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Biomimetics: process, tools and practice

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Abstract

Biomimetics applies principles and strategies abstracted from biological systems to engineering and technological design. With a huge potential for innovation, biomimetics could evolve into a key process in businesses. Yet challenges remain within the process of biomimetics, especially from the perspective of potential users. We work to clarify the understanding of the process of biomimetics. Therefore, we briefly summarize the terminology of biomimetics and bioinspiration. The implementation of biomimetics requires a stated process. Therefore, we present a model of the problem-driven process of biomimetics that can be used for problem-solving activity. The process of biomimetics can be facilitated by existing tools and creative methods. We mapped a set of tools to the biomimetic process model and set up assessment sheets to evaluate the theoretical and practical value of these tools. We analyzed the tools in interdisciplinary research workshops and present the characteristics of the tools. We also present the attempt of a utility tree which, once finalized, could be used to guide users through the process by choosing appropriate tools respective to their own expertize. The aim of this paper is to foster the dialogue and facilitate a closer collaboration within the field of biomimetics.

1. Introduction

For over 3000 years, people have 'learned from nature' in order to inspire human design (Vincent *et al* 2006). Several terms exist to describe the concept of 'learning from nature' (see section 2.1) and as a systematic approach it is still an emerging field of research, especially within engineering design (Von Gleich *et al* 2010). Biomimetics encompasses a broad variety of research topics, it impacts several fields of application and it is considered to have a significant scientific, societal and economic impact for the quality of life (Lepora *et al* 2013). However, research areas are broad and fragmented and most of the significant results have remained in their own field. Studies have shown that biomimetics has been practiced primarily by individual parties rather than through an institutionalized approach (Von Gleich *et al* 2010), and that the relatively low number of documented biomimetic products on the market is due to several reasons (Goel *et al* 2013), one of which is the lack, from a general perspective, of a clear methodology in the field (Vincent *et al* 2006). To contribute to the research in the field, we analyzed the process of biomimetics and existing tools which facilitate the process, with the aim of making the existing tools and the information about the process more transparent for potential users. First, we give an overview of terms and definitions to clarify the terminology. Next, we present a unified problem-driven process model of biomimetics as a framework for the practical implementation of biomimetics. Lastly, we assessed tools, which are reported as being used within a bioinspired design process, in order to validate their facilitation of the process and to gain knowledge about users' perception of the tools. The assessment was performed with three small-sized workshops involving highly specialized professional profiles (i.e. bioinspiration and problem-solving experts) as well as through a broader field survey. This analysis resulted in the design of a 'utility tree' which provide a guiding through the process model by using appropriate tools. This presentation is considered to be a first attempt and further studies will serve the purpose of improving this utility tree. We consider experts from various disciplines (e.g. biology, engineering, industrial design, architecture and many more) to be the beneficiaries of our work. The target group is referenced, in this work, as practitioners, i.e. engineering designers.

2. Definitions

Several terms exist to describe the process of 'learning from nature', such as bioinspiration, biomimicry, bionics, or biologically-inspired design (BID). In the scientific literature these different terms are presented as if they were synonyms (e.g. Vincent *et al* 2006, Shu *et al* 2011, Goel *et al* 2013). We consider this appropriate, if one refers to the final outcome of these approaches, which is an invention that has been made possible with knowledge originating from nature. But differences occur by looking at the respective scopes of each word and the development processes (see section 3). For a better understanding of these differences, we provide definitions of important terms.

2.1. Terminology

A recent work within the ISO/TC 266 Biomimetics committee has led to the following definitions (ISO/TC266 2015):

- Bioinspiration: 'Creative approach based on the observation of biological systems'.
- Biomimicry: 'Philosophy and interdisciplinary design approaches taking nature as a model to meet the challenges of sustainable development (social, environmental, and economic)'.
- Biomimetics: 'Interdisciplinary cooperation of biology and technology or other fields of innovation with the goal of solving practical problems through the function analysis of biological systems, their abstraction into models and the transfer into and application of these models to the solution'.
- Bionics: 'Technical discipline that seeks to replicate, increase, or replace biological functions by their electronic and/or mechanical equivalents'.

Terms related to bioinspiration can be distinguished according to a specificity of analogy and an axis of related fields, as presented in figure 1. Bioinspiration ranges from mere inspiration fostering creativity in general (related to the divergent phase of creativity), up to novel design solutions (through the implementation of the convergent phase of creativity). This concretization of ideas could either be based on an analogy schema by adapting principles extracted from biology (BID) or through the abstraction, transfer and application of knowledge from a specific biological system (biomimetics).

According to the definitions, field wise (i.e. mechanics, sustainability and other fields), bioinspiration can be specific to mechanics (bionics) (ISO/TC266 2015), specific in its striving for sustainable solutions (biomimicry), or non-specifically labeled, e.g. related to nanotechnology, materials science, architecture, aerodynamics or molecular engineering.

The variety of operational definitions of bioinspiration demonstrates that the field of biomimetics consists of differing subjects and research priorities. Regarding the above outlined definitions, we further refer to the approach of biomimetics.

2.2. The two approaches of biomimetics

In general, biomimetics practice can be carried out either as solution-based (solution-based Helms *et al* 2008, Badarnah and Kadri 2015, solution-driven Vattam *et al* 2007, Helms *et al* 2009, biology to design Baumeister *et al* 2013, biology push ISO/TC266 2015, bottom up Speck *et al* 2008, biomimetics by induction Gebeshuber and Drack 2008) or as problem-driven (problem-based Badarnah and Kadri 2015, problem-driven Vattam *et al* 2007, Helms *et al* 2008, 2009, challenge to biology Baumeister *et al* 2013, technology pull ISO/TC266 2015, top down Speck *et al* 2008, biomimetics by analogy Gebeshuber and Drack 2008). Both the solution-based and problem-driven approaches have different starting points and differing characteristics as design processes (Goel *et al* 2014).

The solution-based approach describes the biomimetic development process in which the knowledge about a biological system of interest is the starting point for the technical design. The biological system of interest performs a function that shall be emulated in technology. This biological system must be understood in depth in order to extract underlying principles and to define design problems which could be addressed using these principles. The knowledge concerning these principles is primarily gained from fundamental research. After their abstraction the biological principles may be applied in technology. The solution-based approach is therefore closely connected to the steps of the technology knowledge transfer process from scientific to industrial organizations. Such process is usually applied by Technology Transfer Office and involves the following steps: Scientific Discovery, Invention Disclosure, Evaluation of invention for patenting, Patent, Marketing of Technology to firms, Negotiation of License, License to firms (Siegel *et al* 2004).

On the other hand, the problem-driven approach is the biomimetic development process that seeks to solve a practical problem, with an identified problem to be the starting point for the process (Goel *et al* 2014, ISO/TC266 2015). New or improved functions may be applied via identifying biological systems, which

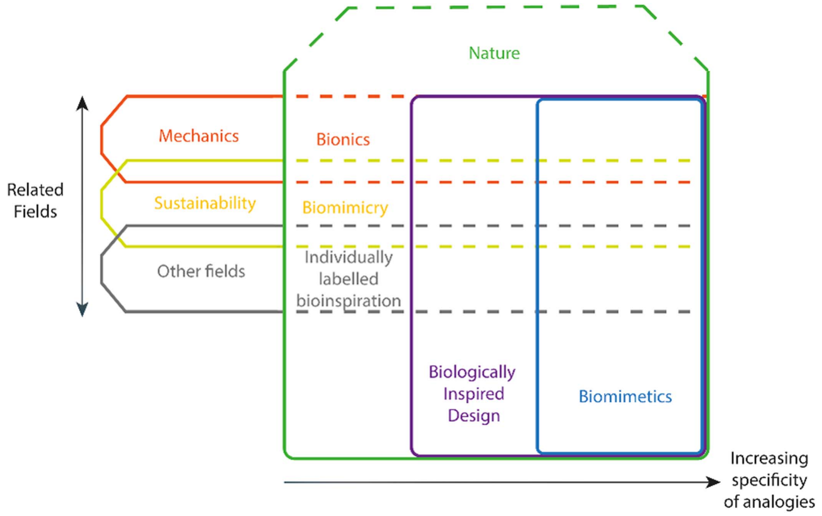


Figure 1. The field of bioinspiration.

perform a certain function or mechanism, and by abstracting and transferring these principles to technology. The problem-driven approach is closely connected to the problem-solving process. Models of this process have already been described within literature (e.g. Bransford and Stein 1984, Isaksen and Treffinger 1985, Adams *et al* 2003, Bardach 2011). The problem-solving process has been summarized by Massey and Wallace's (Massey and Wallace 1996) consisting of 5 stages: identification, definition, alternative generation, choice of solution and implementation and testing.

Both approaches show intrinsic differences and a deeper understanding of each of the processes requires a detailed analysis. The aim of this paper is to foster the usage of biomimetics in the industrial sector. Therefore, the following presented work will focus on the problem-driven approach of biomimetics, as this approach seems more appropriate to be initiated by industrial companies (i.e. the process starts within the technical field)—even though this approach is less represented among commercially available biomimetic products (Jacobs *et al* 2014).

3. Biomimetic process model

Within the last decade the problem-driven approach of biomimetics has often been described in literature (e.g. Vattam *et al* 2007, Helms *et al* 2009, Goel *et al* 2013). A representative set of different presentations of the process is shown in figure 2. Twelve presentations were aligned with the problem-solving process (Massey and Wallace 1996) to illustrate a holistic perspective on the state of the process models.

Lindemann and Gramann (2004) describe a model consisting of four steps strating from the formulation of the intention up until the realization of the technical solution. The progression of the steps is connected to iterative loops and internal check lists.

Bogatyrev and Vincent (2008) describe a process which focuses on extracting essential features from biological models and transferring these features to technology by performing a six steps process.

