Internship Report

Developing a method to help engineers find solutions from nature and technology within the TRIZ method.

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ABSTRACT

Nature provides a near endless resource of evolved systems and incredible inventions; a great source of knowledge that is currently barely used in engineering.

In this report, research is done on how to use the theory of inventive problem solving (TRIZ) to aid engineers in finding solutions for functional descriptions of problems, using existing solutions from different disciplines; but most notably, how biology can be added to the (existing) set of solutions. One of the main questions is how to structure biological information using TRIZ. Engineers that use this method might find new, innovative, and possibly biomimetic solutions, often improving the eco-efficiency and multifunctionality of systems. Challenging problems in the development of this method are, amongst others, the construction of a database system, quantifying and extracting biological phenomena, dealing with the hierarchical structure of natural systems, and the transfer of knowledge between biological and technical systems. It is suggested that using TRIZ' functional analysis as basis for the database entries will aid in successfully integrating biomimetic solutions into the existing TRIZ method.

To provide background information on the discussed subjects, the report also includes an introduction to some methods and tools that deal with the automatic extraction and databasing of knowledge in the form of Physical Effects, the state-of-the-art of combining TRIZ, and a brief introduction of biomimetics and several TRIZ tools.

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1. INTRODUCTION

The aim of this report is to shed light on the development a method for professional engineers to aid in the ideation phase of the design process. Based on functions, the user can search an extensive database of solutions from physical, chemical, mathematical and biological resources.

In this chapter, the method of reaching this goal is discussed, as well as an introduction to the two main tools that inspired the research topic and are used in this report. After expanding upon the research objectives and how these are achieved, the powerful problem solving method TRIZ is briefly introduced, and several of its tools are highlighted. Next, biomimetics is introduced; it is the imitation of nature to solve human problems.

The following chapter will review papers containing both biomimetics and TRIZ. The search for these keywords yielded a list of 32 papers. This is used to review the current state-of-the-art, find common subjects in groups of papers, review which TRIZ tools are used, and see if there are any apparent trends.

The next chapter will deal with the actual development of the tool. First, some existing tools are discussed, such as AskNature and TechOptimizer. Next, shortcomings of the mentioned tools are addressed, combined with other challenges that need to be overcome. This is then combined and used as guideline for the new method.

After the tool development, it is again compared to existing tools and the proposed challenges, to find the shortcomings and discuss the feasibility of the proposed idea.

1.1. RESEARCH OBJECTIVES

The primary objective of this research is to tap into the wealth of knowledge that nature has developed over millions of years. To approach this objective systematically, there are several hurdles to be tackled along the way.

First of all, it is valuable to gain some insights in the two main drives of the to-be developed method: TRIZ and biomimetics. This is done in the remainder of this chapter.

Next, it is important to find out what has already been done on the subject, and whether the area of research is increasing in popularity or not. This has been done through a keyword search in Scopus [1]. This dataset will provide insights in the usage of TRIZ and biomimetics and in its popularity in recent years.

Furthermore, some popular and promising tools and methods are analyzed, to see how they tackle the hurdles, such as the database used, how the database is constructed, how the entries are structured, how it is accessed, and different methodologies to get a solution to a posed problem. This is then used to define the steps in the proposed new method.

1.2. TRIZ

After many years of trial-and-error development of technology, a need for a methodology in inventive problem solving arised. This is where the research of Genrich Altshuller is focussed on; he and his colleagues researched many patents which eventually lead to the development of the

Theory of Inventive Problem Solving (Russian acronym: TRIZ). The first mention of TRIZ is in a Russian paper by Altshuller and his colleague Shapiro [2].

One of the earliest mentions of TRIZ in the western world was made in the book of Salamatov [3]. He states that there are objective evolution laws for technical systems. When these laws are studied and applied to inventive problem solving, there will be no need to resort to a search for variants. A strong reliance was placed upon the intuition or insight of the inventors, while Altshuller actually discovered that only a very small percentage of the inventions were actually 'new'. Most relied on commonly used solution principles instead of pioneering new inventions, and therefore new inventive problems could be solved by structurally applying previous experience.

This lead to his development of TRIZ: the theory of inventive problem solving. His goal was to transform the inventive process from trial-and-error to a clearly defined technology. By researching about 40.000 patents (no original source for this number is to be found, but is mentioned often in literature), he developed the 'theory', which has been used and adapted by numerous researchers. The method consists of a multitude of tools, developed to target specific problems in a structured manner. The next paragraphs will introduce a selection of these tools that are used in the found literature.

Function Analysis

The first efforts towards functional analysis of a system was made by Lawrence D. Miles, in his systematic method 'Value Engineering' [4]. Value relates to function by taking the ratio of function to cost; 'function' is the result expected by the consumer. Another key method is the Function Analyses System Technique (FAST) as developed by Charles W. Bytheway [5]. For a system, its components can be expanded and connected through functions. This yields a *Function Diagram*, or *Function Model,* and can be created by constantly asking the questions 'why' and 'how', to find the functions respectively lower and higher in the hierarchy of the system. This defines the goal of the function and a method for performing the function.

Function analysis for engineering systems, as developed by Simon Litvin and Vladimir Gerasimov, is the basis for the currently used method in TRIZ. They recommended using a triad for the description of a function, a function carrier, an action, and the object of the function. Functions can be either harmful, neutral or insufficient. Litvin et al. used the example of cleansing teeth with a toothbrush to illustrate the method; a part of the function model is displayed in Figure 1

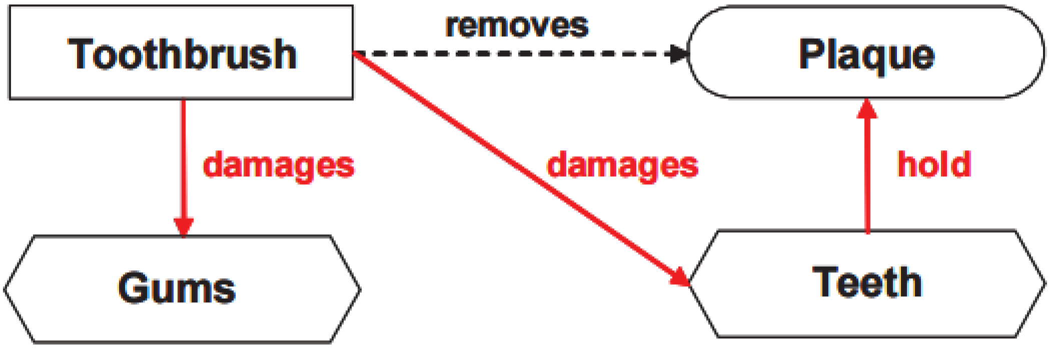


FIGURE 1 | FRAGMENT OF THE FUNCTION MODEL CREATED BY LITVIN ET AL [6]

Using this function model, the user can identify possible weak points of a system, which can subsequently be addressed with other tools of TRIZ.

Contradictions and 40 Inventive Principles

Contradictions were first introduced by Altshullers original research on TRIZ, and are divided into Technical and Physical Contradictions [7]. A Technical Contradiction (TC) occurs when a useful action creates a harmful action. A Physical Contradiction (PhC) is defined as follows: a system or component has to be one thing at one time to do an action, but an opposite thing to do another conflicting action. Litvin also provided a clear example for the different types of contradictions [6]. A TC would be: 'If teeth are being cleaned by a toothbrush for a long period of time, then all dirt will be removed, but the gums will be severely damaged.'. A PhC can be formulated as follows: 'The cleaning time should be long-lasting in order to remove dirt and the cleaning time should be short in order not to damage the gums'.

The Physical Contradiction is used as input for Altshuller's *Contradiction Matrix* (visit [8] for an interactive contradiction matrix). This matrix contains *39 generalized parameters*; mapped vertically are the positive effects, horizontally the negative effects. These are matched with the previously constructed *Physical Contradiction*. On the intersection of the two generalized parameters, there are several numbers; these correspond with the *40 Inventive Principles* (40IP). These inventive principles recommend solutions - or, more generally, strategies - that have been proven to be successful in previous design problems. This is an often used tool to generate many different and potentially successful ideas.

9 Windows or System Operator

The original version of the *System Operator* was developed by Altshuller, and had 18 'screens' and has also been called the *multi-screen scheme* [7]. It was later adapted by modern TRIZ users to have 9 or less windows [9].

The *9 Windows* technique is used to structurally define the problem that needs to be solved, which reduces the apparent complexity [10]. Vertically, it asks the user to think about the hierarchy of the initial system. In the sub-system one defines what components of the system are interesting to the problem solving, and in the super-system the environment of the original system is described. Horizontally, the time-component of the system and its sub-/super-systems is explored; what is/are past versions of the system, what happens to the system after use or what could a future version of the system be?

A different way of interpreting the time-component is to think of what could have been done in the past to prevent the problem from occuring, or what can be done in the future to negate the negative effects. Figure 2 displays a filled-out version of the *9 Windows Diagram*, using the problem of a soggy slice of pizza. The tool encourages the user to find solutions in the past and future, and to use components of the sub- and super-system to solve the problem.

