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Assessment of BioPattern in Novel Idea Generation for Bio-Inspired Design

Foo Chin Toong[1], Badrul Omar[1*], Azlis Sani Jalil[1]

[1]Universiti Tun Hussein Onn Malaysia (UTHM), Parit Raja, Batu Pahat, 86400, Johor, MALAYSIA

*Corresponding Author

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Abstract: BioPattern is a novel ideation tool for Bio-Inspired Design, built based on TRIZ, SAPPhIRE, and pattern language. It consists of an ontology, known as pattern-based ontology, and a sustainability evaluation, known as Ideal Windows. However, this framework has not been tested yet. Therefore, this article is to present the results and analysis of the case study conducted to assess this biomimicry framework. Two different groups of students, Creative & Innovation class (controlled group) and Integrated Engineering Design class (experimental group), are asked to generate innovative ideas where the experimental group employed BioPattern as the ideation tool. It is found that the level of innovation for the inventive ideas generated by the experimental group is much higher compared to that of the controlled group. Based on the inventive ideas produced by the experimental group, BioPattern is found to be efficient in ideation, able to generate effective solution, the problem-solution pairs of the ontology are adequate, and the biological solutions suggested are transferable as technological solutions. It can be concluded that BioPattern is able to bridge the biology-engineering gap.

Keywords: Biomimicry, TRIZ, SAPPhIRE, pattern language, sustainability

1. Introduction

Bio-inspired design (BID) is the engineering design approach of designing functional products or processes by the inspiration of nature, which is biomimicry. The term "bio" means life and "mimicry" means an aptitude of copying. In other words, biomimetic is the development of innovative technologies, products, and processes based on the use of biological concepts. Biomimicry is used specifically to assist the conceptual design stage where the main problems are identified via abstraction, searching for appropriate working principles, and so determines the principle of a solution. Nature have been intelligently designed where various engineering problems have been resolved countless times in countless ways. This is the reason why BID exists. The word 'biomimicry' was first introduced by Otto Herbert Schmitt in 1969 [1]. Biomimetic is the development of innovative technologies, products, and processes based on the use of biological concepts. Biomimetic, or biomimicry, aims to understand successful strategies adopted by nature to counter human problems. There are numerous successful knowledge transfer from biology to engineering such as Velcro® [2], thermal insulation textile composite [3], lily impeller [4], gecko tape [5], self-cleaning surfaces [6], autonomous self-healing concrete [7], self-reinforced composites [8], oil repellent coating [9], acid resistance surface [10], water distribution and power grid networks [11], [12], and underwater adhesive [13].. However, that is not all. There is still countless knowledge that are yet to be discovered from nature which have the ability to solve engineering problems we face today.

Nature may be a source of inspiration and solution to the engineering world. However, engineers often struggle with the huge amount of biological information available from nature and not knowing which own to use [14]. This is often because the terminologies in biology is not common to engineers. This had made the adaptation process in BID difficult as they do not know how to extract or where to find these inspirations from. Ontology-based search method is

*Corresponding author: badrul@uthm.edu.my

claimed to be the best way to bridge the biology-engineering gap [15]. But existing ontologies are not robust enough; either it is incomplete [16], abstracted models of poor quality [17], or having a small database [17], [18]. Foo presented that there are three potential approaches to bridge the biology-engineering gap [19]; which are TRIZ (*Teoriya Resheniya Izobretatelskikh Zadach*) translated as the Theory of Inventive Problem Solving [20]–[22], SAPPhIRE model of causality [23], [24], and pattern language [25].

Based on the research gap discovered by Foo, a novel biomimicry design approach is developed, called BioPattern. This paper aims to present the assessment result of this newly developed framework by comparing inventive ideas generated by two groups of students, where one is the controlled group while the other group used BioPattern as the ideation tool. The following sections describes how the level of innovation of each project titles are evaluated qualitatively, the methodology of the case study, and finally the results and comparison between the ideas produced by the two groups.

2. Creative process

Considering inventive activity from multiple levels during each stage of creative process is necessary in order to understand the technique of the inventive process. Altshuller presented the creative process, as shown in Table 1, where letters A to F represents the process while the numbers in the first column represents the levels of innovation [21]. The characteristics of each creative process are defined as:

Level One: Using an existing solution without considering other objects.
Level Two: Choosing one solution out of several.
Level Three: Making partial modifications to a selected system.
Level Four: Develop a new system.
Level Five: Develop a completely new complex discovery.

