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Innovative technical creativity methodology for Bio-Inspired Design

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Abstract. The present research primarily focuses on building an effective rationalization of the knowledge which can be extracted from biological experts. To achieve such results, a structural framework, allowing knowledge integration from different fields at specific phases of the creative process is proposed. The formalized methodology along with its associated frameworks relies on principles from C-K Theory, TRIZ, and their links with biologically inspired design.

To assess such design process methodology, an initial application within a case study has been implemented. This case study has been conducted through an industrial partnership with a Research & Development service department from a company working in the offshore oil production sector.

But more than the concepts themselves, this new approach of biologically inspired design has emphasized, within this study case, an interesting potential in its propensity to quickly guide designers in accessing the most relevant knowledge from the biological field.

Keywords: Bio-Inspired Design, TRIZ, CK, Methodology, Innovation

1 Introduction

Bio-Inspired Design (BID), supported by a growing number of works for the past 20 years, succeeds in attracting attention of more and more industrial R&D department. Sometimes considered as a 3.8 billion years old R&D process [1], BID has been identified as one of the eight pillars to convey innovation during our century [2]. One major challenge when it comes to BID revolves around implementing it, in a robust way, within existing R&D processes [3]. In industrial structures, technical competences are usually mainly carried by a culture of general engineering. It is thus a tedious work for them to draw their inspiration from living systems [4]. The presented work aims therefore at clarifying both the interest and the feasibility of the implementation of such process, combined with a willingness to create an accessible method focusing on engineers with no biological background.

Presented methodology thus focuses on:

- Effectively integrating knowledge from Life Sciences experts by guiding engineering profiles towards the understanding of biological phenomena with a high degree of relevance.
- Identifying specific area of knowledge to tap into through a more precise the formalization of the function to perform.
- Generating a proper structure allowing to transpose a specific knowledge related language, used to understand the organization of potential systems (engineer vision) to a language dedicated to knowledge acquisition from living systems experts (or living systems literature).
- Providing a multilevel systemic dismantling, from macro to micro, targeting more and more precise expertise.

2 Towards a new model to strengthen biological research efficiency within a problem-driven BID approach.

2.1 Existing BID approaches

Approaches.

In general, BID practice can be carried out either as solution-based or as problem-driven [6-9]. Both the solution-based and problem-driven approaches have different starting points and different characteristics as design processes [10].

The solution-based approach describes the biomimetic development process in which the knowledge extracted from a biological system of interest is the starting point for the technical design. On the other hand, the problem-driven approach is the biomimetic development process that seeks to solve a practical problem with an identified problem as the starting point for the process [9,10].

Our aim being to foster the usage of the biomimetics throughout the industry, 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) while being less represented among commercially available biomimetic products [11].

Processes.

Within the last decade the problem-driven approach of biomimetics has often been described in literature (e.g. [6, 10, 12]).

All the identified BID processes include a step of biological analogy research. This critical phase is tackled with great disparity as some work are only including it without any mention of how to perform it.

The following table attempts to classify some of the BID processes of reference according to the level of detail they provide to search for biological analogy.

Table 1. Level of details disclosed by the BID processes of reference on the biological analogy search step.

Publication	Disclose how to search	Disclose what to search for	Disclose where to search	Prescribe a partnership with biological experts
[12]	✗	✓	✗	✗
[13]	✗	✓	✗	✗
[5]	✗	✓	✗	✓
[14]	✗	✓	✓	✗
[15]	✗	✓	✓	✓
[10]	✗	✓	✓	✓
[16]	✓	✓	✗	✗
[17]	✓	✓	✗	✗
[18]	✓	✓	✓	✓
[19]	✓	✓	✓	✓

It is noticeable that among the listed processes, only the “what to search for” is clearly stated every time. Only two processes [18, 19] appears to clearly disclose their entire strategy of analogical research. Furthermore, invoking a partnership with biologists is not a common recommendation, despite that it seems inevitably beneficial prima face: one could hardly consider initiating the construction of a plane without the supervision of an aerospace specialist. As a conclusion, even if it seems reasonable to rapidly be confronted to the diversity of the living world without attempting to create a dedicated research strategy, a proper description of the task seems of great importance.

