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Biomimetics from practical feedback to an interdisciplinary process

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Abstract

Biomimetics has been a subject of increasing interest but, where it has proven its scientific relevance and innovative potential from a theoretical standpoint, it remains rarely used in practice. Facing this lack of implementation, our work aimed at asking practitioners for their help to better understand the remaining impediments preventing biomimetics' blooming. Thus, practitioners' feedback and experts' opinion on risks, adequacy and weaknesses of the current biomimetic practices were gathered and structured to present an extensive descriptive phase on biomimetic processes. Key levers for improvements, such as the need for a better risk management, the need for biological expertise and the need for clear guidance during the process, were then identified. Based on these insights various methodological contributions are prescribed. Among these inputs, the duration of the various steps of the biomimetic process was estimated through industrial projects' feedback, semantics misunderstandings were tackled, and the integration of a new transdisciplinary profile combining an expertise in both design and biology is proposed. From these improvements, a new version of the unified problem-driven biomimetic process is proposed. A final descriptive phase performed through the evaluation of the new process by professionals underlined its relevancy along with the remaining research axes. Through the integration of a new profile matching the practitioners' current needs and the adaptation of the process to their feedback, this article aims at proposing a biomimetic process fitting the reality of biomimetic practice in order to support its implementation.

Keywords Biomimetics · BID · Multidisciplinary team · Design process · Practical feedback · Risk evaluation

1 Introduction

Biomimetics is defined as "the 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" (ISO/TC266 2015). The innovative potential of this approach has already been proven in many studies (Ahmed-Kristensen et al. 2014; Keshwani et al. 2017) and would not be tackled in this article. Instead, we will focus on the methodological framework surrounding the use of biomimetics as a technical problem-solving approach, referred to as the technical-pull approach (ISO/TC266 2015). Few argue against biomimetics, but its implementation and practice are still highly limited. After the overwhelming awareness of its potential, industrials soon faced a major question: how to use biomimetics as a systematic innovative strategy? Using nature as a source of inspiration for analogical reasoning appears economically and technologically promising, not to mention the potential opportunities it can offer from a sustainable point of view (Gamage and Hyde 2012; Helfman Cohen and Reich 2016; Lenau et al. 2020) through biomimicry (ISO/TC266 2015). However, it also involves great challenges. From the inherent difficulty of multidisciplinary work, to the practical difficulties of manipulating biological data, to the definition of key actors in biomimetic teams, those large questions encompass a range of issues that will be pointed out in this article. Facing the gap that has emerged between research and practice in biomimetic, this article tackles the following research question: How can we adapt the current theoretical framework designed and used by scientific researcher to a theoretical

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framework supporting the implementation of biomimetics in practice? To tackle this question, this article was written by a multidisciplinary team gathering profiles from artistic and industrial design, biological engineering, product design and engineering design. Following the design research methodology (DRM) (Blessing and Chakrabarti 2009), difficulties faced by practitioners are identified before clarifications, optimizations and guidelines are proposed. This article will then conclude on the acceptance of the proposed optimized process and the perspectives it offers.

2 State of the art

Through the presentation of the main biomimetic methodological approaches, this state of the art underlines the current limitations of biomimetics, highlights the research's resolution axes and points out the difficulties to reach biomimetic practice.

2.1 Current biomimetic technology-pull processes, a theoretical approach

For the past decades, a great number of methods have been designed to help implement a technology-pull approach. The first type of reasoning is to formalize the biomimetic process through the observation of design teams practicing biomimetics, and the identification of the main cognitive steps followed by the participants. These methods are said to be analytical (Wynn and Clarkson 2005): the procedural model of doing bionics (Lindemann and Gramann 2004), Biomimetic design methodology (Lenau 2009), Problem-driven analogical process (Goel et al. 2014), etc. These processes describe the practice of biomimetics at an overall scale, without specifying how, at the level of the different steps, the challenges identified in the introduction are dealt with.

In addition to these approaches, and based on their insights, some procedural processes have been designed and described in the literature. Due to semantic formalizations, like SAPPhIRE (Chakrabarti et al. 2005), biomimicry taxonomy (Baumeister et al. 2013) or FBS (Vattam et al. 2011), etc., these processes are organized around well-structured modelling phases linked with databases, IDEA-Inspire (Chakrabarti et al. 2005), AskNature (Biomimicry Institute 2002), DANE (Vattam et al. 2011), etc. They thus rely on semantic modelling and databases to answer biomimetic challenges. Because of the specific formalization related to each process, these approaches can be hard to use without training. Moreover, their efficiency highly depends on the quality of their respective database. This strong reliance leads to a situation where, in practice, the process that is the most used is the ones with the most efficient search tool, AskNature (Deldin and Schuknecht 2014), without considering the abstraction relevance or, more generally, the methodological viewpoint. Developments in artificial intelligence (AI) have led research teams of the Toronto University to work on computational processes based on the semantic analyses of biological literature databases from requests formalized in a natural language (Ke et al. 2010; Cheong et al. 2011). These promising studies are still under development and so do not represent a currently available solution (Kruiper et al. 2018).

Finally, the last kind of methodological solutions are approaches based on the abstracted principles. These processes are based on the abstraction of biological knowledge into generic solving strategies, avoiding the understanding issues related to the use of raw biological data. Inspired from TRIZ, the most advanced abstract process was formalized by Vincent (2016) and focuses on trade-offs (Vincent 2017). Because of its very high level of abstraction, the process does not need actual biological data as it is based on a previous determination of the main trade-offs and natural generic strategies associated with their resolutions (Kruiper et al. 2018). To have access to those strategies, a tool is currently under development in the form of an ontology (Vincent and Cavallucci 2018). The potential limitations of this strategy can be compared with the ones of TRIZ. Concepts at such a high level of abstraction are often hard to manipulate and even if it may become an extremely powerful approach, it also may require an intensive training to be used efficiently. Bypassing the pathways leading to highly abstracted concepts may then appear as both a problem and a solution depending on the user's expertise.

According to Fayemi all these processes can be described with the same eight main steps. As a result, he proposed a unified technology pull biomimetic process (Fayemi et al. 2017) that will be considered in this article as our reference process (Fig. 1).

This process is based on the high-level procedural abstraction of the existing biomimetic approach which makes it interesting for research purposed but makes its implementation for practical use difficult in an industrial

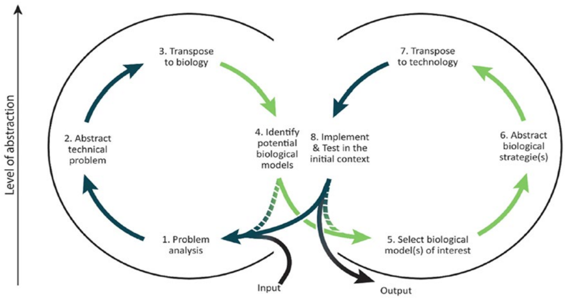

Fig. 1 The unified technology-pull biomimetic process (figure from Fayemi et al. 2017)

context. Lots of the studies above-mentioned are still under-development and it is too soon to evaluate their efficiency, but they all have in common to focus on tools and modelling to solve the challenges of biomimetics.

Thus, engineering design research on biomimetics is very active but so far it has not reached its final objective: to turn biomimetics into a considered and efficient innovative practice. Where we can observe a clear increase in the research effort targeting biomimetic methodological framework (key word "biomimetics" on the design society library, 0 articles before 2009, 13 articles published between 2009 and 2014 and 36 published since 2014), in practice, few of those findings are actually used for biomimetic projects. Put another way, researchers struggle to find the appropriate level of granularity to transfer information from research to practice and so, to support biomimetics implementation. On the one hand, very specific processes, such as the ones based on TRIZ thinking (Vincent et al. 2006) or on highly structured models of biological systems (Chakrabarti et al. 2005; Nagel et al. 2010), bring fundamental insights from a scientific perspective but, due to their complexity, require deep training to be specifically used in practice. On the other hand, general processes, like the unified process by Fayemi et al. (2017), are quickly learned by practitioners but do not bring enough information to be used without prior knowledge on how to actually perform the key steps. This first observation is not limited to biomimetics, there is often inertia between research findings and industrial appropriation. Still, it appears that the current situation leads to a first question: can we speed up research findings appropriation by practitioners through the adaption of the process to a more practical end? This question does not call the previous work into question, on the contrary, it wonders about the transfer of those fundamental findings to practitioners.

In addition to the process itself, and in order to make the various steps possible, researchers have been working on a great number of tools to guide biomimetic practice.

2.2 Current biomimetic tools, the unrealistic expectations

Wanieck et al. performed a classification and analysis of more than 40 tools related to the practice of biomimetics (Wanieck et al. 2017). As often in engineering design, the increasing number of tools leads the user into an unclear path as it becomes more and more complicated to choose which tool to use, and in which conditions (Lahonde 2010). A deep analysis of the tools used in biomimetic design has underlined three main origins (Fayemi 2016): engineering—like 5-Whys (Ohno 1978), technical contradictions (Altshuller 1984), etc.—biology—like 16 patterns of nature (Hoagland and Dodson 1995), functional modelization (Tinsley et al. 2008), etc.—or have been conceived for biomimetic purposes—like the biomimicry taxonomy (Baumeister et al. 2013), BIOTRIZ (Vincent et al. 2006), etc. In this context, it has to be specified that the tools that are said to come from biology, are neither biological tools nor tools designed to be used by biologists. They have been mainly designed for engineers to learn about biological findings.

Tools aim at helping design teams to overcome challenges such as the findability, recognizability and understandability of biological data (Vattam and Goel 2013; Kruiper et al. 2018), but the expectations towards them appear unrealistic. For example, the requirement for biological data is mainly solved through databases (Rovalo et al. 2020), which are extended manually, with information that have to be scientifically verified and supported by scientific articles before being translated from biology to a given semantic formalization (example with AskNature (Deldin and Schuknecht 2014)). It appears clear that such type of tools is of great interest but faces a considerable difficulty which is the trade-off between the quantity and the quality of the referenced data. The biggest biomimetic database yet designed—AskNature—encompasses 1922 elements (1726 biological strategies and 196 inspired ideas on the 30th of January 2020) and even if this number is substantial, it is far from being sufficient to be used as the source of biological data by design team at a global scale. As previously explained, AI may be the future answer to the problem of biological data's accessibility, but sorting algorithms are for the present time under development and, as a result, do not represent an actual fitting solution (Cheong and Shu 2012; Vandevenne et al. 2014). The limitation of biomimetic tools can be observed for each of the biomimetics' challenges. Another example is the understanding of biological data which is not linked with a specific step but is transversal to all steps related to biology. Tools that enable the understanding of biological data are mainly thesaurus, ontologies or algorithms leading to their formalization into models (Wanieck et al. 2017). These tools give some strong research intakes in terms of abstraction and analogical reasoning, but they are hard to handle for novices and severely time-consuming if performed by users who do not have any background in biology. Moreover, they tend to model biological systems separated from their extended environmental and conceptual context which may imply the loss of crucial information. Besides, the risk of misinterpretation or misunderstanding is high (Vattam et al. 2007; Helms et al. 2009) and can lead to a technical dead end, which would cost time, money and potentially the appeal of the industrialists for biomimetics. As a result, where they are highly valuable, it is unlikely that these tools will solve all by themselves the challenge of understanding biological data.

