(Bio-ID4S): Biomimicry in Industrial Design for Sustainability, An Integrated Teaching-and-Learning Method

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1. KEYWORDS: industrial design, integrative education, biomimicry, sustainability, ecodesign.

2. ABSTRACT: Ecodesign (environmentally friendly design) had its origins around the 1950`s and has been taught worldwide in most programs of Industrial Design (ID) since the early 1990`s. However since early 2000`s, this view has slowly changed to the broader perspective of sustainable design (also called Design for Sustainability, or DfS), which not only considers the environmental, but also the social and economic aspects of design. The aim of this research is to develop, test, evaluate and refine an integrative and cross-disciplinary teaching method for DfS applicable to undergraduate ID Education. This method is based on the integrated study of nature, human society and design. It focuses on the use of biomimicry, combined with ecodesign tools and theories of human needs analysis. After an extensive literature review about education for sustainability, bio-inspired design and ecodesign, a theoretical model was developed and explained through diagrams. Then a course curriculum and guidelines for an experimental workshop were defined, and later tested during 2 consecutive years with 2 different groups of students. The process and outcomes of the workshop are described through case studies and examples of student works. Afterwards, the course is evaluated by the students through feedback questionnaires. The results of this survey are analyzed and used for improvements to the teaching method. Finally, the theoretical model of the relationship of biomimicry and design is further developed, in order to evaluate, classify and understand different types of biomimetic design projects. Results in terms of projects developed by the students show the practical applicability of the model, while the diverse approaches suggest stimulation of creative thinking. Teaching results from the student's feedback require that the method should be simplified and made less time-consuming, in order to improve it. Positive feedback from students suggests that the method enhanced their awareness of DfS by linking sustainability and design through biomimicry. In the future, such methods can radically change the way ID`s think and work, proposing new viable designs inspired in nature, for the benefit of all forms of life.

3. SUMMARY OF THE RESEARCH

3.1 Precedents in Industrial Design Teaching

The teaching of Industrial Design (ID) must be redefined constantly to address the new challenges faced by designers in today's fast evolving society. Problems generated by traditional "industrial production" cannot be solved with the same thinking paradigms of the system that generated them. Ecodesign (also known as Design for the Environment, or DfE) is currently mostly taught through application of diverse ecodesign tools found in specialized textbooks and websites. This is standard practice worldwide in diverse programs in ID, Product Design, Product Design Engineering and other related disciplines. Although many useful ecodesign tools and teaching methods have already been developed (i.e. Okala curriculum by IDSA)[1], it is necessary to continue exploring and developing cross-disciplinary methods that enhance sustainability in design.

3.2 Objective of the Research

The aim of this research is to propose, test and refine a new pedagogic model for teaching bio-inspired thinking tools for design for sustainability (DfS) to undergraduate industrial design (ID) students. This holistic approach is based on the integrated study of life and nature and their multilayered relationships with diverse aspects of human society. The teaching and learning method studied through this research focuses on sustainability [2] in a broad sense, integrating social, environmental and economic aspects [3].

For this purpose, significant study cases from different disciplines (engineering, materials research, nanotechnology, architecture) were discussed in congresses or meetings in Kobe University (Japan), Georgia Tech University (USA) and Los Andes University (Colombia) among others. Also a close collaboration with the Biomimicry Institute provided up to date information about a relevant range of teaching strategies and state of the art case studies of biomimicry design in various

disciplines. To illustrate just few examples related to bio-inspired design and industry, below are depicted a walking cane developed from the study of bat echo-location (figure 1) and a concept car from Mercedes Benz in 2005 (figure 2).

Figure 1. Walk cane for blind from bat echolocation [4]

Figure 2. Concept car inspired in the boxfish [5]

3.3 Research Timeline

Very briefly, the research was conducted as follows:

2005: Preliminary Research and Research Proposal

2006: Literature Review, Theoretical Developments, Planning and Implementation Workshop 1(WS 1).

2007: Literature Review, Analysis of WS 1, Planning and Implementation Workshop 2 (WS2).

2008: Literature Review, Comparison of WS1 and WS2, compilation of the Doctoral Dissertation.

2009: Expected finalization of Doctoral Research.

3.4 Theory and Methods

Environmental aspects were considered through diverse Ecodesign tools, such as Industrial Ecology [Frosch et. al. 1989] [6] and were integrated with the methodology of Biomimicry [Benyus, 1997][7]. Social aspects were considered through the study of human needs analysis in their classic [Maslow, 1943] [8] and contemporary [Max-Neef et.al. 1987] [9] versions. Finally, economic aspects were discussed through the views of green economy [Hawken et.al. 1993] [10]. The integration of the three components of sustainability derived in a holistic and cross-disciplinary teaching method. Two variations of a practical project developed by undergraduate ID students during the tutorial of an "Ecodesign & Sustainability" module were also tested in two consecutive academic years and later analyzed and discussed. The generic design methodologies [11] used were namely a *"biology to human needs"* approach and subsequently a *"human needs to biology"* approach. Both approaches are compared and discussed though the analysis of student's works in order to evaluate the learning process and outcomes. The basic course plan, as well as several aspects of the implementation of the teaching method, such as course curricula, cross-disciplinary work and other academic activities are also discussed.

3.5 Results

Results suggest that although time-consuming and initially difficult to assimilate by undergraduate students, the teaching and learning method proposed through this research can be a useful tool to enhance cross-disciplinary undergraduate research and motivate creative and critical thinking abilities in the students, while providing basic understanding of the implications of sustainability within the profession of ID.

4. SUMMARY OF THE DISSERTATION

This doctoral dissertation is composed mainly by four parts, which are summarized and briefly explained below.

