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How to help Mechanical Engineers to find a conceptual idea in Biomimicry?

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> *“If you want to go fast go alone. If you want to go far go together.”*

Abstract

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How to help Mechanical Engineer to find a conceptual idea in Biomimicry?

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Abstract

It is possible to decrease the workload, timing and the costs of the innovation process by biomimicry. The problem is that mother nature does not keep track of its inventions of living organisms, their functions, and ecosystems.

This thesis work seeks to build an innovation process model with the use of biomimicry and assist it with all available tools and accessible databases. Data was collected from secondary sources from different relevant books, online materials, credible journals, and articles. The final model was built as the combination of existing schemes and trees within adjustments. It provides an engineer with the list of methods for choosing the concept, its abstraction to and from biology, and final election.

The represented documentation also provides found recommendations for future regulations and standards to achieve sustainable impact of a result.

Keywords

biomimicry, innovation, idea generation, innovations process model, biomimetic databases

Contents

LIST OF SYMBOLS AND ABBREAVIATIONS

BioM	Biological Modelling
DANE	Design by Analogy to Nature Engine
KARIM	Knowledge Acceleration and Responsible Innovation Meta network
SAPPhIRE	The State change, Action, Part, Phenomenon, Input, oRgan and Effect
TRIZ	Theory of Inventive Problem Solving

1 Introduction

This bachelor's thesis aims at investigating a language of transforming a request from an engineering problem to the domain of knowledge about nature. The work is based on biomimicry as a science, but the problem is that nature does not bear a record of what it invents. There are many studies of biologists of various mechanisms and wonders of the alive world, but it does not look like a patent database. To assist a mechanical engineer with a structured route from a wish to final solution via biomimetic instruments, data is collected from secondary sources from different relevant books, online materials, credible journals and articles.

1.1 Background: Biomimicry as a science

A combination of Greek words bios (life) and mimikos (imitation) has combined in single word biomimicry. There are several words with the same definition such as biomimetics, bionics, biognosis and bionical creativity engineering. However, the proper definition was presented by Kennedy as studies on the most successful evaluations of nature and its imitating implementations on design and processes in order to fulfil human needs. (Kennedy 2004, presented by Volstad, N. L. & Boks, C. 2012, 190.)

For the last 3000 years, nature was the inspiration for many human inventions. Historically, it started from the first trial of the Chinese to make synthetical silk and could be highlighted by Leonardo da Vinci, who was curious in studying the structure of a flight of birds (Romei, F. 2008, 56). His observations provided the first sketches of a "flying machine" as shown in Figure 1. First flying machine sketch by Leonardo da Vinci, which was used later in 1903 by the Wright Brothers for the first successful heavier-than-air aircraft (Howard, F. 1998, 33).

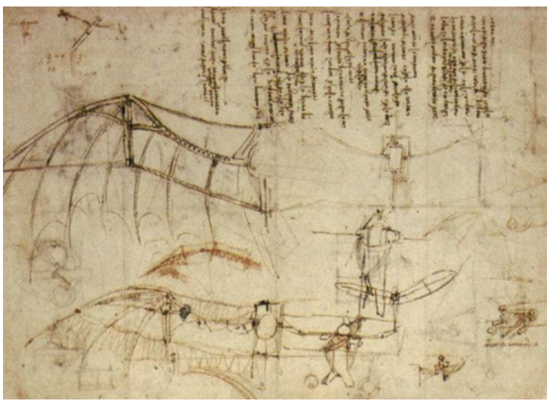

Figure 1. First flying machine sketch by Leonardo da Vinci (Wikipedia 2021.)

After many years of working on the topic, humankind came to model 3 approaches to biomimicry. They are based on form, process, and system.

The natural form is the first and basic level of biological imitation for the engineering field. It represents a copy of the physical characteristics of the living organisms and may produce efficiency in designing. For instance, a wind turbine blade was developed on a basis of humpback whale fin by Dr. Frank Fish. As a result, it caused an improvement in ascensional power and reduction of the resistance in the turbine. It was an example of a successful invention in a sustainable approach. Nevertheless, biomimicry does not compliment green technology on the regular lever.

Figure 2. Wind turbine (DMA Europa 2017.)

Figure 3. Humpback whale (Harvey, D. & Harvey, F. 2016.)

On the opposite side stands the bionic car presented by the Mercedez-Benz. Excluding the loss of strength and safety, radical development of the automotive aerodynamics and fuel expanse was achieved by the adaptation of the form and bone structure of a boxfish. At the same time, the manufacturing of the machine causes pollution.

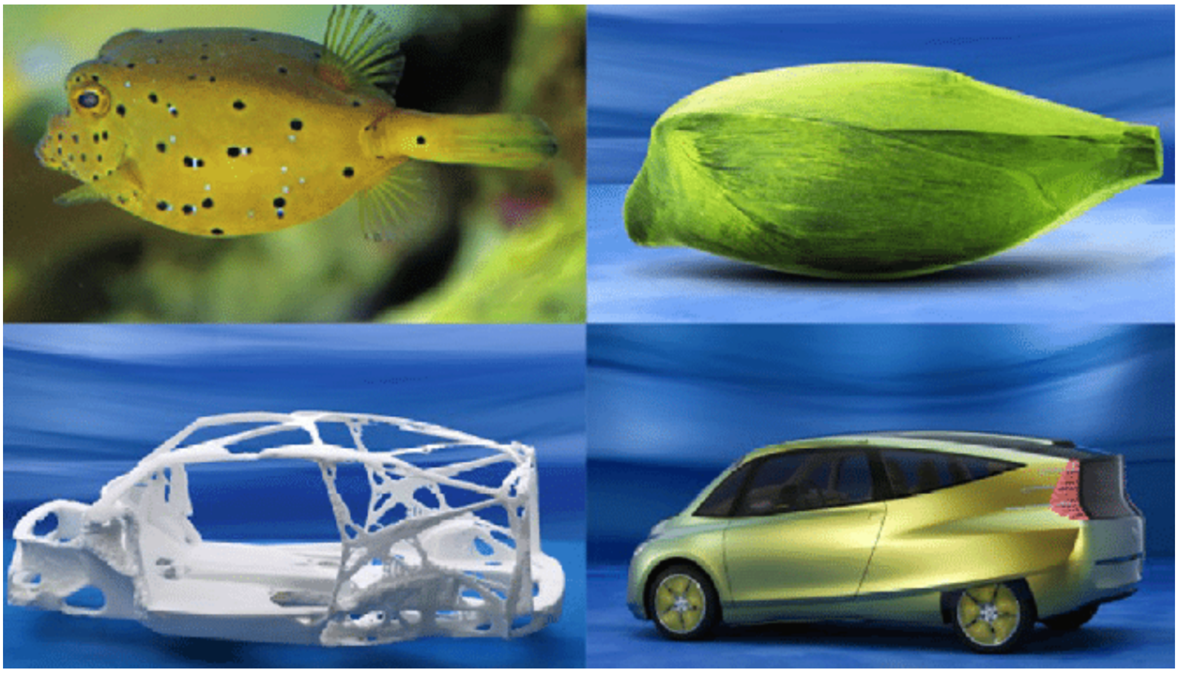

Figure 4. Bionic car inspired by form and bone structure of a boxfish (Abdel-Rahman, W. S. M. 2020.)