These observations bring us to the following conclusion: most of the biomimetic tools are highly relevant but are not enough to overcome the challenges of biomimetics. Tools constitute the bones of the biomimetic skeleton that is the biomimetic process, but some pieces of the puzzle are still missing. The next section focuses on the composition of the biomimetic design team as one of the main levers of innovation. More specifically, it targets biologists' expertise/knowledge during the biomimetic process and the importance of good communication between stakeholders who come from different backgrounds.

2.3 A multidisciplinary team, a highly recognized yet ignored starting point

Multidisciplinarity in design is not a new thing. Because of their intrinsic link with engineering, physics, chemistry and mathematics have always been related to the design practice. One could argue that engineers constitute a type of mathematicians, chemists or physicists or even a combination of them all. Throughout the history of design, several profiles have been added to the typical design teams (Cross 1993). Thus, with the rising awareness of the consumers' needs and expectations profiles from human and social sciences—like ergonomists (Aoussat et al. 2000) and designers (Cooper 2019)—have been included in design teams and processes. Biology emerges as the last 'hard science' remaining out of the design scope, explaining why this association through biomimetics appears so promising. However, even if the potentialities of biology in design are well established, biologists remain mainly excluded from the design practice. Facing this paradox, several articles have been published with the objective of exposing the assets that are biologists in biomimetics (Hashemi Farzaneh et al. 2015; Snell-Rood 2016; Graeff et al. 2019a), like their inputs during creativity steps (Schöfer 2015) or during innovative problem-solving approach (Schöfer et al. 2018).

The integration of such a new profile face various difficulty. First, most of the articles dealing with biomimetic processes or tools are not specifying the required profiles of the practitioners. Readers (mostly researchers in engineering or engineering design), logically assume that these processes are expected to be followed by "typical design teams" (mechanical engineers, designers, ergonomists, etc.) but the question "who is the target of those methodological innovations?" is not clearly answered. Some articles presenting the design of databases, AskNature for example, explain that biological data available through such tools are translated by experts in biology, in order to ensure the quality of the information and make databases usable for engineers (Deldin and Schuknecht 2014). On processes, some articles underline without any further details, that biologists are assets to be included during the process (Vattam et al. 2008; Yen et al. 2014; Badarnah and Kadri 2015; Fayemi 2016). However, little information is given on the manner they should be integrated, for what exact role(s) or at which step(s), etc.

Finally, biologists form a highly varied community with very different expertise, thus, which "biologists" are we talking about in biomimetics? Are we talking about biologists or about biological expertise and knowledge? The lack of information in the literature towards biologists' characteristics in the context of biomimetics is one of the reasons why they are not currently included in the biomimetic process. Companies that want to do biomimetics with biologists actually do not know which biologist to include and how to include them. In projects where biologists are included, they are mostly restricted to the role of punctual external experts. This approach considers biologists either as outsiders or as tools, preventing them to properly join the teams, play an active part and bring their specific standpoints, cognitive reasonings, tools and conceptual frameworks to the table.

It is then acknowledged that biologists are a profile of interest in biomimetics, the remaining question is then how to integrate them. In addition to the difficulty of properly defining what is a biologist in biomimetics, considering the integration of a new actor with an unusual profile brings out the stakeholders' communication issues. Even if highly relevant, this aspect would not be tackled in this article.

3 Research question

As we have seen in the state of the art, research efforts focus on biomimetic impediments from an engineering design standpoint. Where the final goal of the scientific community is to help practitioners and so biomimetic practice, the way biomimetic methodological framework is designed is based on the research's concepts, logic and objectives. One question then arises, who are the actual final targets of methodological innovation? Researchers or practitioners? If this observation can be made for the processes it is also true for tools and is fundamentally linked with the considered team's composition. The question of integrating biologists, for example, has been postponed because most researchers do not have to integrate one for biomimetic purposes. From a company's decision-makers standpoint, the question appears crucial, who should they hire? On which criteria? Is it worth their money?

It cannot be ignored that where we struggle to make the Biological and Design world communicate, we have at least as much difficulty to make the research and practical world communicate. Biomimetics is about breaking the silos between science, but also about transferring knowledge from theoretical science (biological and engineering design research) to practical science (design). Research only for research itself is alienating and leads to a lack of efficiency through misinterpretation both by researchers and practitioners. The above-described state of the art brings us to the following research question: How can we adapt the current theoretical framework to support the implementation of biomimetics in practice?

Our hypothesis then focuses on perceived and actual risks to be able to identify misunderstanding, required restructuring and practical needs, and so adapt the theoretical biomimetic framework. Following the design research methodology DRM (Blessing and Chakrabarti 2009), this article first presents a descriptive phase before describing various methodological contributions on both the biomimetic design process and team to answer our research question. A final description phase then evaluates the relevancy of our findings and underlines perspectives.

4 Material and methods

The first step of the DRM, the description phase, will be presented in Sect. 5. This section will be based on the key verbatim from interviews, a failure mode and effects analysis (FMEA) of the biomimetic process of reference (Fayemi et al. 2017) evaluated by experts, experimental observations and scientific literature. All along this article we will take the unified problem-driven biomimetic process (Fayemi et al. 2017) by Fayemi as the process of reference.

Interviews have been performed with researchers in biology (4) and designers (5) (Table 1).

None of them had prior knowledge in biomimetics. The pursued goal was to assess the perception of the process of reference and the amount of information extractable from it. In practice, interviewees looked at the process for few minutes until they felt they had understood it as much as possible. Then, a series of question was asked, first at a general scale before focusing on specific key steps. Interviews verbatim will be used to illustrate the descriptive phase and a qualitative analysis of the interviews is presented in a supplementary table (supplementary Table 1). Results of these interviews appeared rather homogenous despite a variability of background. Background-based specificities are specified in the text.

The FMEA has been performed by the authors focusing on the biomimetic process of reference. The various results were then evaluated by six experts based on their experience on biomimetic industrial projects. The experts' panel is composed of biomimetic researchers and members of the French institute CEEBIOS (framing the French biomimetic network). To extend our sample and obtain a different standpoint, the evaluation was also performed by 9 students that performed a biomimetic project from September 2019 to January 2020. The scenarios considered the riskier, both in total (11) and by each expert (13), were gathered in a table and illustrated by literature references and quotes from the interviews (Table 1). The FMEA combining all results is made available in a supplementary table (Supplementary Table 2).

Experimental observations were performed by the authors first through the supervising of four student projects on a period of 2 years and through the analysis of feedback from industrial project performed by the CEEBIOS. These observations will be used to illustrate the descriptive phase and will provide insight for the prescriptive phase.

This description phase will thus lead us to identify various key elements to tackle in order to answer our research question. The prescriptive phase (Sect. 6) then propose various methodological contribution to the identified key elements. Among other aspects, the question of the biologist integration is thus tackled through the introduction of a new profile, the biomimetician. An interdisciplinary biomimetic process (the TPIB process) adapted from the process of reference is then proposed to combine all the above-mentioned results.

Interdisciplinarity is used throughout this article to characterize an approach which "analyses, synthesizes and harmonizes links between disciplines into a coordinated and coherent whole" (Choi and Pak 2006; Alvargonzález 2011). Thus, interdisciplinary teams or process are considered to include interdependent contributing actors (Lotrecchiano

Table 1 Characterization of the interview sample

ID	Interviewee	Job	Sector
B.1	Biologist 1	Researcher	Microbiology
B.2	Biologist 2	Researcher	Nanomedicine delivery and molecular biology
B.3	Biologist 3	Researcher	Microbiology
B.4	Biologist 4	Teacher–Researcher	Micro and molecular biology
D.1	Designer 1	Executive director	Industrial and product design, Innovation, Entrepreneurship
D.2	Designer 2	PhD Candidate	Urban, service and graphic design, UX, ergonomics
D.3	Designer 3	Acoustic industrial designer	Industrial, product, acoustic and spatial design
D.4	Designer 4	Creative director	Brand, graphic and product design
D.5	Designer 5	Researcher	Architecture, industrial and product design

2010) with various backgrounds and structured as a "coordinated and coherent whole" to reach a common goal. In this context, transdisciplinarity also combined various discipline but refers to an approach which "transcends each of their traditional boundaries" (Choi and Pak 2006).

An evaluation of the prescriptive contributions is then presented to complete the DRM approach. This last phase was performed through the comparative evaluation of three biomimetic process, the unified biomimetic design process (Fayemi et al. 2017), the process from the ISO norm (ISO/TC266 2015), and our newly optimized process, by 32 professionals on the attractivity, the understandability, the wealth of information and the ability to reduce the fear of risk. Statistical analyses are performed with a Fisher test on the qualitative variables and with a Student test for quantitative variables.

5 Descriptive phase, identification of key elements

Proposed in its current form by Fayemi in 2017, the unified problem-driven biomimetic process is considered as our process of reference. Where a vertical axis represents the abstraction level, the process' shape leads the user from a first cycle, the problem transposition (clockwise), to a second one, the solution transposition, (anticlockwise) and back through an iterative reasoning (Fig. 1). This structure leads to an organic-shaped process which synthesized the overall phases to consider in biomimetics. With the aim of keeping on improving this process, we performed interviews to gather feedback on its understanding. On the process perception, Sect. 5.1 identifies the lack of well-defined axes as a first obstacle toward information retrieval and Sect. 5.2 identifies the semantic difficulties as an impediment for practitioner's proper guidance. Section 5.3 presents the FMEA and discusses its results.

5.1 Ill-defined axes leading to a scary process

First, in the absence of a horizontal axis (usually a step/time axis) and facing a representation shaped after an infinity sign, the lack of information on the time and resources to consider quickly emerges. If *89%* of all respondents perceived the overall iterative shape as "logical" to represent an "iterative reasoning" (D.2), its specific formalization was often questioned by both communities. For example, respondents wondered "why iterations appear possible only between these steps?" (B.1) or argued that "the main iteration should not be between the 8th and 1st step" (D.4). Besides, 50% of the biologists and 80% of the designers criticized the overall infinity shape of the process which "can lead practitioners to feel they will ultimately fail" (D.3).