Part I. Generalities

The initial part of this dissertation describes in general the structure and methodology of the research. This part starts with a general overview of today's society in relation to some of the different challenges that we are currently facing, such as global warming, environmental problems or the development and possible applications of new and powerful technologies such as biotechnology, artificial intelligence and many others. This general context, from the point of view of the author and in relation to his previous professional and academic experience, provides an introduction to the study. Other elements discussed in this first chapter are the significance and relevance of the study, a statement of the problem, a hypothesis and some related research questions, the aims and scope of the research and finally a brief research timeline with the expected outcomes. Due to the integrated, experimental and heuristic character of the research, diverse methodologies were used, such as an extensive literature review to define a theoretical and historical background, the construction of a theoretical model, a practical application of the model to test and verify its validity through quantitative and qualitative analysis and finally a comparative study for final refinements of the model, all these within the framework of *action research.*

Part II. Information Search & Literature Survey

The second part of this doctoral dissertation mainly provides a theoretical background, defining and discussing several topics relevant to the main proposal. In this section, extensive and substantial information and literature review of the main topics is discussed from different points of view and within different contexts.

Chapter 2 discusses mainly the concepts of *design* and *industry*, by elaborating on the definitions and ideas related to Industrial Design. After this, **Chapter 3** studies mainly diverse *Bio-Inspired Design* disciplines, with a special focus on the contemporary approach of *Biomimicry*. **Chapter 4** then explains the ideas of *ecodesign* and *sustainable design* (*design for sustainability, or DfS)* by describing the historical process of sustainable development and defining what is sustainability. The relationship of *design* with the *social, environmental and economic* components of sustainability is also discussed. Subsequently, **Chapter 5** reviews and compares diverse generic design methods within design education, in order to establish a generic design model to support the educational proposal. The corresponding teaching and learning methods relevant to this field, such as the teaching of problem solving and creativity development tools are also discussed. The second part of the dissertation finishes with **Chapter 6**, which presents a comparative study of diverse *Industrial Design*, *bio-inspired* and *sustainable design* courses currently taught in different universities throughout the world. This comparison not only provides an important insight into the state of the art curricula in bio-inspired research and teaching, but is also an important basis to compare and refine the teaching and learning model proposed in this thesis.

Part III. Theoretical Developments & Experimental Application

The third part elaborates on the main thesis and theoretical proposal of this dissertation and discusses the practical application of the proposed education method, through the description, further analysis and discussion of two experimental workshops, named WS1 and WS2. As such, **Chapter 7** starts with an historical background of biologically inspired design, from the industrial revolution to our days. By looking at form, function and process or systems inspired in nature, different contemporary approaches of the relationship between design and nature are investigated and discussed. Subsequently, Chapter 7 discusses in depth the proposed theoretical model by establishing the relationships between biomimicry and diverse ecodesign tools as instruments for environmental sustainability, as well as the analysis of human needs based on the classic work of Maslow and the contemporary proposal of Max-Neef as tools for social sustainability. **Chapters 8 and 9** describe and discuss two different methodologies used to implement the proposed model, as part of a 13 week course with emphasis in the areas of *ecodesign* and *sustainability* taught by the author for two consecutive years (2006 and 2007) in the second year of a four-year bachelor in arts program of industrial design (BAID), in the National University of Singapore. These two chapters are followed by **Chapter 10**, which provides a comparison and discussion of the two methods previously described for the design workshops, which compares the positive and negative aspects of each workshop through the study of the followed procedures, as well as the projects developed by the students. These projects are part of the results of the implementation of the educational model and provide diverse case studies, some of which are analyzed and discussed for further development.

Part IV. Final Conclusions & Further Research

Finally, this dissertation ends with Part IV., **Chapter 11**, in which the diverse results and findings are analyzed and discussed, providing some conclusions and also guidelines for further research on the topic.

5. SUMMARY OF THEORETICAL DEVELOPMENTS

The main elements of the theoretical proposal were organized through the use of diagrams for clear visualization.

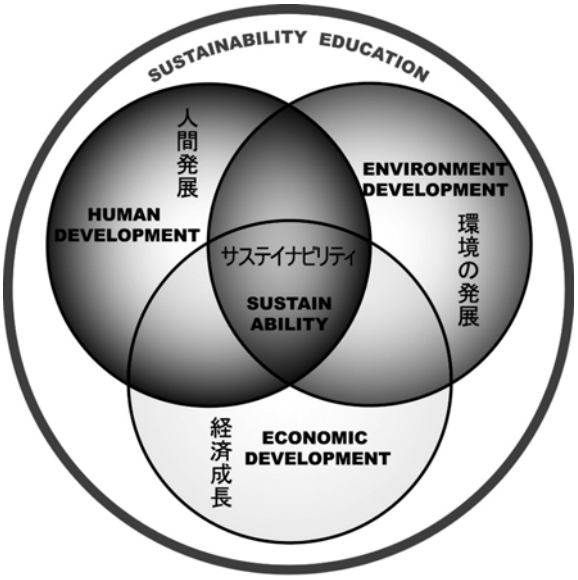

Figure 3. Sustainability diagram (level 1 of learning spiral in figure 6)

Briefly, the main issues of sustainable design comprise the integration of social, environmental and economic aspects (Figure 3). Within this triad, ecodesign can be referred specifically to the environmental considerations of design, especially related to the life cycle of the product. In other words, how the product is conceived (designed), produced, used, and finally disposed of or recycled, and the diverse implications that the actions within these different phases

have on our environment. A general description of the elements and the relationships between them (for the sustainable design education method proposed in this research) is illustrated in the following figure. In relation to ID education and practice, Ecodesign (Design for the Environment, or DfE) is only the environmental aspect of design, and should not be confused with sustainable design or DfS. For an integrated view of DfS, a simplified description of some elements and relationships within *industrial design education* which are relevant to *sustainability* are illustrated in Figure 4. Main components are: (a) *human factors*, related to the social aspects; (b) *ecodesign*, related to the environmental aspects; and finally (c) *economic factors*, evidently related to economic development within sustainability, and areas such as marketing in traditional ID.