TABLE 1 | 9 WINDOWS DIAGRAM

	Past	Present	Future
Super-system			
System		*System to be evaluated*	
Sub-system			

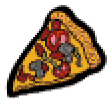
	Past (Preventive)	**Present**	**Future** (Corrective)
Sub-system	Can we change a component to prevent going soggy?	Crust, Cheese, Sauce, Pepperoni, Mushrooms	Can we do anything to a component to re-crisp the pizza?
System	How can we prevent the pizza from going soggy?	Soggy Pizza 	How can we make a soggy pizza fresh and crisp again?
Super-system	Can we prevent wilting by changing the packaging and delivery system?	Pizza, Box, Carrier Pouch, Delivery Car, Driver	Can we use the package and delivery system to re-crisp the pizza?

FIGURE 2 | EXAMPLE OF A 9 WINDOWS DIAGRAM ON THE PROBLEM OF SOGGY PIZZA [10]

SUBSTANCE-FIELD

Seemingly similar to the previously described *Functional Analysis*, *Substance-Field (Su-Field)* analysis is also an often used TRIZ (actually ARIZ) tool. A basic *Su-Field* model is composed of three elements, two substances (S_1 and S_2) and the field, which can be an energy or a force. Going back to the toothbrush example, this would mean that the subject (toothbrush) is the tool (S_2), the object (teeth) is S_1 and the verb (*remove*) is fulfilled by a mechanical force (field). In this case, the function to remove is a useful one; but useless or harmful interactions between the substances can also be identified, as was seen in Figure 1. Altshuller devised a list of *76 inventive standards*, which are standard patterns of modifying the *Su-fields* [11] .

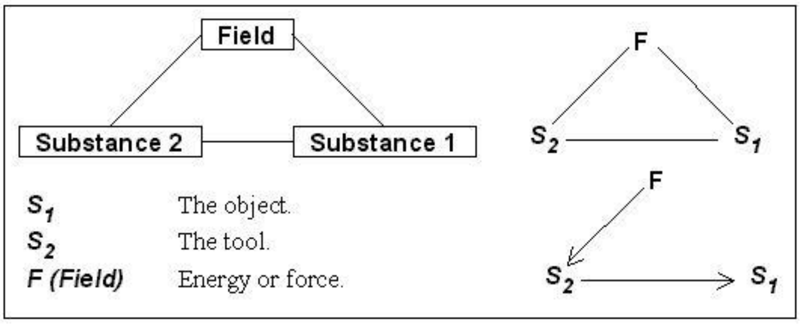


FIGURE 3 | SU-FIELD MODELS OF THE SIMPLEST USEFUL SYSTEM [12]

Ideal Final Result

The *Ideal Final Result (IFR)* almost explains itself, but the method is a bit more refined than that. Altshuller says that the *IFR* is a fantasy, which (most often) is not possible to obtain but will build a path for the solution [13]. However, Salamatov argues that one should not too easily think that the ideal solution is unobtainable, as to keep an open mind [3].

As defined in Salamatov's book: "The *IFR* is reached when one of the elements of the system or environment eliminates a detrimental (superfluous, redundant) effect preserving the capacity to produce a useful effect **all by itself**"[3].

To get to a solution, one can make changes to the *operating time* and *operating space*; the operating space should provide the tools to execute the function during the *operating time* [14]. In the ideal situation, no other tools than already available will be used.

Modeling with Miniature Dwarfs

The method where the user tries to model the problem with miniature dwarfs seems more far-fetched than the previously mentioned methods, but can again overcome the mental inertia in problem solving by changing the way the user thinks. In this method, the user starts out by drawing three diagrams; one before the conflict, one where the problem occurs, and one of the desired situation. By moving away from real physical objects and fields, the way the user thinks changes. The next step requires the user to think how the dwarfs in the first diagram (before conflict) can go to the desired situation without causing the problem. Several of these transitions are drawn, and then 'converted' back to the technical system [15].

Trends of Evolution

The *Trends of Evolution* are a set of recurring patterns in product development, and are known by a large variety of names. Altshuller formulated a system of nine laws of *Technical Systems Evolution* [16]. This later formed the *Theory of Engineering (Technical) Systems Evolution (TESE).*

The laws are subdivided into three categories: static, kinematic and dynamic laws

- Static
    - Completeness of the parts of the system
    - Energy conductivity of the system
    - Harmonizing the rhythms of parts of the system
- Kinematic

- Increasing the degree of ideality of the system
    - Uneven development of parts of a system
    - Transition to super-system
- Dynamic
    - Transition from macro- to microlevel
    - Increasing the *S-field* involvement

The *S-curve* is a part of *TESE*, and it plots the degree of the system's performance over time. The entire system will strive towards ideality; this means that the benefits increase, and/or the cost and harm factors of the system decrease.

As depicted in Figure 4, the different phases in a system's lifetime correspond with different speed in improvements. In a new system, development starts out slow but increases rapidly when the system has entered the market. The speed of development slowly decreases as the system approaches ideality. When the system development enters the *Old Age* phase, a new technology needs to be introduced to further strive for ideality. This is a new generation of the system and will start a new S-curve.

$$Ideality = \frac{benefits}{cost + harm}$$

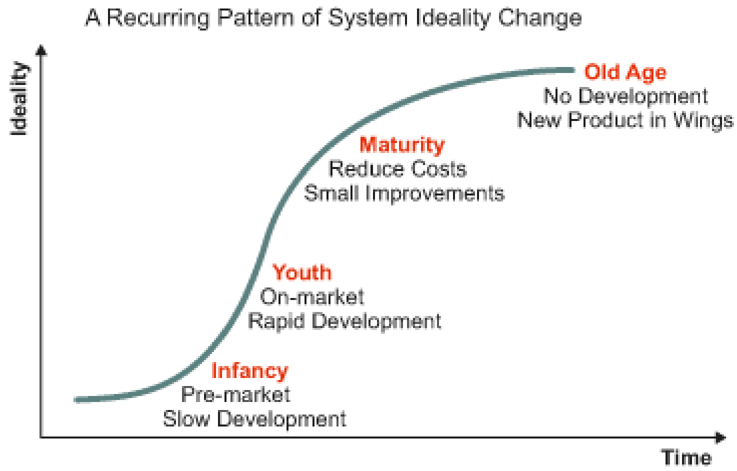


FIGURE 4 | S-CURVE PHASES [17]

Resource Analysis

In the *Resource Analysis*, all resources available to solve the problem are identified and listed in a table or tree diagram. Different types of resources can be identified; TRIZ lists the following types: *substances, fields/forces, shape/geometry, space* and *time*. Resources are separated on basis of sub- and super-system. The results of this analysis can be used as input for many other TRIZ tools, such as *Su-Field analysis* and when generating ideas with *Inventive Principles.*

1.3. Biomimetics

Biomimetics (also often called biomimicry) is the study of imitating elements of nature to solve human problems. The term was introduced by Otto Schmitt when he was designing a physical device that mimics the electrical action of a nerve [18]. This is however far from the first example of biomimetics; the Chinese tried to fabricate an artificial silk, and Leonardo da Vinci designed flying machines by studying birds in flight.. Many famous examples are the development of Velcro, water-repellent surfaces based on the lotus leaf, and even modern composite materials; these are inspired by the cellulose fibers in wood. Many more examples can be read in [18] and can easily be found on the internet; searching for 'Biomimetics' on Scopus (in Article title, Abstract and Keywords) yielded over 20,000 results.

With this great source of 'biological patents' that may hold many solutions for currently existing problems, or that can improve current technologies, designers can tap into many years of biological evolution. The main issues are to find and extract the relevant information. Some methods have tried to incorporate biomimetics in a structured design approach, but this will be discussed later in this report.

2. LITERATURE STUDY

To sketch a background to the research field of biomimetics and TRIZ, a paper search was conducted. Using the Scopus [1] search function, and searching in Abstract, Keywords and Title with the search terms `Biomimetics AND TRIZ`, a set of 32 papers was found (February 2017). These are displayed in Table 5. It was suggested that only the papers with the most amount of citations would be closely reviewed, but since 32 papers is still a manageble amount, all papers were analyzed.

From this group of papers, the usage of TRIZ is analyzed; how is the method used and combined with biomimetics, and which tools are most commonly used? Next, a quantitative analysis on the amount of papers is conducted.

To see if the field of biomimetics and TRIZ is growing, the amount of papers per year in the field is compared with the data from the total amount of papers, the total amount of TRIZ-related papers and the total amount of biomimetics-related papers.

To conclude this chapter, the state-of-the-art in the field will be extracted. Other interesting sources of information have been found, but will be discussed later in the report.

2.1. ANALYSIS

In analyzing the papers, they were sorted on their relevance to the search terms; one result was omitted immediately, since it contained little to no scientific value to this research [19]. The other papers were placed in categories as described in the following paragraph. Several articles were not available at the moment of the search, so the conclusions on the contents of the paper have been made on the abstract only. The papers in which the full text was used are marked with a green color in Table 5.

