function needs, integrate life's principles, discover natural models fitting required need(s), abstract biological strategies, brainstorm bio-inspired ideas, develop design concepts and evaluate these using Life's Principles (Biomimicry3.8, 2015).

4.1.1 Dependent variables

While following basics design phases of Biomimicry Thinking from the scoping phase to the evaluation phase, students demonstrated their competences of the following:

- Ability to recognize a functional need for their design challenge (model) Indicator: relevant functions (use BMY-taxonomy diagram): filter, channel, capture, collect.
- Ability to recognize biological models useful for design needs (model) Indicator: relevant organisms (biological models) fitting client-function-need such as: whale, coral.
- Ability to measure and evaluate these models via Life's Principles (measure) Indicator: Correct use of Life's Principles in a design context (see Life's Principles diagram)
- Ability to recognize intrinsic value of Nature and not simply instrumental value (mentor). Indicator: resourceful, valuable, circular, sustainable.

4.1.2 Independent variables

Educational variables having an impact on the ability of students to perform these tasks

- Materials: availability of scientifically researched natural models
- Time: length of class vs number of assignments
- Workshop venue – conducive to creativity, inspirational
- Design challenge topic - real, relevant, awe inspiring, require inquisitive research and, use actual science using Naturalis guiding philosophy (Big 5 of education)

4.2 Data gathering and content analysis

Keywords were first chosen to prove certain IDE competences such as, "demonstrate synthesis of learnings and integrate new knowledge", "conceive basic concepts and solutions" and "communicate the undertaken design process, ideas, concepts and design via design language". Within these, course specific sub-competences were chosen such as "recognition of function need" and "recognition of organism meeting that same function" as well as "Recognize value orientation in reference to Nature as Mentor" where keywords might include "valuable, resourceful, sustainable, and circular". These were recorded in the coding sheet to gather insights and form initial conclusions. Statements regarding difficulties were also recorded here. To ensure unbiased results, data gathering must have a control-phase where external researchers fill in the same coding sheets and come to at least similar results on their own. This control phase will be completed before July 2019.

4.2.1 Observations

Data is collected by observing and recording keyword indicators of the various dependent variables during the workshop, in the photos or recordings, as well as individual reflections. An observation sheet collects data and scores 41 students' visual and verbal work according to the learning objectives of each workshop.

4.2.2 (Qualitative) Content Analysis

A summative content analysis counts and compares keywords in relation to the learning objectives and variables, following with an interpretation of the underlying context. Keywords identified before and during data analysis were derived from interest of researchers and review of literature. This analysis discovers what terms might be used to imply recognition of natural models and value propositions and this method was chosen to gain insights into what students were thinking when reflecting on their design process. Keywords were clustered to represent similar meanings (Weber, 1990). This approach aimed to both statistically quantify the patterns in verbal and visual communication as well as to qualitatively interpret and define correlations between these patterns. Why? Recognition of natural models followed by application of these models in a design concept requires a basic understanding of the function and how this might work in the design. Keywords implying intrinsic value associate acknowledgement of such value as well as raise awareness. Final validation occurs first via biomimicry content experts from the Biomimicry Practitioners Reef (online network of Biomimics) on what terms are used to replace 'function' etc. and later through interviews sampled from the participants to inquire if the analysis meets their intended meaning. The analysis is to fill the gap between what the students said and the first research conclusions.

5 WORKSHOP CASE STUDIES

During three case study workshops of the 2017 course Design Exploration, 57 students worked individually and in teams with the learning goals of recognition and application of natural organisms to be their model and measure and mentor, with the goal that students may start to recognize how natural laws of nature can be used to measure the success of their designs and to address the essential elements of biomimicry emulation (or creation). While recordings of 41 of these students aided in initial observations, the course included other facets of design such as form study, ergonomics and color usage. Design Exploration aimed to introduce first year students to design and did not include an entire set of biomimicry course characteristics. Future phases of this research intend to address a more holistic approach and use the series of Biomimicry Design Thinking methodology to gain deeper insights into its effectivity.

5.1 Case study 1: Biomimicry Design Jam – Nature as Model

Challenge-to-Design – An introductory lecture and pop-quiz, acquainted students with the idea of noticing functions in nature, identifying functions matching our fictive client needs to remove micro-plastic particles from the ocean. After researching natural models and creating concepts inspired by these models, a quick prototype and five-minute pitch of ideas concluded the workshop and demonstrated their intake of knowledge and their application of learned biological model principles. Student deliverables reflected on their design concept, on the function-need and the organisms that already carry out this function, as well as on their process and what they have learned. The aim of this workshop was to teach students how to recognize Nature as Model (biological organisms' mechanisms and strategies that fulfill the same function need as their client has).
Venue: Innovation Playground at THUAS (3hrs).
Topic: (Fictive) client was NOAA. Solutions to clean up micro-ocean-plastic.
Materials: reader providing scientific texts of organisms from AskNature.org performing functions - water absorption, filtration, etc.