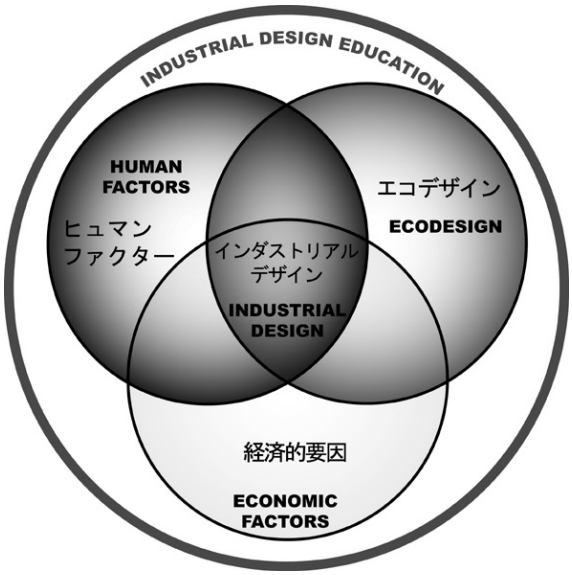

Figure 4. Proposed industrial design education elements (level 3 of the learning spiral in figure 6)

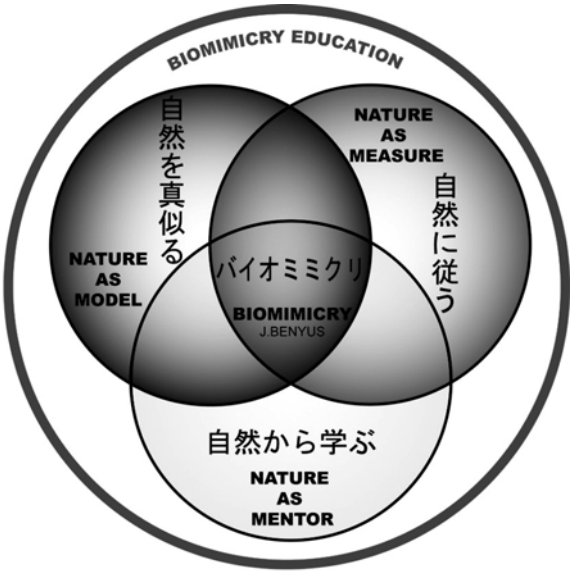

Figure 5. Biomimicry [Benyus, 1977] diagram (level 2 of the learning spiral in figure 6)

On the other hand, since the origins of human kind, people have studied nature in diverse ways to find inspiration to solve their design problems. History is full of examples of diverse approaches to the relationship of nature and design, both with an artistic or technological focus. To briefly mention some few examples of bio-inspired design, technological inventions include Da Vinci's projects, Bionics, Biomechanics and Robotics, among many others. From an artistic point of view, movements such Art Nouveau, Organic Design, Biomorphism or even contemporary "blobjects" also have a close relationship with nature. Within this research, the contemporary approach of *Biomimicry* [Benyus, 1997] was chosen for this teaching and learning method, due to its relationship to sustainability. Biomimicry proposes the study of nature from a systems point of view, in which all elements are interdependent. It understands nature as model, measure and mentor (Figure 5). By understanding nature as *measure*, it respects the limits of nature and thus respects the principles of sustaining life in our planet. This is the main difference of Biomimicry with other bio-inspired disciplines. Biomimicry not only explores the shapes of nature (organic shapes & biomorphism) or its mechanisms (bionics, biomechanics) but also understands nature as a system, encouraging imitation of processes and ecosystems. As such, it is currently used within disciplines as diverse as engineering, materials science and agriculture, among others.

Finally, the teaching-and-learning method proposed was visualized as a growing spiral, in which the three previous diagrams were interrelated. (Figure 6) The proposed model starts from a basis of understanding the elements of sustainability. Afterwards, sustainability is viewed through the filter of biomimicry. Diverse elements related to design are interrelated to provide a holistic view of the complete process. This methodology was explored from the point of view of Industrial Design (ID), and subject to further research might be deployable in related disciplines, such as engineering and architecture.

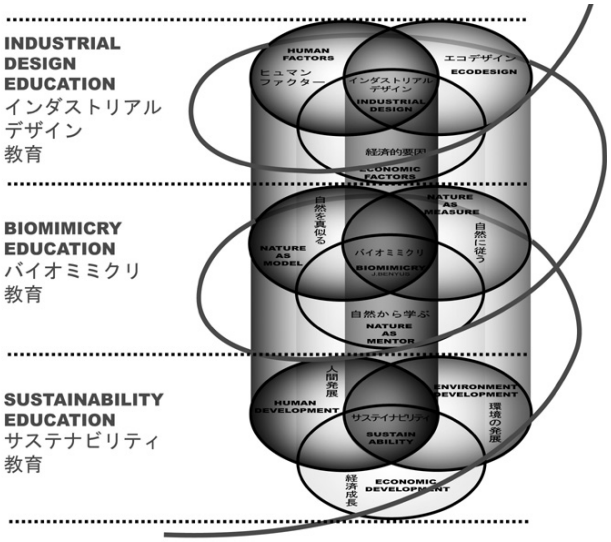

Figure 6. Learning spiral of the proposed sustainable design bio-inspired methodology, integrating 3 previous diagrams.

5.1 History of Bio-Inspired Design

Inspiration from nature has been present in most manmade works, artistic or scientific. Bio-inspired design is not a new approach, but rather current applications and research of very old ideas. As seen through many examples compiled for this research and organized according to the three levels, namely 1) form from nature, 2) function from nature, 3) process and system from nature, inspiration and research from nature and life are increasingly becoming important. Some authors even propose that we are in a period of transition between an industrial society, towards a biological society, in which biological manufacturing processes, biotechnology and all fields related to the study and development of life will be of ever increasing importance. However, looking in retrospect, we can see that since the industrial revolution, in diverse periods the interest for nature as a source of inspiration and ideas has been very important.