The next level of biomimetic implementation is an imitation of biological processes. One of the successful engineering sustainable examples was inspired by spider silk. The technique is based on proceeding raw materials through blood heat and pressure. Additionally, it neglects water and toxins.

Ecosystems are more complicated to be copied. The goal is to create a network of functional materials and operation, which will fulfil the needs of an engineering field and act green. (Miller, J. D. 2010.)

As viewed, mother nature has never been such inspirational for innovations as it has been nowadays. The connection between technical problems and existing biological solutions has been recognized and applied in mathematics, engineering, material science, medicine, architecture, and arts (Sharma, S. & Sarkar, P. 2019, 88).

1.2 Research problems and questions

Biomimicry is a rapidly evolving science, and despite the abundance of literature, there is currently no clear operating system that would allow for the clear step-by-step explained application of biological discoveries in engineering. It is widely known that the theory itself provides an excellent foundation for work in design and engineering, but it is not enough. There is no functional structure or strategy to use, and biomimicry requires going all the way from scratch in every invention: the literature review, numbers of trials and errors in its approach and the final result. Nevertheless, it is not simple as it sounds. (Vincent, J.F.V. et al. 2006) A straight imitation is not enough, and thesis questions can be represented as follows:

1. How to build a general approach to adapt biological ideas in engineering innovations?

2. What are available and accessible biomimetic instruments for each step in innovation process?

1.3 Objectives and motives

The objective of the bachelor's thesis is to find or build a cross-disciplinary dialogue between mechanical engineering and biology. The main idea of engineering is technological optimization through studies on materials, their structure and operation to achieve reductions in weight, costs, and speed. The evolution of the idea happens with original slant, technical innovations, and brand-new ideas. At the same time, biology mostly focuses on the awareness of living systems and their principles. The intersection point of both sciences has been showing successful results of inventions. (Gebeshuber, I.C. & Drack, M. 2008, 1282.) While most of the answers have already existed in mother nature, the functional framework of its application is required. It will save time, costs, and work at the beginning stages of technical projects.

1.4 Research Methods

For the drafting of this thesis, different methods of research are used. To start, a literature review is conducted into relevant existing books, online materials, credible journals, and articles in the scope of this work. Related aspects of other projects are noted and discussed. With the help of sample data, a biomimetic framework will be created to represent the route from the field needs to a final emulated idea from nature. Moreover, a list of available biomimetic databases is collected. In the end, it is followed by found recommendations for future adjustments in existing list of regulations and standards to achieve sustainable results from biomimetic concepts.

2 Role of biomimicry in idea generation process

2.1 Idea generation process and techniques

Product development is based on the competence to invent, create, and innovate of an engineer (Linsey, J. S. et al. 2008, 277). All innovations start from an idea, which is proven by its definition. Heap (1989) explained innovation as an application of the synthesis of novel concepts. Level of the creativity from the beginning impacts on dynamics of the company (Gore and Gore 1999, according to McAdam, R. 2004, 697). Furthermore, a result of the step directly affects manufacturing expenses and costs of a final product.

There are numerous numbers of idea generation methods in psychology, business, and engineering in order to aid in the process of product development (Adams 1986, VanGundy 1988 and Higgins 1994, found in Linsey, J. S. et al. 2008, 277). In the same work, Linsey and team (2008) discussed five techniques within writing and sketching basis in teamwork:

1. Osborn's Brainstorming – verbal discussion of all possible concepts in a team. The main rules of the method are covering huge quantities and avoiding any judgement to empower "wild ideas", its adjusting by group members.

2. Brainsketching – a silent exchange of sketches and further modifications within the team.

3. Gallery – similar practice to brainsketching with the only difference of discussion of each concept between two sketching.

4. C-Sketch and/or 6-3-5 – a technique, where six colleagues work on three concepts during an established time and switch their papers five times around the table.

5. Experimental approach – a trial to combine four mentioned methods above via a factorial experimental design.

Described methods are mostly focused on quantity rather than quality. A large quantity of generated ideas in a team may be limited and require a lot of time. At the same time, inventiveness can become artificial and automated with the use of analogies implementation. It drives to interdisciplinary dialogue in the early stages.

2.2 Biomimicry: motivation for the dialogue

Busby and Lloyd (1999) called humans imperfect search engines. Moreover, Schild, Herstatt and Luthje (2004) proved that designers invented within a narrow circle of cognitive capabilities, according to the theory of bounded rationality by Simon (1976, 1983, 1996).

Analogies transition is frequently utilized in engineering design with the aim to rise above these boundaries. (Wilson J. O. et al. 2010, 169.)

Biomimicry as an analogical approach is beneficial in both directions. It assists engineers with a novelty of concepts and benefits in costs. Furthermore, bionics greatly supplies biology with product creation and the structure of living systems.

2.2.1 Motivation for engineers

Mechanical engineer goes through several stages from the human need to the ready to use the product. The success of the final result and a plan for its realization straightly depends on the beginning stage of the idea generation process. Biomimetics provides huge support right in this step.

Biomimicry is based on the transmission of expertise in living organisms, their functions, and the system they belong to into technology. A direct replica of biological processes will never lead to a fruitful result. Science calls for creativity to the modified and abstracted version of the mechanism of nature.

Gedeshuber and Drack (2008, 1282) proposed to divide biomimicry into two leagues according to the performance time and potentials:

- Biomimicry by induction – engineering approach of general rules from nature without a specific goal from the beginning.
- Biomimicry by analogy – implementation based on individual solving of engineering problems via comparable examples in nature.

Biological analogies in engineering enhance the novelty of concepts and avoid a large number of variations. As a rule, it provides efficiency in time management. Biomimicry by induction initiates a solution for a potential problem and provides strategy in advance. On the other hand, biomimicry by analogy wins time in concept generation. After the analysis and description of occurred engineering issue, it explores nature for a correlative solution instead of inventing the brand-new idea. Moreover, biomimetics may provide the decrease of costs for manufacturing and may cause more sustainable impact of the product.