Lenau (2009) presents biomimetics as a process using natural language analysis, which includes subactivities and often requires refinement.

Helms *et al* (2009) outline a problem-driven biologically-inspired design process model as a non-linear and dynamic progression of six steps, including iterative steps as well as feedback and refinement loops.

Nagel *et al* (2010a) implement a concept generation approach for biologically-inspired solutions which uses six steps. These steps start with the functional model of a desired engineering system to explore biological solutions for inspiration and ends with a conceptual or detailed design. This description is intertwined with the development of a specific tool, developed or utilized by its authors. The same holds true for the presentation of the problem-driven process from Chakrabarti *et al* (2005) and Shu *et al* (2010).

Cheong *et al* (2011) outline a process model based on natural language processing. The model starts with the definition of an original functional keyword to describe a problem and ends with the identification of biologically meaningful keywords.

Baumeister *et al* (2013) use their Design Spiral Methodology to address a practical challenge to biology. In a circular eight-step process this Biomimicry Thinking approach is used for the emulation of biologically-inspired design principles.

Goel *et al* (2014) have set up a generic task model of analogical design and have matched it with the solution-based and problem-driven approaches of biomimetics.

ISO/TC 266 (2015) Biomimetics shows an overall simplified flow chart of a biomimetic process. The

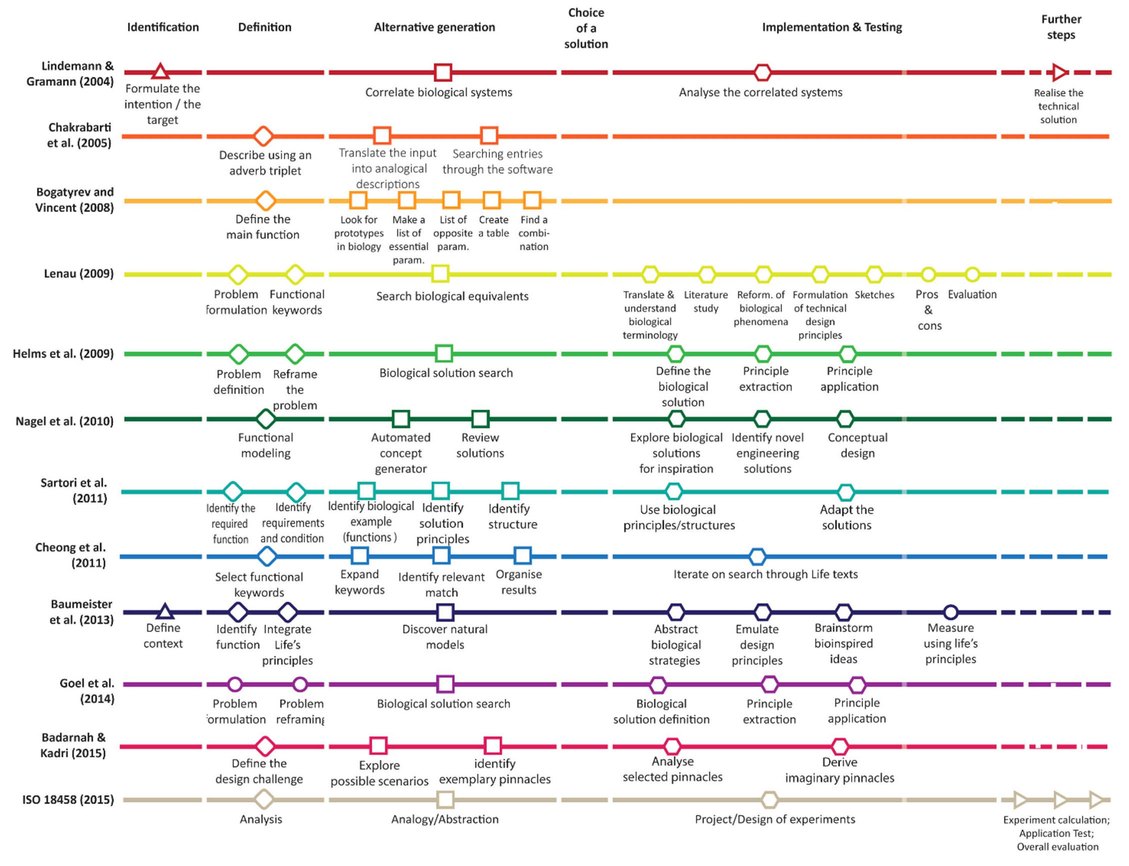


Figure 2. Problem-driven biomimetic process models correlated with the general problem-solving process.

standard points out that the particular sequence of steps during a development process in biomimetics differs within scientific disciplines.

There have already been attempts in analyzing different descriptions of the process of biomimetics and establishing a general methodology for the generation of design concepts (Sartori *et al* 2010, Nagel *et al* 2014, Badarnah and Kadri 2015). Sartori *et al* (2010) offer a model based on Function-Behavior-Structure (FBS) modeling dividing functions and structures in the search for biological analogies. Nagel *et al* (2014) outline a systematic biologically-inspired design methodology which closely follows five steps of the problem-solving model (Massey and Wallace 1996), presenting flowcharts of the problem-driven approach, with cues for iteration. Badarnah and Kadri (2015) present their BioGen methodology that enables designers, especially architects, to face the challenges of the process of biomimetics by following several phases. Furthermore, they present tools that facilitate the implementation of different phases.

4. The unified problem-driven process of biomimetics

Biomimetics demands from potential users a deeper insight into existing process descriptions and the knowledge about existing tools (ISO/TC266 2015). Therefore, we consider it to be beneficial to unify the above mentioned descriptions. The purpose is to give practitioners a better understanding of the field by combining the existing process models.

Figure 3 shows the unified problem-driven process model consisting of eight steps. The outline of the process model is divided in two phases designed as a double symmetrical abstraction-specification cycle. The first phase (step 1–4), focuses on a technology to biology transition while the second phase (step 5–8) tackles its way back from biology to technology. The required contribution of either biologists or technologists are indicated with the light (biology) and dark (technology) arrows.

The initial entry point of the unified biomimetic process model, is the problem analysis (step 1). This can either encompass the assessment of the situation and/or the problem description. In the first case, a specific problem to address has not yet been identified. Step 1 then aims to identify a development axis of improvement for the technical system of interest and focuses on system optimization. In the latter case, a concrete problem has already been identified and the problem description provides a proper problem formalization. The abstraction of the technical problem (step 2) leads to a functional model which encompasses the context as well as constraints of the problem. After this, it is clear which function should be achieved. With this abstraction and the envisaged

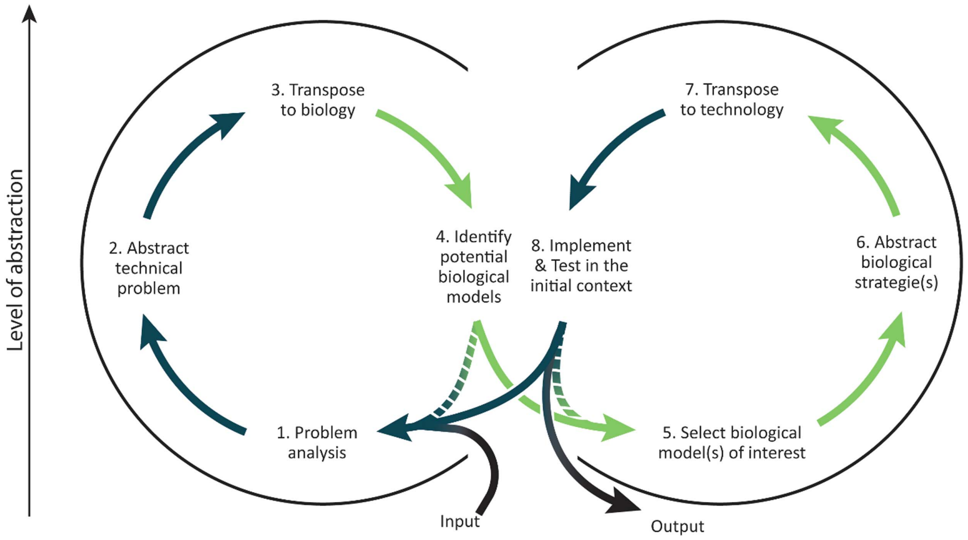


Figure 3. The unified problem-driven process of biomimetics.

function, the problem and its environment can be transposed to biology (step 3). Usually, a question towards nature is formulated in order to explore how nature has achieved a certain function. This is an important step, as the results may highly differ depending on how the question was formulated. With the transposed question, biological models can be identified by searching through literature, using web engines and databases, or by gathering existing knowledge. After step 4, there is a first iteration loop. The identification of biological models can lead to a deeper understanding of the initial problem, which might require a new circle of step 1–3. This interaction is due to the fact that a comparison of biology and technology may lead to a gain of knowledge in both fields.

The process is continued by selecting a biological model of interest (step 5). The strategy of the biological model needs to be understood in detail and then abstracted (step 6). Step 5 and 6 allow the combination of several biological models and thus biological principles in order to solve the initial problem (which has been labeled as compound analogy Vattam *et al* 2008, Goel *et al* 2014). The abstraction of the biological strategy is crucial as an exact biology-technology match is usually not feasible. In general, the abstraction leads to a functional model of the biological system (e.g. Helms *et al* 2009), extracting principles independent of the living system (e.g. Baumeister *et al* 2013) which may be emulated in technology. A transposition of the biological strategy to technology is the next step (step 7), which enables designers to embody the outlined biological principles according to technical functionalities. Such transposition usually requires the available technological knowledge to act as a grid for interpreting the biological solution(s) and enabling its implementation into the technical world. The biological to technology conversion then leads to the final implementation and testing in the initial context (step 8). At this point the cycle can be finished successfully with a biomimetic design as output. If the results are not adequate the cycle can either be started all over again or there may be an iteration within phase two, selecting a new model of interest.