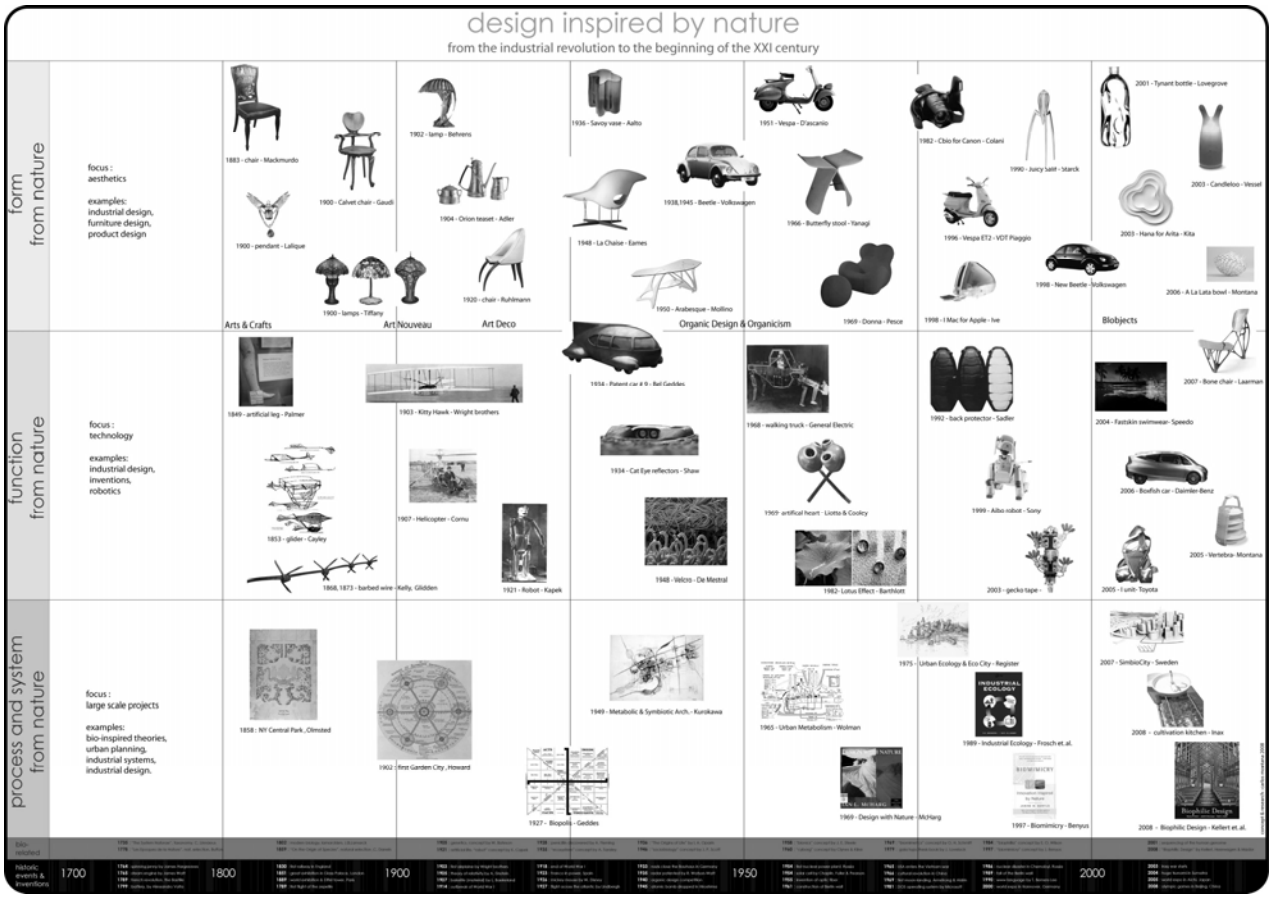

Figure 7. Historic Chart of Bio-inspired design.

6. SUMMARY OF THE EXPERIMENTAL RESULTS:

In view of the previous model as a basis, two consecutive experimental workshops to apply and evaluate two variations of the described teaching and learning method were developed and tested during the academic calendars 2006-2007 and 2007-2008, in the BAID program of the National University of Singapore (NUS). We will briefly summarize the results and findings of these two experiments to implement and test the teaching-and-learning method.

The general learning objective of this experimental module was to stimulate an ethical and responsible approach of ID towards our society and the environment. Lecture sessions covered a wide variety of interrelated topics. Some topics were explained by the lecturer and also guest lecturers from other disciplines or industry. Other topics were prepared and presented by the students. In relation to the environment, diverse texts were extracted from *Okala Curriculum*, as well as related bibliography such as *Cradle to Cradle* [McDonough and Braungart, 2002] and *Industrial Ecology* [Graedel and Allenby, 1995]. In relation to economic aspects, extracts of the book *The Ecology of Commerce* [Hawken, 1993] were discussed. Finally, in relation to *human needs analysis*, classic [Maslow, 1943] and contemporary [Max-Neef et. al., 1987] theories were studied and linked with human factors. An interdisciplinary approach is definitive for this type of course. As such, many of the lectures, as well as some field trips and outdoor classes, were conducted with the help of students from ecology and biological sciences, who kindly volunteered to support this educational module.

In parallel to the lectures, practical projects were developed by teams of students in order to apply the studied concepts. Two variations of the practical project, namely a *"biology to human needs"* and subsequently a *"human needs to biology"* approach were tested within the two academic years.

6.1. Experimental Workshop 1 (WS1) - *"biology to human needs" approach*:

In groups of three students, one practical project was developed during thirteen weeks of the course, in order to apply the design methodology summarized in figure 8. The five steps followed by the students were: 1) biomimetic analysis, 2) biomimetic solution, 3) human problem analysis and 4) eco-design analysis, to finally arrive to 5) the proposal of a design solution.