Table 1 - Structured diagram of the creative process [21]

Level	Choosing the task	Choosing search concept	Gathering data	Searching for idea	Idea found	Practical implementation
	A	B	C	D	E	F
1	Use an existing task	Use an existing search concept	Use existing data	Use an existing solution	Use ready design	Make an existing design
2	Select a task out of several	Select a search concept out of several	Gather data from several resources	Select an idea out of several	Select a design out of several	Modify an existing design
3	Alter original task	Modify search concept to support new task	Modify gathered data to support new task	Modify existing solution	Modify existing design	Make new design
4	Identify new task	Identify new search concept	Collect new data relative to new task	Identify for new solution	Develop new design	Use design in new way
5	Identify new problem	Identify new method	Collect new data to new problem	Find new concept / principle	Develop new useful concepts	Change all systems in which new concept is applied

When a part intended for a function is used directly, while no technical contradictions are resolved, it is a *Level One* invention. Based on Altshuller's analysis of 14 classes of inventions from 1965 to 1969, 32% of the patents are Level One. However, if the technical contradictions are resolved by transferring a solution from a similar technical system, causing a slight modification to the original system, it is then considered as a *Level Two* invention. Altshuller found out that 45% of his analysed patents fell in this category, making 77% of the analysed patents a low novelty innovation. Only 19% of the analysed patents are Level Three, where at least one component is radically changed, or eliminated, to resolve technical contradictions. The problem and solution are still within a single discipline. What differentiates Level Four from Level Three is that the newly developed system that resolves technical contradictions uses a solution that is from another discipline. This percentage of this category is less than 4%. Finally, if an invention is invented based on recent discovered phenomena, it is considered as a Level Five invention. This is the level with the least number of patents where it is only less than 0.3%. [21], [26], [27]

TRIZ is considered as a very holistic design tool where it is able to elevate the level of innovations of inventions with the different tools offered to its users. By utilizing the *Inventive Principles* of TRIZ, the user is able to achieve Level One inventions. With *Contradiction* and *Principles*, Level Two and Three, respectively. *Trends* and *Contradictions* will be able to push the idea to Level Four, while *Ideality* for Level Five. [28]

3. Qualitative assessment for level of novelty

TRIZ doesn't only assist designers to invent new inventions, but also plays an important role in accelerating the process of patent analysis by highlighting the contradictions claimed to overcome by the patent [29], including computer-aided patent assessment to determine the novelty of a patent [26].

On the other hand, SAPPhIRE model of causality also have the capability to assess patent novelty by breaking down the patent according to SAPPhIRE's seven levels of constructs and analyse it one by one [30]. According to Srinivasan, when a function is performed by the new product which no other product has ever did before, it has very high novelty. If the function has already existed and the structures are the same as existing products, then it has no novelty at all. Only when the parts and organs are modified, the product is of low novelty. If the phenomenon and effect are also changed, it has medium novelty. But if the state change and inputs are also changed, it has high novelty [31]. By breaking down the working systems of the case studies with SAPPhIRE model, each component can be analysed clearly and evaluated according to TRIZ levels of innovation.

With closer inspection and comparison of the constructs of SAPPhIRE and the criteria of TRIZ's level of innovation, inventions that modified the physical effects and phenomena involved should be of higher level of creativity compared to that of state changed and input methods. This is because a Level Five invention is created based on a newly discovered phenomenon. In other words, the new phenomenon is still not used in any other inventions yet. Furthermore, a Level Three invention employs solutions of the same discipline, which means the effects are still the same. As a result, Table 2 is yielded as the benchmark to evaluate each and every project title submitted.

Table 2 - Assessment tool for Levels of Innovation

Levels of Innovation	Criteria from TRIZ	Criteria from SAPPhIRE
Level One	Direct employment without considering system contradictions.	No modification.
Level Two	• Some components are changed. • Solution from similar technical system.	Change of parts or organs.
Level Three	• At least one component is radically changed. • The solution is from the same discipline.	Change of parts, organs, state, and input.
Level Four	• At least one component is radically changed. • The solution is not from the same discipline.	Change of parts, organs, state, input, effect and phenomena.
Level Five	Created based on a new discovered phenomenon.	New function.

4. BioPattern

BioPattern is a TRIZ-based and pattern-based design framework with a Function-Behaviour-Structure (FBS) abstraction tool to abstract biological information. ARIZ is used as the foundation of the design process. This is because ARIZ is able to guide its user to search for solution pattern from various perspectives such as the opposite situation, existing patents, and operator STC (size, time, cost). The source of solution for the framework will be based on nature's pattern.