Secondly, the vertical axis which presents the level of abstraction was identified as a difficulty by 100% of the biologists, which didn't "know what abstraction levels are" (B.3). Where 60% of designers understood the concept of "abstraction axis", recognizing that "an axis on abstraction levels is very interesting" (D.2), all of them questioned its structure which "is not graduated, leading to an unclear link between steps and hypothetical abstraction levels" (D.3). Figure 2 then sums-up a few questions that quickly emerged: Why are there only three levels of abstraction? What do these three levels represent? Do practitioners know how to get from one level to another? Can they use this vertical axis to actually extract information? Should all technical problems be abstracted at the same level?

Finally, on additional element, colours were instinctively understood by all interviewees as referring to the biology-centred or technological-centred steps.

From the standpoint of professional not trained in biomimetics, the two axes thus appear ill-defined, leading to ambiguity when looking at the process, specifically the first few times. Since we want to support biomimetics implementation, those instants are key moments for biomimetics acceptability. By better defining the axes and structure of the process, we think that practitioners should be able to autonomously extract more information and so reduce the fears and risks associated with the process. Following the same logic, the next section will study the semantics associated with the process and focus on critical steps.

5.2 Ill-named steps leading to an unclear guidance

Where steps composing the process are described through a theoretical prism in the literature, we wanted to evaluate their understandability by people that are only looking at the process (Fig. 3).

The first step, the problem analysis, and the last step, where biomimetic ideas are implemented and tested in their initial context, appear as the best understood by all interviewees. Such result appears logical since the semantics

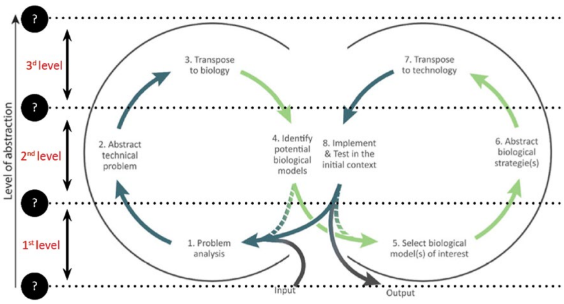

Fig. 2 The unified technology-pull biomimetic process: the level of abstraction (adapted from Fayemi et al. 2017)

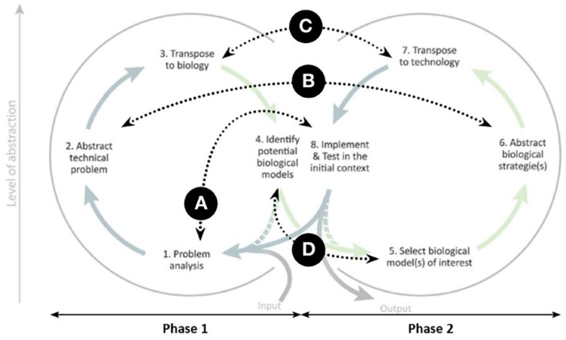

Fig. 3 The unified technology-pull biomimetic process: semantics (Fayemi et al. 2017)

does not present any difficulties and these steps are similar to classic innovation processes (Kruiper et al. 2018) (A, Fig. 3).

On the contrary, the steps of abstraction (B, Fig. 3) and transposition (C, Fig. 3) appeared as the most difficult. In interviews, the concept of "abstraction" was considered as "a mysterious word" (B.2) and overall an unclear concept for all biologists. If designers appeared to be familiar with the concept, its practical application in the context of biomimetics was also perceived as a clear difficulty for both steps 2 (60%) and 6 (100%). Interviewees thus focused on "technical problem" or "biological strategies" when describing their understanding of the abstraction steps. Doing so, they almost replaced "abstract" by "identify", which appears as a reductive way of dealing with these steps. Thus, these steps are misunderstood from the very beginning, leading some people to "skip this step as it appears more logical to directly perform the transposition" (B.4).

The concept of "transposition" was better defined from a theoretical standpoint. However, interviewees hardly extract any information on how to actually perform the step. When asked what would they do at the 3rd step, more than 55% of the respondents answered they "would look for organisms, their properties of interest and published articles" (D.1), mixing-up the "transposition to biology" with the "identification of biological model". For the 7th step "transpose to technology", the concept was interpreted as an application. People quickly understood this step as the moment to "adapt and modify" (B.4) extracted biomimetic strategy to technological systems.

On a different perspective, a significant drift must be underlined on the 3rd step. In practice, this step is always guided by the type of tools that will be used during the 4th step. The goal of the third step then changes as it becomes the formalization of the problem, out of its environment, into a format fitting the requirements of the 4th step's tools (Biomimicry Taxonomy requests for AskNature). The notion of biology fades away as practitioners struggle to apprehend the biological world and so rely on engineering tools. It then appears that no cognitive switch towards biology is performed, the "transposition" only appears because of the required format. Practitioners will keep a technological standpoint, but with biological words, leading them to be highly dependent on databases. The theoretical shift between the initial goal and the practical implementation represents a complete drift of the process. To face this situation, Sect. 6.4 will redefine and rename this step and Sect. 6.5 will underline the need to include biological expertise within the team.

The identification of potential biological models (step 4) and their selection (step 5) are semantically understood steps (D, Fig. 3) but they raise a lot of questions like: How should teams perform those highly unusual steps? Where to find biological data? Which scientists should be interviewed or integrated? And how can we choose the most relevant biological models?

Where steps have therefore been identified in research, and theoretically validated, their implementation in practice remains a major challenge. From our experimental feedback, in both student and industrial project, biomimetic design teams have faced the question of how to perform these steps and in particular the critical abstraction and transfer of knowledge. Therefore, it appears that the process should be better guided in order to increase biomimetic design teams' understanding. Contribution to that extent may allow the recent findings to pass from a representation made for research to a representation made for practice and considering new stakeholders. Based on these observations, some optimizations are proposed in Sect. 6.3 to help biomimetic design teams understand the process representation. Besides, the guidelines on the definition and integration of a transdisciplinary profile, having a specialized know-how and knowledge are presented in Sect. 6.5.

All these challenges lead to an increase in both the perceived and the actual risk of biomimetics. The following section will assess and characterize biomimetic design process' risks in order for them to be better understood and so dealt with.

5.3 A risky process

As previously presented, the biomimetic process is perceived, rightfully, as a risky process. It costs an important amount of resources, both in terms of time and of highly qualified stakeholders. Where it is perceived as money from the standpoint of strategic decisions makers and investors, it is perceived as work and engagement from the practitioners' point of view. From both sides risks are anticipated, loss of money for some and frustration for others (too much time and engagement for too little results). Addressing both these aspects then appears crucial to successfully implement a systemic biomimetic innovation strategy.

Based on this initial observation, risks should be assessed in order to bring relevant contribution. To identify risks associated with biomimetic practice, we gathered information from the literature, from interviews, from experts' analysis and from the authors' experience in biomimetic practice (both industrial and student projects). Then, in order to answer the need for risk's characterization we based our reasoning on the Failure Modes and Effect Analysis tool (FMEA) adapted from Lipol's work (Lipol and Haq 2011). Table 2 presents an extract of the FMEA results focused on the elements that were identified as the more critical (see Sect. 4 for methodological information and supplementary Table 2 for the whole FMEA). From Table 2, various risks can be identified and characterized within their methodological context. Rather than going back on explaining all results obtained in this table, we will point out three overall causes for these various risks (some risks are linked with multiple causes).

1. The lack of guidance and training on specific steps (Table 2. R3, R4, R5, R11, R13, R15, R16, R17, R18, R19, R21). Since biomimetic is quite new in practice, most practitioners have no idea what is expected during the various steps. As previously mentioned, the semantic concepts of "transposition" and "abstraction" can be quite obscure for people not used to perform analogies (such as students) and even for experienced design team's members, performing abstraction, when they are not trained to, can be challenging.
2. The lack of experience in the field and so the lack of hindsight (Table 2. R1, R2, R11, R12, R20, R21). More specifically, it's the inability of teams to detect their errors or poor choices that put the whole project at risk. It is also crucial that team leaders have the ability to characterize the project progress, the team's needs in terms of resources and to evaluate the obtained results relevancy.
3. Finally, the lack of biological knowledge and know-how (Table 2. R6, R7, R9, R10, R12, R14, R19, R20). This observation thus confirms what was mentioned in the state of the art, the lack of biological expertise leads to deep impediments in terms of search, evaluation and understanding of the biological models of interest.

In its current form, the biomimetic process thus still appears as an unknown territory and appears risky for untrained stakeholders.

The last three sections have presented the descriptive phase of our study. The structure, semantics and risks associated with the current biomimetic process of reference have been characterized and various levers have been identified to further develop the unified problem driven process towards a more practical end. To prevent the risk thus identified, the next section focuses on the causes above-mentioned and prescribes various methodological contributions to optimize the process. To tackle the overall cause (1), we restructured the process axes and renamed the steps to allow practitioners to easily extract information and so reduce the risk of errors. To deal with cause (2), we suggest the team to define evaluation time to take a step back and compensate the lack of experience by an increase of the communication within the team and between the team and the decision makers. Finally, cause (3) is tackled through the integration of a specialized profile as a new member of biomimetic design teams, increasing the team's biological knowledge and ability to perform transdisciplinary work.

6 Prescription phase

6.1 Implementation of a chronological, duration-related axis

The descriptive phase underlined the need for a more coherent and accessible referential in which to represent our process. Such new representation should allow design teams to extract more information so they can be better guided.

A horizontal axis representing the duration of each step is thus proposed. Giving practitioners an idea of the steps' timeframe for their project and so the distribution of the cost during the process appeared highly relevant to reduce the fear towards biomimetics. Moreover, having a clear understanding of the process' progresses and the remaining steps appeared crucial from a strategic standpoint. To be able to generate this axis, we studied 15 biomimetic projects and extracted the time dedicated to each step of the process. From these data, we then established a horizontal axis representing the mean percentage of time dedicated at six steps of the biomimetic process (Table 3). As the 1st and 8th steps are highly variable depending on the project, it would not be particularly relevant to estimate a proper duration for these steps. Therefore, they are left aside in this analysis. Along with these industrial feedbacks, the authors prescribed estimated duration for the various steps based on their experience in the field, supervised projects, faced difficulties and research findings. The overall means then offer an estimated duration for each of the six analyzed steps taking into account both the practical and research standpoint.