2.2.2 Motivation for biologists

Although the focus of this work is on beneficial sides for mechanical engineers, a specialist in biology earns their own profits. As a science, biology deals with a wider scope of knowledge about life from the cells of organisms through evolution and to the process of moving, growing and reproducing. And engineering contributes it to the solution of creation of products, modifications, and regulations in natural systems.

Nachtigall (1997) disseminated a term of technical biology, which concentrates on utilizing principles from physics to explore organic forms, structure, and behaviour. In practice, it assists biomimicry by induction via explaining biological principles. It inspired Barth (2002), who produced spider mechanosensory modelled on basis of strain gauges. (Gebeshuber, I.C. & Drack, M. 2008, 1283.)

3 Biomimicry approach in engineering innovation process

The first and most common appearance of biomimicry in engineering occurs at the design stage. Generation of new ideas, the performance of its usefulness and progress to complete functionality led to inventions done by designers (Skogstad, P. & Leifer, L. 2011, 20). Additionally, Skogstad and Leifer (2011, 41) presented universal model of the design process from wish and/or problem to solution, as it is shown in Figure 1. Unified Innovations Process Model for Engineering Designers and Managers. The model consists of three phases (Plan, Execute, Synthesize) and interruption of the flow to see the possibility of building communication tools for designers and project managers. At the Plan stage, a blueprint transforms into a few concrete ideas and management of labour is done within a risk analysis. Execution is followed by developed drawings and prototypes. It is an opportunity to test ideas and provide the results to the Synthesis part, where parts are assembled into a whole system.

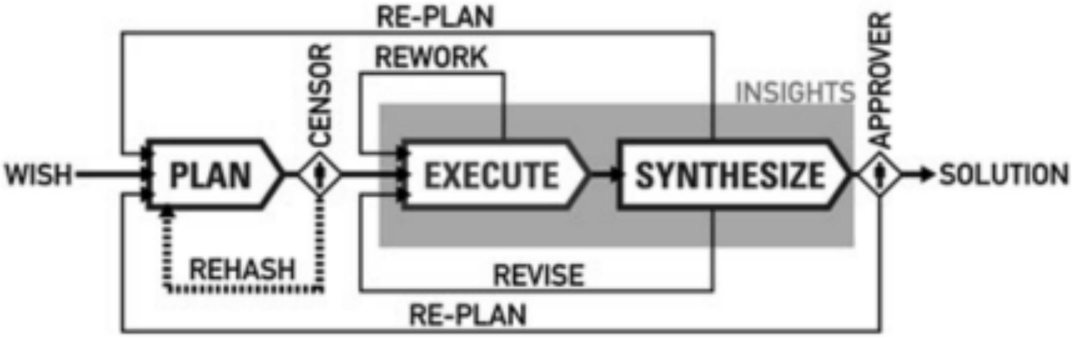

Figure 5. Unified Innovations Process Model for Engineering Designers and Managers (Skogstad, P. & Leifer, L. 2011, 41.)

As a result of the published work, it was proposed to serve with more space at Execution and Synthesis for designers without management intervention. It allows to examine and accomplish concepts before censor since the fruitful idea generation is based on encouragement to try all ideas without judgement. That path can be chosen as the possibility to implement a biomimetic solution and observe its behaviour.

The concept of the work in biomimicry does not have significant differences from basic engineering procedures. It starts from problem recognition and goes all the way to a solution inspired by nature. Usually, human need identification is followed by brainstorming new ideas during the engineering workflow. Although, biomimetic proceeds with an analysis of all possible root-cause in order to start research on the familiar issues in living organisms and systems. Figure 2. Problem-solving strategy for biomimicry in engineering represents the clear path of biomimetic solution strategy in mechanical engineering.

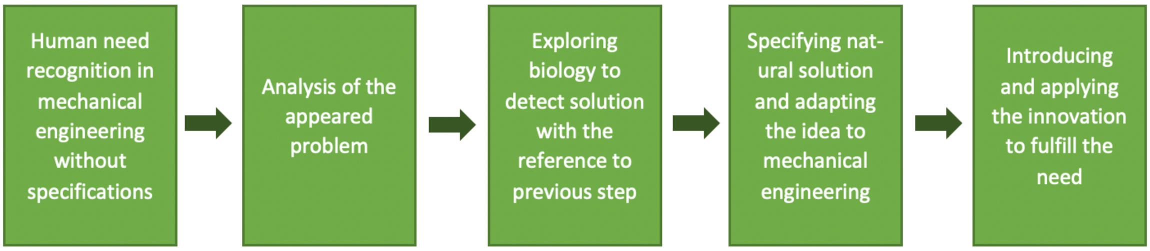

Figure 6. Problem-solving strategy for biomimicry in engineering

By comparing both figures, they have the same start point of recognition of the wish and one output as introducing a final solution to an approver. Analysis of the problem with the biomimetic research should be done in the mentioned Plan part from Figure 1. Meanwhile, the step of solution specification and its adaptation to engineering from Figure 2 unfolds to two stages of Execution and Synthesis. Execution allows a mechanical engineer to develop design drawings if needed and to model, code, build or machine first prototypes. It provides a realistic picture of future innovation and its first tests. Success from the Execution part goes through Synthesize step for completed improvements before the final solution. Usually, it consists of the adjustment and final testing. (Skogstad, P. & Leifer, L. 2011, 21.)

The goal of the current thesis report is to insert a problem-solving strategy for biomimicry in engineering inside the unified innovation process model including available and accessible tools.

4 Scoping phase of the engineering innovation process

The transmitting stage of a Wish to idea generation process is the scoping phase. Basically, it is a brief description of future concepts within expected functionality and design criteria. According to Rowland (2017), the synopsis consists of the following information:

- the selected design challenges
- background of the appeared problem and possible solution performance
- a list of the specific functions
- strategic view of required result and its impact
- principles of life relevant to the established challenges.

The potential concept should be fully studied. Detailed context facilitates the future discovering phase for an engineer. There is a numerous collection of research tools. However, a decision of a particular scheme depends on different prospects such as functionality or systemic sustainability (Rowland, R. 2017, 105).

Focus on the action of the future innovation stimulates an opportunity to utilize abstraction of analogical processes from nature. The aim is to work with the operational part to achieve the required result instead of concentration on future solutions as an object in order to avoid probable gaps in concept generation. It is enough to answer in a verb form to the next question: What a future product assumes to do to achieve a final result? An arisen response usually satisfies an engineering language and should be translated to a biological one to explore a world of nature for analogues.