TRIZ is used as the backbone of this framework, but it does not have the ability to abstract biological systems and functions because it is derived from artificial and non-living technical systems. Therefore, SAPPhIRE model of causality is employed as the abstraction tool because it is able to abstract behaviour of both biological and technological system. 200 biological systems are abstracted and are compiled into a nature's pattern-based ontology. The ontology addresses a total of 86 problems grouped within 19 categories with 254 strategies from nature.

The sustainability evaluation tool, which is Ideal Windows, is an integrated model of 9-Windows and the Law of Ideality. With a list of criteria from the Law of Ideality classified based on their level of influence, these criteria evaluate how can the system be improved to be more self-sustaining; how does the system react with the super-system, and how can the sub-system be even more efficient.

5. Methodology

In order to assess BioPattern, the research strategy of case study [32] is employed. To implement this case study, a group project is given to a group of students for the subject Creative and Innovation (C&I) in Universiti Tun Hussein Onn Malaysia (UTHM). C&I is a subject where students are needed to apply creative problem-solving techniques in generating new and innovative concepts. The students are required to solve a mechanical problem with traditional ideation method, which is brainstorming. Another group project is given to a group of students for the subject Integrated Engineering Design (IED) (BDA40804) in UTHM. This group will be the experimental group where the students are required to use BioPattern as the ideation tool to produce a concept with biomimicry. Note that the scope of this research is conducted only at the ideation stage of a concept. The outcome will be classified according to the Levels of innovation. Then, BioPattern is evaluated by four study propositions based on the generated inventive ideas:

(1) the efficiency of ideation, (2) the effectiveness of the solution suggested, (3) the adequacy of the problem-solution pairs, and (4) the transferability of the biological solutions to technological solutions.

Table 3 - Description and level of innovation of 28 project titles inC&I class (controlled group)

Project title	Description	Remarks	Level of innovation
Air Cond dryer	Dry clothes with heat released from air conditioner compressor.	Creative reuse of waste energy.	3
Energy harvesting concrete	Generating energy from vehicle vibration on the road with piezoelectric sensor.	Already available in market.	1
Portable grass-cutter	Powered by automotive battery.	Did not solve any system contradiction.	1
Water pump vacuum cleaner	Collects trash from water body.	Improvised version is available in market.	1
Dry leaf crusher machine	Sucks dried leaves and crushed by the chaff cutter in it.	New hybrid of technology.	4
Pocket-sized solar cell mobile phone charger	Charge phone with solar energy. The charger is pocket-sized.	Improvised version is available in market.	1
Mega vacuum	Sucks trash/dust on streets.	Already available in market.	1
The paper Blitzer	Paper is shredded in a blender.	Did not solve any system contradiction.	1
Auto-portable fertilizer mixer	Installed fertilizers are released on the plant when the sensor detected a plant.	New mechanism in agriculture technology.	4
Drinkable seawater distiller	Collect distilled water from evaporated seawater in a dish.	Improvised version is available in market.	1
Air cooler	Channel hot air through water bottle to increase the airflow thus reducing the temperature of the air.	Already available in market. More to handcraft than a technology.	1
Sea cleaner	Trash is collected in the catch bag with water pump in it.	Improvised version is available in market.	1
Loose fruit collector	Collects loose fruits on the ground with rubber band net.	Did not solve any system contradiction.	1
Self-light up sport shoe	LED lights up with piezoelectric sensor instead of battery.	Solution is from a similar technical system.	2
Solar printer	Charged capacitor with solar energy to power the printer.	New power source alternative implemented on printer.	4
Wind turbine mobile charger	Charge phone with wind energy for superbike.	Solution is from a similar technical system.	2
Footstep power generator	Generating energy from footsteps vibration with piezoelectric sensor.	Already available in market.	1
Automotive thermoelectric generator	Charge phone with heat energy from car exhaust heat from engine.	Already available in market.	2
Hydro turbulent	Generating energy from river streams	Already available in market.	1
Green flexible charger	Charge phone with wind energy for superbike.	Did not solve any system contradiction.	1
Caravan turbine	Harness wind energy when travelling to generate electricity	Improvised version is available in market	1
Rain energy harvester system	Generate energy from raindrops vibration with piezoelectric sensor.	The solution is from the same discipline.	3
Eco-gym	Generate electricity with dynamo at rotating parts of a machine.	Did not solve any system contradiction.	1
Foldable laptop table	Adjustable height of laptop platform.	Already available in market.	1
Adjustable water tap	Saves water by altering water spraying pattern.	Already available in market.	1

Roof cooling system	Reduce temperature of roof by spraying water for evaporative cooling.	Already available in market.	1
Smart cooking stove	Portable stove with butane gas.	Did not solve any system contradiction.	1
Plant watering system	Self-watering system with Arduino controller.	Improvised version is available in market.	1