The unified biomimetic process model does not pursue the objective of being a new process model per-se but can be rather be seen as an instrument to make existing biomimetic process models converge. With an explicit link to the outlined problem-solving process, practitioners may implement the bio-inspired process more easily, as it is connected to their prior knowledge of such design processes. The unified process is descriptive and leaves space for feedback loops and iterations.

5. Biomimetic tools

Along with the growing interest for bioinspiration (Goel *et al* 2013), tools were designed to fit its specificities (e.g. interaction between technologists and biologists Nagel *et al* 2011, use of biology as a specific source of knowledge Baumeister *et al* 2013). Other tools originating from the design field have also been used for biomimetics (e.g. TRIZ Vincent and Mann 2002, FBS Chakrabarti *et al* 2005, Vattam *et al* 2011a). A combination of tools from these two originating sources defines the biomimetic toolset considered in this work.

Within this work, a set of tools was chosen for analysis, according to the following parameters:

- Biomimetic implementation: has the tool/method been documented as being used in a biomimetic case study?

Table 1. The biomimetic toolset and its match with the steps of the unified problem-driven process of biomimetics.

	Considered tools
Step 1	*S*-Curve, Domino, LP, KLP
Step 2	MSD, Uno-BID, TC, IFR, CW, DANE, SAPPhIRE, 4-Box, 5-Whys
Step 3	IP, Resources, Taxonomy, BIOPS
Step 4	BIOPS, Bioniquity, AskNature, Brainstorming
Step 5	T-chart
Step 6	Uno-BID, DANE, SAPPhIRE, BioM, 4-Box
Step 7	IP, Resources
Step 8	—

- Theoretical description: has the tool/method and its development been described and discussed in literature?
- Illustrative case study: has the tool/method been disclosed in a practical environment?
- Usage guidelines: do the authors provide any document to help the proper use of the tool/method?

These parameters were thought to identify tools which more likely provide a required maturity for an industrial implementation. 22 tools were selected and are shown in table 1.

TRIZ tools were distributed based on Schöfer's work (Schöfer *et al* 2013) which emphasizes Savransky's (2000) and Nakagawa's (Nakagawa *et al* 2003). Other tools were assigned according to a theoretical literature analysis ran by the first author and reviewed by the second. Furthermore, the biomimetic tools were divided into four categories, as shown in table 2, in accordance with creative activities during problem-solving (Wallas 1926, Amabile 1983, Nelson 2003). For consistency, the chosen categories were aligned with the definition of biomimetics (ISO/TC266 2015), which states that the initial problem is solved through the analysis, the abstraction, the transfer and the application of knowledge from biological models to the technical field. Therefore, the four considered categories of tools are: abstraction (preparation Wallas 1926; problem or task identification Amabile 1983; naming Nelson 2003), transfer (incubation Wallas 1926; preparation Amabile 1983; framing Nelson 2003), application (illumination Wallas 1926; response generation Amabile 1983; taking action Nelson 2003) and analysis (verification Wallas 1926; response validation Amabile 1983; reflecting Nelson 2003).

5.1. Analysis tools

The tools identified to facilitate the Analysis step are:

Life's Principles (*LP*). The collection of design patterns from currently living species constitutes the LP (Baumeister *et al* 2013). LP could therefore be used as a measurement instrument and/or as design principles, allowing designers to identify new ways to improve the sustainability of their object of study.

KARIM's version of LP (*KLP*). The European project 'Knowledge Acceleration and Responsible Innovation Meta network' (KARIM) has developed a complement to the KARIM Responsible Innovation manual, based on the LP. This version presents the same principles than the LP (Baumeister *et al* 2013) with sample questions, advantages, and biological and technical examples (Michka Mélo *et al* 2015).

S-Curve. One of the axioms upon which TRIZ has been built is the development of technological systems according to Evolution Laws (Cavallucci and Weill 2001). These laws state that the development of technical products follow certain patterns (Altshuller 1988). From this statement, the *S*-Curve analysis has been developed to identify product life cycle stages and to offer guidelines to move from one stage to another (Terninko *et al* 1998).

Domino. The Domino or Task Analysis, a part of the Synectics which was developed by Nolan (1989), is a four steps questionnaire. The method focuses on reframing a given problem by identifying ownership, foreseeable problems and the problem's root cause (Nolan 1989).

T-Chart. The T-Chart (Helms and Goel 2014) allows the comparison of two 4-Box representations (one for the problem description, one for the identified biological analogues), providing an evaluation of the analogy.

5.2. Abstraction tools

Tools among this category are:

Brainstorming. Brainstorming (Osborn 1953) is a well-known group activity that provides a democratic way to quickly generate many ideas , requires few material resources, and helps foster social interactions.

SAPPhIRE representation. The State change, Action, Part, Phenomenon, Input, oRgan and Effect model (SAPPhIRE) is a causal language developed to describe structural and functional information of both natural and technical systems (Chakrabarti *et al* 2005). Originating from the Function, Behavior, Stucture (FBS) model proposed by Gero (Gero 1990), the model has been made to emphasize the physical phenomena on which the described function relies.

Design analogy to nature engine (*DANE*). DANE is an interactive tool for supporting BID (Vattam *et al* 2011a). It is based on Structure-Behavior-Function (SBF) model (Goel *et al* 2009) which refers to the Functional Representation (Vattam *et al* 2011b). Functions are modeled through a progression of states, linked together by behavioral causal explanations, along with structure box diagrams.

Uno-BID. Uno-BID seeks to combine existing functional-causal models into a single ontology (Rosa *et al* 2014). It thus hybridizes both the detailed description of system internal structure of SAPPhIRE

Table 2. Types of biomimetic tools and their match with the unified problem-driven process of biomimetics.

Step 1: Problem analysis	**Step 2:** Abstract technical problem	**Step 3:** Transpose to biology	**Step 4:** Identify potential biological models	**Step 5:** Select biological model(s) of interest	**Step 6:** Abstract biological strategies	**Step 7:** Transpose to technology	**Step 8:** Implement and test in the initial context
Analysis tools	Abstraction tools	Transfer tools	Application tools	Analysis tools	Abstraction tools	Transfer tools	Application tools

representation (Chakrabarti *et al* 2005) and the modeling approach provided by DANE (Vattam *et al* 2011a).

Multi-screen diagram (*MSD*). The MSD (also called System-Thinking Operator, or 9-Windows) is a mental exercise segmenting a technical system into boxes, starting from the central box which refers to the current system, and varying according to two axes, time and systemic levels (Altshuller 1988). By creating a dynamic picture, the multi-screen serves as a reminder to perform a gradual transition between different subsystems and states of technology as any division of a technique into subsystems is arbitrary by nature (Savransky 2000).

Ideal final result (*IFR*). IFR, is about picturing the ideal representation of a system by overcoming current technological limitations. Ideality is reached when an action is fulfilled without the need of the system (Altshuller 1996). The identification of the IFR can be facilitated by methods such as the Innovation Situation Questionnaire, which is a structured thinking questionnaire (Terninko *et al* 1998).

Technical contradictions. Technical contradictions occur when a system improves a technical characteristic or parameter which at the same time deteriorates another one. Not overcoming technical contradictions leads therefore to trade-off solutions. Technical contradictions are often hidden or vaguely formulated only (Altshuller 1988). As a tool, Technical Contradictions, aim to identify and to define such conflicts.

5-Whys. 5-Whys is an iterative process tool focusing on identifying the root cause of a problem. The technique explores the chain between cause and effect by repeatedly interrogating users on the problem cause (Ōno 1988).

Closed world approach (*CW*). The CW originates from the Unified Structured Inventive Thinking (Sickafus 1997), a derivative of TRIZ (Altshuller 1988, 1996). It provides an analysis of a problem by describing the functional interactions between objects of a given system according to their effect (i.e. useful or harmful) and their attributes (Sickafus 1997).

Four-box method (*4-Box*). The four box method (Helms and Goel 2014) consists of a 2 × 2 matrix, facilitating the problem description according to its Operational Environment, Function, Specifications and Performance Criteria.

Biological modeling (*BioM*). BioM is a set of guidelines proposed by Nagel *et al* (2011), leading to the functional representation of a given biological system. Generated models may tackle different levels of granularity and the modeling process is facilitated by an engineering-to-biology thesaurus (Nagel *et al* 2010b).

5.3. Transfer tools

The identified transfer tools are:

Taxonomy. Taxonomy allows designers to translate a technical problem into a biological one thanks to the use of a functional ontology which seeks to organize biology by challenge (Baumeister *et al* 2013).

Inventive principles (*IP*). Altshuller's work has shown that 40 principles are used by patent authors to solve a problem (Altshuller 1997). Inventive Principles have been outlined to overcome design trade-off. Awareness of these heuristics is important, but knowing which principle(s) to use in order to solve a given problem is equally essential. For this purpose, Altshuller (1997) synthetized the typical design parameters of a system into a matrix of 39 generic parameters. This matrix, known as the Contradiction Matrix, allows designers to link formalized problems through technical contradictions to the inventive principle(s) of interest in order to solve the initial contradiction and thus the problem.

Resources analysis. The problem solving tool Resources Analysis focuses on resources that exist within the analyzed system or its environment. The initial purpose is that providing a database of resources would allow designers to recognize things that they usually might not consider as resources. Once the resources have been identified, the tool uses heuristics that help designers navigate among them (Savransky 2000) with the goal of turning unexpected and harmful things into useful resources.