Useful tools at this point were presented by Fayemi and the group of scientists in 2017. Life's Principles, KARIM's version of Life's Principles and S-Curve were specified to support the problem analysis step:

Life's Principles are the cluster of design patterns from living organisms. Moreover, an engineer could utilize the technique as a measurement tool and/or design principle to develop the sustainability of the final product.

Another version of Life's Principle was created with the addition of sample questions, advantages, biological and technical examples. It was made by the European project 'Knowledge Acceleration and Responsible Innovation Meta network' (KARIM) to supplement the KARIM Responsible Innovation manual.

S-Curve determines the life cycle path of the product and offers instruction for migration between the stages, according to the technological systems development by Evolution Laws.

(Feyami, P. E. et al. 2017, 6.)

On the other hand, it is possible to execute analytics of the whole system the solution should be part of. The level of that system and its assorted leverage points for entering are compulsory to be studied. The set of leverage points of Meadows was selected as an exquisite method to perform the analysis. (Fayemi, P. E. et al. 2015, according to Rowland, R. 2017, 105.)

In 1999 an American environmental scientist Donella Meadows published an essay based on the discussion of key points for transformational capacity. She ascertained that there was a number of intervention points affecting the system the most and ones, which made fewer changes. As the result, Meadows offered a hierarchical collection of 12 leverage points. It starts from the intervention with simple application and small impact on the structure and reaches so-called ‘deep’ points of possible novel transformation. (Abson, D. J. et al. 2017, 31.)

Furthermore, Abson and team (2017) grouped 12 intervention points into four vast categories to target future interference: parameters, feedback, design, and intent. Modified system of Meadows (1999) with the characteristics of each group is shown in Figure 3. Four system characteristics of Meadows’ twelve leverage points (Abson, D. J. et al. 2017, 32). It was declared that most of the changes were usually made on the first two groups with the smallest influence on a result, while points in design and intent were less considered. Although, big transformational change calls for adjustment on a deep level.

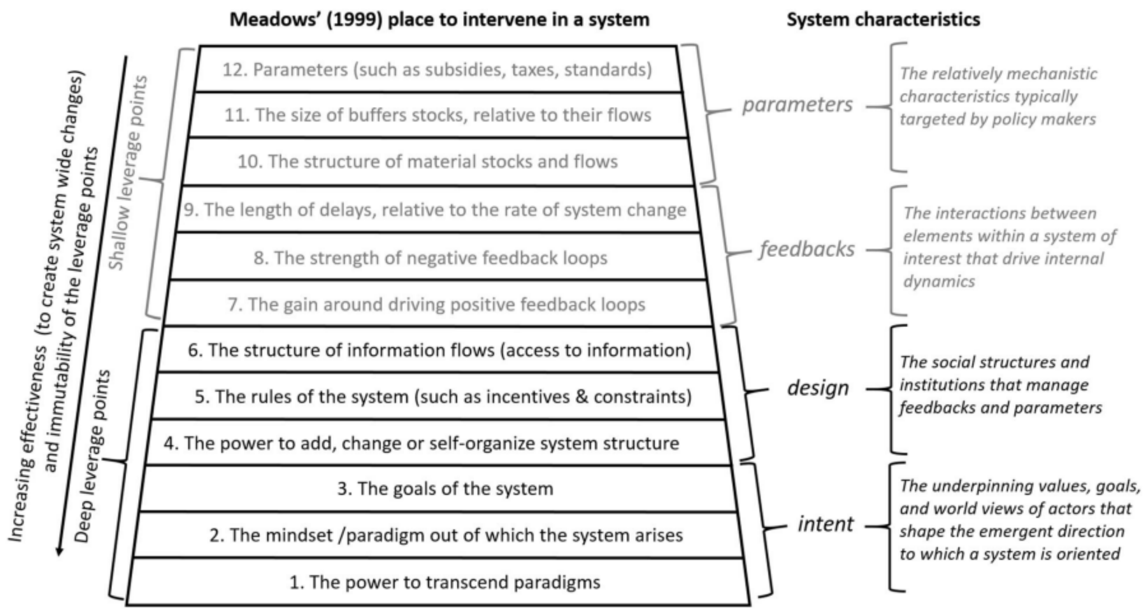

Figure 7. Four system characteristics of Meadows' twelve leverage points (Abson, D. J. et al. 2017, 32).

Method of Meadows' leverage points set scans the problem and detects its different layers to determine the entry points for a future phase. It is followed by a root-cause analysis. Rowland (2017, 105) suggested a technique of five-whys-question series at this step. The elementary tool was created by Japanese inventor Sakichi Toyoda during the evolution of the Toyota Motor Corporation he owns. The cause-and-effect relationship of a particular issue is considered through five repeated questions "Why?".

In order to start the next stage of exploring biology for future innovation, the scoping phase has to be successfully completed by satisfying the following criteria:

1. Several layers of the system are determined, and its entry points are specified.

2. Appeared Wish is shaped into a function-based design statement, according to the desired result image and its significance in the chosen system layer.

3. A (beginning) set of design principles consists of life's principles and the desired function of a potential solution to build a connection with a future expected outcome.

(Rowland, R. 2017, 106.)

5 Exploring phase of the engineering innovation process

5.1 Schematic process of data finding

The result of the scoping phase progresses to a final task brief through the exploring stage and concludes the Planning part of the engineering innovation process. It is a route of creation the Function Bridge instrument to perform efficient conversion of organic strategies to forward the original design challenge (Rowland, R. 2017, 108). Sharma and Sarkar (2019, 89) framed a simple schematic process for biomimetic data research based on a keywords system, which includes four steps to achieve full data analysis:

1. Finding a database of studies in biomimicry and establishing the period of literature review and keywords if needed.

2. Data gathering with the use of common keywords and their variations.

3. Cleanup of the appeared a numerous number of publications.

4. Complete data analysis after cleaning unrelated information.

The goal of the exploring phase is to select certain biological analogues from the recorded data. There are several methods to gather data, detect analogue from nature, arrange election and abstract biological solutions to transform it into technology. Rowland (2017, 108) considered discovering step as a successful one when the final task brief covered the following details below:

- the design challenge explanation
- the context description of the raised problem from the challenge and its potential solution performance
- the statement for the specific function of the solution
- the strategic view of the expected outcome and its impact
- the biologized research questions
- the function cards of chosen analogues
- the final specification list for design.