Several tools have proven themselves to provide a relevant analysis of how living systems work in order to transpose their strategies to the technical world [3]. However, the identification of potentially relevant organisms shows methodological weaknesses:

- Their lack of recommendation during the search phase
- Their lack of organizational framework to classify the research results.
- Their lack of short iterative loops during the search phase

The presented work relies on the Unified Problem-Driven Process of Biomimetics on its process aspect [3]. This metaprocess is based on a representative set of 12 different presentations of the process aligned with the problem-solving process [20] to illustrate an holistic perspective on the state of the process models.

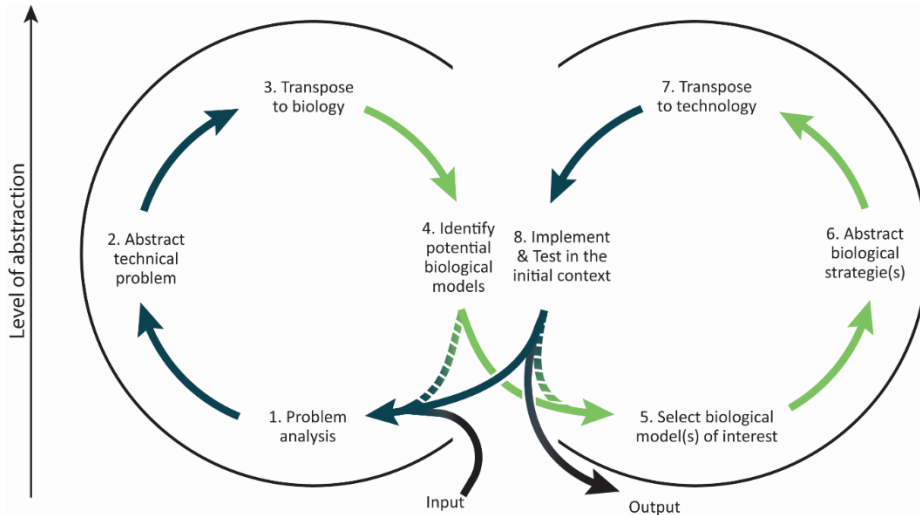


Fig. 1. The unified problem-driven process of biomimetics [3]

2.2 How do design theories may contribute to BID

TRIZ

TRIZ, the Russian acronym standing for theory of inventive problem solving, offers a theoretical frame to the evolution of technical systems. In addition to that, TRIZ provide a wide array of methods and tools in order to guide the cognitive process of designers towards innovative solutions. Based on the analysis of many patents, on the study of psychological behavior of inventors and on the scientific literature, Genrich S. Alshuller, inventor of the theory, formulated evolutions laws for technical systems, concepts, framework and tools allowing to better understand essential problematics to guide the creative process towards effective and usually innovative paths.

TRIZ originality resides both in its deterministic frame of reference, technical systems (regardless of their environmental context), follows a set of evolution laws [21], and in its ability to provide models of solutions (e.g. generic principles, separation principles and standards) [22].

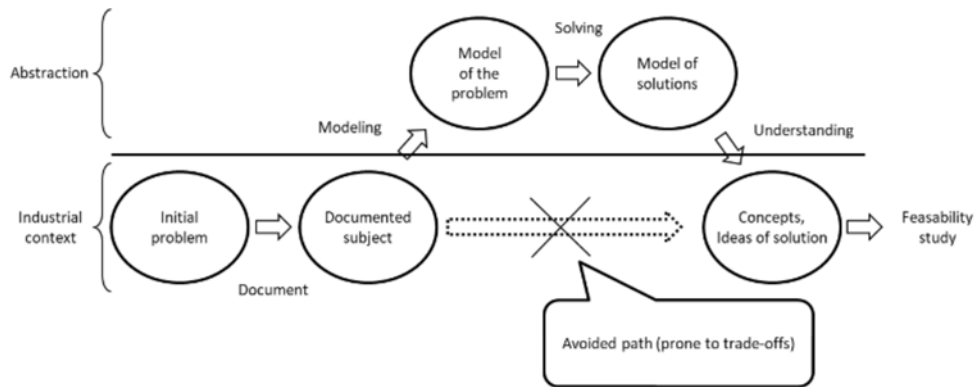


Fig. 2. General overview of TRIZ

During the modelling phase, resources from the working group are largely engaged to describe the technical system investigated by the project. TRIZ key concepts, such as evolution laws or ideality, provide a highly structural work frame to build a shared and innovative vision of both the technical problem to be solved and of the goal to reach to meet the established target [23]. Through the implementation of the TRIZ modelling tools, the level of understanding of the investigated system rapidly clarifies itself to create a shared area of knowledge, common to every participants.