GROUPING

While all papers contain both search terms, not all combine both concepts. Figure 1 shows in which way biomimetics and TRIZ are used. Five groups were identified in the paper review: the first group of papers contains both TRIZ and biomimetics, but fails to connect the two. The second group contains no direct links to TRIZ and/or biomimetics, but provides summaries of the available papers, is based on the general TRIZ idea of abstraction, or contains no TRIZ or biomimetics in the main part of the paper. The third group uses one or more TRIZ-tools in a biomimetic design process. The fourth group adapts TRIZ to include biomimetics. The fifth, for this project the most promising group of papers, uses TRIZ to structure entries to a database containing biomimetic solutions. The results of this grouping are expressed graphically in Figure 5; which paper belongs to which category is displayed in Table 5 by using the same color coding as in Figure 5.

It can easily be seen that more than half of the papers are on the subject of adapting TRIZ to include biomimetics and using TRIZ as a template for a biomimetic effects database. While the papers using one or more TRIZ-tools in a biomimetic design process could definitely be interesting, they currently prove little use to this research.

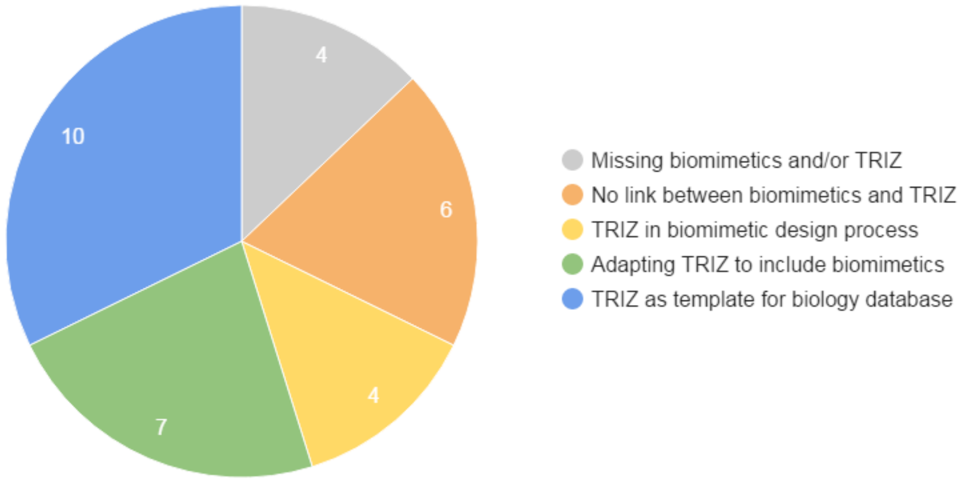


FIGURE 5 | PIE CHART OF CATEGORIZED PAPERS

TRIZ TOOLS USED

Since one of the main questions of the report is how to structure biological information using TRIZ, it is interesting to see what researchers in the field have used in their research, and thus are already familiar with. From Figure 6, it can be seen that by far, the *contradictions* and *40 Inventive Principles* are the most used tools, followed at a distance by the *Function Analysis.* Descriptions of all tools mentioned in the graph can be found in Paragraph 1.2. *BioTRIZ* and *PRIZM* are tools developed based on TRIZ, but not included in the original TRIZ method, and are explained in Paragraph 2.2. A more specific overview of which tool is used in which paper is given in Table 4.

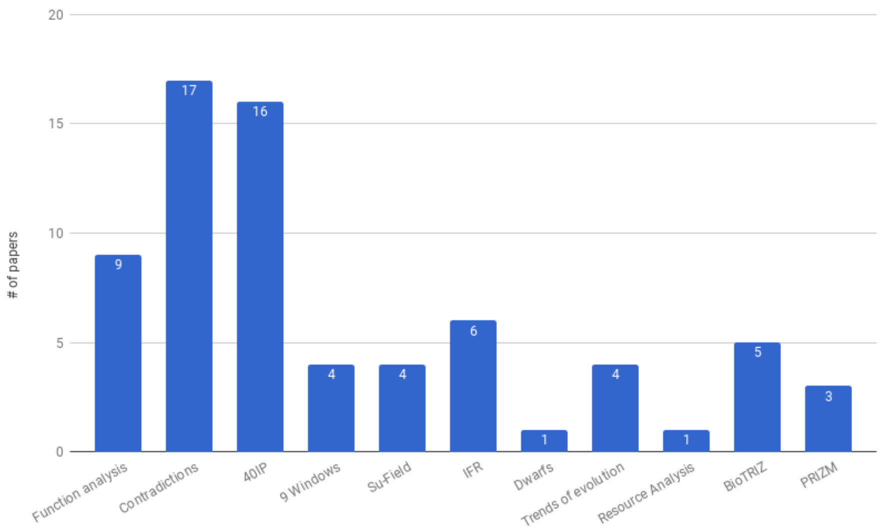


FIGURE 6 | TRIZ TOOLS USED IN SET OF PAPERS

TRENDS

The search yielded results from 2002 to 2016. It seems that more papers were published in recent years in this field, so to visualise this, a bar graph and its trend line are plotted in Figure 7.

To see if this is unique for the field, or if the total amount of papers is also increasing at the same rate, a comparison was made between the specific papers containing the keywords as indicated in the legend (`Biomimetics + TRIZ`, `Biomimetics`, `TRIZ`), and all papers published on Scopus in the same time period. The data used for the creation of this graph can be found in Table 5. The results of this comparison can be seen in Figure 7. The amount papers per year is divided by the total amount of papers in the chosen range, to make a fair comparison between the datasets.

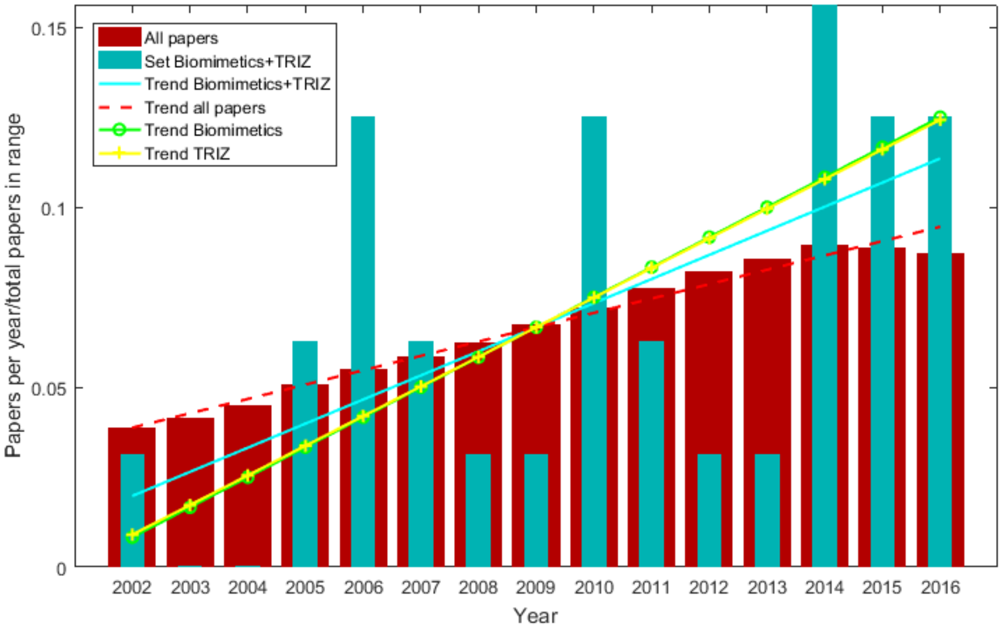


FIGURE 7 | GRAPH DISPLAYING PAPER TRENDS

From this graph we can see that all datasets display a trend of increasing amount of papers. The trend of the total amount of papers shows a smaller growth than the datasets with the chosen keywords, which could indicate that the fields of biomimetics, TRIZ and their combination are growing. This is however a risky statement to make, since only a crude, linear approximation is made (in reality, and over more time, it is more like an exponential curve). Added to that, the dataset for the trend in `Biomimetics + TRIZ` is quite small and therefore there is a large amount of uncertainty.

Another interesting thing that can be seen in the graph, is that the last few years (2015, 2016) have less papers published than the year before; this could be due to 2014 being an extremely prolific year for paper-publishing, or that the most recent papers are not entered into Scopus' database yet.

2.2. STATE-OF-THE-ART

Besides some insight in the statistics of the subject matter, the set of papers also gives a bit of an overview in the current developments on using biology and TRIZ. The most apparent effort that was observed in the set of papers was the development and use of BioTRIZ.

The development of BioTRIZ started out in the beginning of this millenium by Drs. Olga and Nikolay Bogatyrev, together with prof. Julian Vincent [20], [21]. They adapted TRIZ to a 'green' version that included the successful principles and ideas to develop new solutions from nature, rather than technology. They analyzed about 500 biological phenomena; analyzing functions at different levels of hierarchy (see *9 Windows*, paragraph 1.2). They also analyzed about 2500 conflicts and their solutions in biology. Six fields of operation were established, by the 'mantra' *things do things somewhere;* all actions with any object are defined. *Things* mean the substance and structure of the object; *do things* means energy and information; *somewhere* points to the time and space [21]. By re-organizing the conflict statements and inventive principles, they constructed the PRIZM matrix (translated: the modernized rules of inventive problem solving): a 6-by-6 matrix that stems from the original TRIZ contradiction matrix, as seen in Table 2.