Biology inspired problem solving (*BIOPS*). BIOPS is developed by Fraunhofer IAO, Germany, and is accessible online as demo version (Fraunhofer). It is a thesaurus for mapping technological functional search terms with biological models. The starting point is a technical problem (e.g. water harvesting) which will then be linked to biological creatures.

5.4. Application tools

Tools among this category are:

AskNature. AskNature, known for being the largest database related to bio-inspiration, is built around the same ontology as Taxonomy. The database seeks to provide knowledge about a biological phenomenon, links to experts and potential design ideas/application (Baumeister *et al* 2013).

BionIQuity. BionIQuity® is a set of creativity techniques which can be used in new product development and for problem-solving activities (Dell 2006). It provides 42 abstracted principles of biological models, which are referenced in this work as Bioniquity. These principles can be used for idea generation on a meta-level (Dell 2006).

BIOPS. BIOPS has also been considered as an application tool as the tool will, once the transfer step has been completed, further guide the user to the websites asknature.org to find more information, to a patent database (freepatentsonline.com) and to scientific literature (sciencedaily.com).

Table 3. Summary of the assessment criteria.

	Analysis tools	Abstraction tools	Transfer tools	Application tools
Theoretical criteria	Analysis completeness (Ac)	Modeling capacity (Mc)	Transposition precision (Tp)	Uniqueness of solution (Uos)
	Analysis accuracy (Aa)	Systemic levels integration (Sli)	Direction (Di)	Knowledge enlargement (Ke)
	Identification of ideality (Id)	Information filtering (If)	Query Versatility (Qv)	Modularization (M)
	Prioritization (Pri)	Generalization capacity (Gc)	Consistency (Co)	Inventiveness (Inv)
		Constraints preservation (Cp)		
Practical criteria	Swiftness (1) Simplicity (2) Stand-alone capacity (3) Field adaptability (4) Group adaptability (5) Precedence (6)			

6. Experimental method and results

We considered a study on how these tools were perceived by their users as a beneficial step. This study should provide insight into practical context specificities of the tools, while validating the distribution made according to the problem-driven biomimetic process model.

6.1. Assessing the biomimetic toolset

Comparison of creative or problem-solving methods and tools have been attempted several times (Alford *et al* 1998, Cavallucci and Lutz 2000, Shah *et al* 2000, Chakrabarti 2003, Thiebaud 2003, Shneiderman and Plaisant 2006, Glier *et al* 2011, Sarkar and Chakrabarti 2011, Reich *et al* 2012). According to these references several assessment criteria have been outlined. These criteria are swiftness (1) (Glier *et al* 2011), simplicity (2) (Thiebaud 2003, Shneiderman and Plaisant 2006, Glier *et al* 2011), the capacity to be used stand-alone (3) (Thiebaud 2003), field adaptability (4) (Thiebaud 2003, Shneiderman and Plaisant 2006), group adaptability (5) (Thiebaud 2003, Shneiderman and Plaisant 2006) and the capacity to ease the following design stage (6) (Glier *et al* 2011). These criteria assess the required operating conditions for a given tool to deliver what it has been designed for, defining the practical criteria subset which will be used for all presented tools.

For each category, specific criteria were defined (see table 3 for a summary). These criteria aim to assess how one tool delivers what it has been designed for. These criteria define the theoretical criteria subset. In contrast to the practical criteria, the theoretical criteria are specific to the four respective categories of tools. The combination of the practical criteria with the specific theoretical ones was used for the assessment of the considered biomimetic toolset.

6.1.1. Analysis tools

Analysis tools should define the problem space (Newell and Simon 1972) by evaluating a situation exhaustively and precisely. They could also define the solution space (Newell and Simon 1972) by describing an ideal situation where the problem does not exist anymore. It is possible that they offer a way to prioritize underlying problems needed to be solved in order to reach the solution space (Jonassen 1997). Assessment criteria, defined in this work, are therefore the completeness (Ac) and the accuracy (Aa) of an analysis, identification of ideality (Id), and Prioritization (Pr).

6.1.2. Abstraction tools

Abstraction tools focus on generating models on different systemic levels. The purpose of these models is to ease the comparison of analogy between technology and biology, in our context, by increasing the level of abstractness (Chi *et al* 1981, Nagel *et al* 2010a) and reducing the amount of information taken into account (Chi *et al* 1981) while maintaining the contextual constraints as much as possible. Considered assessment criteria are modeling capacity (Mc), systemic levels integration (Sli), generalization capacity (Gc), information filtering (If), and constraints preservation (Cp).

6.1.3. Transfer tools

One of the challenges of biomimetics is the difficulties in communication between technologists and biologists (Helms *et al* 2009, Nagel *et al* 2010a). Their different backgrounds lead to divergent disciplinary or functional understanding of a concept (Dougherty 1992), whether due to perception (Dearborn and Simon 1958), languages (Tushman 1978), or ‘thought styles’ (Fleck 2012). Transfer tools are thus meant to precisely transpose concepts from biology to technology and vice versa.

They may handle different types of queries and provide outputs with different level of abstraction Considered assessment criteria are transposition precision (Tp) and direction (Di), query versatility (Qv), and consistency (Co).

6.1.4. Application tools

Application tools seek the concretization. They are the ones contextualizing back transposed models to produce embodiments. They are expected to lead to the identification of a small number of high inventiveness solutions (Savransky 2000) that solve the initial problem either by themselves or combined (Henderson and Clark 1990). Assessment criteria are therefore the knowledge enlargement (Ke), the uniqueness of solution (Uos), the inventiveness (Inv), and the modularization (M).

6.2. First study: workshops

The assessment of the biomimetic toolset has been performed with conditions as close as possible to an actual industrial implementation, involving experts in their working environment.

6.2.1. Context and protocol

Workshops were set to involve small groups of participants (i.e. five) and to last from one to two entire workdays. The first type of participants were the industrial representatives, acting as problem owners and setting up the industrial context for a given workshop. Workshops involved one industrial representative per workshop. The other two types of participants, were engineers and biologists. The engineers involved were researchers in design methodologies and innovation consultants, experts in problem-solving and design processes. Involved biologists were both renowned biomimetics/biomimicry lecturers and leading figures of their national bioinspiration related organization. Workshops involved two engineers and two biologists per workshops.

Due to the rarity of the population that was targeted, combined with the length of the workshops, only three workshops were implemented: two of them included an industrial partner and the third was carried out as a theoretical case study. Workshop participation redundancy reduced the total number of participants to 8.

The first workshop was held in collaboration with a French small-sized company working in the field of temporary accommodation for eco-tourism or one-time events. Studied products were spherical structures made out of a plastic film supported by an air flow generated through a compressor. The purpose of the workshop was to provide a way to integrate the temporary accommodation solution with less environmental impact. This led to the initial question: ‘How can fluxes of energy be managed dynamically?’

The second workshop took place with a 3D-printing company. The selected topic was ‘How to reduce the amount of input material without reducing structural strength?’

The last workshop, extrapolated from Azad *et al*’s (2015) and Malik *et al*’s (2014) work, focused on ‘Designing a water bottle which harvests clean and non-salty water from the atmosphere for individual daily usage’. For the third workshop, no industrial representative was involved and has consequently been replaced by one of the authors to even the number of participants.

Facilitation was made by the two first authors of this work who are familiar with creative workshops in industrial environments. The participants received a methodological training depending on the tools’ complexity and the overall existing knowledge of participants. The average training duration was approximately one to two hours per tool, conforming to the guidelines generated by their developers. Trainings were implemented according to the following procedure:

- General introduction on the theoretical background of the tool.
- Introduction to the means and purposes of the tool.
- Explanatory case study, performed by the facilitator.
- Pedagogical case study, performed by participants.

The achievement of the pedagogical case study allowed to ensure the proficiency of participants to a given tool. At the end of the training, tools were put to the test on the actual workshop case study. Instructions, such as templates and/or guidelines, were given to the participants.