5.2 Biological problem abstraction

When a task was briefly discussed in the scoping phase, it ought to be abstracted from nature. The separation of the problem from its field (biology in our case) is called abstraction. Those step models a focused view on key factors of the problem. It provides an engineer with the keywords or functions for future research. (Bergsma, M. 2018, 31.)

Scientists have designed plenty of instruments to support the design process in biomimicry and to match biomimetic specifications. However, there are additional tools based on TRIZ and the Chakrabarti System, which take their roots from the design field (Fayemi, P. E. et al. 2017, 5). Both systems seek new ideas by searching analogues from different fields. However, there is a difference in the principles of each tool.

Chakrabarti and his team of researchers (2005) produced a method to invent novel solutions for product design requests. In the Chakrabarti System, new ideas are generated according to biological or artificial analogues. Biological analogues are function-based. For instance, the explanation of the jumping process for grasshoppers or swimming for fish. Another type of copy consists of descriptions for the motion of the artificial mechanical systems such as suction of vacuum cleaner, gear transmission. (Volstad, N. L. & Boks, C. 2012, 194.)

One of the most popular tools for creative innovations is TRIZ, which is a Russian acronym of the Theory of Inventive Problem Solving. It was developed in 1946 by Genrich Altshuller, who was a Soviet engineer and inventor. Altshuller studied thousands of innovations in widely differing fields to highlight familiar patterns of evolution (Vidal, R. et al. 2015). As a result of the research, it provided TRIZ with a list of 40 inventive principles and algorithmic approaches for artificial inventiveness. The abstraction model of the theory acts through a contradiction matrix, which draws a connection of the principal problems with the inventive principles for a general state of a task (Volstad, N. L. & Boks, C. 2012, 194).

The collection of the instruments from both mentioned systems were discussed in 2017 by Fayemi and his colleagues. They have summarized founding in the Problem-driven Process of Biomimetics Utility Tree. The abstraction part of the Utility Tree is shown in Figure 4. Abstraction of the problem from the Problem-driven Process of Biomimetics Utility Tree (Fayemi, P.E. et al. 2017, 17).

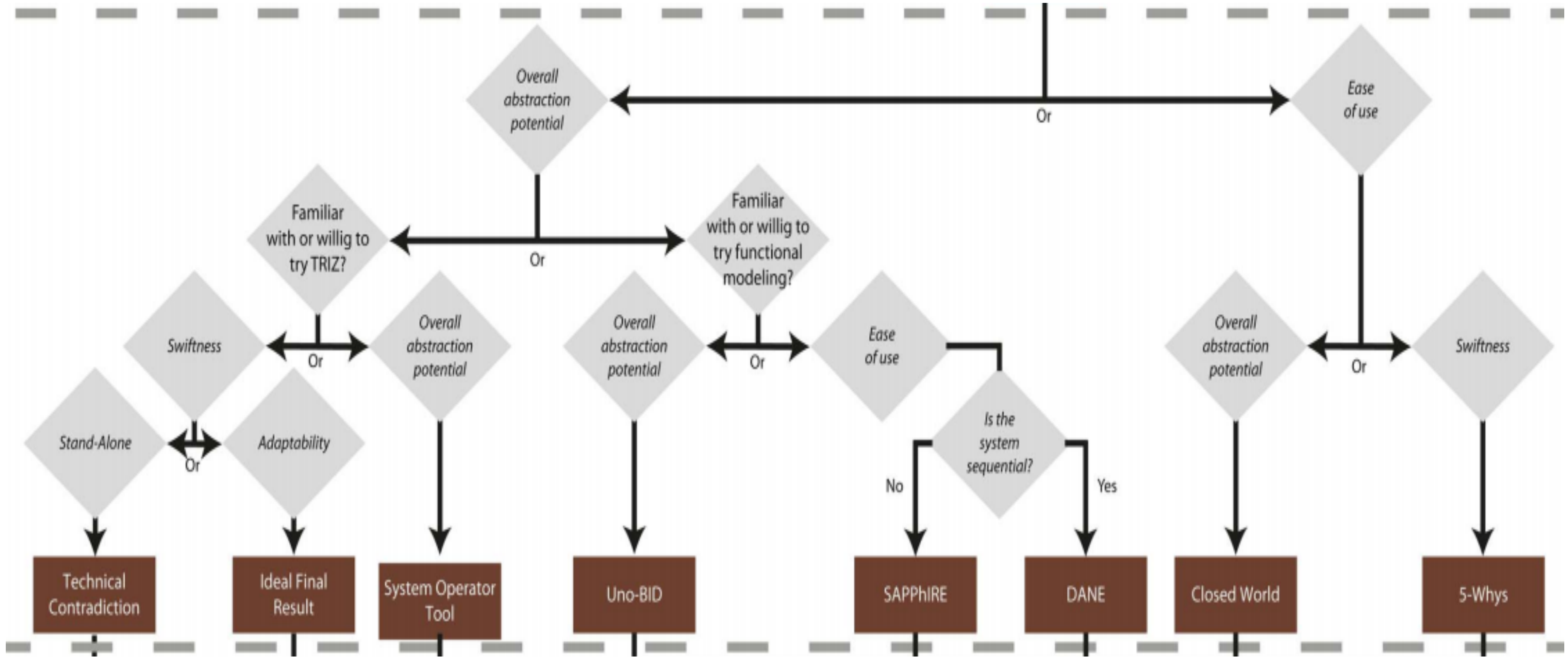

Figure 8. Abstraction of the problem from the Problem-driven Process of Biomimetics Utility Tree (Fayemi, P.E. et al. 2017, 17).

Fayemi et al. (2017, 16) structured instruments according to the criteria of swiftness, simplicity, stand-alone capacity, field adaptability, group adaptability, and precedence. Abstraction methods are named in brown boxes (Figure 8) and briefly discussed below.

The Technical Contradiction method helps to recognize points of conflict situation when the advancement of certain technical characteristics causes a decline in other parameters. It is quite challenging since technical contradictions are concealed or roughly formulated (Altshuller 1988, according to Fayemi, P. E. et al. 2017, 8).

Ideal Final Result is a tool to build the perfect representation of a system via solving ongoing technical limitations. It may consist of a structured thinking questionnaire based on the Innovation Situation Questionnaire (Terninko et al. 1998, according to Fayemi, P. E. et al. 2017, 8).

Altshuller (1988) explained System Operator Tool or Multi-Screen Diagram as a mental practice, where a technical system is divided into boxes. The current system should be represented as a box in the centre, and over boxes are placed on two axes as time and systemic level. Later in 2000 Savransky added that this method allows remembering the importance of a gradual transition between states of product and subsystems. (Fayemi, P. E. et al. 2017, 8.)