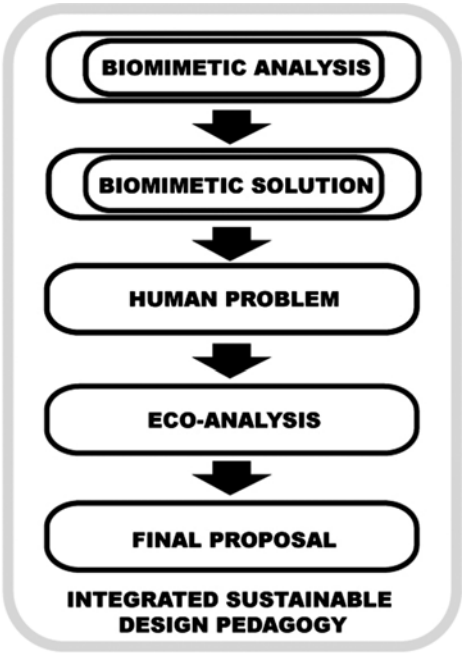

Figure 8. Flowchart of process, practical project in WS 1.

6.2. Results of WS1:

During this course, nine groups of students analyzed the following natural elements: a)Tendrils, b)Dragon Fly Wings, c)Sea Shell, d)Ant, e)Bat, f)Pill Bug, g)Aloe Vera, h)Snail Shell, i)Octopus Suckers. The course produced some very interesting results from the students which will be briefly described and illustrated through some images. As an example, the two most advanced and well developed projects were the following. (Figures 9 and 10)

Figure 9. Clothes-hanger designed and developed from the analysis of aloe vera plant.

In this case the array of the leaves, which provides maximum exposure area to the sun, was translated into more space for clothes hanging. (By students: Lu Yang Fan, Pauline Lazareff, Koay Siwei and Machimon Suwansaksri).

Figure10. Diving fin and flexible material designed and developed from the analysis of dragonfly wings.

The analysis this group made of the relationship between the geometry and the structural properties and flexibility of the wing was very useful for the final proposal. (By students: Lee Wei Chung, Dominic Poon and Sanny, son of Paiman). Following are some images which illustrate the students' process.

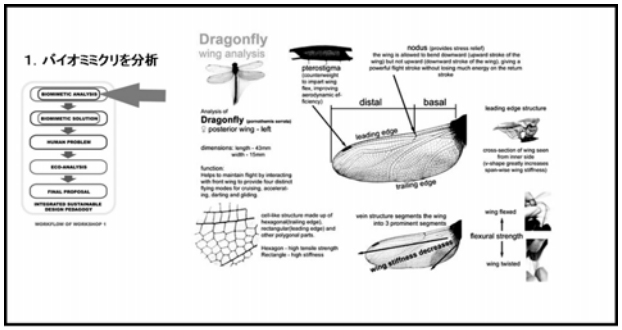

Figure 11. Biomimetic analysis of dragonfly wings.

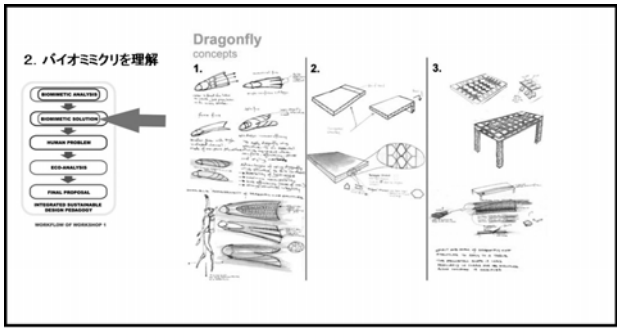

Figure 12. Three alternatives of biomimetic solutions: a) diving fins, b) new cardboard structure, and c) structural table.

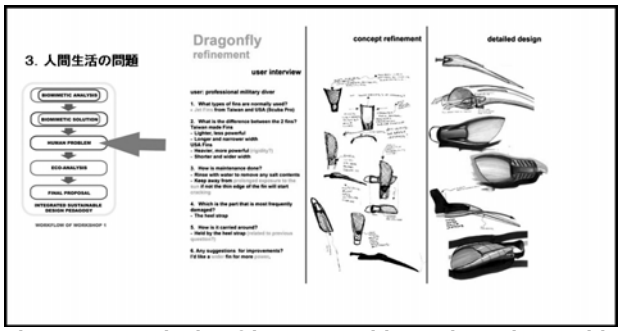

Figure 13. Analysis of human problems, interviews with potential users of diving fins (professional divers).

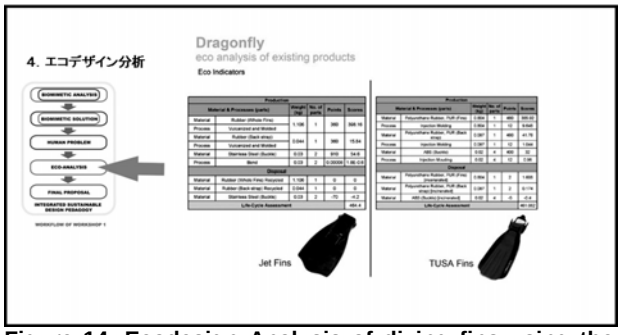

Figure 14. Ecodesign Analysis of diving fins using the Eco-Indicator 99 environmental impact tool.

The previously illustrated case study was considered as one of the best results of the application of the particular methodology. However, during the careful revision of the case study, it was noticed that there were aspects which were worth of revision and improvement. As keenly commented by one of the reviewers (Prof. Takaki, who has a scientific background)[12] one of the most arguable aspects of the case study from WS1 (diving fins developed from the analysis of dragon fly wings) was the incoherence between the structural properties of the geometry of the veins in the wings, and the analogy students proposed through some cardboard sheets which had similar geometries cut into the material. The lack of precision and scientific accuracy (which is common in the design profession and specially in courses from bachelors in arts, as opposed to more technical bachelors in sciences) is evident, and thus should be a point to improve in further courses, probably by looking for the help of a specialist in the technical areas, such as a materials or mechanical engineer.