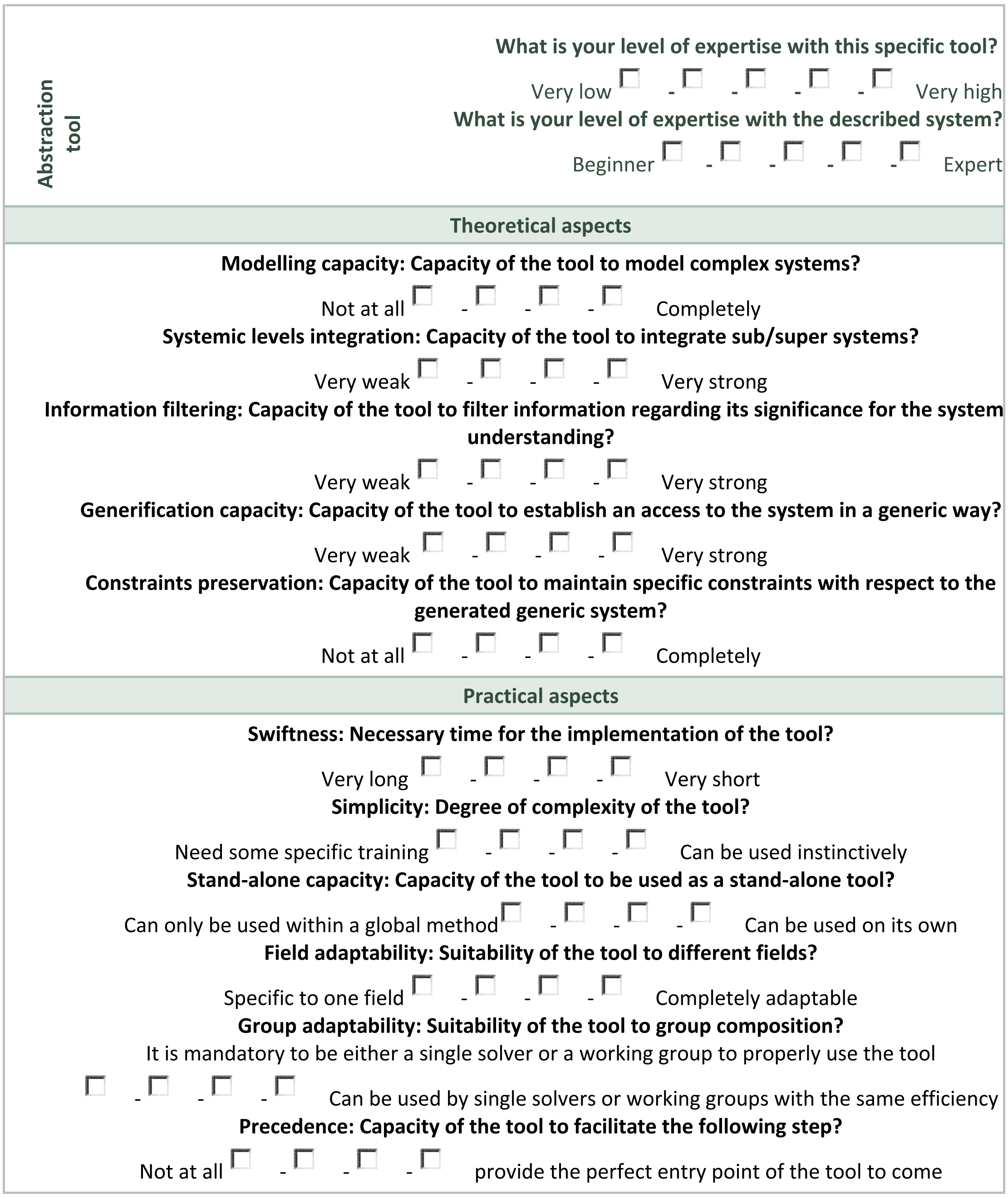
Each tool was introduced individually through their specific training and afterwards they were used for the case study. Tools were sequentially implemented according to the unified process presented in figure 3. Introduction, training and application took place during the individual workshops.

Ultimately assessment sheets, illustrated in figure 4, combining theoretical and practical criteria listed in section 6.1, were distributed among participants in order to assess the tools.

6.2.2. Results

Though the workshops tackled different topics, the experimental conditions remained close. Results of workshops have thus been combined. The analysis of the results was performed by using the Wilcoxon Signed-Ranks Test.

Measurements showed a high degree of reliability (Cronbach’s alpha range: 0.703–0.970), except for DANE and Domino which obtained questionable



Abstraction tool

What is your level of expertise with this specific tool?

Very low ☐ - ☐ - ☐ - ☐ - ☐ Very high

What is your level of expertise with the described system?

Beginner ☐ - ☐ - ☐ - ☐ - ☐ Expert

Theoretical aspects

Modelling capacity: Capacity of the tool to model complex systems?

Not at all ☐ - ☐ - ☐ - ☐ Completely

Systemic levels integration: Capacity of the tool to integrate sub/super systems?

Very weak ☐ - ☐ - ☐ - ☐ Very strong

Information filtering: Capacity of the tool to filter information regarding its significance for the system understanding?

Very weak ☐ - ☐ - ☐ - ☐ Very strong

Generification capacity: Capacity of the tool to establish an access to the system in a generic way?

Very weak ☐ - ☐ - ☐ - ☐ Very strong

Constraints preservation: Capacity of the tool to maintain specific constraints with respect to the generated generic system?

Not at all ☐ - ☐ - ☐ - ☐ Completely

Practical aspects

Swiftness: Necessary time for the implementation of the tool?

Very long ☐ - ☐ - ☐ - ☐ Very short

Simplicity: Degree of complexity of the tool?

Need some specific training ☐ - ☐ - ☐ - ☐ Can be used instinctively

Stand-alone capacity: Capacity of the tool to be used as a stand-alone tool?

Can only be used within a global method ☐ - ☐ - ☐ - ☐ Can be used on its own

Field adaptability: Suitability of the tool to different fields?

Specific to one field ☐ - ☐ - ☐ - ☐ Completely adaptable

Group adaptability: Suitability of the tool to group composition?

It is mandatory to be either a single solver or a working group to properly use the tool

☐ - ☐ - ☐ - ☐ Can be used by single solvers or working groups with the same efficiency

Precedence: Capacity of the tool to facilitate the following step?

Not at all ☐ - ☐ - ☐ - ☐ provide the perfect entry point of the tool to come

Figure 4. Example of an assessment sheet (abstraction tool) used during the workshops.

correlations (Cronbach's $\alpha_{\mathrm{DANE}} = 0.540$ and Cronbach's $\alpha_{\mathrm{DOMINO}} = 0.491$).

Analysis tools. LP were assessed through the first workshop, the KARIM's version of LP (KLP), *S*-Curve and the Domino were assessed through the second workshop and the T-Chart through the third one. The grouped histogram in figure 5 introduces the result obtained across the assessed tools for each of the considered criteria, setting the means as the *x*-axis. Said results are compared, per criterion, to this overall mean in order to highlight their differences.

LP and KLP show low theoretical results with only Ideality (Id) scoring over 1. Results indicated that LP group adaptability (5) scores, Mdn = 2 were higher than KLP's. KLP appears to be relevant for many topics (Field adaptability's scores) and obtained Swiftness (1) scores, higher than LP ones.

The *S*-Curve analysis has shown strong capabilities in providing a complete analysis (Ac) of a given situation coupled with an idealized vision (Id). The fulfillment of these two criteria seems to allow designers to take the next step of the biomimetic process in a proper manner (Precedence's score (6)).

Unlike the LP or the *S*-Curve targeting to outline one or several strategic axes for an innovative process, the Domino focuses on the problem description. Through its results the domino differs from the prior analyzed analysis tools. Its theoretical impact has been recorded high on both the accuracy measurement (Aa) and the ability to prioritize (Pr). In view of its

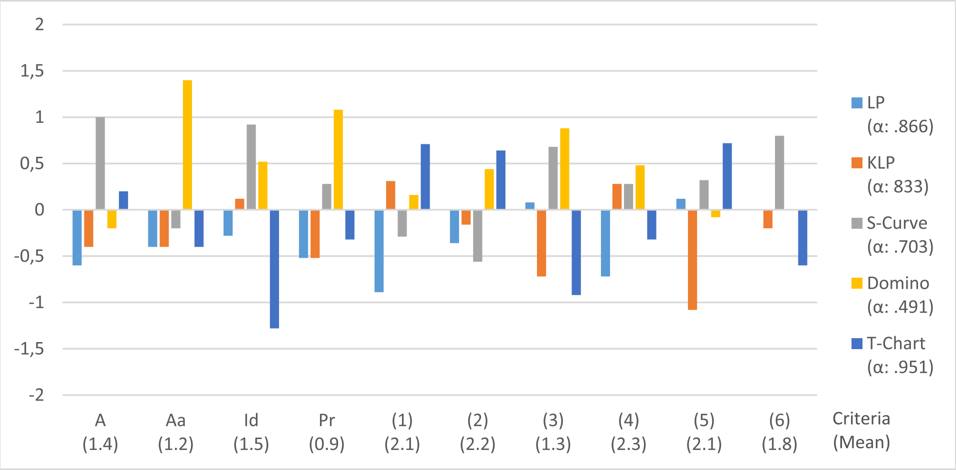


Figure 5. Workshops' analysis tools assessment results. With theoretical criteria Ac: analysis completeness; Aa: analysis accuracy; Id: identification of ideality; Pri: prioritization; and practical criteria 1: swiftness; 2: simplicity; 3: stand-alone capacity; 4: field adaptability; 5: group adaptability; 6: precedence.

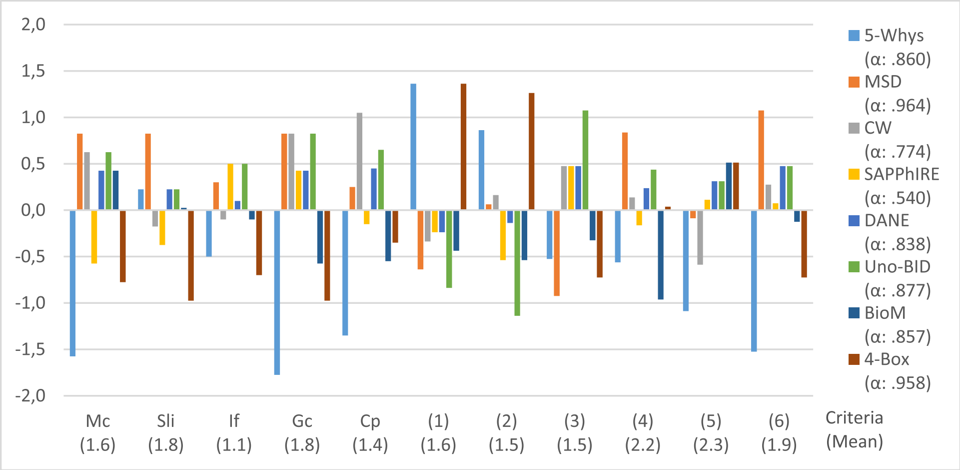


Figure 6. Workshops' abstraction tools assessment results. With theoretical criteria Mc: Modelling capacity; Sli: systemic levels integration; If: information filtering; Gc: generalization capacity; Cp: constraints preservation; and practical criteria 1: swiftness; 2: Simplicity; 3: stand-alone capacity; 4: field adaptability; 5: group adaptability; 6: precedence.

Simplicity (2), Swiftness (1) and Stand-alone capacity (3), the Domino seems to be a tool that one should consider while attempting to state appropriately a problem.