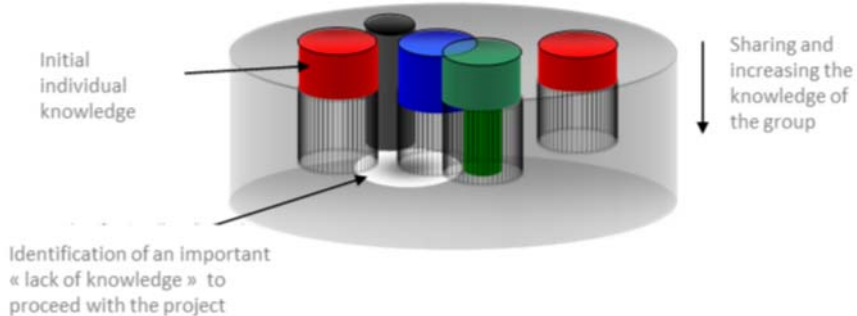


Fig. 3. Illustration of how the area of knowledge evolves during a TRIZ study

The shared vision of a problem to be addressed as a matter of priority, combined with a strong convergence of perspective on the objectives to establish, condition the productivity of the models of solution required to be implemented from a performance standpoint: quantity, quality, level of details of the concepts of idea cards, comprehensiveness, convergence (especially through the concept of contradiction to overcome).

The modelling step is, by itself, a way for designer to acquire a creative posture through the creation of a skewed understanding, obtained by the definition of the Ideal Final Result (IFR) or the Multi-Screen Diagram (which provides a way to

overcome mental inertia through the description of an ideal solution and the definition of the evolution of a system according to several systemic levels). This is reinforced through a deeper analysis of the technical scope (qualification and quantification of the physical phenomena involved).

While constituting a systematic approach in certain steps of the creative process (formalization of key contradictions), these methods induce significant adjustments within the problem space. It is thus quite common to observe brief iterations of the initial set of specifications in advance of a refocus on subtopics blocking the designers in a trade-off situation. According to Deguio and Cavallucci [24], formalizing a contradiction can be perceived as solution concept within the C space of the C-K theory [25, 26]. Solution space is also subjects to alterations: concepts are concentrated (channeling of the cognitive process by the problem models and prior expression of the IFR) and more precise, from a technical standpoint, through the implementation of generic principles of solution (initial tool resulting from the synthesis of the patents analysis during TRIZ infancy) or by standards related to su-field modelling (descriptive then optimized forms of interaction defining the functioning of technical systems).

It is particularly noticeable that the convergence concept could be more or less required by designer and thus looked for. Its most converging approach is obtained through the implementation of ARIZ, algorithm describing step by step the process from which the formalization of the most relevant (according to the key contradiction of a given problem) inventive solutions is expected [27].

The expected TRIZ contributions to the proposed approached are:

- The detail and comparative understanding of living organisms process according to the expected performances of technical systems.
- A methodological support in creativity to overcome the technological barriers identified.

C-K theory

The C-K theory [25] is a theory upon design reasoning. The theory is rooted in the distinction of a Knowledge Space (K) from a Concept Space (C), structuring the mutual nurturing of both spaces through operators interconnecting them (See Fig. 3).

The $K \rightarrow C$ operator describes the addition or subtraction of knowledge chips from the Knowledge Space to the Concept Space. One example of $K \rightarrow C$ operator embodiment is the generation of alternatives.

The $C \rightarrow C$ operator involves the expansion of the Concept Space through the mathematical elaboration of partitions and inclusions, resulting in a tree arrangement of concepts. Concepts horizontal expansion refers to the divergent thinking process, where vertical expansion results from convergent thinking processes [26].

The $C \rightarrow K$ operator describes activities usually involved during the detail design phases. This operator models actions such as concept validation or invalidation though the attribution of a logical status within the Knowledge Space.

The $K \boxplus K$ operator refers to activities related to the Knowledge Space expansion. Such activities are induced by experimental deduction mechanisms. Activities related to knowledge creation may thus be modeled through this operator [26].