6.3. Experimental Workshop 2 (WS2) - *"human needs to biology" approach*:

In workshop 2 (WS2) again students worked in groups of 3 persons. Briefly, the process is summarized in Figure 15. The five steps followed by the students were the same as in the previous workshop, but in different order. This project started with human problem analysis, and then proceeded to biomimetic analysis, biomimetic solution, eco-design analysis and finally the proposal of a design solution.

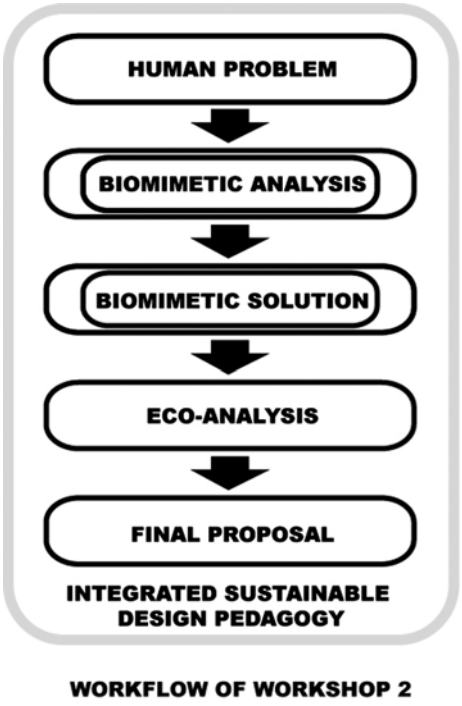

Figure 15. Flowchart of process, practical project WS 2.

6.4. Results of WS2

Several projects providing interesting solutions to human problems were developed under the general theme of *"waste"*. As such, some of the project topics developed by the students were: (a)*Waste of Energy in Air Conditioning:* Moss Wall, (b)*Waste of Disposable Chopsticks in Asia:* Chopstick Repurposing, (c)*Waste of Water in the Shower:* Water Saving Shower, (d)*Waste of Water in Car Washing:* Water Saving Car Wash, (e)*Waste of Energy for Production of Light in Discotheques:* Kinetic Powered Disco, (f)*Waste Generated in the ID Studio:* Internal Waste Management System, (g)*Waste of Tinted Glass in Construction:* Tinted Glass Recycling Proposal, (h)*Waste of Disposable Diapers:* Biodegradable & Compostable Diaper System, (i)*Waste of Material in Shoe Packaging:* 30 % Less Material Shoe Box, and (j)*Waste of plastic bags for wet Umbrellas:* Umbrella drying rack. As an example, two well developed and different projects of WS2 were the following. (Figures 16 and 17)

Figure 16. Chopstick repurposing developed from the analysis of bird nests and cycles in nature.

In this case different techniques of bird nest weaving provided inspiration to develop handcrafted products with discarded disposable wooden chopsticks. (By students: Yvonne Chua, Yong Lin, Sophie Maiko Thornander).

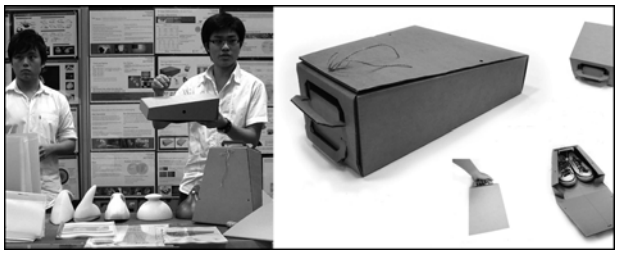

Figure 17. A shoebox which saves 30 % cardboard and can be re-used as a shoe hanger or rack.

The analysis this group made of existing shoe boxes in the market, combined with a biomimic analysis of packages in nature (especially cocoons) proved very useful for the final proposal. (By students: Toh Teck Chye and Ang Wei Quan).

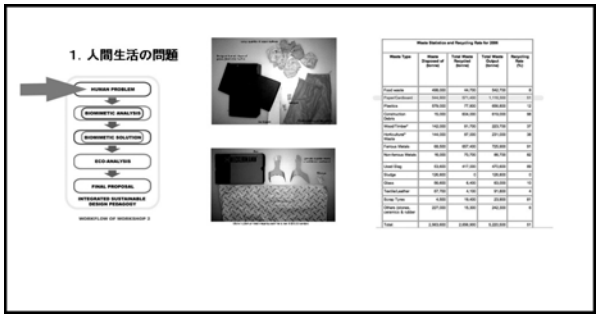

Figure 18. Human problem analysis: packaging materials and statistics of waste generated by disposal of shoe packages.

Figure 19. Biomimetic analysis of packages in nature (cocoons and nests) and cycles in nature.

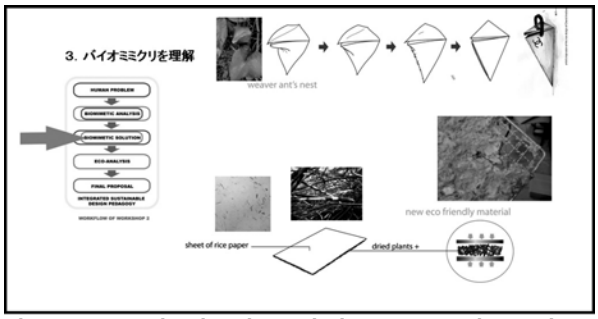

Figure 20. Biomimetic solutions: new box shapes inspired in cocoons, and new package materials inspired by nests.

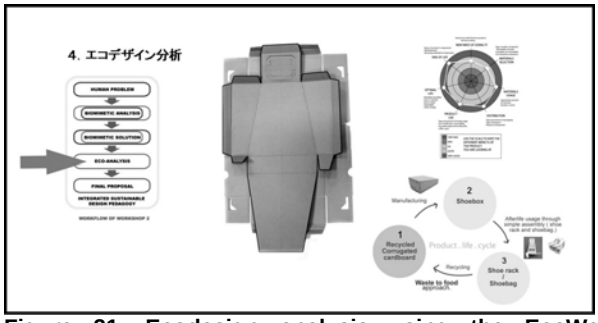

Figure 21. Ecodesign analysis using the EcoWeb indicator and Life Cycle Analysis (LCA) of the new shoebox design.