Results obtained in Table 3 clearly show that the 4th step of the biomimetic process is the step that takes the more time to be performed. Overall, authors' prescriptions match the feedback but tend to advise practitioners to spend more time on the abstraction steps. Based on this new axis, practitioners then have a quick estimation of the mean time they may dedicate to the different steps of the conceptual design

Table 2 Key risks extracted from the FMEA applied to the unified problem-driven biomimetic process

Risk ID	Step	Failure mode	Potential cause	Potential effect	Student	Expert	Interview	References
R1	1. Problem analysis	Problem wrongly defined	The design team does not find it necessary to re-question and analyze the problem	The whole project is highly likely to fail		X		Helms et al. (2009); Chirazi (2019)
R2			The design team lacks a systemic standpoint and does not take the whole context into account	The solution may not work in the initial context		X		
R3	2. Abstract technical problem (TP)	Inability to abstract the TP the step is considered skipped by the team	The semantic concept of “abstraction” is unknown from the design team	Team frustration. Steps 3 and 4 are poorly performed and appear difficult	X		“That’s the word I found mysterious”	
R4		Irrelevant abstraction	The design team makes mistakes during the abstraction			X		Rovalo et al. (2020)
R5	3. Transpose to biology	Inability to transpose to biology, the step is knowingly skipped	The semantic concept “Transposition” is unknown from the design team	Team frustration The search for solutions is passively performed, difficult, and restricted		X	“Not clear “	
R6		Irrelevant transposition	The design team doesn’t have prior biological knowledge and chosen keywords aren’t relevant for biological models		X	X		Rovalo et al. (2020); Yen (2019)
R7			The design team chooses only one semantic form for each keyword and/or choose a poorly relevant form			X		Shu (2010)
R8	4. Identify of potential biological models	Inability to find biological model considered relevant	The design team only searches for direct analogies, other models are perceived as irrelevant			X		Mak and Shu (2004)
R9		Identification of inappropriate biological models	The design team identifies a biological model without having enough information (lack of time to study, of data, of expertise)	Risk of fixation on inadequate model. Loss of resources		X		Rovalo et al. (2020); Yen et al. (2014)
R10		Identified models appear redundant	The design team creates fixation points	Loss of resources, feeling of being stuck		X		Helms et al. (2009); Rovalo et al. (2020)

Table 2 (continued)

Risk ID	Step	Failure mode	Potential cause	Potential effect	Student	Expert	Interview	References
R11	5. Select biological model(s) of interest	Selection of technically relevant models but inappropriate for a given biomimetic project	The design team forgets to consider some elements of the context (stakeholders, market, etc.) leading to the selection of model inappropriate for the project	Final product may be inappropriate, Loss of resources		X		Chirazi (2019)
R12			The design team selects a potentially relevant biological model, but there is a need for biological research before any application is made possible	Highly increase the cost or risk of fixation on inadequate model	X	X		Jacobs (2014)
R13	6. Abstract biological strategie(s)	Inability to abstract the biological model the step is considered skipped by the team	The semantic concept of abstraction is unknown from the design team	Leads to failed attempt to direct transposition in step 7 Switch towards Bio-morphism, Bio-utilization, etc	X		"I skip this step when I'm looking at it"	
R14		Poorly performed abstraction	Misunderstanding of the biological data, wrong elements are abstracted	Miss the interest of the approach, appears too complex		X		Rovalo et al. (2020); Chirazi (2019); Yen et al. (2014)
R15			The design team thinks that they performed it well, but they actually have a misconception of what abstraction is			X		Rovalo et al. (2020)
R16			The design team has no idea what a level of abstraction is or which level to look for?		X	X		
R17	7. Transpose to technology	Inability perform the step (step is not completed)	The team doesn't know what "transposition" means in the context of the step	Switch towards Bio-morphism, bio-utilization, etc		X		
R18			The design team knows the semantic concept of transposition but does not know how to perform the step	Very high frustration, failure of the project		X		Rovalo et al. (2020)

Table 2 (continued)

Risk ID	Step	Failure mode	Potential cause	Potential effect	Student	Expert	Interview	References
R19	8. Implement and test in the initial context	Loss of the biological model during the implementation	The design team, with or without knowing it, fixate on existing technological strategies and try to adapt the concept to it, losing the interest of a biomimetic approach	High frustration. No interest in biomimetics. Not a biomimetic product		X		Helms et al. (2009)
R20		Ability to implement the concept but the tests show a lack of efficiency	The generated prototype is based on misunderstanding/misabtraction of the biological model, the expected results aren't observed	High frustration. Loss of resources, project failure		X		Rovalo et al. (2020); Yen (2019); Helms et al. (2009)
R21		Ability to implement the concept but the tests show a lack of efficiency	The design team did not consider the context of the project	Project can adapt or be discontinued. Loss of resources. Might not be profitable		X		Chirazi, (2019); Yen (2019)

phases. The idea behind this approach is for teams to be able to:

- establish an estimation of the Gantt chart associated with their project if the project's duration is predefined,
- estimate the duration of the remaining steps if the duration of their project is not predefined,
- evaluate the project progress and/or delays and so the team's strength and weaknesses,
- better evaluate the costs and so better assess the risks and the required investments at the different steps.

Far from being an absolute truth or a static representation, this axis should be seen as a generic guideline that can be adjusted to the team's convenience and experience in the field or to the project requirement. Some teams like to spend more time on some steps than others without being less efficient and some teams may think the above-established duration are not relevant with their practice. However, this new representation is precisely a way to consider this highly variable context through the structuration of the process in an easily customizable framework, allowing the implementation of further research findings, internal feedback and teams' preferences.

Choosing a linear, chronological horizontal axis, leads to the disappearance of both the default of the infinity shape (a process that "never ends" and a frustrating feeling of "starting over") and its benefits ("highly logical" iterative loops and a "very natural reasoning"). As a result, new iterative loops and reasoning will be implemented during the process and presented in Sect. 6.4, to maintain these assets from the original process.

Next section focuses on the vertical axis and aims at clarifying various associated concepts through the implementation of a graduation.

6.2 Characterization of the abstraction axis

The existing vertical axis represents the level of abstraction (Fig. 2). Even though abstraction is a core concept in biomimetics, Sects. 5.2 and 5.3 pointed out a lack of understanding of what is abstraction and of how to perform abstraction steps. This section will thus describe the implication of abstraction in biomimetics before the variation of abstraction's levels relevant to the vertical axis are specified. These levels will then be characterized along the process and key associated outputs will be added to the representation to provide practitioners with some hints on how to connect the dots between abstraction and their practice.

Abstraction is a process that extracts information from reality to generate conceptual representation or ideas. It's a natural human skill intrinsically linked with learning abilities (Piaget 1977) and is mainly performed without realizing it. It allows cognition mechanisms to sort information and create conceptual networks to model reality and so predict, anticipate, adjust and progress. Concretely, during abstraction, choices are made on what will be used to represent reality. In his work, Piaget described several types of abstractions: empirical abstraction and reflective abstraction (Piaget 1977). Where empirical abstraction focuses on classifying reality into concepts sharing traits, reflective abstraction is a higher cognitive process which leads to the connection of these concepts, their dynamization and the formalization of models that can produce new knowledge (Campell 2001). In the following section, we will discuss the link between abstraction and biomimetics and use two main modalities (Nagel et al. 2010) that we will name prisms (Table 4) and levels (Table 5) to prescribe a new formalization of the vertical axis.

6.2.1 Prisms of abstraction

Often combined and associated with the abstraction levels, various prisms have already been listed in the literature (Gero 1990; Mak and Shu 2004; Chakrabarti et al. 2005; Vincent et al. 2006; Helms et al. 2009; Nagel et al. 2018; Bhasin and McAdams 2018) (Table 4). The above-mentioned notion of prisms is linked with the standpoint chosen

Table 3 Results of the timeframe analysis ($n = 15$) compared with authors' prescription

Process	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7
Min duration (%)	4	4	28	4	9	5
Max duration (%)	12	19	60	25	30	24
Median duration (%)	7	11	44	11	15	11
(1) Mean duration (standard deviation)	7% (2%)	9% (4%)	41% (10%)	14% (5%)	17% (6%)	11% (5%)
Step n vs Step $n-1$ p value (Fisher test)	–	0.146	2.0e–07**	1.9e–07**	0.2174	0.5765
(2) Mean duration prescribed by the authors (%)	19	10	33	5	19	14
Mean (1) & (2) overall prescription (%)	13	10	37	9	18	13

p value: '***' < 0.001; '**' < 0.01; '*' < 0.05; '.' < 0.1

Table 4 Prisms of abstraction, leading to analogies categories

Proposed prisms	Gero (1990), Goel (2009)	Mak and Shu (2004)	Bhasin and McAdams (2018)	Nagel et al. (2018)	Chakrabarti et al. (2005)	Vincent (2006)
What?	Structure	Form	Material and structures Mechanism and processes	Form Surface Architecture Material	Parts	Substance and structure
How?	Behaviour			Process	State Organs Inputs Physical phenomenon	Energy and information
Why?	Behaviour	Principles		System	Action Physical effects	
	Function	–		Function	–	–
When and where?	–					Space and time

Table 5 Levels of abstraction

Proposed abstraction level	Keshwani and Chakrabarti (2015)	Gentner (1989)	Cheong and Shu (2012)
0. Reality	–		
1. Low	Surface (should not be confused with the prism surface)	Superficial	
2. Intermediate	Shallow	Relational	Causal
3. High	Deep		

by the observer to represent the idea of interest. These prisms are often combined to generate extensive, dynamic representations of reality, called models. If you are taking an aesthetic standpoint, forms and structures will be at the centre of your model, where if you're taking an organizational standpoint, energy, information and systems may be the centre of interest. In biomimetics, since the field is part of the field of design, the functional consideration is most of the time the focus of attention. In order to guide practitioners that have not a specific training on such concepts we decided to separate the prisms from the levels, even though these two concepts can be undoubtedly linked. Table 4 then sums up some of these prisms and presents four general questions, derived from Yen's work (Yen et al. 2014), to help practitioners perform this step:

- The "What?", through the understanding of the physical embodiment of reality, key elements associated with specific patterns and structuration at multiple scale of a determined material can be identified. It is the prism that is the easiest to access since it mostly relies on observation. As a result, it is often the first step to consider when performing abstraction, which elements are to consider? And which elements are just "noises". Since it is very close to reality, through direct observation, it is linked with a low level of abstraction (Table 5). However, we want to underline that various abstraction level can be considered within the "what?" prism by focusing on some attributes of the element of interest (ex: seawater < saltwater < saline solution < ionic solution). This prism then appears at the core of Piaget's "empirical abstraction". To take a simplifying analogy, this prism can be seen as a picture.
- The "How?", through the understanding of the consequences of the dynamic interactions of the elements identified in the "what", key mechanisms, on how the described reality occurs, are pointed out. The notions of time, states and processes are intrinsically linked with this prism. Through the identification of key steps, inputs and interactions, the causes leading to the observed changes of states can be extracted. Since it is quickly, intuitively, interpreted in a causal manner, this prism is often linked with an intermediary to high level of abstraction. However, we again want to underline that various abstraction level can be considered within the "How?" prism. In other word the rise of the abstraction level depends on the cognitive analysis and causal relationship established by the observer and so her/his knowledge (ex: the various ions of an ionic solution move in specific direction when a tension is applied < charge particles are sensitive to the movement of other charged particles). This prism then leads us to extract causal interactions along with their consequences and so to also increase the abstraction level of the "what?" prism by identifying the required attributes (here the charge of ions in the solution). This prism then appears to find it source in Piaget's "empirical abstraction" and reach "reflective abstractive" through causality. To pursue the analogy, this prism can be seen as a video.
- The "Why?", lead us to wonder about two aspects: "Why (= what natural principles explain that) do interactions cause the observed consequences?" (= why of causality) and "Why (= for what purpose) do the subject performs the action?" (= why of intention). The first aspect leads us to the notion of scientific principles and physical effect, "Why does the apple fall from the tree?", because of gravity, where the second interpretation leads to the underlying functional needs, in order to spread the seeds. Interestingly, it's often through the previous prisms and their confrontation with physical, natural, principles that the core mechanisms of phenomena finally emerge. If the why of intention will be a key for knowledge transfer through functional reasoning, the why of causality is here at the centre of the abstraction process. Again, various levels of abstraction can be distinguished for these prisms. As a striking example, where a functional reasoning applied to the organs of an animal lead to various functions, to breath, to move, etc., at a high enough level of abstraction, all biological phenomena can be interpreted as having a single function: "survival" (Yen et al. 2014) (why of intention). These prisms then fall right into Piaget's "reflective abstraction". To keep on using the same analogy, this prism can be seen as an interview of the filmmaker or the photographer, explaining the rational, the function, behind is work (why of intention) and the choices in composition (why of causality).
- The "Where and when does it work?" this last prism is less considered in the literature as it is often dispatched between the other prisms. However, we decided to consider it as a singular one since it stimulates a holistic vision and the gathering of another type of information, focusing on context and environment in all its meanings. Where elements directly interacting with the action are well-defined in the previous prisms, wider scales are often left aside. This prism is even more important with living beings since they act autonomously, sometime because of deeply anchored mechanisms such a circadian cycle. This prism can point out inputs that would be ignored otherwise, if a phenomenon happened at a specific season, the amount of light can be a triggering mechanism, element that would not be detected without taking into account the overall context and slower mechanisms, far from human's high speed and direct framework. This prism oscillates between "empirical" and "reflective" abstraction, it's the accommodation of the assimilated conceptual models to their context. To

end the analogy, this prism presents the social mores, marketing tendencies, etc. composing the deeply impacting context allowing the proper understanding of a photo or a movie.

Even if prisms and levels are intrinsically related as pointed out previously, we argue that defining them separately will allow practitioners to better understand these two concepts. Where the information in this section should support the understanding of abstraction and so the 2nd and 6th step of the process, the next section focuses on levels of abstraction to allow the prescription of graduation on the vertical axis.

6.2.2 Levels of abstraction

Several articles have also been published on the definition of the level of abstraction (Gentner 1989; Cheong and Shu 2012; Keshwani and Chakrabarti 2015). To make this notion easily understandable, we formalized four levels (Table 5). These levels are mainly based on the literature but, in order to give practitioners a baseline, we added a first level, "Reality", which is a level where no abstraction is performed. Furthermore, the second level, called "Surface" in Keshwani and Chakrabarti (2015) can lead to a confusion with the abstraction prisms above mentioned (Table 4) (Gentner 1989; Cheong and Shu 2012; Keshwani and Chakrabarti 2015). We then choose to use more general terms to represent the rise of the abstraction level to prevent any confusions. Levels used in the rest of the article are then defined as follows:

- "reality" that represents so much information that it is just impossible to handle as a whole,
- "low" from its low-end "Embodiments" to its upper end "Specific traits",
- "intermediate" from its low-end "Generic traits" to its upper end "Dynamic patterns",
- "high" from its low-end "Causal models" and to its upper end "Generic models".

As previously explained, as humans, we are always performing abstraction, we choose which details are important and which are just unnecessary. If a dog passes in front of you ("Reality") and you want to describe its physical attributes (the "What?" at "low" level) over the phone, you would not mention the size of the 2d finger of its front left paw. However, this finger is nonetheless both real and part of the information you will observe, you've just decided that it was, in this situation, an irrelevant detail. You've then performed a rise in abstraction within the low-level. The fact that this specific element is or is not relevant is key and depends on two aspects: the idea you want to represent and the information you have and so the technological or biological expertise you possess in the context of biomimetics.

6.2.3 Levels of abstraction during the biomimetic process

In biomimetic practice, abstraction is a crucial process. Indeed, the underlying mechanism of biomimetics, and analogical approaches in general, is to increase the abstraction level and reach an extreme to allow transposition. The higher the level of abstraction, the less intricate with a specific embodiment the concepts are and so the easier it is to perform the analogy (Drack et al. 2018).

With this in mind, we will wonder about the variation of the abstraction level along the biomimetic process of reference (Fayemi 2016) and try to characterize it to guide practitioners. Keep in mind that we focus here on the levels, several prisms are then often considered in each step but would not be specified.

First step During this phase, the team first wants to face reality, to observe and gather information, the number of details thus increases and so the level of abstraction decreases a little to focus on reality. Based on their observations on the embodiment of the problem and on its specific traits, teams then increase back the level of abstraction through a new formulation of the problem. We consider that all along this step, the level of abstraction oscillates within a "low" abstraction level.

Second step Design teams further increases the level of abstraction of the problem representation through two phases. The first phase brings practitioners to decompose specific traits to be refined into generic traits (subsystems, attributes, flows, states, material, etc.). This step of generalization of specificities leads the team to enter the intermediary level. The second phase leads the design teams to reach the high level of abstraction by linking the various information together, and with principles coming from their environment (gravity, energy conservation, etc.). Once the conceptual model of the problem can be extrapolated to function autonomously in a generic context (rather than out of it) then the abstraction has reached a high enough level for the design team to move on to the next step.

Third step The third step leads users to enter the biological world. Even though the level of abstraction slightly decreases because of the identification of biological space fitting the technical problem (analogy of constrains or functions), design teams enter the biological world through a conceptual bridge at a high abstraction level.

Fourth and fifth step Within those spaces, biological models can be searched, identified, evaluated and selected (steps 4 to 5). These phases then lead to a decrease of the level of abstraction toward the low level. The team select the models of interest and then gathers as much relevant specific information as possible to tackle the design problem.

Sixth step The same way then in the 2nd step, the 6th step leads to the selection and refining of specific straits and the large increase of the abstraction's level toward the high level. In this context, several studies have shown that a high level of abstraction allow teams to reach more easily a far analogical field such as the technical field from a biological standpoint (Srinivasan and Chakrabarti 2009; Sarkar and Chakrabarti 2011).

Seventh step The difficulty of the steps of transfer then depend on the chosen level of abstraction. If it is too low, the abstracted guidelines can be restrictive. If we consider the well-known example of the lotus leaf, "Use wax nanocrystal to reduce water adhesion through hydrophobic interaction" focuses on the embodiment existing at the surface of the Lotus leaf, which will probably not be directly applicable to a technical system (Mak and Shu 2004). On the other hand, if it is too high, it can be hard to generate concepts. For example, to "prevent bonds' formation" is a guideline formalized at a high abstraction level, but the solution in the form of an embodiment is not trivial. Very high abstraction levels then require both training and creativity skills. Thus, this step of transposition often sees a small adjustment of the abstraction level to be able to consider suitable guidelines for transposition. Regardless of the chosen level of abstraction, the output of the 7th step is the conceptual technological embodiment of the abstracted biological solutions (intermediate to low level of abstraction). This phase of transposition leads to a stronger decrease in terms of abstraction level than the previous step of transposition (step 3).

Eighth step The last step of the process is the implementation and test. Technological concepts are then prototyped and tested (from low level to reality). The level of abstraction then oscillates at a low level between short increases of the abstraction level after testing phases (concept optimization at a low level of abstraction) and decreases through the implementations of modifications (new embodiment implemented on the prototype).

Through this section, the evolution of the abstraction level along the process has been described, next section will then combine the observations made in the last sections and implement a new vertical abstraction axis.

6.2.4 Implementation of the new abstraction axis

Based on the elements presented in the precedent sections, a new abstraction axis is formalized to guide practitioners during their practice through coherent graduation. Figure 4 presents the new vertical axis illustrated by the evolution of the abstraction level during the various steps of the biomimetic design process as described in Sect. 6.2.3.

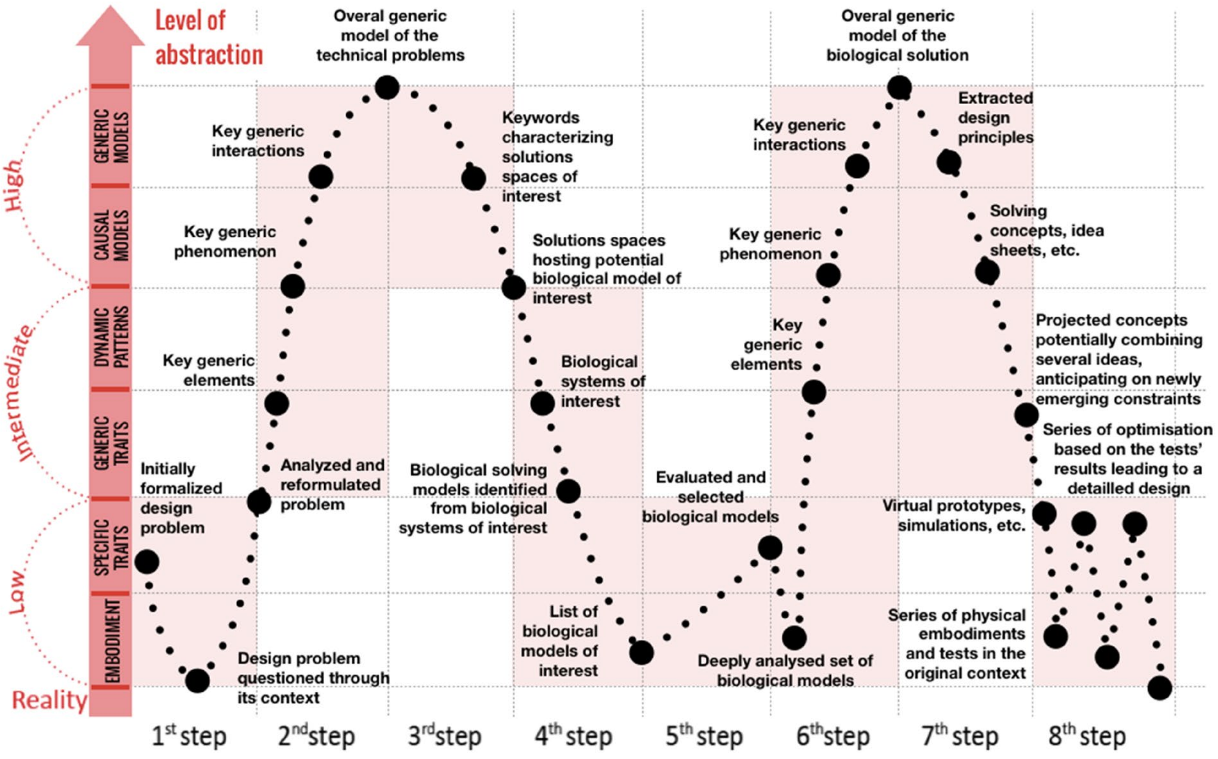

Fig. 4 Illustration of the level of abstraction axis along the various steps of the biomimetic process

All together these methodological contributions should allow practitioners to track their progress and prevent the risks caused by a lack of guidance during abstraction phases. Again, this contribution is not strict rules to follow on how to perform biomimetics, the abstraction's levels described in this section are guidelines that can, and should, be adapted to the subject and teams. In contrast, regardless of the actual considered levels, the pattern of increase and decrease of the abstraction's level between steps appears rather generic. The abstraction axis will then be represented with a main structure and adaptive levels. The same way as with the horizontal axis, the underlying idea is to give design team a structured but customizable methodological framework.