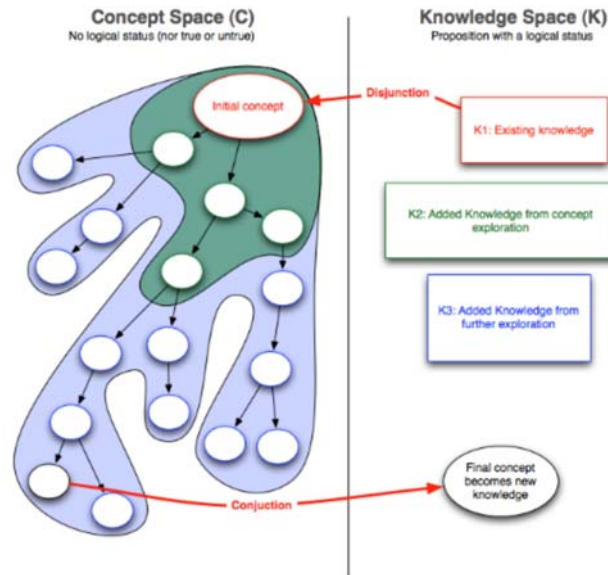


Fig. 4. Illustration of the Concept Space and the Knowledge Space as described by the C-K theory

The main C-K Theory contribution to the presented approach is the creative posture induced by the constitution of two distinctive space (Concept and Knowledge) and the formalism through the process of building the tree to identify, in an exhaustive way, the physical process related to a given function.

2.3 Proposal of a new model

The proposed approach aims at making it easy for industrial structures to be able to build their own solutions database which could be used on various problems. Autonomy is thus set as an important criterion, as no methodological prerequisites should be required. The proposed model is based on the work of APTE® [28] and their technological path tree. Similarly to a tree, the initial focus is set on the trunk, representing the main goal. The trunk is then subdivided in branches, representing the principles, themselves leading to a spray of solutions, the leaves. This model has notably been used in offshore oil projects [29].

In order to nurture the existing biomimetic toolset, the presented proposal is an hybridization of the technological path tree and the C-K theory. The APTE model contribution is its ability to decompose and to precisely describe functions to performs, while C-K theory is used for its formalism of relevant knowledge spaces.

In regards of the processes introduced in section 2.1, the construction of the tree has been thought to occur between steps 2 and 3, when the initial problem is known and properly defined and when designers are able to depict an initial set of specification, in particular through the identification of contradictions (especially from a TRIZ perspective).

The tree, as illustrated in figure 4, has been made to be built in a team effort, allowing an immediate gathering of a larger knowledge base while generating dialogue upon its layout.

In its first cell, on the left, is stated the main objective, a concept, as induced by the C-K definition: a neither right or wrong proposition. This objective can be formalized from an expressed need by the working group thanks to the disjunction principle. Close to this initial concept, designers are invited to add a supplementary box to precise the different expected conditions to be realized through the concept.

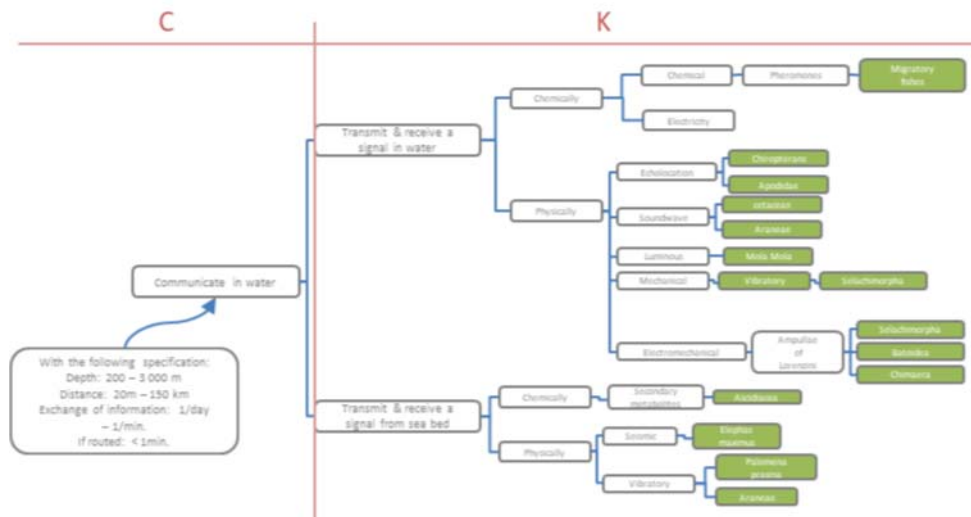


Fig. 5. Technological path tree applied to offshore oil [29]

The implementation of the tree is then achieved from the left to the right, by adding proposals allowing to reach the stated objective from the box they are originating. To fulfill this model, designers are asked to answer the “How?”. From a C-K point of view, the transition from the first box to the second is correlated to the K->C operator.