A very similar 6-by-6 matrix was constructed from the researched biological effects, pairing other inventive principles to the cells; this matrix is called BioTRIZ (Table 3), and can be used to apply biological knowledge to technical problems, without being directly inspired by nature. In this research, a difference between the original TRIZ and BioTRIZ was found, mainly caused by the difference in how natural and technological systems are created. Biological systems are highly hierarchical, and biological materials are mainly constructed of two types of polymers: proteins and polysaccharides. While people have produced over 300 polymers, none of these are as versatile or responsive as the biological ones. In [18], this difference has been visualized by arranging both engineering TRIZ and biological solutions according to their size and amount of conflicts in the field. This is seen in FIGURE 8; from this it was concluded that while engineering heavily relies on energy and substance, the studied biological solutions are mostly found in the fields of information and structure.

Vincent and his team aren't the only ones doing research in integrating biomimetics in TRIZ. In [22], Lim et al. propose a method in which only one contradiction matrix is used, and the inventive principles are rewritten to include biological solutions as well as the existing technological solutions.

TABLE 2 | PRIZM MATRIX DERIVED FROM STANDARD TRIZ CONTRADICTION MATRIX [18]

Fields	Substance	Structure	Space	Time	Energy	Information
Substance	6 10 26 27 31 40	27	14 15 29 40	3 27 38	10 12 18 19 31	3 15 22 27 29
Structure	15	18 26	1 13	27 28	19 36	1 23 24
Space	8 14 15 29 39 40	1 30	4 5 7–9 14 17	4 14	6 8 15 36 37	1 15–17 30
Time	3 38	4 28	5 14 30 34	10 20 38	19 35 36 38	22 24 28 34
Energy	8 9 18 19 31 36–38	32	12 15 19 30 36–38	6 19 35–37 14	14 19 21 25 36–38	2 19 22
Information	3 11 22 25 28 35	30	1 4 16 17 39	9 22 25 28 34	2 6 19 22 32	2 11 12 21–23 27 33 34

TABLE 3 | PRIZM MATRIX DERIVED FROM BIOLOGICAL EFFECTS: BIOTRIZ [18]

Fields	Substance	Structure	Space	Time	Energy	Information
Substance	13 15 17 20 31 40	1–3 15 24 26	1 5 13 15 31	15 19 27 29 30	3 6 9 25 31 35	3 25 26
Structure	1 10 15 19	1 15 19 24 34	10	1 2 4	1 2 4	1 3 4 15 19 24 25 35
Space	3 14 15 25	2–5 10 15 19	4 5 36 14 17	1 19 29	1 3 4 15 19	3 15 21 24
Time	1 3 15 20 25 38	1–4 6 15 17 19	1–4 7 38	2 3 11 20 26	3 9 15 20 22 25	1–3 10 19 23
Energy	1 3 13 14 17 25 31	1 3 5 6 25 35 36 40	1 3 4 15 25	3 10 23 25 35	3 5 9 22 25 32 37	1 3 4 15 16 25
Information	1 6 22	1 3 6 18 22 24 32 34 40	3 20 22 25 33	2 3 9 17 22	1 3 6 22 32	3 10 16 23 25

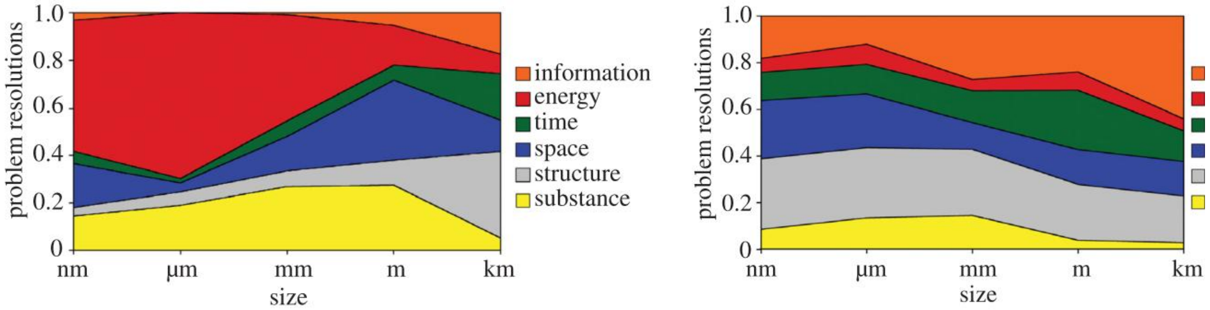


FIGURE 8 | ENGINEERING TRIZ SOLUTIONS (LEFT) AND BIOLOGICAL EFFECTS (RIGHT) ARRANGED ACCORDING TO SIZE/HIERARCHY [18]

Furthermore, Vincent and his team developed a database based on the TRIZ definition of functions. In the original set there are several references to this database but the links provided are decommissioned. The details on how the database entries were structured are in a different paper; this is further discussed in the next chapter.

3. Developing Method

This chapter will take the findings of the previous chapter, combine them with shortcomings and strengths found in other tools and methods described in the next paragraph, and combine them to find a set of challenges that need to be solved. This provides the basis for the method that is proposed at the end of the chapter.

3.1. Existing tools and methods

The previous chapter already shed some light on existing methods to include biomimetics in a design process. This paragraph will discuss these and other tools into more detail, to find out how (or if) they incorporate biomimetics and/or TRIZ, and what their shortcomings are. The list is by no means complete; these were found during the research period and/or provided by the supervisor.

The tools that are going to be discussed are (in no specific order):

- AskNature (online database and Biomimicry Taxonomy)
- TechOptimizer
- Research on databasing using physical effects
- Biomimetic Database
- Integrating TRIZ Function Modeling in CAD Software
- Lexical analysis

AskNature

The webpage and underlying database of AskNature provide an insight in what biomimetics can offer an engineering designer [23], [24]. It features a collection of over 1600 biological strategies, biologically inspired ideas, resources to teach and learn about biomimicry, and collections on common subjects in its database (eg. *'Energy in nature', 'life-friendly packaging', 'managing waste'*).

The content is classified by *The Biomimicry Taxonomy* (see [24], or Figure 9 for a small shard of the full image), which defines a hierarchy of functions and attributes. The page of a biological strategy provides a summary of the relevant literature, connecting focal biological systems, the hierarchy (sub- and supersystems), and resulting functions.

While the AskNature repository provides a starting point for finding inspiration, it lacks a quantitative definition of the described functions, and the database is but a fraction of the information available from nature.

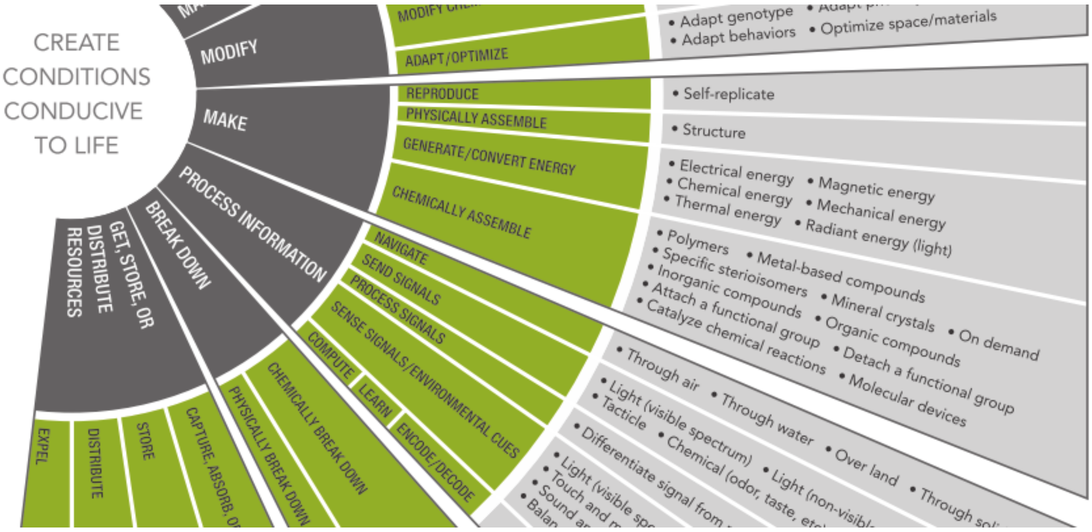


FIGURE 9 | SHARD OF THE BIOMIMICRY TAXONOMY [24]

TECHOPTIMIZER

TechOptimizer [25] is a program that was developed to provide a digital program and user interface for several TRIZ tools. Even though the information in this program is rather old, originating from early 2000, it still provides an interesting example of how a tool can actively help the engineer come up with solutions outside of their own field of expertise. It includes tools to find an *inventive principle* to a *contradiction*, to create a *functional diagram*, search through a database of effects, and find *Trends of Evolution* etc.