6. Results of BioPattern assessment

In this section, the lists of projects are presented in detailed and also analysed based on the level of innovation. There are a total of 28 projects in C&I class and 12 projects in IED class. Each project team consists of six students, making a total of 168 student and 72 students for C&I and IED, respectively. Table 3 presents the brief descriptions of the generated ideas for C&I projects. Some of the project titles in Table 3 are remarked as '*did not solve any system contradiction*' because when a new solution is introduced, certain contradictions, or trade-offs, appeared and it is not solved. Let the project title portable grass-cutter be an example. The main idea of this project is to use automotive battery as the power source and a motor instead of internal combustion engine to power up a portable grass-cutter. Instead of using an internal combustion engine to power the motor of portable grass-cutter, that could cause air pollutions by carbon emission, this concept addresses the issue of carbonless power source for portable grass-cutter. Furthermore, the motor is much quiet and have lesser vibration compared to that of an internal combustion engine. There will not be any combustion that conduct heat to the back of the user as well. The main aim of this concept is also to reduce the overall weight of the grass-cutter machine to prevent backache. However, the average weight of an automotive battery is over 15 kg, while batteries for trolleys weights around 9 kg [33], which is much heavier than the overall weight of a conventional portable grass-cutter, which only weighs not more than 6 kg [34], [35]. The students could have considered a lighter alternative as a power source so that the overall weight of the grass-cutter can be maintained low.

Another remark that appears frequently in the Table 3 is '*already available in market*'. This remark meant that such innovation was introduced and invented by someone else previously. Some of these innovations are published while some are not. The third remark that frequently appears is '*improvised version is available in market*'. This remark is unlike the previous one where the concept available is still underdeveloped. This remark notifies that the idea generated by the student is outdated because a newer version of that concept is already available. Taking the project titles that are themed reusable energy as example, most of the groups used the same technology to generate electricity for the same function. Similarity reduces novelty. There are four project titles that used piezoelectric sensor to detect vibrations and generate electricity, two project titles that used solar panels, four project titles that used electromagnetic induction method, such as wind turbine, water turbine, or dynamo, while only one project title used thermoelectric generator which is a method that no other groups use. Out of all these similarities, seven project titles achieved Level One, three achieved Level Two, and only one for both Level Three and Level Four, which is rain energy harvesting system and solar printer, respectively, because the ideas are not found in other applications and the similar technology is applied in a new setting. This is also why there are so many level one innovative idea generated from the controlled group.

Another project title that achieved Level Four from the controlled group is the dried leaf cutter machine. This project title describes that by combining a vacuum cleaner and a chaff cutter, a new concept of machine which can suck up dried leaves, and at the same time crushed it into small pieces for better storage, is yielded. By combining two different working principles from two different disciplines, mechanics and fluid dynamics, the level of innovation this concept achieved is Level Four. Furthermore, this concept is not found in any other patent.

Table 4, however, presents a summary of the generated ideas for IED projects. The summary of inspirations from nature are listed in the second column of the table while the final column lists out all the references of *similar* innovations that is already patented, except for project title *waste chute system for apartment*, where no similar patent is found but a commercial product instead. Note that the word 'similar' is used because no exact innovations are found for IED projects except for project title *waste chute system for apartment*.

6.1 Efficiency, Effectiveness, Adequacy, and Transferability of BioPattern

Fig. 1 shows the percentage different between the Level of Innovation achieved the projects of C&I and IED. In other words, the comparison between the novelty level of two different ideation method, brainstorming and BioPattern. The bar chart clearly shows that BioPattern is more efficient in generating ideas with higher novelty. 71% of the ideas generated in the C&I class are Level One ideas, 11% are Level Two, 7% are Level Three, 11% are Level Four, and no Level Five. This makes a total of 82% of the project titles are of low novelty. This trend should not be surprising as Genrich Altshuller found 77% of the patents he came across over four years span were of Level One and Level Two [27].

Table 4 - Description and level of innovation of 12 project titles in IED class (experimental group)