T-Chart, as an analysis tool, shows medium to low theoretical criteria scores. However, the tool scored high on its practical criteria. The Stand-alone capacity (3) is the only practical criteria to score low. Designers are thus suggested to pick the T-Chart's previous and/or subsequent tool in accordance with its use.

Abstraction tools. The 5-Whys and the MSD were assessed through the first workshop, the CW through the second one and DANE, SAPPhIRE representation, UnoBID, BioM and the 4-Box through the third one. The results are shown in figure 6.

5-Whys show low results on the theoretical criteria ($M_{5\text{-Whys}}$ range: 0–0.6), with only a better result on the sub/super system integration criterion (Sli). The tool's high score for Simplicity (2) and Swiftness (1) can hardly, in the context of the workshop, counterbalance its lack of theoretical efficiency.

The MSD showed a high capacity to deal with sub/super systemic levels (Sli). Its lower score (i.e. Information Filtering (IF)) still belongs to the top of abstraction tools. The tool scored a perfect Field Adaptability (4) and Precedence (6). On the other hand, MSD does not seem to be a stand-alone tool and therefore needs to be coupled with specific other tools to reach its full potential, making it relatively complex to use and difficult to implement.

The CW shows overall good theoretic abilities for modeling, except for its capacity to filter information. CW's highs are its capacity to maintain constraints (Cp) and its Generalization capacity (Ge). However, its use seems to require specific group typology (5) in order to be effective.

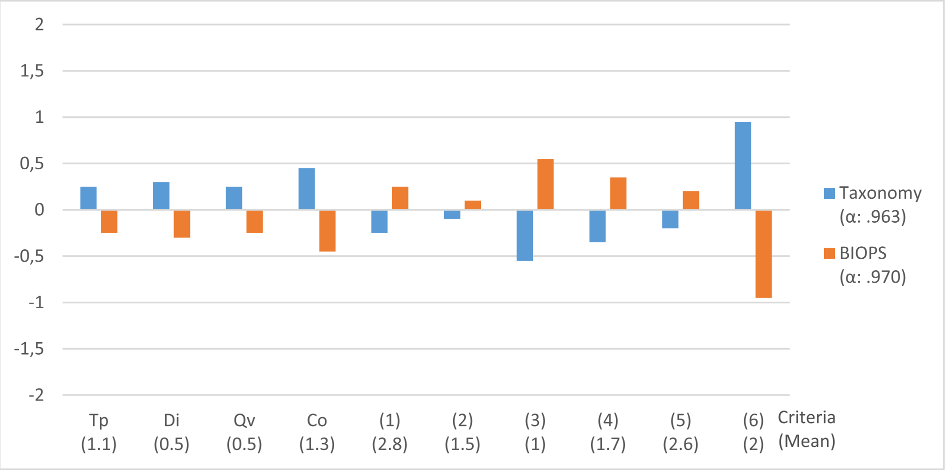


Figure 7. Workshops' transfer tools assessment results. With theoretical criteria Tp: transposition precision; Di: direction; Qv: query versatility; Co: consistency; and practical criteria 1: swiftness; 2: simplicity; 3: stand-alone capacity; 4: field adaptability; 5: group adaptability; 6: precedence.

The function-based modeling tools all scored high on theoretical criteria. Participants voiced their struggle at modeling a system involving several sub- steps with the SAPPhIRE representation, while DANE allowed them to do so without difficulty with its sequential state changes. Nevertheless, participants voiced the capacity of SAPPhIRE representation to highlight causal relations of the systems, leading to possible higher abstraction level modeling. Looking at the result, Uno-BID seems to achieve advantages of both SAPPhIRE representation and DANE with the downside of being difficult to handle and requiring time in order to be implemented.

The 4-Box showed medium to low theoretical scores, suggesting that other abstraction tools should be preferred to generate models. Results indicated that 4-Box ease of use (2) scores (Mdn = 3) were higher than MSD (Mdn = 2), CW (Mdn = 1) DANE (Mdn = 1) SAPPhire representation (Mdn = 1), UnoBID (Mdn = 0) and BioM; the same results indicated that 4-Box swiftness (1) scores (Mdn = 3) were significantly higher than MSD (Mdn = 2), CW (Mdn = 1) DANE (Mdn = 1) SAPPhire representation (Mdn = 1), UnoBID (Mdn = 1) and BioM (Mdn = 1). This makes, from our workshops results, the 4-Box the quickest and easiest tool, aside from the 5-Whys, to perform an abstraction. However due to the high interdependency of 4-Box and T-Chart (Stand-alone capacity score), the prior use of the 4-Box is recommended whenever T-Chart is implemented.

BioM results showed higher Modeling capacity (Mc), Mdn = 2, and higher Generalization capacity (Gc), Mdn = 1, than the 5-Whys (Mdn = 0 for Mc and Mdn = 0 for Gc). Therefore, BioM seems to outclass the 5-Whys when it comes to theoretical criteria. Compared with the results of function-based modeling tools BioM's theoretical and practical criteria do not differ statistically, except for the Generalization capacity (Gc), which appeared to be lower than Uno-BID's (Mdn = 3), SAPPhIRE representation's (Mdn = 2) and DANE's (Mdn = 2). Thus, BioM should be preferred under specific requirements (e.g. avoiding the relatively longer learning of functional modeling).

Transfer tools. The Taxonomy was assessed through both the first and the second workshop. BIOPS was assessed through the third workshop. The results are shown in figure 7.

BIOPS scores very low on every theoretical score and its practical scores are average to good. This seems to indicate that its use as a transfer tool in an industrial environment might be difficult. Its use could be contained to very specific operating conditions or needs related to one of its feature (e.g. Participants voiced its ability to perform queries into patent database). BIOPS obtained better Stand-alone capacity (3) results (Mdn = 1.5), than Taxonomy's (Mdn = 0).

The Taxonomy scored average to low on theoretical criteria. Its capacity to handle different types of queries input is especially low, meaning the input has to be formulated specifically before being transposed to the biological world. This underlying specificity is correlated by its low stand-alone score, leading to the use of a specific tool in order to perform adequately. Taxonomy obtained better Precedence (6) results (Mdn = 3), than BIOPS's (Mdn = 1).

Application tools. AskNature has been assessed through the first and the second workshop. Brainstorming has been assessed through the first workshop, and BIOPS and Bioniquity have been assessed through the third workshop. The results are shown in figure 8.

Due to its fundamentals, Brainstorming can hardly score high in the theoretical part. It has been designed to provide the largest quantity of concepts

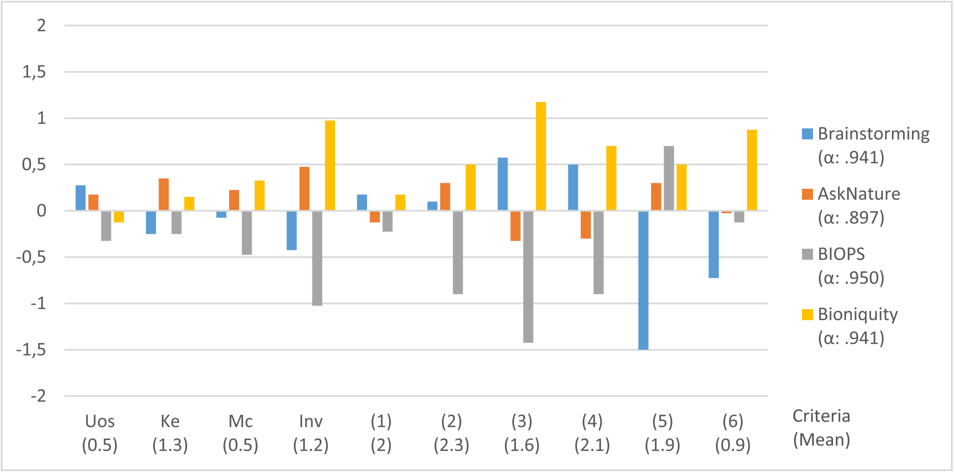


Figure 8. Workshops' application tools assessment results. With Uos: uniqueness of solution; Ke: knowledge enlargement; M: modularization; Inv: inventiveness; 1: swiftness; 2: simplicity; 3: stand-alone capacity; 4: field adaptability; 5: group adaptability; 6: precedence.

(low score at pointing at unique solutions) while profiting from the embedded knowledge (i.e. few to no knowledge enlargement) of the gathered participants (groups are mandatory, i.e. low group adaptability). As expected, brainstorming scored poorly in these criteria, along with the two other theoretical ones. Unlike theoretical, brainstorming shows high scores in 'Swiftness (1)' and 'Simplicity (2)'. Brainstorming group adaptability (2) scores (Mdn = 0) were lower than all the other assessed application tools, i.e. BIOPS (Mdn = 3), Bioniquity (Mdn = 2) and AskNature (Mdn = 2). Brainstorming Inventiveness (Inv) scores (Mdn = 1) were also reported lower than Bioniquity's (Mdn = 2) and AskNature's (Mdn = 2).

AskNature showed a high enlargement capacity of the designers' knowledge while still being a quick and easy tool. Nonetheless AskNature was voiced as requiring the use of Taxonomy to reach its potential, and its Precedence (6) indicated that further work would be necessary to fulfill the step it has been designed for (i.e. identification of potential biological systems).

BIOPS, obtained in the overall limited scores with Inventiveness (Inv) scores, (Mdn = 0) even lower than Brainstorming's, (Mdn = 1); and Field adaptability (4) scores, (Mdn = 1), lower than Brainstorming's, (Mdn = 3), and Bioniquity, (Mdn = 3).