This section tackled the lack of understanding surrounding the vertical axis of the biomimetic design process representation. Through the definition of the concept surrounding the process of "abstraction" and the description of its application during the biomimetic process' steps, this section described the design and implementation of graduations on the vertical axis of the biomimetic process along with intermediary outputs all along the process. This increase of available knowledge displayed in the process' representation also aims at leading practitioners to better understand the link between biomimetics and theories that can appear rather complex outside of a research context (FBS, SAPPhiRE, TRIZ and Trade-Offs).

6.3 Steps redefinition and renaming

Based on the descriptive phase, we have seen that semantics associated with the biomimetic process was sometimes hardly understood by untrained practitioners, leading them to fixate on false interpretations and reducing their ability to perform biomimetics. The following section will prescribe renaming of several steps based on their (re)definition and on the observations made in the descriptive phase. The goal remains the same, support practitioners in their understanding and appropriation of the biomimetic design process. In this logic, we chose to use a purely prescriptive formulation with short imperative names as instructions for practitioners to follow.

First step: Analyze the problem Since the first step appears classic and properly understood, we will just harmonize the process by giving it a name fitting the instructional form: "Analyze the problem". We would only remind practitioners that, since the results of this step will structure the rest of the project, it appears as one of the, if not the, most important step of the process.

Second step: Identify technical problems, their generic patterns, causes and effects From the descriptive phase, we can see that the name "abstraction of technical problem" is not properly understood. As the concept of abstraction has been extensively described in the previous section (see Sect. 6.2), we refer the reader to this section for extensive information. Based on the description of the 2nd step made in Sect. 6.2.3, we know that it encompasses the extraction, refinement and structuration of information characterizing the technical problems. Problems are then turned into connected concepts or patterns, and the abstraction level is further increase through the formalization of dynamic causal models representing the problem. As a result, we rename the 2nd step "Identify technical problems, their generic patterns, causes and effects". This renaming overall resumes the abstraction process, core of the second step, in more accessible terms, while conserving the link this the initial term of "abstraction" through the vertical axis.

Third step: Project problems into biology to identify solutions spaces To start with, we propose the following definition as a common ground of reflexion: transposition, in the context of biomimetics, is the cognitive process through which generic, field independent, conceptual models can be paired with elements of both the technological and the biological world (Fig. 5). Transposition then appears as a conceptual projection from one field to another, made possible by the abstraction step, and so as the core of analogical reasoning, the establishment of "relational commonalities independently of the objects in which those relations are embedded" (Gentner 1989). By crossing that bridge, and so projecting concepts into the targeted field, practitioners shift away from one specific conceptual framework to another. We named spaces the results of this analogical mapping process.

In that context, spaces can be of various kinds, such as environmental spaces or functional spaces. The interest of stakeholders having biological expertise then appears obvious during this step. Independent of their nature spaces are identified because they display analogical constraints and so contain organisms adapted to these constraints, in other words, potential solutions. As a result, we rename the 3rd step "Project problems into biology to identify solutions spaces".

Fourth step: Search and identify biological models potentially solving the problems of interest The fourth step appears to be intrinsically iterative, search phases lead to the identification, within the search results, of relevant outputs that create new cognitive links, generating new keywords and so leading the team to start a new search phase. Each iteration leads the team to better define or identify new solution spaces and so increases their chance of finding relevant models. These observations are not new, various approach choose to distinguish these two phases (search and identification) (Weidner et al. 2018), but, in our opinion, their intrinsic link (user will always make choices during a search to prevent an overwhelming number of irrelevant results) justify their gathering as one step. However, to harmonize the state name with the literature and the observed practice,

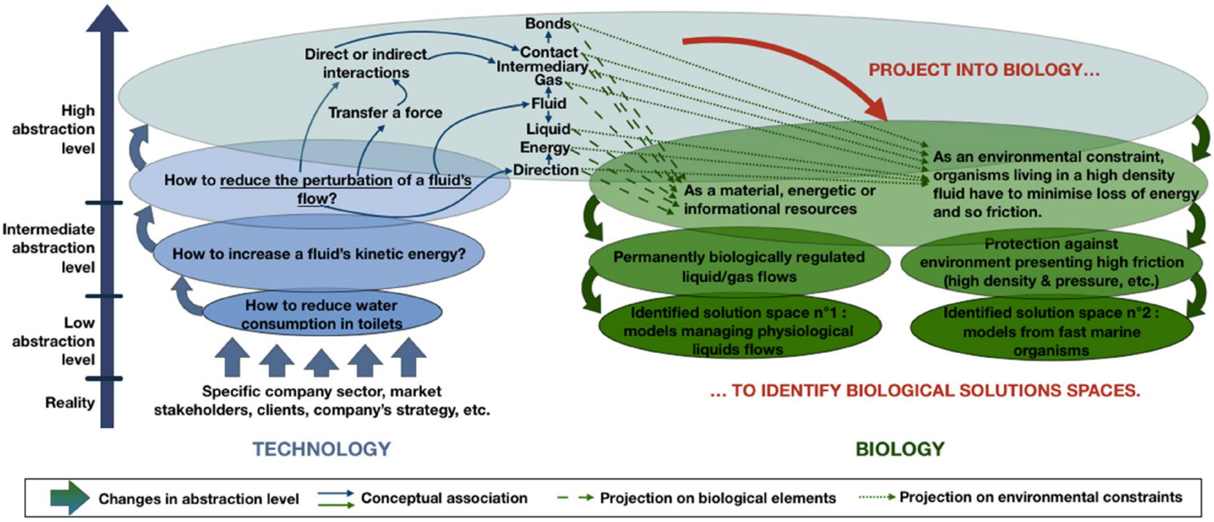

Fig. 5 Identification of solution spaces through conceptual projections into biology

we will name the 4th step "Search and identify potential biological models".

Fifth step: Evaluate and select relevant biological strategies The descriptive phase has underlined the practitioners' difficulty at selecting biological models of interest. To underline the need for a proper selection process we will rename this step "Evaluate and select relevant biological strategies". The concept of evaluation is then directly associated with the idea of judging the value of biological strategies (that can be shared by several models) based on criteria. The selection step then relies on the comparison of those evaluations to identify the best fitting strategies. For more information on the selection criteria to consider, we refer the reader to several articles that have been describing this phase (Helms and Goel 2014; Fayemi et al. 2015; Weidner et al. 2018).

Sixth step: Identify biological resolution elements, their generic attributes, patterns, causes and effects In a very similar way, then with the 2nd step, the 6th step is renamed "Identify biological resolution elements, their generic attributes, patterns, causes and effects".

Seventh step: Project solution into technology to generate design principles and concepts In a very similar way, then with the 3rd step, the 7th step is renamed "Project solution into technology to generate design principles and concepts". Through the projection of abstracted biological solutions into the technological field, design team will generate design principles applied into conceptual embodiment. This step can be linked with creativity steps: from highly abstracted solutions what kind of design concepts can the team generate? The creative cognitive reasoning will then act as a projection catalyzer.

Eighth step: Implement and test After the embodiment of biological strategies into technical concepts, design teams will have to implement these concepts into the initial context through prototypes (numerical simulations first and then physical prototyping) and test the result, as they would with any other type of design process.

Based on the descriptive phase, we identified several key levers of optimization for the biomimetic process. Tackling the FMEA overall cause (1), the lack of knowledge and know-how on specific steps of the process, Sects. 6.1, 6.2 and 6.3 presented various methodological reflexions and their implementations on the biomimetic process. Next section will tackle the lack of hindsight identified as the risks' overall cause (2) in the FMEA. To deal with these risks, "Go/ No Go" milestones are described before being implemented on three key steps of the biomimetic process.

6.4 Go/No Go and iterative loops to limit the risk

"Go/No Go" milestones are evaluation of the project progress, validating each time if the required elements have been gathered during the achieved steps and if the conditions are in place to properly perform the coming steps of the biomimetic process. The following section describes when (which steps and why) is "Go/No Go" implemented, and presents decision trees to help design teams in their validation of those "Go/No Go" and exposes the various scenarios that can be faced and their associated feedback loops.

6.4.1 When to perform the "Go / No Go" evaluations?

Since "Go/No Go" aims at evaluating progress to limit the risks, the parts of the process that are the most resources consuming (time, external experts and so money) have been identified and "Go/No Go" implemented in between these parts.

The first part gathers the steps 1, 2 and 3, representing 7 of the 21 key risks identified in the FMEA. The second part gathers the steps 4 and 5, representing 39% of the conceptual design duration and 5 of the 21 key identified risks. The third part is the 6th step, representing by itself 14% of the conceptual design duration, 4 of the 21 key identified risks along with a potential need for external experts (Graeff et al. 2019b). The fourth part gathers the steps 7 and 8, representing a highly variable duration and 5 of the 21 key identified risks.

These four phases have also been identified because they all end at points where evaluation is particularly relevant. Evaluating the project at the end of step 1 or 2 will not give any information on the biomimetic potential of the project and evaluating the project at step 4 does not make a lot of sense since the actual choice of biological model to consider would not have been performed yet. The implementation of three "Go/No Go" points at the end of steps 3, 5 and 6 should then allow design teams to validate the project's progress and to describe if, based on the obtained results, the resources at their disposal are sufficient to perform the remaining steps.

Furthermore, steps 3, 5 and 6 represent steps where outputs can be used even if the project must be terminated. It then represents an opportunity for decision makers to decide whether they want to keep on using a biomimetic approach or to back up the outputs for latter usage and go back to a more "classic" innovation strategy.