Project title	Nature's inspiration	Description	Similar technology	Level of Innovation
Air conditioner compressor unit relocation device	Ants	A device used to transport air compressor unit with motored wheels.	[36]	2
Candlenut Cracker	Common toucan, Double-wattled cassowary	Cracks candlenut with a rotating lightweight shaft.	-	4
Delivery Drone Attachment	Boxfishes	Streamlined shape for courier attachment to reduce drag force.	[37]	3
Effortless Chain Cutter	Smalltooth sawfish	Sawing mechanism (sprockets) is man-powered by legs.	-	3
Fan Blade Dust Cleaner	Tropical pitcher plants	Extendable fan blade cleaner with sponge and a dust bag.	[38]	2
Floating Garbage Collector	Basking shark, knifefish, aba	Trash-collecting drone controlled by Arduino.	[39]	4
Multipurpose winnower	Mammals, Woodpecker, Birds	Removal of unwanted by-products	[40]	2
Ping pong ball launcher	Tammar wallaby, Chameleon, Bushbabies and Galagos	Launches ball with half-crank mechanism with spring.	[41], [42]	3
Semi-Automatic Seed Planter	Razor clam, Earthworm	Using springs pull open the seed release opening under the soil.	-	4
Shuttlecock collector	Florida manatee	Collects shuttlecocks with a series of flat plates.	[43]	3
Tornado Mixer	Calla lily, Whirlpool	A mixer with an impeller of spiral shape.	[4]	2
Waste chute system for apartment	Darkling beetles, Peepul tree	Trash sorting system for apartment.	[44]	1

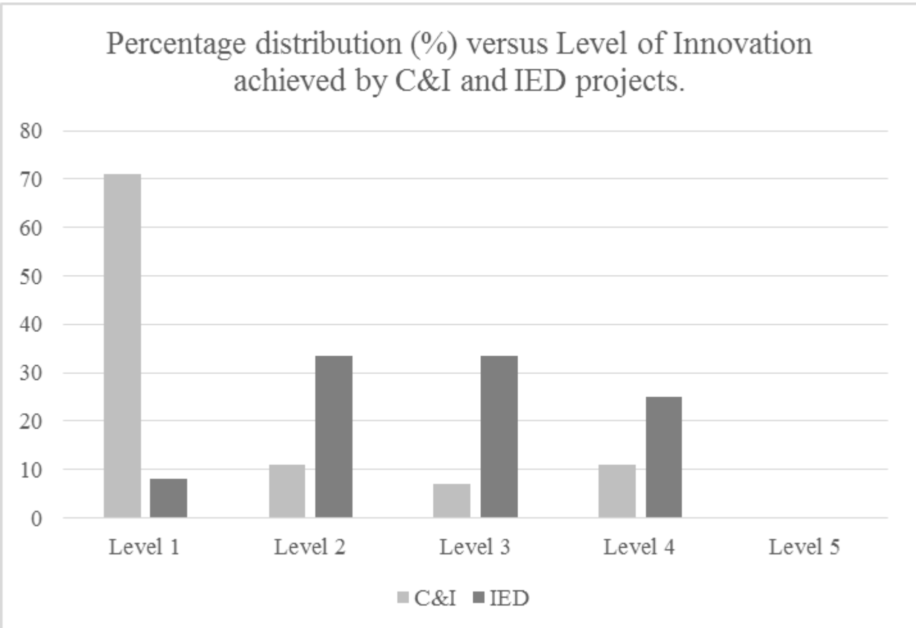

Fig. 1 - Percentage distribution of Level of Innovation achieved by C&I (controlled) and IED (experimental) projects

On the other hand, there are 8% of the ideas generated in IED class are Level One, 33.5% are Level Two, 33.5% are Level Three, 25% are Level Four, and no Level Five. None of the inventive ideas generated by the experimental group resembles each other and none of it perform a same function even though the theme is the same. All of the projects are Level Two and above except for project title waste chute system for apartment. The reason why this project title is the only Level One inventive idea is because this system is already available on the market. This solution is exactly the same as the product of WasteTech Engineering as shown in Fig. 2 [44]. The fact that this solution is already available and not new, this idea is considered to have no novelty with no modifications done to existing products.

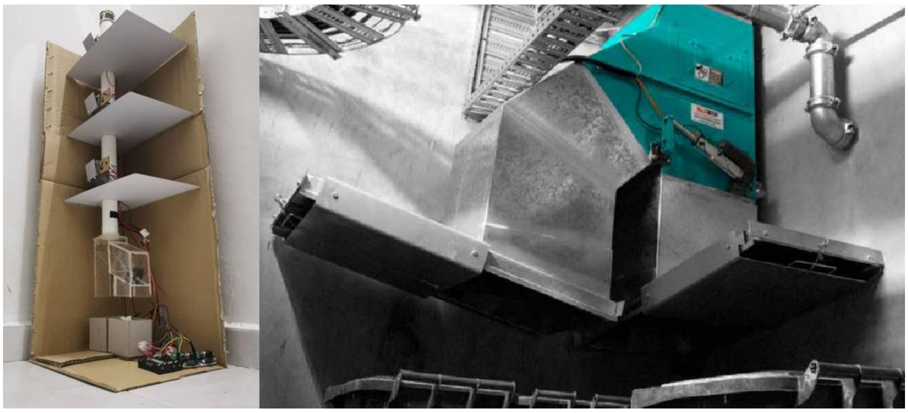

Fig. 2 - Prototype of waste chute system (left), and waste chute system by WasteTech Engineering [44] (right)