SAPPhIRE is the abbreviation for the State change, Action, Part, Phenomenon, Input, oRgan and Effect, which are the components of the method. The model was inspired by the Function, Behaviour, Structure model of Gero (1990), and was developed by Chakrabarti et al. in 2005 (Fayemi, P. E. et al. 2017, 6). SAPPhIRE is a functional/behavioural representation for biological systems based on seven named components (Bianciardi, A. et al. 2016, 90).

Vattam et al. (2011) developed the Design by Analogy to Nature Engine (DANE) instrument to form functions with the use of states progression and structure box diagram. The states are mostly familiar with each other according to the behaviour and causes. (Fayemi, P. E. et al. 2017, 6.)

The combination of SAPPhIRE representation and the DANE approach is the Uno-BID method. On the one hand, the primary concept of SAPPhIRE is the causal chain from phenomena to action. On the other hand, DANE focuses on the detailed illustration of behaviour, structure, and state transitions of a system. Based on both tools, Uno-BID seeks to universally divide general concepts rather than concentrating on a specific form, which achieves flexibility of the method. (Rosa, F. et al. 2014, 205.)

Sickafus (1997) extracted the TRIZ of Altshuller (1988, 1996) to the Unified Structured Inventive Thinking tool. The tool provided the basement for the Closed World approach for biological problem abstraction. Closed World considers functional effects and attributes of the system to the summary correlation of system objects as an analysis of a problem. (Fayemi, P. E. et al. 2017, 8.)

5-Whys method is based on repeated questioning, as it was mentioned before.

Described methods provide the abstraction of the engineering problem to future search in biology. Potential analogies could be found from nature, and the next step for an engineer is to start research across available databases.

5.3 Biomimetic databases

Mother nature does not bear a record of its inventions and explanations. However, there was a number of attempts to develop databases to support the biomimetic approach for engineers and designers.

Rovalo, E. et al. in 2019 studied the usage of search tools in biomimicry, which resulted from the AskNature.org site as the most popular database according to its availability and accessibility. The Biomimicry Institute, a non-profit organization, first launched the site at Greenbuild International Conference and EXPO in 2008. It is a free and easily accessible database of biological abstracts to support biomimetic designs for engineering, architecture, industrial design, chemistry and more (Deldin, J. M. & Schuknecht, M. 2013, 18).

The first concept of Bio-TRIZ was proposed by Vincent in 2000, when he studied function with high capability and its biological analogues through 40 invention principles of TRIZ. He structured the result inside the matrix. (Kobayashi, T. et al. 2017, 277.) Additionally, Kobayashi presented the first digital prototype system for realizing the technology transition from biology to engineering. By the present moment, the Bio-TRIZ database consists of biological system solutions according to the analysis of about 500 organic phenomena (Parras-Burgos, D. et al. 2020, 296).

Biomimetics Image Retrieval platform provides the possibility for biomimetic idea research based on visualization. It enables specialists to look for new information on different fields via image and video data. In detail, an algorithm of the platform was created by performing dimensionality reduction. It is a 2D space-based reorganization of the pictures within the distance between the visual characteristics extracted from the images in the platform. (Haseyama, M. et al. 2017, 1566.)

Findstructure.org database consists of functional solutions from biology, according to its nature structure-function model. Cohen and Reich (2016) listed the searching ways in the database as by structures, by functions, by organism and with the use of contextual key-words. Results represent detailed data including name, structures, functions, function object context, functional mechanism, biomimetic innovation, reference, and images.

Jacobs and the team introduced the BioM Innovation database in 2014. The new database stepped further than assisting the design process, it stands for the study of the professional biomimetic design process and includes individual cases. Nowadays, BioM Innovation offers over 350 cases of products or ideas related to the process, focus, geography, and vocabulary (Parras-Burgos, D. et al. 2020, 297).

DANE database is a CAD system within access to functional patterns of complicated natural systems according to four features such as cognitive, collaborative, conceptual, creative (Parras-Burgos, D. et al. 2020, 296).

Idea-Inspire database proposes beyond 700 results with a functional decomposition model, text, SAPPhIRE model, and digital support (Siddharth, L. & Chakrabarti, A. 2018, 436). There are seven attributes to identify functionalities, behaviors, and structures in order to support an engineer with automated research for a biological analogue (Parras-Burgos, D. et al. 2020, 296).

There were more search tools besides available databases considered by Rovalo, E. et al. (2019). For instance, popular sources as media or documentaries, the use of own knowledge of natural systems or academic literature. Also, one of the tools was direct communication with a biologist or independent observation in the fieldwork. Statistics showed that biomimicry practitioners use mentioned methods more often rather than databases.

6 Concept specification phase of the engineering innovation process

The problem-driven process of biomimetics utility tree of Fayemi et al. (2017) provided the list of tools for biological model selection and its abstraction to engineering. The team offered 4-Box and T-Chart instruments in order to decide on the final analogue from the results found in databases.

The 4-Box method is utilised to contribute a formulation for the task. It is easily made through a two-by-two matrix according to the Operational Environment, Function, Specifications and Performance Criteria of the problem. The method requires an engineer to write a detailed description for each box. (Helms, M. & Goel, A. K. 2014.) When the matrix is fulfilled, the next step is to evaluate the analogy through T-Chart.

The T-Chart tool is a diagram, which contains problem descriptions from the matrix on the left side and respective 4-Box characteristics for biological analogues on the right one. Later, a specialist should compare both sides as "same", "similar", "different" or "N/A" (not applicable) in the middle column. (Helms, M. & Goel, A. K. 2014.)

As soon as the final analogue is chosen, a biological strategy should be abstracted. Abstraction tools for this step are represented in Figure 5. Abstraction of the biological strategy from the Problem-driven Process of Biomimetics Utility Tree (Fayemi, P.E. et al. 2017, 17). Uno-BID, SAPPhIRE and DANE have been discussed in the previous chapter. Biological Modelling or BioM is a collection of guidelines for the functional image of a natural system (Nagel, J. K. 2011, according to Fayemi, P.E. et al. 2017, 8).