The program works by prompting the user to create a Functional Diagram of the system under scrutiny or to be designed. Parts of the system and supersystem are connected by *Actions*. This is a general description of how two components are related, and can be classified as *useful* or *harmful*, and from *insufficient* to *excessive*. The part of the program that is relevant to this research, is the *Effects* module (see Figure 10 for a screenshot of the program's module), containing more than 4,400 effects from different areas of knowledge [26]. The effect page contains a short description, related effects, advantages and limitations, a formula to how the effect is related to other parameters, conditions, and at least one reference. However, not all this information is available for every effect; a lot of pages only have a short qualitative description of the effect. This might be enough for ideation, but a qualitative description is often necessary in the rest of the design process. Also, this module currently does not contain effects from the biology area.

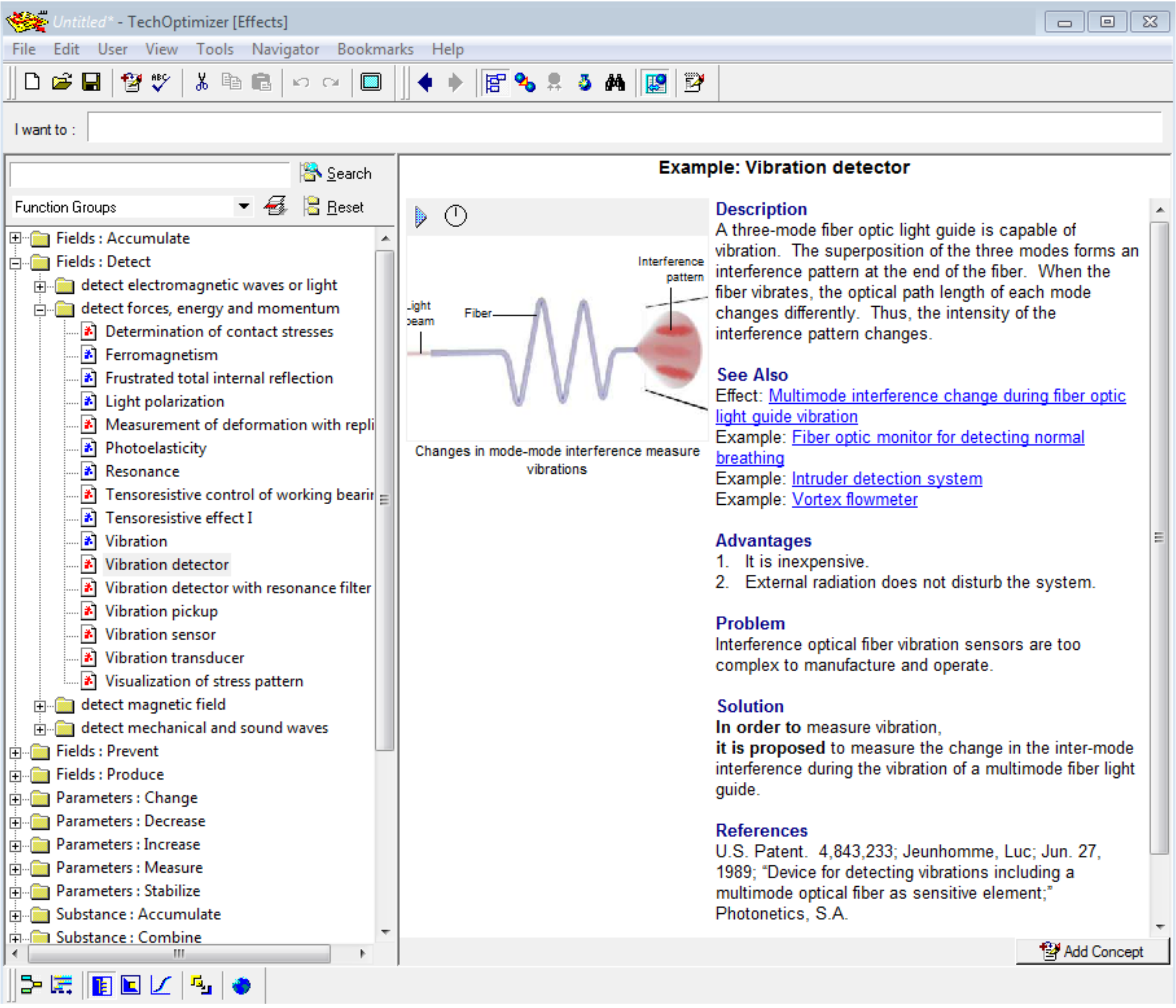


FIGURE 10 | SCREENSHOT OF TECHOPTIMIZER 3.0 - EFFECT MODULE [25]

Research on Automated Databasing using Physical Effects

More recent research efforts by a team of the Volgograd State Technical University discuss and test several methods on automatically processing physical data[27]. Several systems have been developed to retrieve information on basis of *Physical Effects*, automated synthesis of the *Physical Operating Principle* and automatic replenishment of the *Physical Effects* database. To try and automate the design process, the systems have been combined into a complex [28].

To use the complex, the user manually enters a search query, which is formalized using the following POP-structure: PE input cause-action (A), initial state of PE object (B^1), final state of the PE object (B^2) and the PE output effect-action (C).

Physical Effect (**PE**)
"The elementary causal link of physical phenomena and processes"

Physical Operating Principle (**POP**)
"A structure reflecting interrelations of physical effects and phenomena, which result, in their own interaction, in the execution of the user-defined function."

For example, the PE for *'reinforcement of polymeric and composite materials'* has as input *'relative concentration of carbon nanotubes'* and as output *'maximum strength'*. The object is *'polymer matrices with addition of carbon nanotubes'* (shortened from [27]). The user request for *'how to improve strength characteristics of materials'* is translated to *'C: Parametrical, mechanics, strength (Pa) (increase)'*. This serves as input for the search for existing PEs.

This database of PEs can be constructed automatically from natural language texts, as is described in, for example [29]. A database is constructed when a specialization is selected; existing PEs need to be updated if new information is available, and new PEs can be added if they fit within the specialization. The algorithm then searches for information in a variety of sources, such as scientific libraries and magazines, patents, and some unpublished sources. Details of this procedure are unfortunately hidden in a paper by Fomenkov *et al.* from 2004 [30], which was not available at the moment of writing this report. The procedure is mentioned to be quite labor-consuming, therefore, research on automation has been executed [28], [31].

A brief explanation of the workings of the complex as described in [28] is given in a previous paragraph. [31] goes more into detail on how different filtering algorithms for natural language can be used to extract PEs. Using cluster analysis, documents are partitioned to find the location of the physical knowledge area in a document. Based on this clustering, filtering techniques will determine whether a document meets the specified criteria. It is mentioned that the determination of the relevance of the found document is subjective, and therefore hard to assess.

BIOMIMETIC DATABASE

Besides developing BioTRIZ, Julian Vincent and his team also created a database of biological effects, which would be accessible publicly, so other researchers could use and add to the database [32], [33]. However, this database has been discontinued (from a mail conversation with Vincent: *"The database was never very effective, actually, and it was far too small and complex"*).

The structuring of the entries in this database is done using the primary TRIZ components of *function, effect* and *conflict.* The entries (may) contain the following fields, besides author, date, etc.:

- Reference to original article
- Function: *'the action needed to achieve the useful/desired future condition'*
- Level of organization: molecule, organelle, .. , ecological system
- Living medium in which entity performs function
- Cause and effect characteristics
    - internal or external
    - reciprocal or non-reciprocal
    - Static or dynamic
    - Object or medium changes
- Table of parameters that cause/limit action
- Picture of the entity
- Effect description
- Links to physical TRIZ

They also provide a table of functions, classified in six '*program functions*' (eg, '*create*', '*preserve*'), which contain 26 '*goal functions*' in total (eg, for '*create*', '*produce*' and '*grow*').

One of the interesting points of the database was that it was open to the (registered) public, which allowed everyone to add new entries. The European Space Agency used the database for a few projects in the Advanced Concepts Team and the Ariadne project [34]. Especially nature's concepts of self-assembly and use of existing resources are of value to space applications. The use of a biomimetic database produced several novel applications, but has also been discontinued unfortunately.

The database used to be accessible online, and registered users could search the database by adding keywords in the fields, as roughly indicated above (see papers for full list of fields). A disadvantage of the database is that it only contains qualitative descriptions, which might prove valuable in early ideation phases, but for practical purposes a quantitative description is necessary.

Integrating TRIZ Function Modeling in CAD Software

An interesting research on a similar topic has been executed by Hans Bakker, with help of Leonid Chechurin and Wessel Wits [35]. It provides a link between *Computer-Aided Invention (CAI)* and *Computer-Aided Design (CAD),* by developing a tool that generates a TRIZ Function Model from an existing assembly in a CAD-program (SolidWorks). It creates an interaction matrix and subsequently suggests functions for the available interactions.