The trend for IED class in Fig. 1 is relatable to the efficiency of BioPattern assisting the users to generate creative ideas, be it for problem-driven design process or solution-based design process, except for project titles waste chute system for apartment and air condition condenser unit relocation device. Furthermore, waste chute system for apartment is out of the scope of small & medium enterprise. The students probably had a hard time in figuring out what problem they can apply the strategy suggested by pattern-based ontology. As for the air condition condenser unit relocation device, the group was inspired by how ants are able to carry load many times heavier than their body mass, thus, proceeded in designing a device that can lift objects heavier than the device itself many times. The students have mistaken the analogy of downsizing as an external support system that enables ants to perform the task of lifting heavy objects. However, that is not the case for an ant. The reason why ants are able to do so is because of scale effect, known as surface area-to-volume ratio. Object with large surface to volume ratio is relatively stronger and vice versa. This is also why whales are unable to support its own weight on shore regardless of how huge its bone structures are. This is an example of misapplied analogy and improper analogical transfer mentioned by Helms where analogy or principles are interpreted and transferred wrongly [45].

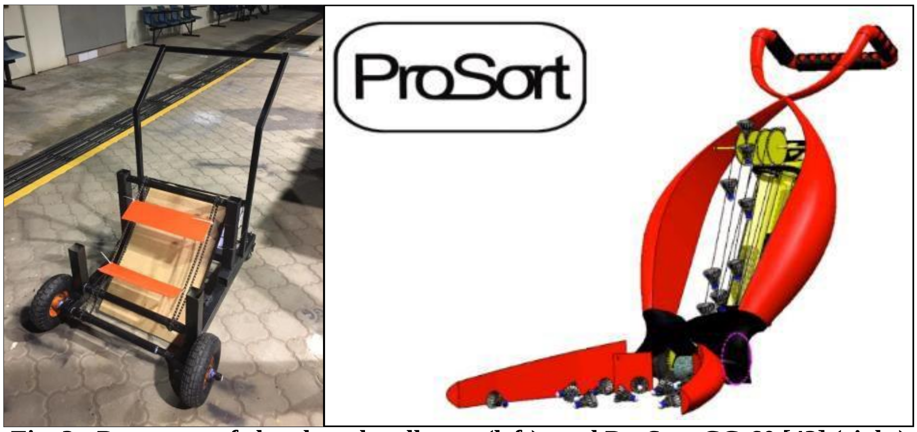

Fig. 3 - Prototype of shuttlecock collector (left); and ProSort CC-60 [43] (right)

BioPattern did not just assisted the students to generate ideas that they need based on the ontology, but also sparked solutions beyond the boundaries of the ontology. For example, the project title shuttlecock collector originally wanted to use brushes to collect shuttlecocks. However, after evaluating the concept with Ideal Windows, they replaced the brushes that imitate the bristles of a Florida manatee to flat plate. Fig. 3 shows a functional prototype of the idea where shuttlecocks are guided by the foam plate, up the inclined plane, and into the basket behind it. However, this does not prove that the solutions provided by BioPattern is ineffective. ProSort CC-60 used brush to pull in shuttlecocks [43]. Ideation can be assisted, but the experience of putting a solution to good use is dependent to each user. Fig. 4 shows the functional prototype of the floating garbage collector, inspired by the tangential flow filter of a basking shark and undulating fins as propagating method. This project is supposed to be a Level Five invention. The reason it is not able to achieve Level Five is because it resembles an invention invented by Richard Hardiman, called the "WasteShark" which is a water drone that picks up any floating trash that comes across its path [39]. Thus, resulting as a Level Four invention. Another project that also shows the effectiveness of the solution provided by BioPattern is the candlenut cracker, where the cracker shaft is strong and yet lightweight. The lightweight structure is inspired by the foamy structure of a toucan's bill. This highly reduces the motor power required to rotate the shaft and transmit the power to crack nuts. Fig. 5 shows the functional prototype of the candlenut cracker. Ping pong ball launcher, as shown in Fig. 6, is also one of the best example of solution effectiveness, where spring is used to load and launch the ping pong balls just like how a chameleon launch its tongue out to catch prey items. It is undeniable that some of the strategies suggested by pattern-based ontology is very common to the engineering world, such as "spring" which is widely used in all sorts of repulsion devices. This proves that the solutions offered by BioPattern is technically feasible and relevant to the engineering world as some of the strategies had already been widely used.