By reducing the risk associated with biomimetics, the pursued aim of these contributions is for practitioners to train little by little until they reach the confidence and hindsight necessary to properly implement biomimetic as a systematically considered innovative strategy.

6.4.2 How to perform the "Go / No Go" evaluations?

As previously presented, "Go/No Go" represents evaluations steps. In order to guide practitioners, this section then offers various instructions on how to perform these "Go/No Go", which criteria to consider and what might be the role of the various stakeholders. These guidelines have been designed based on the experimental feedback and discussion with practitioners. However, they should be adapted to each team's specificities and given project since parameters can have highly variable impacts depending on the context specificities.

6.4.2.1 First Go/No Go: validation of the project's technological and biological framework To perform the first "Go/No Go" (end of step 3), six criteria have been identified covering the three main aspects previously identified: the project's progress, the relevance of obtained results and the evaluation of resources required in coming steps. Based on these criteria, the first "Go/No Go" milestone allows the team to assess the risk and decide on the further course of action. To help design teams performing this step, a decision tree presents the various criteria and the consequences of a failure to validate (Fig. 6).

This evaluation is crucial since this part of the process represents relatively little investments specific to biomimetics, problem analysis must be performed regardless of the chosen innovative strategy, but it defines the entire project. Several scenarios involving iterative loops will then be implemented on the final representation of the process (Sect. 7) to describe the Go/No Go results.

6.4.2.2 Second Go/No Go: validation of the compatibility between the selected biological strategies and the project's context. To perform the second "Go/No Go" (end of step 5), six criteria have been identified following the same logic as the first one and are presented in Fig. 7.

In the same way as with the first "Go/No Go", the risk is thus assessed and the various scenarios involving iterative loops are implemented on the process representation (Sect. 7).

6.4.2.3 Third Go/No Go: validation of the compatibility between the abstracted principles and the project's context The last "Go/No Go" is implemented at the end of the 6th step and presented in Fig. 8. Since the rest of the process can be considered as a "classic" product design process, we would not specifically implement further "Go/No Go", which does not mean the rest of the process is easy, but it holds fewer impediments specific with biomimetics. About the results' relevance, since the team has reached this step, we will consider that the criterion has already been validated during the previous Go/No Go steps.

Based on the criteria exposed in Fig. 8, the last "Go/No Go" allows the team to assess the risk and decide on the further course of action. Abstracted biological models may be validated by teammate having a deep biological knowledge (see Sect. 6.5) or by biological researchers as proposed by Nagel et al. (2011). Experienced team member may also ensure the relevancy of the chosen level of abstraction. Again, various scenarios involving iterative loops are implemented on the process representation (Sect. 7).

Through this section, the guidelines on how to perform the newly implemented "Go/No Go" have been described. The next step will then tackle the last overall cause of risk identified in the FMEA, the lack of biological expertise. The integration of a new profile along the process is then prescribed to improve the team's ability to perform

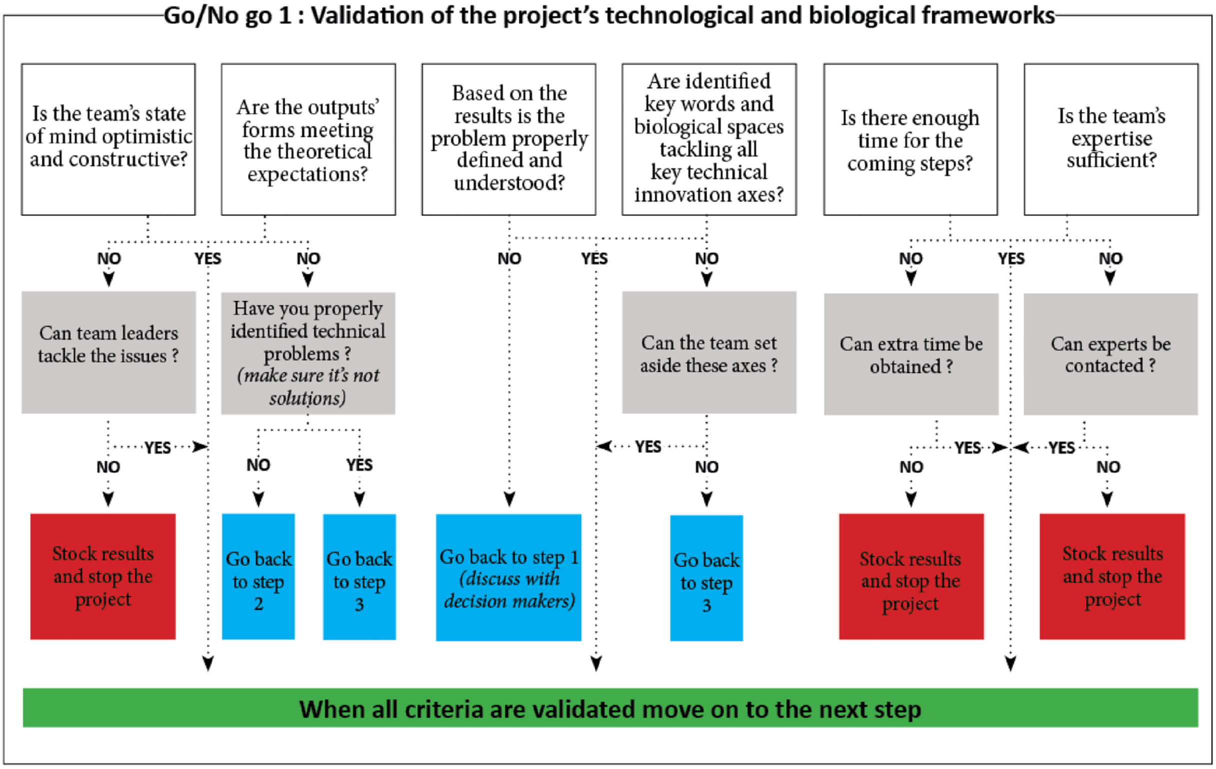

Fig. 6 Decision tree of the first Go/No Go milestone

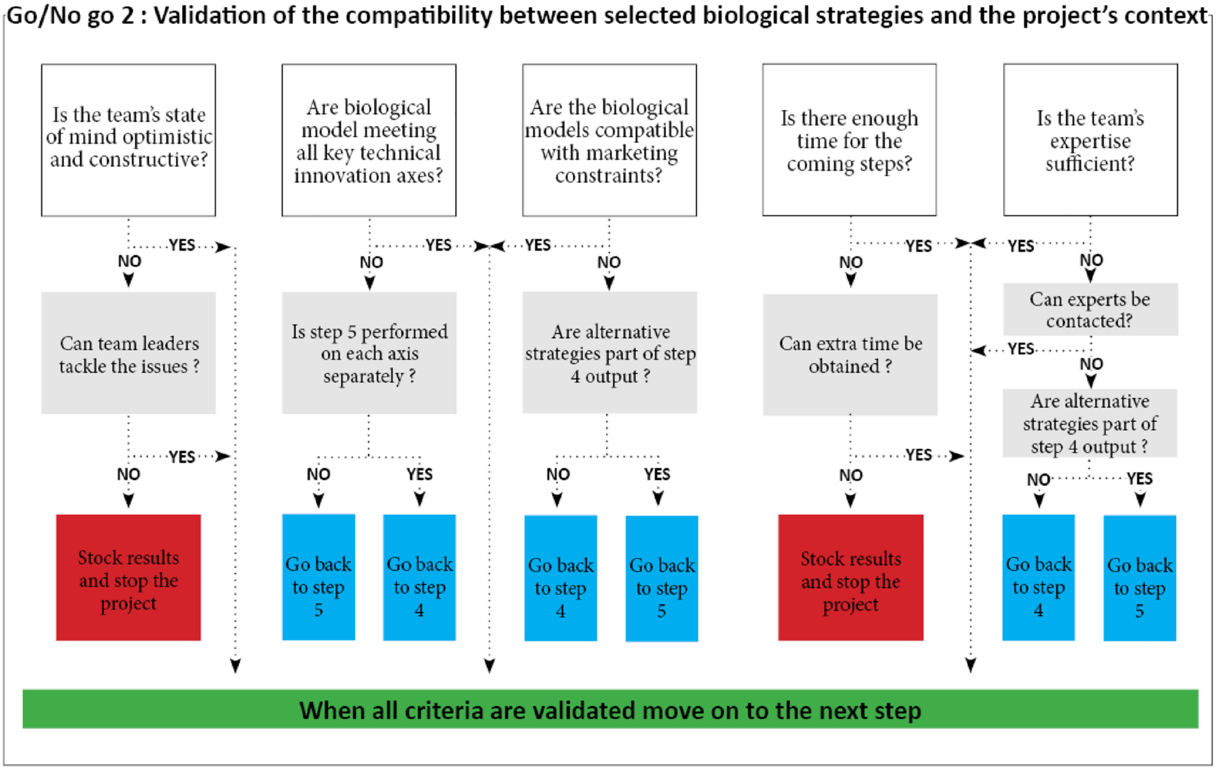

Fig. 7 Decision tree of the second Go/No Go milestone

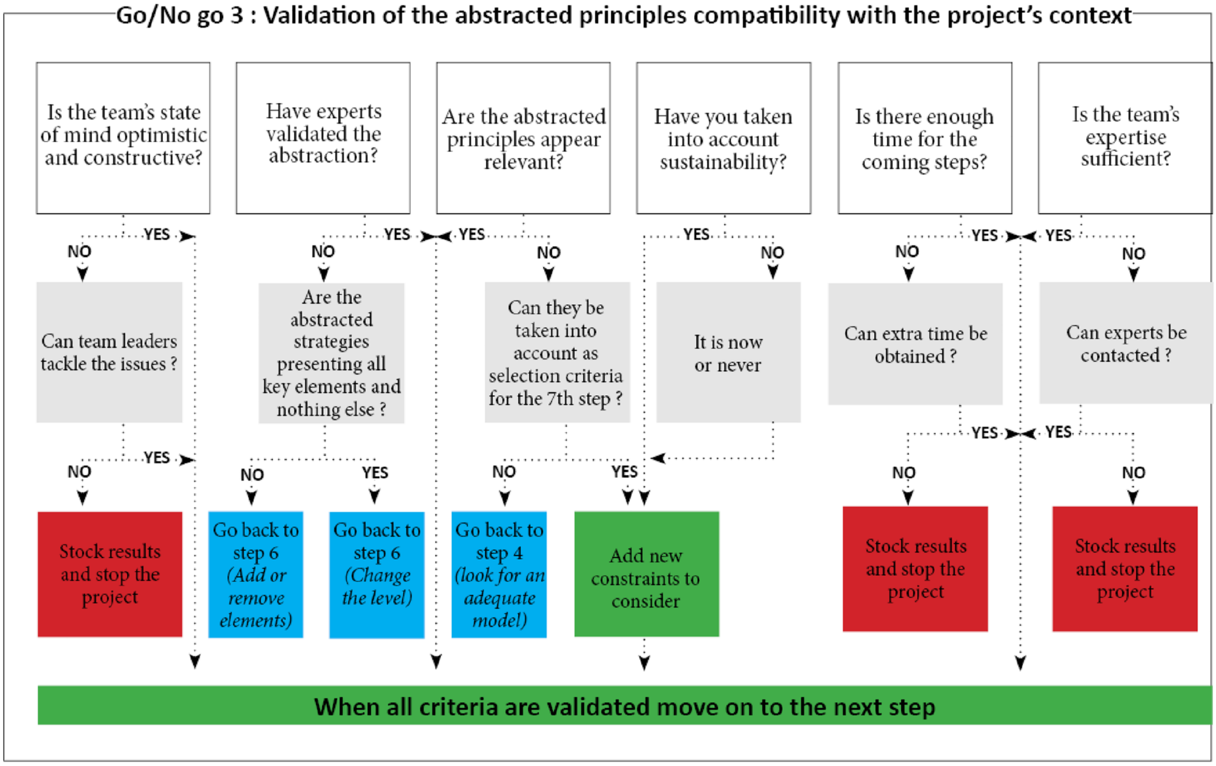

Fig. 8 Decision tree of the third Go/No Go milestone

biomimetic reasoning and bridge the gap between biology and technology.