6.5. Evaluations of Teaching Experiments developed in WS 1 and WS 2

In order to evaluate the two workshops, a questionnaire, to be answered individually and anonymously, was handed to the students of both courses. As noted by the reviewers (mainly Prof. Sagara)[13] it is important to clarify that a direct quantitative comparison of both workshops is not possible, as no control group was used and the students were different in both workshops (thus, their skills and opinion could vary and influence the results). Also, (as noted by CDTL members) mere student feedback cannot be considered conclusive in terms of the effectiveness of a teaching method, except in broad qualitative terms. However, the analysis of the feedback provides important qualitative information useful in appreciating students' perceptions of the course, and thus identifying areas for possible improvement. As such, similar student feedback is also used by diverse universities (as is the case of NUS) to evaluate their teaching staff and programs.

The survey questionnaire (prepared ad hoc for this research) was composed of twelve questions which were to be graded from 1 to 5 according to the following parameters: ***1*** *strongly disagree;* ***2*** *disagree;* ***3*** *neither agree nor disagree;* ***4*** *agree;* ***5*** *strongly agree.* The survey for WS1 was answered by 24 students, while the survey for WS 2 was answered by 26 students. The data in the table below show the results for each workshop in the following order: average of WS 1, standard deviation of WS1, average WS 2 and finally standard deviation of WS2.

Question	**Av. WS1**	Sd. WS1	**Av. WS2**	Sd. WS2	
1. The course fulfilled your expectations and was coherent to the original plan.	**3.42**	0.86	**3.31**	0.91	achievement
9. At the end of the course, there is a clear understanding of the basic themes.	**4.13**	0.53	**3.92**	0.67	
3. The balance between lecture and practical exercise was good.	**3.17**	0.94	**3.46**	0.89	
4. The lectures and material were easy to understand.	**3.54**	0.71	**3.46**	0.69	process
5. The practical exercise was easy to develop according to the information received.	**2.92**	0.95	**2.88**	1.01	
6. The level of difficulty of the practical exercise was appropriate.	**3.58**	0.76	**3.08**	1.11	
7. The workload was manageable.	**3.42**	0.95	**2.77**	0.89	
8. The course is suitable for the second year undergraduate level.	**4.09**	0.65	**3.65**	0.78	
10. There is a clear link between your profession and the course.	**4.50**	0.71	**4.27**	0.81	future
11. The material studied in the course is useful for your future professional life.	**4.21**	0.71	**3.81**	0.96	
12. The information and methodology is valuable and can be applied in future projects.	**4.25**	0.60	**4.00**	0.78	
2. The course was interesting, dynamic and enjoyable.	**3.92**	0.86	**3.62**	0.68	satisfaction

As noted by Prof. Koga[14] and Prof. Takaki, a second survey was conducted with each group 6 months after the course had finalized, in order to further validate the results. The final chart is in the dissertation, but not included in this paper. Also, as suggested by Prof. Saiki[15], the main questions were grouped according to: a) achievement, b) process, c) future, d) satisfaction.

In terms of learning outcomes, when the group who took WS2 was asked if the module had enhanced their critical thinking skills, 65% of the students answered positively. Furthermore, 8% also mentioned that the course "helped them to think out of the box" and to "look at things from many different points of view", which suggests an improvement in creative thinking skills.

Finally, answers to the question: *"What was the most important thing you learned in this course?"* also provide some insight into what the students mostly remembered from the module. Some of most relevant answers by the students were:

"Sustainability, too, is not only about saving the environment. It has social and economic factors as well. That is because even if we designers do our part in making ecodesign possible, there has to be a market for this as well, so the human behavior and how receptive they are to such designs are equally crucial in making the entire sustainability issue".

"In order to achieve a sustainable way of life we should study nature and imitate natural elements and systems. Nature has already solved many problems that could be related to human needs."

"What I have learned from this module is to not just look at a product by itself, but its whole process. For instance its life cycle: manufacturing process, disposal, and so on. I feel that every one of us really has the responsibility to save the planet."

7. SUMMARY OF DISCUSSIONS & CONCLUSIONS

7.1. Discussion:

The experimental results from the noted design projects indicate reasonably strongly that the teaching method proposed in this paper can stimulate industrial design students to generate innovative and sustainable designs inspired by nature. Also, results of the feedback from the students suggest that their awareness of sustainability issues and their relationship with ID increased substantially. According to the student's evaluation of the course conducted by the lecturer (and which was compared to and further validated with the survey conducted by the university), the two most positive aspects of the workshops developed were: (a) the link between the method and the industrial design process and the applicability of the method in future projects, and (b) an understanding of the topics of sustainability and ecodesign after the course. On the other hand, items that got the lowest scores and should be further refined were: (a) the workload of such a course, especially in relation to the balance between lecture and time for guidance for the practical projects, and (b) the clarity and simplicity of the method for the practical project.

Comparing WS1 the *"biology to human needs"* strategy developed in the first run of the course with the second run WS2 *"human needs to biology"* strategy, evaluation and discussions with the students suggested that the second strategy proved more difficult for the students to follow and apply. This observation is consistent with observations by other researchers in the field of biomimicry education [Hoeller, 2006]. It is also important to note that the process followed in WS1 is more related to traditional "bionics" or "bio-inspired" approaches where the designer starts without any constraints with an observation of nature, trying later to find practical application to his findings. WS2 started from human problems and real necessities, thus providing real-world constraints and projects with greater complexity for the students. However, the process of WS2 is closer to the real challenges an ID would face in his professional life and should therefore be encouraged more widely in this type of education methods.