Bioniquity's Inventiveness (3) results (Mdn = 3), were higher than Brainstorming's (Mdn = 2) or BIOPS (Mdn = 0). Other significant differences were Precedence (6), Mdn = 2, and Stand-alone capacity (3), Mdn = 3, scoring respectively higher than Brainstorming on Precedence (6), Mdn = 1, and BIOPS on Precedence (6), Mdn = 0, and Stand-alone capacity, Mdn = 0. Bioniquity could, from the workshops results, be considered as a tool to generate potential disruptive inventions quickly and easily.

6.2.3. Conclusion of the workshops

The small amount both of workshops and participants are of relevant limitations and the lack of statistical data does not allow to draw any firm conclusions. However, certain tendencies have been outlined.

Abstraction tools tended to score high on the theoretical criteria, higher than the other categories of tools assessed. This tendency to provide well what these tools have been designed for, seems to come with a more limited user-friendly ability (i.e. simplicity and swiftness). However, these two trends do not seem to stand true for the 5-Whys and the 4-box. These tools presented good simplicity and swiftness scores combined with low theoretical criteria scores (combining theoretical scores leads to $M_{\text{5-whys}} = 0.52$, $\mathrm{SD}_{\text{5-whys}} = 0.8$ and $M_{\text{4-Box}} = 0.76$, $\mathrm{SD}_{\text{4-Box}} = 0.5$).

The main trends among transfer tools identified from the workshops is their low capacity to transpose both from technology to biology and from biology to technology (direction $M_{\text{Taxo,BIOPS}} < 1$). The fundamental principles of these tools show that they have mainly been thought to transpose from technology to biology. This observation constitutes a threat, as it could lead to a potential bottleneck when considering the whole process.

Results also showed that Transfer tools share low to medium Stand-alone capacity (Sla) ($M_{\text{Taxo,BIOPS}}$ range: 0.4–1.5). Taxonomy, which has been developed jointly with AskNature, and BIOPS, which is both a transfer and an application tool divided in two parts, leading to the consideration that these two tools might not be considered without their application counterpart. It is thus a combined Transfer-Application set of tools that should be selected to 'Transpose to biology' and 'Identify potential biological models', rather than two subsequent tools.

To strengthen the results of the workshops, the assessment would benefit from being put to trial with a

Table 4. Participants' subjective expertize on the assessed tools.

Tools	Mean	Standard deviation	Skewness	Kurtosis
TC	3.44	1.14	−0.327	−0.718
IFR	3.88	1.27	−0.797	−0.560
MSD	3.69	1.44	−0.733	−0.864
IP	3.46	1.12	−0.323	−0.788
Resources	3.47	1.35	−0.528	−0.967
Brainstorming	3.58	0.98	−0.452	0.143

larger audience, which was performed in a second study.

6.3. Second study: field survey

To assess the considered biomimetic toolset with a larger audience implies different conditions of assessment. The results of this second study should therefore show, to some extent, if the tendencies identified during the workshops are supported or undermined with a larger sample size.

6.3.1. Context and protocol

This second study makes it also possible to tackle the TRIZ theory which was yet to be investigated. The use of tools originating from TRIZ within biomimetic approaches has been promoted by a research group from the University of Bath (from which the consulting firm BioTRIZ derived), leading to the adaptation of some tools to the specificities of the biomimetic process (e.g. Bogatyreva *et al* 2003, Vincent *et al* 2005). Several tools from TRIZ have been presented as being of interest for biomimetics (Vincent and Mann 2002). The assessment of these five different tools (i.e. Technical Contradictions, IFR, MSD, Inventive Principles, Resources analysis) seized upon the 13th International Conference of the European TRIZ Association (TRIZ Future Conference 2013), which annually gathers TRIZ experts from across Europe.

Due to the context, training and implementation of actual case studies were unmanageable. Participants evaluated tools with questionnaires including the same list of criteria as during the workshops. As the precedence criteria (6) requires the following type of tools to be represented, brainstorming was added to the study. 86 participants, 51 industrial practitioners and 35 scientific researchers, answered the questionnaire. The average number of years of TRIZ experience over the participants was 7.05 (range: 1–16, $SD = 4.52$). The experience was non-normally distributed, with skewness of 0.41 ($SE = 0.26$) and kurtosis of −0.76 ($SE = 0.51$). The mean of participant's subjective expertize on TRIZ was 2.97 ($SD = 1.26$) out of 5 with skewness of −0.11 ($SE = 0.26$) and kurtosis of −0.46 ($SE = 0.51$). The subjective expertize of participants regarding the individual tools is presented in table 4.

6.3.2. Results

The Shapiro-Wilk W test has been used to evaluate each variable for normality. The majority of the observed distributions were identified as non-normal. The Wilcoxon Signed-Ranks Test was thus used as a non-parametric test for ordinal data. Cronbach's alphas (range: 0.815–0.971) showed a good to excellent internal consistency of the measurements.

Abstraction tools. The results of the abstraction tools' assessment are shown in figure 9.

Regarding the tested tools, MSD seems to be the best tool to model systems (Mc) ($Mdn_{MSD} = 3$, $Mdn_{TC} = 2$ and $Mdn_{IFR} = 2$), combined with a better integration of super/sub-system levels (Sli) ($Mdn_{MSD} = 3$, $Mdn_{TC} = 2$ and $Mdn_{IFR} = 2$). MSD however provides a lower level of abstraction (Gc) when compared to the other tools assessed ($Mdn_{MSD} = 2$, $Mdn_{TC} = 3$ and $Mdn_{IFR} = 3$).

TC was assessed as offering a higher stand-alone capacity (3) compared with MSD and IFR ($Mdn_{Tc} = 3$, $Mdn_{MSD} = 2$ and $Mdn_{IFR} = 2$).

IFR, compared to TC and MSD, seems to better preserve constraints (Cp) ($Mdn_{IFR} = 2$, $Mdn_{TC} = 2$ and $Mdn_{MSD} = 2$), combined with a better adaptability regarding group composition (4) ($Mdn_{IFR} = 3$, $Mdn_{TC} = 2$ and $Mdn_{MSD} = 2$). As a counterpart IFR seems to require more time than the two other tools to be implemented (1) ($Mdn_{IFR} = 1$, $Mdn_{TC} = 2$ and $Mdn_{MSD} = 2$).

Transfer tools. The results of the transfer tools' assessment are shown in figure 10.

IP results showed higher transposition capacity (Tp) ($Mdn_{IP} = 2$) than Resources ($Mdn_{Res} = 1$) but lower stand-alone capacity (Sla) ($Mdn_{IP} = 1$ and $Mdn_{Res} = 2$ with $Z = 6.846$, $p = .000$). As IP are usually paired with Technical Contradiction, the stand-alone capacity results seem to confirm the necessity to combine them.

While offering less transposition capacity, Resources scored higher than TC on direction (Di) ($Mdn_{Res} = 3$ and $Mdn_{Ip} = 1$), consistency (Co) ($Mdn_{Res} = 3$ and $Mdn_{IP} = 1$) and group adaptability (5) ($Mdn_{Res} = 3$ and $Mdn_{Ip} = 2$ with $Z = 5{,}006$ $p = 0.000$).

Application tools. The results of the brainstorming's assessment are shown in figure 11.

Being the sole tool assessed in this category no direct comparison was possible. Brainstorming scored low on the theoretical criteria, while presenting intermediate to high scores on the practical criteria, except for group adaptability (5).

6.3.3. Conclusions of the field survey

The experiment has been run with a very specific target group; the International TRIZ Future Conference audience consisted of individuals who are at least initiated to TRIZ use, if not properly trained to it. For this reason, some of the practical criteria must be considered with caution, especially the ease of use.

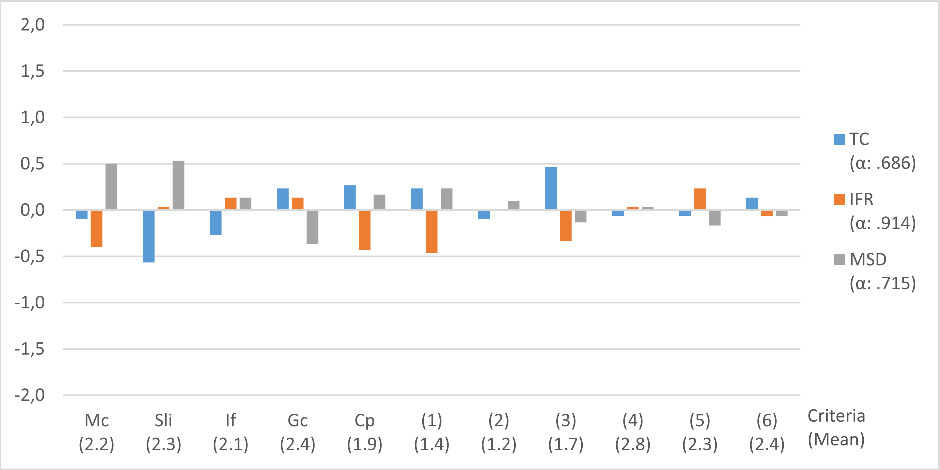


Figure 9. Field survey's abstraction tools assessment results. With Mc: modelling capacity; Sli: systemic levels integration; If: information filtering; Gc: generalization capacity; Cp: constraints preservation; 1: swiftness; 2: simplicity; 3: stand-alone capacity; 4: field adaptability; 5: group adaptability; 6: precedence.