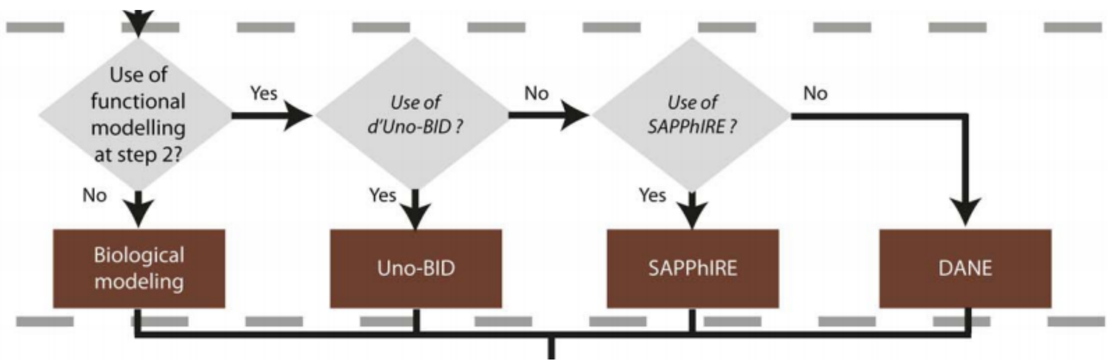

Figure 9. Abstraction of the biological strategy from the Problem-driven Process of Biomimetics Utility Tree (Fayemi, P.E. et al. 2017, 17).

The summary of this phase is a biomimetic concept ready for future manufacturing or/and assembling. It is the end of the Planning step in the engineering innovation process.

7 Discussion

The objective of the thesis was to build a model for an engineer to support the invention process by providing ready solutions from biology in order to reach time, costs and work decrease. Researchers in psychology, business and engineering have proposed several techniques for idea generation. However, they are mostly focused on quantity rather than on quality and are possible to be limited due to humankind mindset.

This findings from the thesis show that biomimicry offers artificial inventiveness for specialists of many fields via solutions existing in nature. The specific case for the thesis was engineering. In practice, a cross-disciplinary connection is beneficial for both engineering and biology fields. Current work was focused on the engineering side rather than biological. However, it is recommended to study the impact of collaborative work with an engineer for biology as a science too. Engineering may provide biology science with structured explanation of living organisms, their functionality, or systems they are a part of.

There are several trials to build an innovation process algorithm, and the goal of the current thesis work was to adjust it with biomimetic techniques. In 2011 Skogstad and Leifer presented the Unified Innovations Process Model for Engineering Designers and Managers from Figure 5, which included three main stages: Plan, Execute and Synthesize. Later in 2017 Fayemi et al. developed the well-structured Problem-driven Process of Biomimetics Utility Tree. However, biomimicry is a continuously growing science, and the collection of tools are updating year by year. This thesis work sought to provide an engineer with all available and accessible methods and databases, which will allow transforming a request from an engineering problem to the domain of knowledge about nature.

As a result, current work offers a step-by-step model of engineering innovation process within the following stages for the Planning phase:

1. The detected Wish of the field should be specified in a function-based design statement and should satisfy a few criteria. Certain methods were selected and studied to briefly describe future concept depending on its functionality or the system it would be a part of.

2. Biomimicry is implemented at the analogue research when the desired result image is received. However, it is important to abstract biological problem description from engineering language first. Few techniques have been discussed to assist an engineer at this step. Selected abstraction tools are mostly based on two systems: TRIZ and Chakrabarti. Both are originated from the design field and seek to search analogues but differs according to the principles of each. A great selection of abstraction methods was presented by Fayemi

and the researchers' team (2017). They managed each tool according to its swiftness, simplicity, stand-alone capacity, field and group adaptability.

3. Data gathering is the next and one of the most important steps at this point. Mother nature is not able to keep a record of its every creation. But a number of databases are being continuously created to support inventors with easy and fast information gathering. The database provides an engineer with independent research, while direct communication with a biologist may lose in timing and costs. On the other hand, it would be efficient collaboration and possibly offer more opportunities in the scope of the work. Moreover, direct communication with a specialist in biology and/or biomimicry would help to avoid future mistakes in Execute phase. Also, there are few more types of data gathering as studies based on own knowledge and experience or/and popular sources. It could be less effective and more time consuming. For the mentioned reasons, the main focus was on collecting all available and accessible biomimetic databases during the work on the thesis.

4. Information gathering could be concluded with huge amounts of variants. At this stage, Fayemi et al. (2017) proposed few methods for the final analogue election.

5. Next and the last step is an abstraction of a biological solution into technology. As the result, the biomimetic concept should be created and the engineer should complete the design challenge explanation, context description, specific function statement, strategic illustration of potential outcome and impact, final design specification list.

To summarize the research on the chosen thesis topic, the Engineering Innovation Process Model with the use of Biomimicry model was built, as it is shown in Figure 10. It is clearly seen that biomimicry was implemented in the Planning phase. Planning is a great opportunity for an engineer to embrace all his creativity and try brave ideas. By the end of the stage, the biomimetic concept is ready to be executed and synthesized. The last two phases of the process take a big role in product development. Because they give an opportunity to examine the biomimetic approach in practice and observe its behavior. Possible adjustments and work on mistakes can be implemented during this. Execute and Synthesize were not discussed in the certain thesis work due to their dependence on a particular problem and selected biomimetic idea. And the output of whole process is ready product and/or solution for the engineering field.