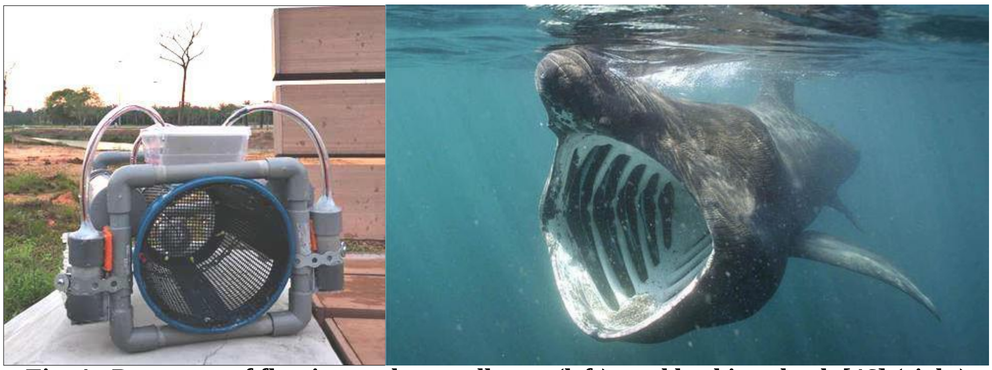

Fig. 4 - Prototype of floating garbage collector (left); and basking shark [46] (right)

Fig. 5 - Prototype of candlenut cracker (left); (a) Common toucan, *Ramphastos toco* [47]; (b) cross-section of toucan beak [48]; (c) scanning electron micrograph of exterior of toucan beak (keratin surface) and (d) scanning electron micrograph of interior of toucan beak [49]

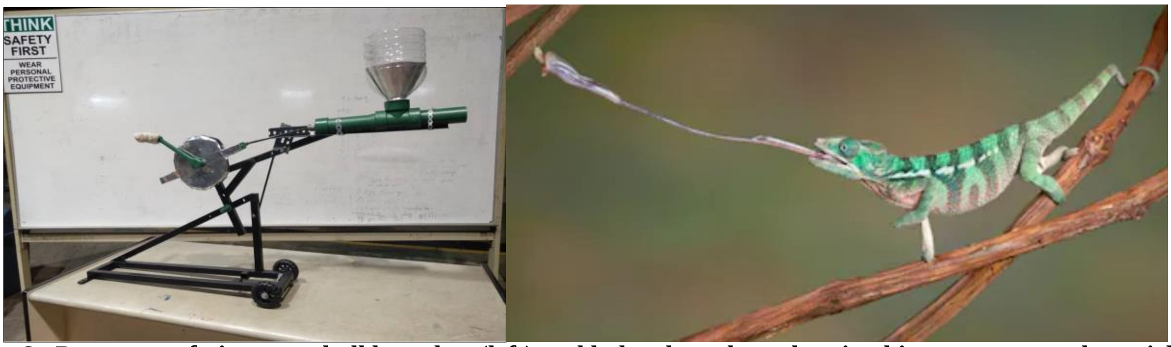

Fig. 6 - Prototype of ping pong ball launcher (left) and baby chameleon shooting his tongue to catch a cricket [50]

In terms of adequacy of the problem-strategy pairs, according on all of the project titles, it can be concluded that the problem-strategy pairs are adequate and is able to perform the desired function. For example, the project delivery drone attachment wanted to save energy by reducing the aerodynamic drag. Mimicking the shape of a boxfish performed the task perfectly. The main objective is achieved. But in some cases, the strategy may not be directly related to the main objective, yet it can still be used as a support to the main objective. For example, the strategy of 'air pockets' is not relatable to the function of cracking candlenuts at all. However, by breaking down the main objective to sub-objectives, the students are able to identify other contributing factors that supports the mechanism that fulfils the main objective more efficiently, that is to make the cracker shaft lighter so that lesser energy is needed to crack the nuts. However, the strategy of 'air pockets' have countered the problem of 'light-weighting' perfectly in this project. This list of functional prototypes also shows that the solution suggested by the ontology is transferable from biology to engineering.