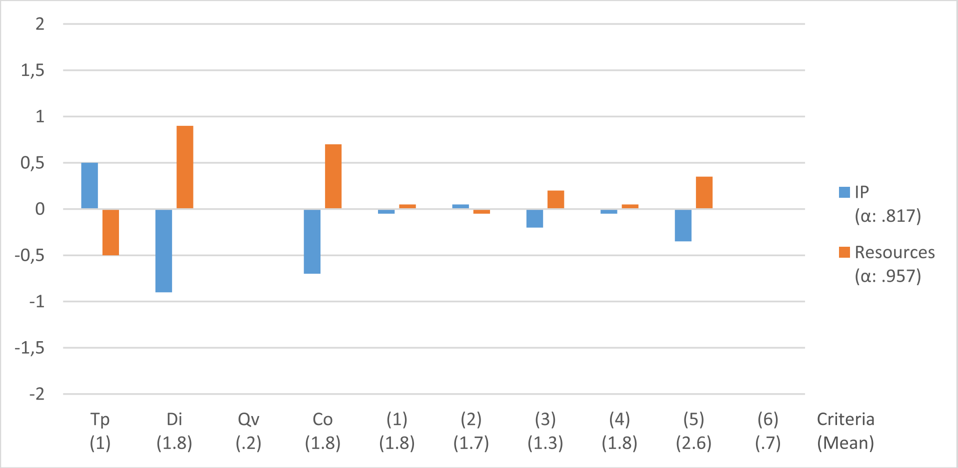


Figure 10. Field survey's transfer tools assessment results. With theoretical criteria Tp: yransposition precision; Di: direction; Qv: query Versatility; Co: consistency; and practical criteria 1: swiftness; 2: simplicity; 3: stand-alone capacity; 4: field adaptability; 5: group adaptability; 6: precedence.

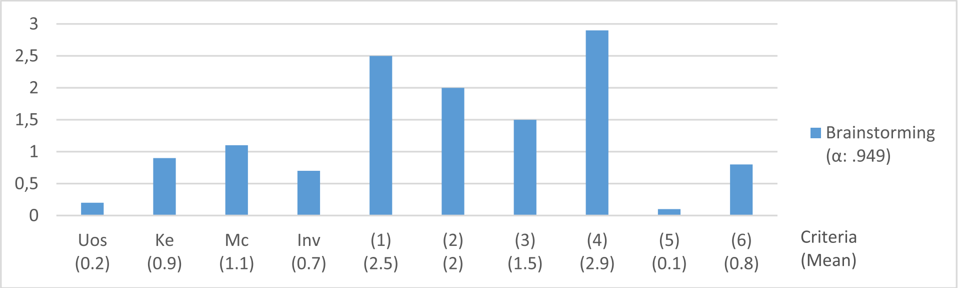


Figure 11. Field survey's application tools assessment results. With Uos: Uniqueness of solution; Ke: Knowledge enlargement; M: Modularization; Inv: Inventiveness; 1: Swiftness; 2: Simplicity; 3: Stand-alone capacity; 4: Field adaptability; 5: Group adaptability; 6: Precedence.

Results from the workshop and the field survey, cannot be compared directly, yet, some of the tools were assessed in both studies, i.e. MSD and Brainstorming. MSD shares the same overall profile (high scores in theoretical criteria with lower stand-alone capacity) and the same observation holds true for the brainstorming (fast and easy tool to implement with low theoretical criteria scores). As the main

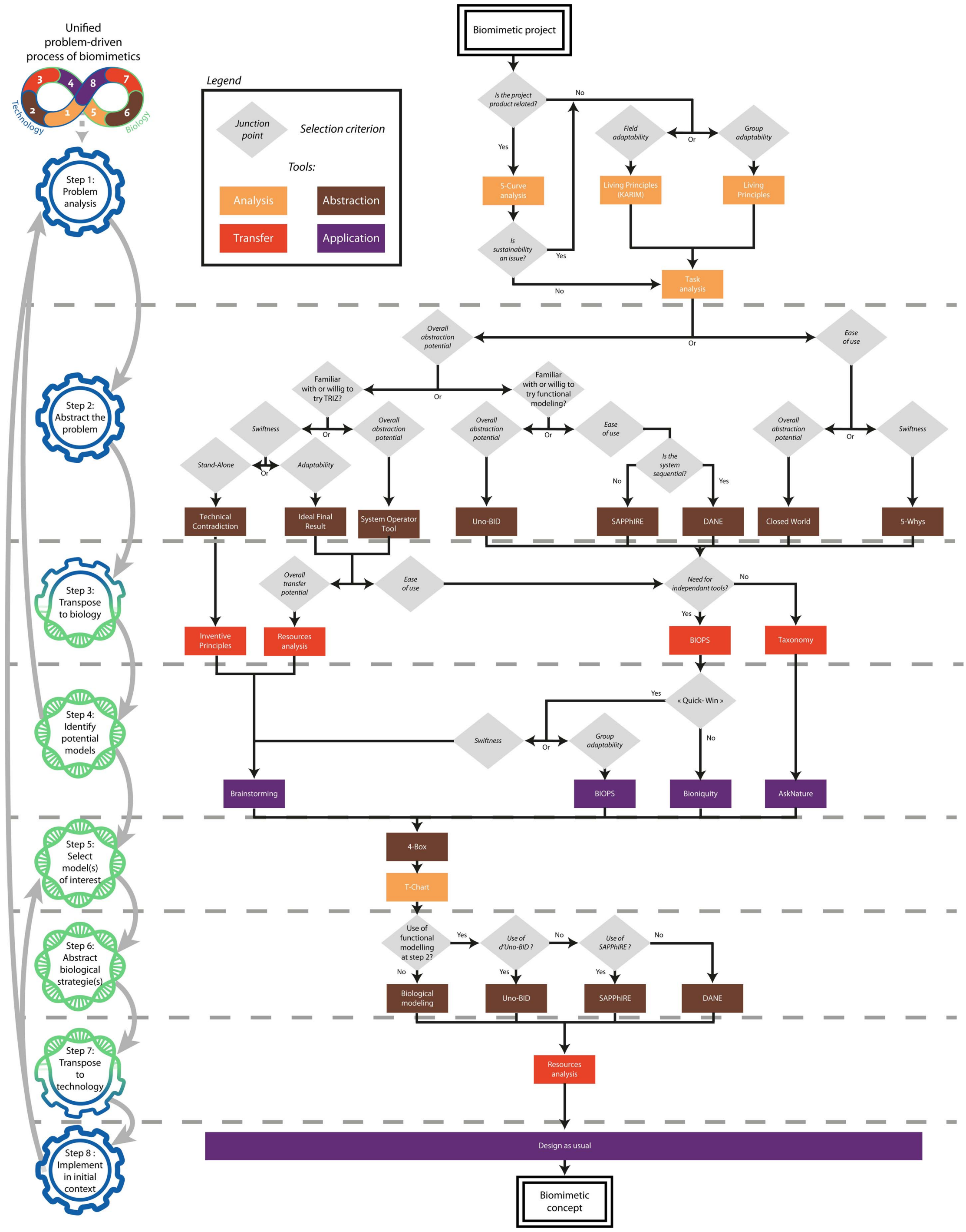


Figure 12. Problem-driven process of biomimetics utility tree.

conclusions drawn from the workshops remain identifiable through the field survey, it is possible to assume that the results from the workshop studies provide some form of representational view.

7. Building a problem-driven biomimetic utility tree

To ease the holistic understanding of the conclusions and tendencies drawn from the assessments, a visualized presentation of the results is proposed. The utility tree presented in figure 12 combines both the unified problem-driven process model of biomimetics (figure 3) and the assessed tools mapped to it (table 1).

Each junction point of the tree is either defined by assessment criteria used during the case studies, characteristics of the project or experience and preferences of the solvers. Tools are distinguished according to their experimental results (i.e. for the considered criteria, or voiced during the case study).

The purpose of such a utility tree is to guide practitioners through the biomimetic process model and its tools. Practitioners are asked to answer questions at the junction points in order to select a tool. This way they can build their own biomimetic process based on the current experimental results. It is necessary to mention that none of the listed steps or tools are mandatory; users can enter and/or exit at any junction point.

The use of the tree can therefore be adapted to support their way through the biomimetic process. Following the entire biomimetic utility tree should result in a bioinspired design, a biomimetic product fulfilling the criteria of ISO TC 266 (2015) Biomimetics.

As mentioned before, the unified problem-driven process model of biomimetics requires knowledge both from biology and technology. The same holds true for the utility tree as biologists are needed at several steps, especially if the offered tools do not provide a deep understanding of biology. As the utility tree is more a framework than a mandatory route to follow, users should decide individually when to look for external expertize. The role of biologists indicated in the utility tree is highlighted when it is considered to be mandatory in most cases. Even at earlier steps their contribution may be needed and is emphasized (Snell-Rood 2016).

The utility tree may be adapted to individual needs as each problem or design task has its specificities. After choosing a way through the utility tree, practitioners need to be familiar with the set of tools referring to the chosen way through the utility tree.

At present, the utility tree consists of a subset of existing tools and shall therefore not be considered to be finalized. It is rather a first version of a guideline through the process which needs to be used for data collection from various cases. We consider it to be a starting point for a broad discussion and it is highly appreciated if the utility tree is used for case studies from different fields. This expected future data, which could be gathered collaboratively, could provide an initial more robust version.

8. Conclusion

The evolution of biomimetics in the near future still requires a lot of research. The work presented in this paper can be a starting point for a systematic advancement of the process of biomimetics, especially for practitioners from the industrial sector.

The assessment of the biomimetic tools led to the premise of a utility tree which, once finalized, could enable practitioners to implement the process of biomimetics in their own context. It is a first attempt to set up a methodological process that has been lacking for a long time. It focuses on the application of biomimetics as a process and provides potential users with the 'how to do biomimetics' practically.

The establishment of this first iteration of the utility tree offers a basic architecture which can be strengthened through the addition of experimental data gained from studies with a broader range of users (with less expertized profiles). This new set of assessment workshops constitutes an ongoing study lead by the authors. Furthermore, comparative case studies, the addition of more tools and the identification of challenges during the use of the utility tree will improve the utility tree towards a robust version.

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