Lexical Analysis

As Julian Vincent wrote in 'Biomimetics – A Review' [36]: *"Since biology is one of the most complex of sciences, biologists will always be needed for effective information transfer, although the lexical analysis by Chiu and Shu [37] would provide a useful 'front end' to the biological part of the process"*

In a previous paragraph the biological database was briefly explained; Chiu and Shu recognized that compiling a comprehensive database is challenging because of the explosive information growth in biological sciences and the dynamic nature of biological knowledge. Using natural language processing and text mining as an alternative to databases, avoids having to categorize biological phenomena for engineering purposes.

In their research, Chiu and Shu describe a method to systematically bridge the biology and engineering domains, using natural language analysis. Keywords that are meaningful for biologists might not occur to engineers due to differences in domain vocabularies. For example, if the required function is to *clean* something, for a biologist the keyword *'defend'* makes sense, since cleaning is simply the defense against dirt. This bridge was established by first finding alternative keywords that are sub- or superordinate to the original keyword, using WordNet. The matches are then examined for relevance and the corpus is searched to find words that often collocate with the search words. Words that appear frequently using this search method are then added to the set of *bridge verbs*. To determine whether these verbs are biologically meaningful, they are compared to biology dictionaries. Figure 11 provides an overview of how the method works.

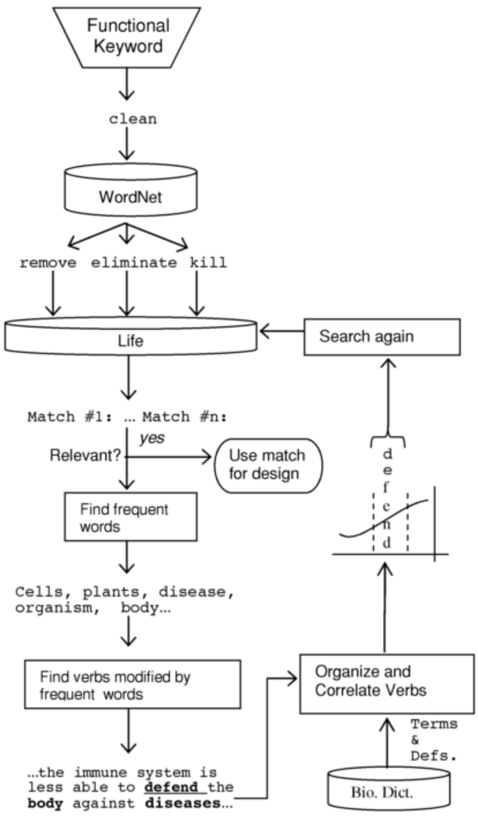


FIGURE 11 | DIAGRAM OF THE METHOD AS DEVELOPED BY CHIU AND SHU [37]

OTHER TOOLS

Some other tools were not discussed in this report, but were mentioned in other papers [38], [39] and might be worth looking into:

- Design by Analogy to Nature Engine (DANE) [40]
- IDEA-INSPIRE [39], [41]
- Hill's catalogue sheets [42], [43]

3.2. CHALLENGES

This paragraph will summarize the challenges and steps needed to complete to develop a new method in using TRIZ to find solutions in all fields of existing 'inventions'.

From the previous paragraphs, the following challenges are extracted:

- Dealing with imperfection in nature, and engineering's drive for perfection/repeatability
- Hierarchical structure of biological systems
- How to bridge engineering and biology and ensure transfer between the disciplines
- How to fill, structure and access database:
  - Where to find data
  - How to extract data
  - How to quantify effects

3.3. PROPOSED METHOD

Possible steps to include in the method algorithm are described below:

- Use TRIZ to find problem definition
    - Function analysis, Su-Field
- Select function to 'improve'
- Search for function in database
    - Database is structured similar to TechOptimizer, but also includes biomimetics
    - Filled semi-automatically using Physical Effects as described by Fomenkov et al
    - Classify database entries on 'completeness'
    - How does TRIZ fit in here?
- Rate and rank suggestions
- Pick solution
- Transfer to original problem (database entry can give suggestions on this)

Please note that these are mere suggestions for the algorithm, and by no means a complete method. Extensive testing and evaluations are necessary to complete the method.

4. CONCLUSION & DISCUSSION

In this paper, research was done on integrating biomimetics in a method to aid engineers in coming up with solutions. A literature research and reviewing other similar tools yielded a set of challenges that need to be overcome for such a tool to become valuable. The main challenge is to extract information and get it to the end user; this can be done by (automatically) building a database or natural text analysis, but both methods are less than ideal. It is suggested to create a database using natural text analysis, and structure it according to *TRIZ Functional Analysis*. The Functional analysis was chosen because it is often used in the found set of papers (see Table 1) and is relatively easy to get a basic understanding of.

While this research provides a starting point for the development of a tool to aid engineers, it is by no means a complete method, and its functionality has not been proven. More research is needed on how to effectively execute all method steps, with a special focus on how to fill the database with valuable information. After the method has been finalized, case studies with engineers (or engineering students) need to be conducted to confirm the effectiveness. Such a study has been described in for example [39].

5. FUTURE WORK/RECOMMENDATIONS

For the method or tool to be successful in aiding engineers in finding solutions, a lot of development is still needed. A sound and complete database or extraction method need to be described, and a solid method for transfer needs to be used. These are well beyond the scope of this research, but interesting topics nonetheless.

After the method has been fully developed, a tool with an user interface (such as TechOptimizer or Hans Bakker's tool [35]) can be constructed. While it is a lot of work to program such a tool, this has the potential to provide the benefits of biomimetics in a comprehensible way to engineers.

It is also wise to seek collaboration with a professional biologist to assess the biological correctness of the information in the database and ensure a fluid transfer between the disciplines.

Another possible interesting topic is to look into the automation of design. While some tools of TRIZ need human input, it is a promising base for automating design steps. Together with an extensive database or automated text extraction system, a tool could suggest design solutions to the engineer and reduce the amount of manual labour.

6. INTERNSHIP REVIEW

In this chapter, a subjective and chronological overview of the internship and my personal experiences is written. A small summary of skills that were acquired over the course of the internship is also given as a conclusion to this chapter.

6.1. GENERAL OVERVIEW

The idea for this internship was generated by my interest in the Nordic countries, my interest in TRIZ that originated from the summer course as taught at the University of Twente, and a connection between Wessel Wits and Leonid Chechurin, who teaches TRIZ at the Lappeenranta University of Technology.

Upon arriving in Finland, a tutor was assigned to me by LUT; Mustafa Choudhury is an international student and after picking me up from the train station in Lappeenranta, he gave me and another student a short tour of the city and campus.

The first meeting with Professor Chechurin was scheduled on the first Monday after arriving (6th of February), and I was presented with a plethora of options: research on patent trends using TRIZ (Big Data), further developing Hans's research that was mentioned earlier in this report, using Real Options for selecting promising ideas, and of course on combining TRIZ with Biomimetics to use nature's knowledge in technology applications. To start orientation in the different subjects, Leonid gave me a book he compiled on all kinds of applications of TRIZ: 'research and practice on the theory of inventive problem solving (TRIZ)'.

The research on biomimetics appealed to me since I have had affinity with biology since high-school. I never really continued this interest throughout my academic career, but when presented with this option, my interest peaked again. Especially since one of the PhD students at LUT had been working on creating a biomimetic walking trail in the beautiful nature surrounding LUT. Her plan is almost finished as I am writing this report, but back then it was still in the concept development phase. Before, a trail existed, but the signs were old and worn, and information was solely information on plants and animals. Her idea was to shed light on clever biological phenomena that are currently (or have potential to be) used as biomimetic solutions. We spent a few hours touring a different trail, and discussing ideas for the biomimetic trail. While this had no implications on the research presented in this report, it made the experience in Finland feel more 'real'.

In researching the state-of-the-art on combining biomimicry and TRIZ, I often came across the name Julian Vincent. As one of the developers of the biomimetic database and BioTRIZ, he is an important player in the field. I have contacted him to ask about the biomimetic database, which was linked in one of the papers but not available anymore. He referred me to the European Space Agency, but unfortunately neither of the contacts resulted in getting my hands on the actual database. Vincent did give me the advice to seek help from a biologist to develop the method further; while this was outside of the scope of the current research, it might be valuable for future development of such a method.

In the final stages of my internship Leonid asked me to look at a paper by Zaripova and Petrova on the automated design of Biosensors. While my knowledge wasn't enough to provide a thorough review on the contents of the paper, it was an interesting read and I got some insights on how papers are generally reviewed. Whilst this might not seem very exciting, it was nice to be included in reviewing a paper and have my opinion heard.

While this section mainly sums up some anecdotes from during the internship, it hopefully provides an overview of my time in Finland. All in all, I thoroughly enjoyed my time in Lappeenranta, and had some interesting contacts with 'colleagues' and friends. There has not been a moment where I did not feel welcome; from the onset and throughout the internship everyone has been incredibly helpful and kind.

6.2. Acquired skills and knowledge

Aside from gaining a wealth of knowledge on biomimetics, and refreshing my knowledge on TRIZ, I also learned a few other things during this internship.