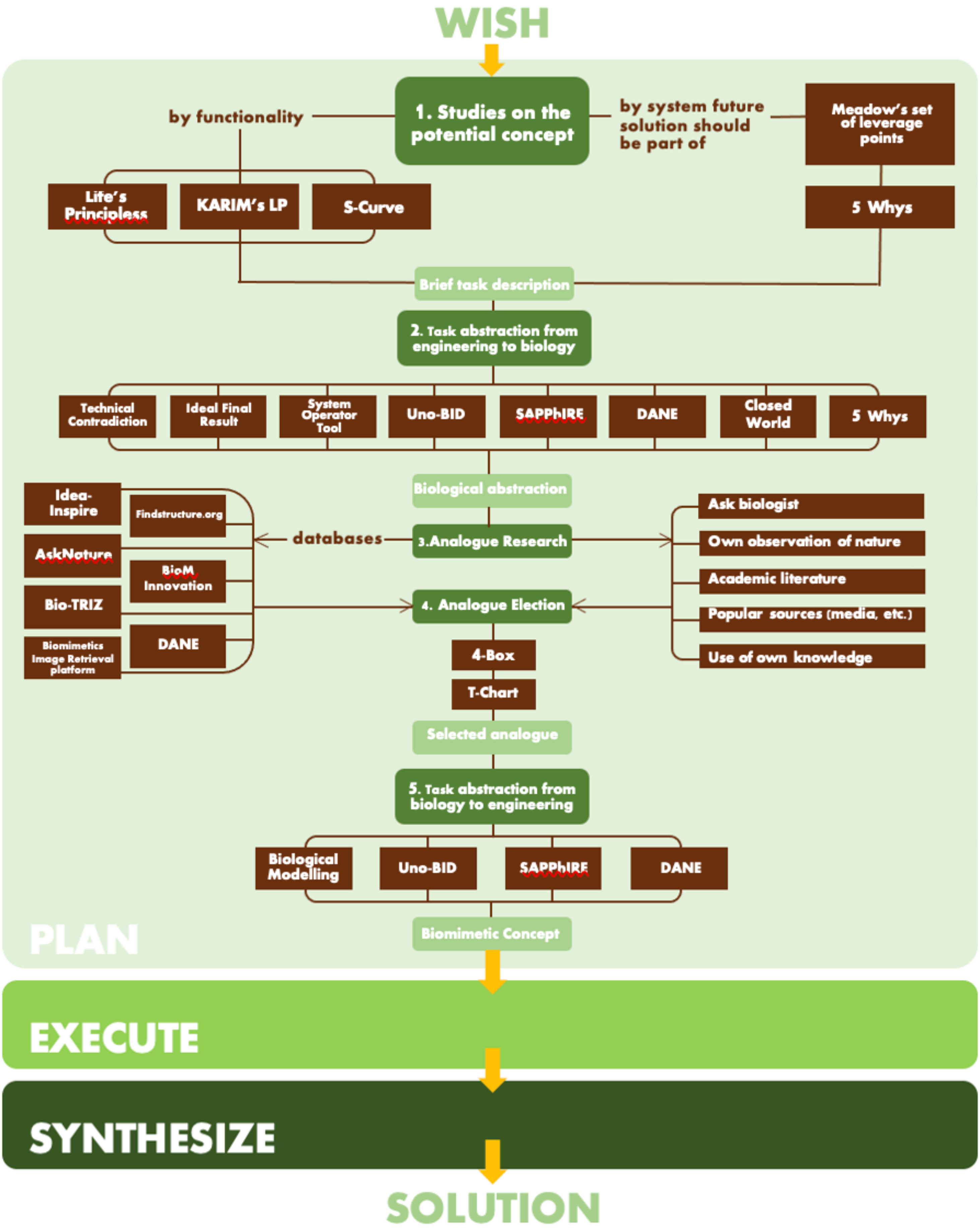

Figure 10. Engineering Innovation Process Model with the use of Biomimicry

8 Recommendations

> *Smart companies now treat sustainability as innovation's new frontier.* (Why Sustainability is Now the Key Driver of Innovation 2009, 58.)

The growth of the human population and industrial production has a dramatic impact on the environment. One of the most highlighted consequences is climate change leading to a series of disruptions. (Albino, V. et al. 2009, 83.) Despite the delusion that sustainability may limit companies, an appropriate implementation provides competitive profits within costs decreasing and generating additional revenues. Sustainability and innovations can be merged through biomimicry. (Kennedy, E. et al. 2015, 67.)

As a science based on nature, it is a collaboration of many specialists: biologists, ecologists, designers, and engineers. They cooperate with the aim to create an efficient and long-lasting product. Furthermore, biomimicry involves economics, industry, and environmentalism too. The result of such teamwork is supposed to provide cost-effective, more efficient, and more sustainable products.

There are approximately 30 million species on Earth, but only 1.4 million or 4.7% are detected. Lack of knowledge may harm the sustainability of a biomimetic innovation. It highlights the importance of careful attitude during the biomimetic idea selection process in order to detect appropriate analogue for mimicking. Solutions in biomimicry should work, long last and be appropriate in the engineering field too. (Miller, J. D. 2010.)

During the innovation process, the mechanical engineer is provided with several codes, standards, and regulations for forming sustainability goals and targets at the beginning. Vierra (2019) listed a few important standards and called the engineering community to develop better ones, which goes beyond and supports the green idea for future inventions. He mentioned the following available grades:

ASHRAE Standards

- ASHRAE 189.1, Standard for the Design of High Performance, Green Buildings Except Low-Rise Residential Buildings (http://www.wbdg.org/references/ihs_l.php?d=ashrae%20189.1)
- ASHRAE 62.1-2007, Ventilation for Acceptable Indoor Air Quality (http://www.wbdg.org/references/ihs_l.php?d=ashrae%2062.1)
- ASHRAE 90.1-2007, Energy Standard for Buildings Except Low-Rise Residential Buildings (http://www.wbdg.org/references/ihs_l.php?d=ashrae%2090.1)

Executive Orders

- Executive Order 13514 (http://www.wbdg.org/ccb/browse_doc.php?d=8151) (PDF 87 KB)

Federal Codes

- Federal Energy Code—Commercial Buildings (http://www.energycodes.gov/federal/)

Legislation

- Energy Independence and Security Act of 2007 (http://www.govtrack.us/congress/billtext.xpd?bill=h110-6)
- Energy Policy Act of 2005 (EPACT) (/ccb/browse_doc.php?d=1361)
- Clean Air Act—US Code Title 42 Chapter 85 (http://www.epa.gov/air/caa/)

9 Conclusion

This thesis aimed to identify a language of transposing an engineering problem to a biological solution to assist an engineer during the innovation process. In particular, it offers the engineering innovation process model with the stages and biomimetic implementation. Every step of the process is structured by a combination of several existing models. Furthermore, the model is supported by studied available tools and accessible databases.

The Engineering Innovation Process Model with the use of Biomimicry provides a specialist with the functional strategy to utilize in workflow and goes beyond the theoretical part. It automates the inventiveness skill and delivers the reduction in timing, costs, workload. There is no need to invent something brand new, while mother nature already has most of the answers after ages of evolution. Moreover, biomimetic implementation helps to avoid cognitive aspects and mind limitations during the idea generation process.

Yet, biomimicry is a comparably modern and constantly growing science. It played as the most complicated challenge in certain thesis work due to material and resources analysis. At the same time, it opens an opportunity to develop the field and contribute with more research. One of the possible future research could be the studies on artificial intelligence utilization during the data gathering stage. Provided databases from the current thesis work are mostly digitalized. Artificial intelligence implementation during data collection and final concept election would have a huge impact for whole engineering innovation process.

By the end of the thesis, recommendations on the sustainable use of biological solutions were discussed. Nature is considered green by default, which is not true. There is a proposed list of standards in biomimicry to achieve a sustainable result. It might be helpful during both stages of biomimetic concept implementation and testing of final solution and its impact on environment.

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