The early disconnection of “chemically” and “physically” within the fulfilling process seems interesting in the way that it allows, in addition of promoting creativity, the quick emergence of two sets of principles.

The physicochemical principles search is a difficult task within the process, to ease it, designers may find assistance from thesaurus, literature or any other existing formalized resources.

Once the principles are identified, the work consists of connecting living organisms or even natural phenomena, in order to answer the “who?” question. For illustrative

purposes, if one identifies the “transmission of a signal in an underwater environment” principle from a “physical” perspective, its personal knowledge may allow him to connect with the “cetacean” (e.g. dolphins) as a living organism embodying the principle. If the initial existing knowledge does not allow to create pathways to a living specie, tapping into formalized and accessible existing knowledge constitutes a good way to proceed. To be in line with the C-K theory, interconnection between identified principles and living species are Knowledge space extension: proposals made are ascertainable, waiting for the acquisition of the specific knowledge related to the implementation of the initial concept.

Following the implementation of the tree, a step to assemble documentation supporting the identified species, in particular the implementation in practice of the principles, is required.

3 Case study

In order to assess the relevancy of the proposed tool, a case study followed-up with meetings and discussions has been implemented. This case study has been conducted through an industrial partnership with a Research & Development service department from a company working in the off-shore oil production sector. Its topic focuses on subsea filtration.

3.1 Hypothesis

The present work revolves around the following issue: “How to nurture the BID toolset to ease its adoption by an industrial structure with no prior biological background?”

Hypotheses are as follows:

- The creation of a double hybrid tree allows the increasing of the comprehensiveness of the potential bioinspired solutions. Thus, the use of an element to structure the techno-centered approach allows the exhaustiveness of the divergent thinking to be increased up. Combined with an analysis of the highlighted technological pathways, the approach will also increase the understanding of the phenomena which correlate technical and biological systems, by refocusing the problematic.
- The creation of a double hybrid tree facilitates the integration of biologists within the BID process. The depth of the tree, from macro to micro, allows to effectively point at areas of expertise to be questioned.

3.2 Methodology

Work with student.

As part of their final project of their penultimate year of engineering school, five students of the “École Nationale Supérieure des Arts et Métiers” agreed to work on a

bio-inspired design product. In accordance to the case study, topic was set to tackle subsea filtration; purpose of their work was to design a “bio-inspired filtering system able to clean sea water”. These students were mainly trained in mechanical engineering:

- Two of them where originating from preparatory classes for the grandes écoles.
- Two of them where orinigating from a DUT (University Technology Degree) in mechanical engineering.
- One of them initially studied medicine two year before its reorientation.

The hybrid tree has not been introduced to the student. Students where instead introduced to “classical” BID process, in order for them to better understand the challenges and issues of each step. They had access to every resources they were able to grasp (scientific literature, internet, experts, AskNature, etc.). The case study went on for approximately 12 hours over 3 days.

Work with biologists.

In addition to the students’ work, meetings with 2 fundamental biologists from the Pierre et Marie Curie University (Paris 5) has been performed. After an introduction to the industrial challenge, a debate on the methodological means to design creative biologically inspired solutions was initiated.

3.3 Results

The work done by the students has led to three bioinspired concepts:

- A set of variants from the sponges (phylum: Porifera)
- The use of mucus secreted by certain jellyfishes (subphylum: Medusozoa)
- The use of a principle of fluid mechanics from carpet sharks (order: Orectolobiformes)

Our goal here is not to delve into all the specificities of the developed concepts but rather to depict and discuss the relevancy of the methodology applied.

Consulted biologists were aware of the bio-inspired design approach as they were already supervising some pedagogical projects on the topic; they were aware of its actual customs and success stories. Focus was thus set on the context of the project and the company requirements.