In both WS1 and WS 2, although a systems thinking was encouraged, with a strong focus in the design of process or systems (and many cycles in nature were used as reference of close loop cycles), many of the final results showed some sort of form analogy with natural or organic elements. This is because mimicking form and function in nature is easier than mimicking processes or ecosystems. However, it can also be a consequence of the student's eagerness to make clearly evident the use of nature as inspiration through a literal form analogy.

In relation to the lectures within the course, presentations of topics by the students are considered of great educational importance due to the self-research involved and the training

in visual communication and oral presentation skills. However, it is also evident that this activity increases the workload on the students. Some students expressed to be very “skeptical” of the quality of the information presented by their peers, and requested more lectures by the lecturer, even though each presentation was fully discussed and complemented in class. In relation to the practical projects, some students mentioned as a weakness of the projects, what they felt as *“great difficulty and complexity”, “too much effort required”* and a *“not well defined methodology which was confusing”.* However, intentionally the students had to organize their own work teams, define their own problems, and even sometimes propose their own project method based on the generic design methods [Bonollo and Green, 2004] studied in other modules. Although it is evident that these decisions might be complex for year-two undergraduate students (average age 20 for females and 23 for males within the studied context), the ability to choose a relevant topic or to find a suitable design problem is fundamental for designers. Although demanding, the choice of their own projects and methodologies also provided critical thinking training, while making the students aware of the implications of their own design decisions. On a final note on this aspect, it is timely to clarify that due to the integrative and cross-disciplinary nature of such a course, it is indeed complex and time consuming. However, cultural and pre-universitary educational backgrounds of the students influence their preparation for such a learning system. In the case of Asian students (mainly Japanese and Singaporean observed during this research) as compared to western students, it was noted that while group–work skills are strongly developed in Asian education, individualistic skills such as discussion abilities or self-guidance seem to be less emphasized. This seems to affect the perception of complexity and difficulty of such learning method within the tested groups of Asian students.

Finally, in terms of the positioning of such a course within the curriculum of a 4 year undergraduate ID program, most students agreed that it was suitable in the 2nd year (3rd semester of 8). Some students did comment that due to the complexity of the projects and the importance of the topic, they would rather develop in depth such a project as part of a main design studio. Discussions with design educators from different backgrounds suggest that a DfS course like the one described here should if possible be linked to a design studio, and preferably be taught in a higher level due to its complexity. An interesting indicator which supports this opinion is the increasing variety of post-graduate courses at masters and doctoral level related to sustainable design, which are currently offered in many universities around the world. However, it is also true that the thinking skills related to DfS should be acquired as early as possible, and thus the possibility of a DfS module taught progressively at diverse levels should be further explored.

In summary, and as described in figure 22, we can conclude that the 3 main pillars of sustainability can be understood in different ways from the point of view of traditional Industrial Design, Ecodesign and Biomimicry. When integrated, these three elements can provide a useful method for design for sustainability.

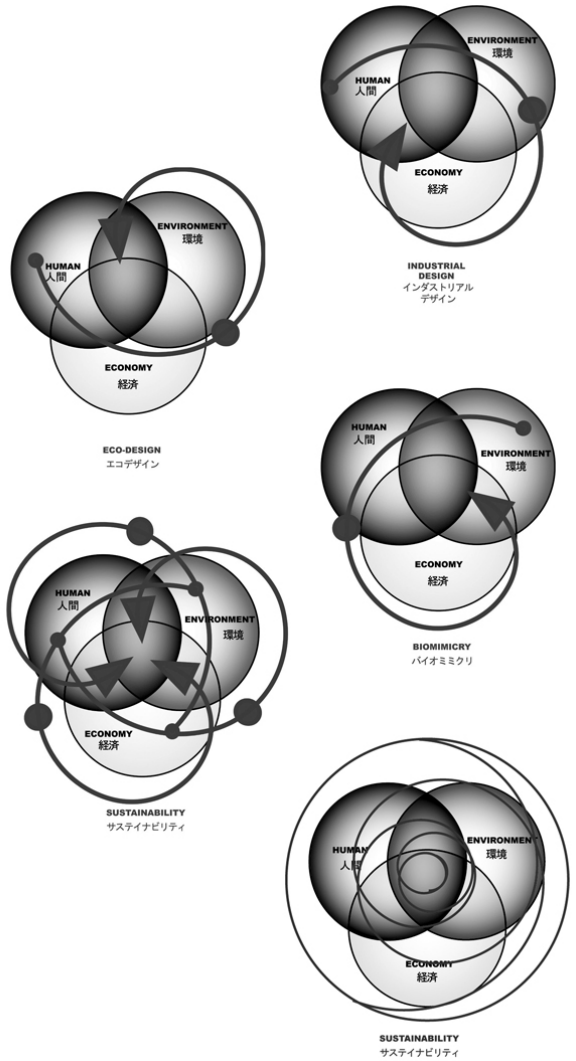

Figure 22. Visual summary of the proposed integrated teaching and learning method of BioID4S.

7.2. Conclusions and Further Research:

Cross-disciplinary studies are very important in professions such as design, as they stimulate creative and critical thinking. An integrated teaching and learning method which combines biomimicry, ecodesign tools and human needs analysis can provide fundamental knowledge for design for sustainability through the integration of social, economic and environmental aspects. However, although stimulating and rewarding, such a process can prove complex and time-consuming for the lecturers as well as for the students and should be further refined. Further short-term research will be conducted in order to simplify the methods and reduce the workload without sacrificing important content and learning activities. A third experimental workshop, WS3, will be undertaken in academic year 2008-2009. It will combine both strategies tested in WS1 and WS2 in the context of the teaching-and-learning method described in this paper. The main project will continue to explore the *"human needs to biology"* strategy, due to its relationship with the common challenges faced by design practitioners. However, the *"biology to human needs"* strategy will also be used in a short session as a sensitizing tool to explore creatively the many possible ideas from nature. Further long term research aims to refine the teaching method, eventually expanding it to a complete ID studio course, a progressive module or even as basis for a postgraduate cross-disciplinary research.

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