5.2 Case study 2: iSites – Nature as Model and Mentor

Students used *iSites* visual communication techniques to individually record field guide data of plants, operating conditions, selection pressures, etc., eventually completing these with researched facts to understand these models in depth. Student deliverables (portfolio page of that week) reflected on the functions the biological organisms (plants) carried out, as well as on their personal learning process. The aim of this workshop was to teach students how to recognize Nature as Model and as Mentor (biological organisms' mechanisms and strategies that fulfill a function need and how designers can recognize Nature as our teacher).

Venue: Hortus Botanicus in Leiden (3hrs).

Topic: Students worked individually discovering forms, structures, systems and/or patterns in nature that provide functions of protection or nutrient consumption. Subsequently, reflecting on how examination at different scales changed their viewpoint, reporting on characteristics not noticed before the exercise and useful insights to them as a designer.

Materials: personal drawing utensils.

5.3 Case study 3: Life's Principles – Nature as Measure

Students became 'experts' in class on one of the 6 main Life's Principles used by Biomimicry 3.8 to measure and audit designs by. *Life's Principles* are guidelines and specify requirements for design as well as benchmarking during integration of these principles into designs. While six main principles delegate 'rules' common to Nature and Life Sciences, there are 26 sub-principles in total such as "Combine modular and nested components" and "Use multi-functional design". The aim of this workshop was to teach students how to recognize Nature as Measure, using Life's Principles as an assessment tool to gauge the sustainability of their design.

Venue: Innovation Playground at THUAS (3hrs).

Topic: Life's Principles as measurement tool both for design briefs and evaluating design concepts. Learning via the expert method, students choose one main principle to learn, discussed its application as design brief requirement with other group "experts" and shared with their original group how they might explain these to their client. They were required to reflect on this process and to design marketing posters demonstrating a way to communicate these principles for their client's product (this client came from both the first workshop and from the students' main project client in a separate course).

Materials: Life's Principles Reader.

6 ANALYSIS

6.1 Observations

Videos and scanned photos recorded students' workshop participation and presentations. Visual observations were made concerning the effects of the available materials, the amount of available time, the effect of the workshop venue and on the choice of the assignment challenge at hand. During the Design Jam which worked on solving the ocean micro-plastic issue, a reader of research materials was given, but the website AskNature.org was also available and advised to use for investigation. The time available per workshop (3 hours) was too short for students to go into the evaluation phase, but the chalkboard covered walls of the Innovation Playground venue were perfect for brainstorming ideation. The Design Challenge topic fit the Big Five of Education that Naturalis Biodiversity Center uses to lead development of educational activities and was clearly motivational. During the iSites workshop at Hortus Botanicus in Leiden, students provided their own drawing materials, while the inspirational venue provided the plants and botanists who offered further information. iSites lessons looked at detail. The Life's Principles workshop was in the same venue as the Design Jam, but the space was not used in the same manner and the assignment required excessive reading. These observations were made by the instructor/researcher and gained from student comments during the workshops as well as from guides from Hortus. A first draft of the summative content coding table recorded potential keywords during the workshops and pitches to later help recognize what students found essential to add to their individual reflective portfolios.

6.2 Summative content analysis

Before the analysis of the 41 portfolio reflections, workshop steps were recorded and tasks and actions of instructor and students that occurred before, during and after the workshop were compared to understand what happened in the workshop that might benefit their recall of the learning objectives. First year student Leonie wrote, "I never thought we would come up with an idea like this in just two hours. For my next challenge, I will definitely look how nature solves the problem. Biomimicry has stolen my heart…" For each action, we identified what might be responsible for usage and recollection of biological analogies, which outcome was unique to each lesson, and which outcome was similar or not recorded at all. The first 21 portfolio reflections were analysed more closely while the second set of 20 portfolios showed repetitions and did not add to earlier insights. A global coding sheet recorded a summary of all student results, recording name, insights per student, and citations. "I was captivated by the patterns of leaves and how everything seems to be planned through to maximize the quality of the plant's life", one student said. Another mentioned, "All forms and shapes of nature could be used everywhere, from building a toy for kids to constructing a building". Students who reflected on drawbacks also gave insights for future reference.