It was my first time doing a structured literature research with a lot of resources; Leonid recommended I use the reference manager Mendeley. While it took a bit of figuring out how the program worked, it proved to be a valuable resource during the internship. Leonid also taught me the importance of, when doing a literature review, keeping track of where you find your sources; the research has to be reproducible. While I did learn some of these things during my Bachelor, it was valuable to me to get a feeling of this. Hopefully it will be a good practice for my Master's thesis.

During the internship period Leonid also included me in some TRIZ-related research currently going on at LUT. I was included in a meeting on the progress on someone who did his masters thesis on TRIZ in business, and Konecranes gave a lecture on how they used TRIZ in some of their recent redesigns.

A last skill that is quite unrelated to any of my studies is a very basic proficiency in the Finnish language. While I couldn't attend any of the classes that taught the language, I was given a link to worddive.com, a website that teaches the user some basic words and grammar. With this program I was able to obtain the A2 level in Finnish (see Figure 12). According to the site, this means I am able to use the language in routine situations and find my way on a tourist trip. In practice, it meant I could say some basic sentences and understand some signs, but understanding anything that was said to me was still too difficult. I do however plan on increasing my knowledge of the language, since the structure and vocabulary has definitely caught my attention!

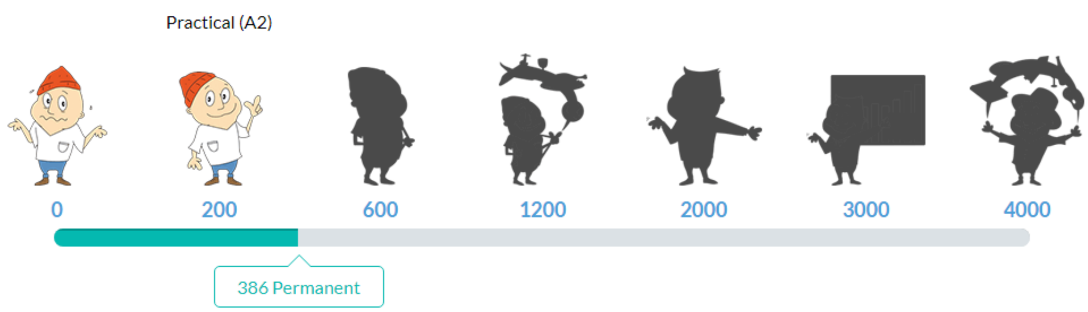


FIGURE 12 | FINNISH PROFICIENCY OBTAINED

6.3. CLOSING WORDS

While it took me some courage to move away for three months from a place I had lived basically my entire life, it has brought me nothing but good experiences. I have made some valuable connections with people, especially with Professor Leonid Chechurin. He motivated me to write a paper on the research done and submit it to the conference he is hosting in October, so I would like to thank him especially, for the challenging discussions we had to the kindness with which I was received. Also, a word of thanks goes out to Wessel Wits, since he got me in touch with Leonid and Lappeenranta University of Technology.

TABLE 4 | TOTAL AMOUNT OF PAPERS PUBLISHED ON SCOPUS BY KEYWORDS

Keywords: *Year*	Biomimetics + TRIZ	Biomimetics	TRIZ	Total
2002	1	194	15	980578
2003	0	350	17	1056851
2004	0	293	31	1144830
2005	2	444	53	1290386
2006	4	782	82	1396294
2007	2	1010	84	1490144
2008	1	1759	89	1586132
2009	1	1857	122	1720122
2010	4	1818	136	1839552
2011	2	2272	227	1976289
2012	1	2250	181	2096820
2013	1	2514	182	2185649
2014	5	2509	179	2280370
2015	4	2293	222	2259688
2016	4	2322	154	2222418
Total	**32**	**22667**	**1774**	**25526123**

TABLE 5 | TRIZ TOOLS USED IN SET OF PAPERS, AND PAPER DATA. 1ST COLUMN COLOUR INDICATES GROUPING FOR USAGE OF TRIZ AND BIOMIMETICS, 2ND COLUMN INDICATES WHETHER FULL PAPER OR ABSTRACT WAS USED.

				TRIZ tool used in paper											
Result No.	*Reference*	*Year*	*Cited by*	*Functions*	*Contradictions*	*40IP*	*9 Windows*	*Su-Field*	*IFR*	*S-curve*	*Dwarfs*	*Trends*	*Resources*	*BioTRIZ*	*PRIZM*
1	[44]	2016	0												
2	[45]	2016	0												
3	[46]	2016	0		x	x									
4	[47]	2016	0						x						
5	[22]	2015	0		x	x									
6	[48]	2015	0	x											
7	[49]	2015	1	x	x	x	x								
8	[50]	2015	0												
9	[51]	2014	3	x				x							
10	[52]	2014	0		x	x									
11	[53]	2014	1		x	x	x	x	x	x	x		x		
12	[54]	2014	0						x						
13	[55]	2014	2	x	x			x	x						
14	[56]	2013	0	x	x										
15	[57]	2012	2		x	x									
16	[58]	2011	1											x	
17	[59]	2011	6	x		x			x			x			
18	[60]	2010	0		x	x									
19	[61]	2010	2												
20	[62]	2010	1		x	x									
21	[63]	2010	4		x	x									
22	[36]	2009	40		x	x								x	
23	[64]	2008	21		x	x								x	x
24	[65]	2007	32					x							
25	[19]	2007	0												
26	[34]	2006	0												
27	[18]	2006	304	x	x	x	x							x	x
28	[66]	2006	2			x	x							x	x
29	[67]	2006	4							x					
30	[68]	2005	0		x	x									
31	[20]	2005	21	x	x	x									
32	[69]	2002	172	x	x				x			x			
Total				**9**	**17**	**16**	**4**	**4**	**6**	**2**	**1**	**2**	**1**	**5**	**3**

7. Bibliography

[1] Scopus, .

[2] G. S. Altshuller and R. B. Shapiro, “О Психологии изобретательского творчества (On the psychology of inventive creation),” *Вопросы Психологии (The Psychological Issues)*, vol. 6, pp. 37–39, 1956.

[3] Y. Salamatov, M. Strogaia, and S. Yakovlev, “The Right Solution at the Right Time: A Guide to Innovative Problem Solving,” *Insytec BV*, pp. 1–20, 1999.

[4] L. D. Miles, *Techniques of Value Analysis and Engineering*. 1989.

[5] C. W. Bytheway, “FAST: an Intuitive Thinking Technique,” *VaLue WORLD*, vol. 28, pp. 2–4, 2005.

[6] S. Litvin, N. Feygenson, and O. Feygenson, “Advanced Function Approach,” presented at the TRIZ Future Conference 2010, 2010.

[7] G. S. Altshuller, *Algorithm of Inventive Problem Solving*. 1956.

[8] TRIZ-tools, “Interactive contradiction matrix.” .

[9] TRIZ-journal, “9 Windows.” .

[10] TRIZ-journal, “Case Study Pizza and the System Operator.” .

[11] V. Souchkov, *TRIZ & Systematic Innovation - Advanced*. Enschede, The Netherlands, 2016.

[12] TRIZ-journal, “Functional analysis tutorial.” .

[13] G. S. Altshuller, *And Suddenly the Inventor Appeared*. Moscow: Detskaya Literatura, 1989.

[14] G. Cameron, *TRIZICS*. CreateSpace, 2010.

[15] V. Souchkov, *Lecture Slides TRIZ Course UT*. 2016.

[16] G. S. Altshuller, “Creativity As an Exact Science. Theory of Inventive Problem Solving,” *Sovetskoye Radio*, 1979.

[17] “Case Study TRIZ: Bite-size candy pouch,” *Trizjournal*.

[18] J. F. V. Vincent, O. A. Bogatyreva, N. R. Bogatyrev, A. Bowyer, and A.-K. Pahl, “Biomimetics: its practice and theory,” *Journal of the Royal Society Interface*, vol. 3, pp. 471–482, 2006.

[19] T. Shelley, “New Fizz Behind TRIZ,” *Eureka*, 2007.

[20] J. F. V. Vincent, “Deconstructing the design of a biological material,” *Journal of Theoretical Biology*, vol. 236, pp. 73–78, 2005.

[21] O. A. Bogatyreva, N. R. Bogatyrev, and A. Shillerov, *Patterns In Triz Contradiction Matrix: Integrated And Distributed Systems*. Florence: Firenze University Press, 2004.

[22] C. Lim, I. Park, and B. Yoon, “Technology development tools in biomimetics utilizing TRIZ: Biomimetic-TRIZ matrix,” *Portland International Conference on Management of Engineering and Technology*, vol. 2015–Septe, pp. 2307–2312, 2015.

[23] AskNature, .

[24] G. Hooker and E. Smith, “AskNature and the Biomimicry Taxonomy,” *Insight*, vol. 19, pp. 46–49, 2016.

[25] *TechOptimizer*. Invention Machine Corporation.

[26] M. A. Orloff, “Inventive Thinking through TRIZ : a Practical Guide,” p. 332, 2003.