Table 5 - Strategy description of "water surface tension" frompattern-based ontology

Category	Problem	Strategy	Description	Organisms
Buoyancy	Float	Water surface tension	Microstructures did not break the water surface tension.	Whirligig beetle, diving beetle

Fig. 7 - Prototype of fan blade dust cleaner (left) and *Nepenthes bicalcarata* intermediate pitcher [51] (right)

Nature is an outcome of intelligent design where engineering principles are applied everywhere, from the ecosystem level to the microscopic level. Every solution that these living organisms used seems to be the most efficient in their respective cases, while the solutions that nature used to counter a similar problem are different for all these different levels. In other words, there is not a solution offered that fits all problem. Even if it is at a same level, nature has numerous solutions for that one problem given the constraints of the specific organism facing the problem. Project title air condition condenser unit relocation device is an example where the strategy is not transferable to the case because the level of application is different. The solution implemented in only feasible and transferable at a microscopic level, while the students attempted to implement it at a larger scale. There are actually more of such example in pattern-based ontology. Another example that is affected by scaling effect is strategy 'water surface tension' used to counter the problem of 'float' as shown in Table 5. Both whirligig beetle and diving beetle are small and have spatula structured legs with micro hairs on it, enabling them to float on water surface. Furthermore, their weight is almost negligible. It is impossible for a marine engineer to design a boat with the same structure of the beetles due to scaling effect. Therefore, as long as the strategy suggested is applied at the right levels, the strategy will be transferable from biology to engineering without any problem. However, it is undeniable that some of the strategies are hard to fabricate and requires higher manufacturing cost due to the unavailability of the technology. An example is the dust bag of fan blade dust cleaner, which is inspired by the wall of a pitcher plant where ridges are found. Because there are no such bag that resembles the ridges of a pitcher plant yet, the students are not able to fabricate one at low cost, even though it is feasible. The students resolve this issue by replacing a cloth bag instead as shown in Fig. 7.

6.2 Applicability of BioPattern for problem-driven and solution-based approach

By utilizing pattern-based ontology, the students are able to not only complete the project with problem-driven design approach, but also solution-based design approach where they are first inspired by a solution from nature. The solutions are basically from the strategy column of pattern-based ontology, before the students have any problem in mind. In fact, there are more solution-based concepts than problem-driven concepts as shown in Fig. 8, eight and four respectively. Students seems to have the tendency to rely on a given solution then only search for a relatable problem in their daily life. This is probably due to the lack of industrial experience in students where exposure to actual industrial problem is low. The same trend where ideas of solution-based approach is higher than problem-driven approach in student's project is also found in Farel's bio-inspired ideation workshop with a total number of 73 solution-based ideas out of 118 generated ideas [52].

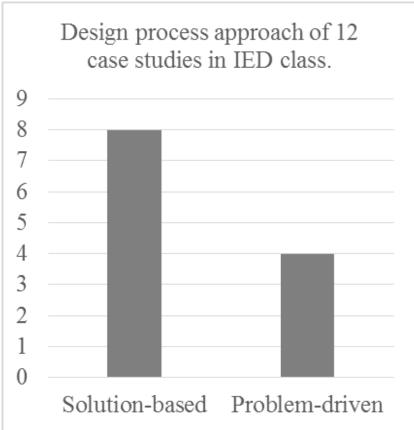

Fig. 8 - Design process approach of 12 case studies in IED class

Based on the student's design approach, it seems that a solution-based approach is more important than problem-driven approach. However, there is no existing tool that facilitate only the solution-based approach. Probably it will be less convenient if a biomimetic tool can only be used to solve problems in a solution-based approach because engineers and designers are working in specific disciplines and each discipline have their own respective problems. It is more effective if the tool is able to support the designer in both directions of design approach. This statement is also confirmed during the validation process where both the two chosen industries voiced out the problems, they faced that requires a solution, instead of referring to the ontology and say *'this sounds like a great idea, so let's find a problem that we have to implement this.'*

7. Conclusion

The biomimetic framework BioPattern had been constructed to bridge the gap between biology and engineering. Based on the analysis from the design projects by the experimental group, it can be concluded that BioPattern is able to facilitate the biology-engineering gap. According to the results obtained, the level of innovation of IED class projects are much higher compared to that of C&I class projects. 71% of the ideas generated in the controlled group are Level One ideas, 11% are Level Two, 7% are Level Three, 11% are Level Four, and no Level Five. While there are 8% of the ideas generated in the experimental group are Level One, 33.5% are Level Two, 33.5% are Level Three, 25% are Level Four, and no Level Five. This clearly shows that BioPattern is more efficient in generating ideas with higher novelty and the solutions generated are effective in solving the target problems. The problem-solution pairs are also matched adequately. The strategies suggested by BioPattern is also transferable from biological context to engineering context. If BioPattern is able to assist students with no industrial experience to generated high novelty ideas, this means that BioPattern also have the tendency to assist engineers and designers in ideation. Furthermore, industrial experiences of engineers and designers will be valuable assets for them to generate innovative ideas of high novelty and ground-breaking inventions.

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