The presentation of the proposed tool, the hybridized tree, was very much appreciated, as they were already projecting themselves in how they could be able to contribute to its fulfillment (in nurturing the branches extremities with both physicochemical principles and specific species). One constructive feedback was the outline of the definition of physicochemical strategies which seemed more suitable, according to them, for engineers than biologists. From their perspective, few biologists would be able to have the appropriate knowledge to contribute on how to “refine the problem” and the “functional analysis”. Second, the discussion tackled the accessibility to resources and knowledge. On that specific topic, they stressed the

importance of integrating biologists early in the design phases. An argument was that they were able to access researcher databases, allowing them to gather a large amount of information. This information could even be completed from their experiences and professional network which they can tap into with great ease. Finally, the subject of the competencies required to correctly interpret biological scientific publication was addressed. When considering the level of detail required by the BID process, possessing skill on that matter might be an important asset to decompose and understand biological strategies.

4 Discussion

The first observation with regard to implementation of the student's work is that species which they have found interest were already identified through the hybrid tree they did not have access to. This tree, composed of around twenty biological inputs, tends to show that it might be a good way to increase the exhaustiveness of the identification of the potential solutions to be investigated. On that aspect, the tree has the advantage to provide a clear methodology to guide the search process of biological strategies comparatively to the intuitive and disorganized research that is, for example, the keyword search.

One could also note that student focused on underwater species. If this may seem logical, considering the fact that the filtration system should, ultimately, operate in an underwater environment, it severely reduces the research scope.

On another note, interesting comments were made by students: they all agreed on the lack of resources they experienced in order to describe the identified phenomena. Being able to describe how the filtering system of the shark works, for example, were not an easy task for them. "Too much text, not enough figures", is one way to summarize their comments, which emphasize the preference of engineering students for schematics. In the following of the study of the variants of existing sponges in order to nurture their concept, students realized the heterogeneity of the filtration function embodiment according to the species considered. Somewhat like technical system, more or less complex, the use of TRIZ and its evolution laws could be used to learn more on the different biological strategies.

Meeting biological experts provided numerous answers. First, introducing an initially fulfilled hybrid tree to them, allowed them to directly contribute to it: they were able to nurture the branches from a biological perspective while being able to formalize some biological strategies.

The hybrid tree also allowed to exchange on the specific topic of filtration. Even with a background in biology, a comprehensive knowledge in macroscopic biology is difficult to possess. However, fulfilling the hybrid tree constitutes a relevant way to gather sufficient information to be able to discuss with experts.

At the end of the case study one question mark remains: should the tree be created with biologists or not? From the gathered experience, the answer slightly leans towards the no side. Working with biologists is interesting in order to obtain a direct competency or a knowledge input, but induces a non-synergetic effect. While the tree

eases the interaction with the biologists and allows them to directly contribute to the work, their early involvement induces process counterparts, i.e. their identification, recruitment and engagement with few gathered knowledge on the topic. When it considering an optimal way for biologists to contribute, the pre-establishment of an initial tree comes to mind, as a way to both formalized a first batch of knowledge and to ease their involvement.

5 Conclusion

The presented work aims at developing a creative approach reinforced by the addition of biological knowledge while working on a design task or a problem resolution context. The paper introduces a hybrid tree including principles from both TRIZ and C-K theory.

During the case study, revolving around designing a new filtration system, new promising concepts has arisen. A concept of a self-cleaning vortex filtration system including a flow separation has notably drawn the industrial partner's attention. Initially, the storage function opposes itself to the flow function. Research is therefore naturally focused on living organisms implementing flow separation in fluid environment. The use of the tree initiated a change of view on the relation of current filters and impurities reservoir, to allow the consideration of an infinite flow capacity reservoir. While the part of serendipity within the process is hard to measure, the use of the presented hybrid tree has unequivocally contributed to the emergence of the new concepts.

Existing BID approaches ranges from methods based on intuition in which users have sufficient space to manoeuvre and automatic methods which use tools such as databases, seeking to disconnect users from the research process, i.e. tools operating as a black box from which a justification of the correlation between the input and the output is not clearly formalized. In our case, the presented approach provides all the reading grids to users performing a manual yet guided search without losing the "why" and the "how" of the considered research. The presented hybrid tree empowers designers in the sense that they remain in charge at any point of the accomplished work, which is not the case when considering automatic methods. The empowering of designers is achieved while their knowledge improvement is enhanced, both on the way to properly conduct the research but also on the underlying biological principles and their relation to their engineering counterparts, which is not covered by intuitive methods.

Future work should focus on the integration of the semantic approach and its considerable potential to populate the hybrid tree. This could be an effective way to reduce the time required to create a hybrid tree while raising its effectiveness to point at potential biological solutions in an exhaustive way.

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