Questions for the final interviews were written during this phase and the insights that needed verification were as follows:

- Providing scientific research materials was essential to save time during the workshop design jam and enable students to complete the assignment;
- Examining models from nature guided students to focus on the function need of their design;
- Students learned how to focus on detail during the iSites lesson;
- Nature as Mentor seemed to be the least understood element;
- Life's Principles were presented as Design Brief (measurement) requirements, but were these used to assess their designs later;
- All three workshops needed more time to carry out the assignments (or should have had fewer assignment parts);
- Students learned about the intrinsic and instrumental value of nature by participating in this series of 3 biomimicry lessons;
- A venue encourages design students to demonstrate their creativity when the space allows for large visual communication of ideas when meant to present these to larger groups; A venue which is outside of school and immersed in nature also inspired students to focus on the beauty and intrinsic value of nature.
- The design challenge addressing a global issue made the workshop feel real and relevant. Students felt they were doing necessary work.

6.3 Interviews

The analysis of the initial conclusions was verified via final interviews with 11 volunteers from the 41 participating students with the request that they be critical on what also was confusing or what did not seem to work for them. Questions were geared towards finding out if students had internalized the basic philosophy of Nature as Model, Measure and Mentor and to verify tentative discussion assumptions, concluding which aspects of the workshops were most effective and which were not. "Nature has a solution to everything" said student Nicky during the interview. The course made her see the beauty as well as the use of nature. Student Sanne replied, "Yes, it [the lessons] made a difference of how I looked at nature" but she also noticed more of an instrumental value and less of the intrinsic value.

The assumption that students would need a set of given materials to gain scientific knowledge on the organisms they studied was not substantiated. Most of the students answered that they did not use the research documents provided, but went online to find scientific articles on organisms' functions to fit their design need. With the use of AskNature.org in the workshops, novice designers focussed on what a design is meant to 'do' and could find Models from Nature to learn from faster than from the reader. Students requested more iteration of this process to aid them to develop their basic design concept ideas into a true product. They repeatedly mentioned how the Design Jam workshop increased their ability to break down products into specific functions. The combination of presenting, drawing and reflecting on the process, also helped them to embed the knowledge and increase comprehension of learnings throughout the 10-week course, but all students mentioned the lack of time available to thoroughly internalize the information.

During the iSites lesson students learned how to focus on detail and how to see nature as a library of design solution ideas. When asked which lesson they wanted to repeat, all but one wanted to go back to Hortus Botanicus to learn from the botanical garden. “We don’t use inspiration from nature in general design classes”, more than one student said. Many have changed their view and now look casually to nature for inspiration when starting a design process.
During the Life’s Principle lesson students seemed overwhelmed by the amount of information, but were still able to present how their design solutions might be improved by these benchmarks. After the lessons, students were not able to mention how these aided in measuring the sustainability of their solutions. “There were a lot of texts and I felt pressure to learn these”. Most did not remember the class. Almost all students remained assured that they would look to nature for inspiration again and the venue where they had their workshop made a difference in how they looked at nature as a source to learn from. When asked about the value of nature, and the value of the challenge they worked on, all mentioned that they see the ocean plastic issue as being relevant and something needing solutions.

7 DISCUSSION AND CONCLUSION

The goal of this research was to develop an applicable model to enhance abilities of in-depth recognition of biological analogies and to demonstrate first how analogies are relevant within biomimicry and secondly how analogical thinking is relevant to designers, beyond the biomimicry examples.
Our students verified that they recognized multiple solutions to similar design challenges while using biomimicry design processes. The goal of the Design Jam workshop was to have students focus on learning, on understanding natural models and on integrating these models functions into solving their design challenge. Recognition of *Nature as Model* is demonstrated during the ideation and prototyping phases of the Design Jam and through the organism choices made by the students. The goal of the iSites workshop was to recognize Nature as Model and Mentor. This too was demonstrated through the portfolio reflections where students examined, drew and explained the functions, structures and patterns of the models they choose and how these relate to design. Their choice of words describing these biological analogies reflected on how they recognized and remembered the beauty and value of nature.
The goal of the Life’s Principles workshop was to introduce these principles as a benchmarking system, useful for inspiration, for specification of design requirements and for assessing if the design solution meets a sustainability standard. The ability to measure sustainability of the solutions however, was not explored in sufficient depth and will be a focus in future phases.
Students learned about the intrinsic and instrumental value of nature in all three workshops, and all needed more time to carry out the assignments (or needed to have fewer assignment parts). To avoid misinterpretation or bias of the results, a ‘second opinion’ must still take place through an external researcher who will repeat the coding phase. After which, interpretation of the results shall be compared. During following phases of the research, explicit care will be taken via simultaneous external portfolio analysers, including comparisons of the results, to ensure unbiased conclusions.
The apparent gap between designing according to IDE methods and using biomimicry lies with how the students looked back to the workshops, remembering how they had reconnected to nature, remembering and upgrading its value in their minds. Through the conscious thoughts of nature having more than simply an instrumental value, a value to use or take, students recognized the intrinsic value of these models as mentors. Many were reminded of things they learned as children or from their parents. During the workshops, the three terms “Model, Mentor and Measure” were not specifically used. The use of these terms will be tested in future workshops to embed the associations in a more tangible manner. While the lack of time remained an issue, students were eager to continue learning these biomimicry principles. Product design results with merely three workshops remained superficial and results of this research show that more time and more iterations of the exercises are needed to improve this application. The development of an applicable model to enhance these abilities continues as the minor “Design with Nature” is in progress during the Spring Semester of 2019 at The Hague University of Applied Sciences, and continually addresses these needs. During this semester, testing occurs to determine how the translation between the biology and engineering can become more effective. From the 2nd year students, 75% have chosen this minor for their semester. Student Marie summed up the student interviews with, “The course, Design with Nature “should not be voluntary for