[27] V. A. Kamaev, S. A. Fomenkov, and D. A. Davidov, “Use of physical knowledge for automation of the initial stages of designing.,” presented at the IEEE International Conference on Artificial Intelligence Systems (ICAIS 2002), 2002, pp. 411–413.

[28] S. A. Fomenkov, D. M. Korobkin, S. G. Kolesnikov, A. M. Dvoryankin, and V. A. Kamaev, “Procedure of Integration of the Systems of Representation and Application of the Structured Physical Knowledge,” *Research Journal of Applied Sciences*, vol. 9, pp. 700–703, 2014.

[29] S. A. Fomenkov, S. G. Kolesnikov, D. M. Korobkin, V. A. Kamaev, and Y. A. Orlova, “The Information Filling of the Database by Physical Effects,” *Journal of Engineering and Applied Sciences*, vol. 9, pp. 422–426, 2014.

[30] S. A. Fomenkov, D. A. Davidov, and V. A. Kamaev, “Modeling and the automated use of the structured physical knowledge,” *Monograph, Mechanical Engineering*, p. 278, 2004.
[31] D. M. Korobkin, S. A. Fomenkov, S. G. Kolesnikov, and Y. A. Orlova, “A multi-stage algorithm for text documents filtering based on physical knowledge,” *World Applied Sciences Journal*, vol. 24, pp. 91–97, 2013.
[32] J. F. V. Vincent, O. Bogatyreva, A.-K. Pahl, N. Bogatyrev, and A. Bowyer, “Putting Biology into TRIZ: A Database of Biological Effects,” *Creativity and Innovation Management*, vol. 14, pp. 66–73, 2005.
[33] O. Bogatyreva and A. K. Pahl, “Data gathering for putting biology in TRIZ,” *Institute for TRIZ Studies*, pp. 16–18, 2003.
[34] M. Ayre and N. Lan, “Biomimetic engineering for space applications,” *European Space Agency, special publication*, 2006.
[35] H. M. Bakker, L. Chechurin, and W. W. Wits, *Integrating Triz Function Modeling In Cad Software*. 2011.
[36] J. F. V. Vincent, *Biomimetics – a review*. 2009.
[37] I. Chiu and L. H. Shu, “Biomimetic design through natural language analysis to facilitate cross-domain information retrieval,” *Artificial Intelligence for Engineering Design, Analysis and Manufacturing2*, vol. 21, pp. 45–59, 2007.
[38] D. Vandevenne, P.-A. Verhaegen, S. Dewulf, and J. R. Duflou, “A Scalable Approach for the Integration of Large Knowledge Repositories in the Biologically-Inspired Design Process,” *International Conference on Engineering Design, ICED11*, 2011.
[39] J. Sartori, U. Pal, and A. Chakrabarti, “A methodology for supporting ‘transfer’ in biomimetic design,” *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, vol. 24, pp. 483–505, 2010.
[40] S. Vattam, M. Helms, and A. K. Goel, “Biologically-Inspired Innovation in Engineering Design: A Cognitive Study,” presented at the ME/ISyE/MSE/PTFe/BIOL 4803: Biologically-Inspired Design; course report, 2006.
[41] A. Chakrabarti, P. Sarkar, B. Leelavathamma, and B. S. Nataraju, “A functional representation for aiding biomimetic and artificial inspiration of new ideas,” *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, vol. 19, no. 2, pp. 113–132, Apr. 2005.
[42] Bernd Hill, *Innovationsquelle Natur : naturorientierte Innovationsstrategie für Entwickler, Konstrukteure und Designer.* Aachen: Shaker, 1997.
[43] B. Hill, “Goal Setting Through Contradiction Analysis in the Bionics-Oriented Construction Process,” *Creativity And Innovation Management*, vol. 14, 2005.
[44] L. Chechurin and Y. Borgianni, “Understanding TRIZ through the review of top cited publications,” 2016.
[45] D. Sunguroğlu Hensel and J. F. V. Vincent, “Evolutionary inventive problem-solving in biology and architecture: ArchiTRIZ and Material-Ontology,” *Intelligent Buildings International*, vol. 8, pp. 118–137, 2016.
[46] L. Xiaomin, B. Huang Shuiping, and C. Yuting, “Research and application: conceptual integrated model based on TRIZ and bionics for product innovation,” *International Journal on Interactive Design and Manufacturing (IJIDeM)*, pp. 1–9, 2016.
[47] A. Weiss, I. Avital, A. K. Das, and M. Gedalya, “‘What Ideality Tool’ (The WIT) for Product Design Briefs Fusion and Confluence in Design Management,” *DS 85-1: Proceedings of NordDesign 2016, Volume 1, Trondheim, Norway, 10th - 12th August 2016*, 2016.
[48] A. Baldussu and G. Cascini, “About Integration Opportunities between TRIZ and Biomimetics for Inventive Design,” *Procedia Engineering TFC*, vol. 131, pp. 3–13, 2015.
[49] N. R. Bogatyrev and O. A. Bogatyreva, “TRIZ-based algorithm for Biomimetic design,” *Procedia Engineering TFC*, vol. 131, pp. 377–387, 2015.

[50] D. Vandevenne, P.-A. Verhaegen, S. Dewulf, and J. R. Duflou, “Product and organism aspects for scalable systematic biologically-inspired design,” *Procedia Engineering*, vol. 131, pp. 784–791, 2015.
[51] Y. H. Cohen, Y. Reich, and S. Greenberg, “Biomimetics: Structure–Function Patterns Approach,” *Journal of Mechanical Design*, vol. 136, p. 111108–1/11, 2014.
[52] W. K. Chung, N. Cui, X. Chen, T. L. Lam, Y. Xu, and Y. Ou, “Optimized methodologies for augmented reality markers based localization,” *2014 IEEE International Conference on Robotics and Biomimetics, IEEE ROBIO 2014*, pp. 1811–1816, 2014.
[53] P.-E. Fayemi and N. Maranzana, *Bio-Inspired Design Characterisation And Its Links With Problem Solving Tools*. 2014.
[54] Y. H. Cohen, Y. Reich, and S. Greenberg, “Sustainability strategies in Nature,” *Int. J. of Design & Nature and Ecodynamics*, vol. 9, pp. 285–295, 2014.
[55] W.-C. Chen and J. L. Chen, “Eco-innovation by Integrating Biomimetic Design and ARIZ,” *Procedia CIRP*, vol. 15, pp. 401–406, 2014.
[56] M. Ognjanovic, J. Babic, and S. Vasin, *Linking of function carriers with physical contradictions*. Seoul, Korea, 2013.
[57] H. K. Ko and K. H. Kim, “Design Evolution of an Actuation System for Manipulator Upper Arm Based on TRIZ,” *Journal of Advanced Mechanical Design, Systems, and Manufacturing*, vol. 6, pp. 131–139, 2012.
[58] M. W. Glier, D. A. McAdams, and J. S. Linsey, *Concepts in Biomimetic Design: Methods and Tools to Incorporate into a Biomimetic Design Course*. Washington DC, USA, 2011.
[59] J. L. Chen and Y.-C. Yang, “Eco-Innovation by Integrating Biomimetic with TRIZ Ideality and Evolution Rules,” *Life Cycle Design - Methods and Tools*, pp. 101–106, 2011.
[60] K. Fung, J. S. Wallace, and L. H. Shu, *Water Management Concepts in PEMFC with Biomimetic and TRIZ Design Methods*. ASME, 2010.
[61] A. P. Wadia and D. A. McAdams, *Developing Biomimetic Guidelines for the Highly Optimized and Robust Design of Complex Products or Their Components*. ASME, 2010.
[62] S. S. Vattam, M. Helms, and A. K. Goel, “Biologically inspired design: A macrocognitive account,” *Proceedings of the ASME Design Engineering Technical Conference*, vol. 5, pp. 129–138, 2010.
[63] H. K. Ko, C. H. Cho, and K. H. Kim, “Design of an Economic Service Robot Hand Based on Biomimetics and TRIZ,” *KOREAN*, pp. 1741–1747, 2010.
[64] S. Craig, D. Harrison, A. Cripps, and D. Knott, “BioTRIZ Suggests Radiative Cooling of Buildings Can Be Done Passively by Changing the Structure of Roof Insulation to Let Longwave Infrared Pass,” *Journal of Bionic Engineering*, vol. 5, pp. 55–66, 2008.
[65] R. H. C. Bonser and J. F. V. Vincent, “Technology trajectories, innovation, and the growth of biomimetics,” 2007.
[66] J. F. V. Vincent, O. A. Bogatyreva, and N. R. Bogatyrev, “Biology doesn’t waste energy: that’s really smart,” vol. 6168, p. 616801, 2006.
[67] A. Morina, T. Liskiewicz, and A. Neville, “Designing new lubricant additives using biomimetics,” *WIT Transactions on Ecology and the Environment*, vol. 87, pp. 157–166, 2006.
[68] J. F. V. Vincent, O. A. Bogatyreva, N. R. Bogatyrev, A. Pahl, and A. Bowyer, *A theoretical basis for biomimetics*. 2005.
[69] J. F. V. Vincent and D. L. Mann, “Systematic technology transfer from biology to engineering,” 2002.