designers. We need this". During ICED19, preliminary results of the following phase of research done may be discussed at the time of this paper presentation. An entire set of unique course characteristics aiding in comprehension and application of these models has been used in the minor and will be analysed according to their effectivity. This paper has become a stepping stone for the university program to accept, encounter and experience biomimicry in the classroom.

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REFERENCES

Baumeister, D. (2014), "Biomimicry Resource Handbook", Missoula, MT: Biomimicry 3.8.
Benyus, J.M. (1997c), "Biomimicry - Innovation Inspired by Nature", HarperCollins.
Biomimicry3.8 (2013, 2014, 2015) worksheets Biomimicry 3.8
Bogatyrev, N. and Bogatyreva, O. (2015), "TRIZ-based algorithm for Biomimetic design", *Procedia Engineering as presented at World Conference: TRIZ FUTURE*, TF 2011-2014. 131 (2015), pp. 377–387.
Casakin, H. and Goldschmidt, G. (1999), "Expertise and the use of visual analogy: implications for design education", *Design Studies*, Vol. 20 No. (2), p. 153e175.
Chai et al. (2015), "Behavioral analysis of analogical reasoning in design: differences among designers with different expertise levels", *Design Studies*, Vol. 36(), pp. 3–30.
Cobb et al. (2003), "Design experiments in educational research", *Educational Researcher*, Vol. 32 No. (1), pp. 9–13.
Dahl and Moreau, (2002), "The influence and value of analogical thinking during new product ideation", *Journal of Marketing Research*, Vol. 34 No. (1), pp. 47–60.
Harnish, V. (2017), "5 Trends to Ride in 2017". *Fortune*, http://fortune.com/2017/03/17/trends-business-career-benefits/
Kennedy, et al. (2015), "Integrating biology", *Design, and Engineering for Sustainable Innovation*. *5th-IEEE Integrated STEM Conference*
Kennedy, E.B. (2017), "Biomimicry: Design by Analogy to Biology", *Research-Technology-Management*, Vol. 60 No. 6, pp. 51–56
Kolodner et al. (2003), "Promoting transfer through case-based reasoning: Rituals and practices in learning by design classrooms". *Cognitive Science Quarterly*, Vol. 3 No. (2), pp. 183–232.
Mead, T. and Jeanrenaud, S. (2017), "The elephant in the room: biomimetics and sustainability? ICE Science", Vol. 6 No. (2), pp. 113–121.
Orniluxcom. (2018), "Orniluxcom". [Online]. [15 November 2018]. Available from: http://www.ornilux.com/
Shu, L.H. (2010), "A natural-language approach to biomimetic design", *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, Vol 24, pp. 507–519.
Swaroop, et al. (2016), "Gatechedu", August, 2016, http://b.gatech.edu/2aW0CCc
Urmann, L. (2016), "Integrating Biomimicry into Higher Education: Designing and Developing a Biomimicry Minor at the University of California", *Santa Cruz*. Thesis University of California.
Vincent, et al. (2006), "Biomimetics: its practice and theory". *Journal of the Royal Society Interface* Vol. 3 No. (9): pp. 471–482
Vosniadou, S. (1988), "Analogical reasoning as a mechanism in knowledge acquisition", University Illinois
Weber, R.P. (1990), "Quantitative Applications in the Social Sciences: Basic content analysis". Thousand Oaks, Ca: Sage
Women of Green (2018), "Womenofgreencom". Retrieved 10 March, 2018, from http://www.womenofgreen.com/2011/02/02/nature-as-mentor-and-other-lessons-from-biomimicry/