6.5 The need for a transdisciplinary profile, the biomimetician

Through various articles, we have been supporting the integration of biological expertise within biomimetic teams (Graeff et al. 2019a). Based on surveys, literature and experimental results we thus supported the integration of two generic profiles, a horizontal biologist (HB) and a vertical one (VB) (Graeff et al. 2019b). Where VBs can be easily associated with researchers (experts in their field), HBs as biomimetic actors remained hard to define. Besides, since these practitioners need to support the formalization of cross-disciplinary analogies (from one field to another), they need to have both technological and biological knowledge. Do existing profiles in biology have the skills to perform the required biomimetic steps identified in engineering design research studies?

6.5.1 A combination of expertise from biology and design

Looking at the team's needs and expectations (Graeff et al. 2018, 2019b), this profile should bring a large biological knowledge, be able to use biological tools and reasoning, have knowledge in design and be trained to perform biomimetic processes. Last, as they will act as bridges between scientific fields within the team and between the biomimetic design teams and VB, they must have strong communication skills and be able to translate crucial information both ways.

Where this profile was first presented as a specific type of biologists to underline the need to integrate biological expertise, it appeared highly restrictive to consider this new profile from a field-centred perspective where the actual underlying goal is to reach transdisciplinarity. Currently, only a few self-made experts fulfil this function, mostly as specialized consultant thanks to their experience in both fields. These existing profiles, which currently appear to be the closest to what we considered as HB so far, may just as well characterize themselves as biologists or designers. Facing the huge impact of semantics in engineering design and the obvious necessity for this actor to bridge the gap from both side of the biomimetics' scientific spectrum, led us to pin down a new profile, which name is restricted neither to biology nor to design but represents its specific training and expertise: the Biomimetician.

This foundation stone in designing a profile specific to biomimetics opens the door on the establishment of a proper description of this new profile's specifications.

First, biomimeticians should be deeply trained in biology. The observation that we previously made about the need for the deep integration of horizontal biological knowledge within biomimetic design team are now thrown on the biomimetician shoulder. As a fully integrated member of biomimetic design teams, biomimetician will be included at each step of the biomimetic process, with variable levels of magnitude and variable roles. On the contrary, VB will only be consulted when the strategies of interest are well identified and when a deeper knowledge is required to properly abstract biological strategies at their core. This two-speed integration strategy aims at solving the need for both large and precise biological knowledge made during the descriptive phase.

Secondly, biomimeticians must ensure a proper knowledge transfer and so should be trained to communicate highly complex ideas. To do so, their ability to perform abstraction and to represent information will be fundamental. In that perspective, expertise in artistic and industrial design appear as a clear asset (Letard et al. 2018). It will also lead them to strengthen the team's holistic standpoint which is often missing to stakeholders highly specialized in their own field (Svendsen and Lenau 2019).

This section introduced the concept of biomimetician and quickly described its combined expertise in biology and design. Coming papers will focus on the extensive description of this profile through the presentation of her/his specific knowledge, know-how, practice and tools coming from both fields.

6.5.2 An integration throughout the process

In addition to this short description of the biomimeticians, this section also presents their integration throughout the process (Fig. 9) and their associated roles based on their skills in biology.

During the first two steps, that are centred on engineering aspects, biomimeticians will have two active roles and a passive one. First, they act as the "naïve member" of the team. As they do not have a deep expertise in technical issues, they will question other members of the team, forcing them to go deeper into detail, to communicate and to propose a well-define problem. Secondly, they bring variability during these steps by reasoning with a different approach, taking a holistic standpoint, considering new parameters and potentially ensuring the sustainability aspect. Finally, their main role during these first two steps will be to assimilate as much information as possible and help during the second step to prepare the analogical steps.

To start the 3rd step, biomimeticians present their understanding of the outputs obtained during the steps 1 and 2 to the rest of the team. When the whole team agrees on the problem and the technical constraints, the biomimetician is charged to identify search spaces within biology. The third step ends with the first "Go/No go" described in Sect. 6.4.2.1. Depending whether the Go/No Go is validated, the process goes on or a retroactive loop can occur.

The 4th step starts with a team brainstorming. The idea is to collect ideas of biological solutions from each member. Everyone has a small biological knowledge or hobbies related one way or another to biology, or have read about biology somewhere. This brainstorming has multiple aims. Firstly, to include nonbiologists in biology-centred steps. Innovation comes from the diversity of ideas, perspectives and interests, this step is a way to stimulate one another. Secondly, it allows the team's members to empty their head and to disregard any fixation points they might already have. The main part of the fourth step will then be performed by both the biomimetician through their knowledge and know-how and by some other team members using specialized biomimetic tools such as databases that were made for them. Combining both these sources of information appear as a profound increase of the search means. A good communication within the team will then lead biomimetician to guide other members in their search while using the results obtained by the rest of the team to feed their own reflexion. At the end of the fourth step, the whole team gathers, and the identified biological strategies are presented.

The 5th step is the first convergent step of the process. Based on the economic, biological, technological, and any specifications previously established, the whole team needs to select which biological organisms will be use for the project. The information gathered during the fourth step must be rich enough to enable this selection. The biomimetician's insights on the biological questions, the overall progress of biological science on a specific question, or the estimation of the best suiting biological strategies then appear as highly

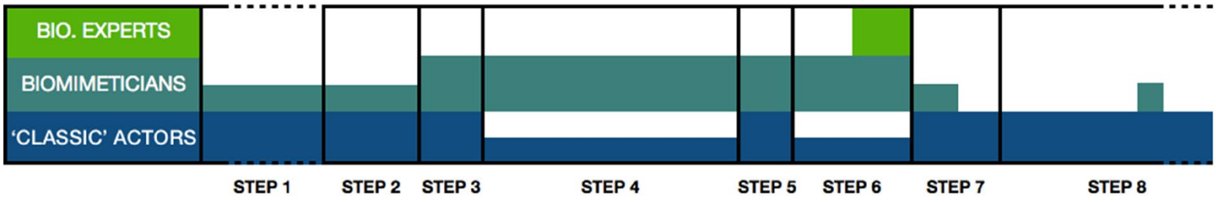

Fig. 9 Team composition and integration of biological experts (VB) during the biomimetic process

valuable. The fifth step ends with the second “Go/No go” milestone described in Sect. 6.4.2.2.

During the 6th step of the process, the selected organisms will be extensively studied. Firstly, through an in-depth analysis of the relevant scientific literature by the biomimetician. Then, and only if necessary, the analysis goes on through the external input of a VB specialized on the selected models. Once the underlying biological strategies are understood by the biomimetician, the team gathers and works on the abstraction of the biological strategies into conceptual models understandable by each team member. Skills from design, like representation and abstraction, should be of great interest for biomimeticians to perform this key step. If needed, the abstracted models thus obtained can be validated by a presentation to the VB. This ends with the validation of the third “Go/No go” milestone to ensure the adequacy of the abstracted biological model with the project’s context (requirements, decision makers, overall strategy, marketing, etc.), leading the team to the final part of the process.

These final steps (7–8) are mainly handled by the other team members. However, diversity is a powerful asset during creativity steps and as a result, we suggest including the biomimetician during creativity steps and for the choice of the final design concept. The rest of the technical development is left to the engineers of the team. Finally, biomimetician can be involved during the testing phase of the eighth step, to evaluate the sustainability of the final product for example.

As a permanent member of biomimetic design teams, biomimeticians represent an investment and so can be integrated at the scale of the laboratory or the R&D department to share human resources and reduce the cost. Their various levels of integration depending on the steps should also allow them to work on various projects at the same time. Whatever the choice, the need for communication and pedagogic skills has been highly underlined in the descriptive phase, and so, it appears necessary to create long-lasting interdisciplinary teams who are used to work together and to communicate as a group.

We are deeply convinced that such investment is worth it, numerous articles have been supporting the theoretical integration of biological expertise, industrial feedback reaffirm this hypothesis and it is time for the biomimetic community to start considering a proper biomimetic stakeholder.

To deal with the final overall cause (3) identified in the FMEA, this section described the characterization of a new transdisciplinary profile, the biomimetician, her/his interaction with other team members and her/his specific role during the biomimetic design process. It also began to describe the structuration of the interaction between biomimetic teams and VB, and so to establish a communication channel between design and biological research. As previously mentioned, our current research effort focuses on the deep study of the biomimetician and other articles will present this profile in further details, focusing either on biological skills or on design skills but also on their transdisciplinary combination through biomimetician’s practice. The next section will propose a graphical synthesis of the methodological contributions and will present the results obtained in the second evaluation phase of the DRM.

7 Synthesis and evaluation phase

7.1 Presentation of the adapted process

Throughout Sect. 6, various contributions have been prescribed, described and implemented within the initial biomimetic methodological framework. Following the optimization levers identified in the descriptive phase of the study (Sect. 5), the restructuring of the process axes, the modification of steps’ semantics, the implementation of “Go/No Go” milestones and iterative loops, and finally the description of a new transdisciplinary profile, have been proposed. Based on these contributions, Fig. 10 presents a Technology Pull Interdisciplinary Biomimetic process (TPIB process) adapted to be better suited for practical use. An extended version of this process for a deeper guidance is available as supplementary Fig. 1.

To assess the relevancy of our work, we performed an evaluation of three processes including our new process by 32 professionals having interest in biomimetics (Sect. 4). The results on the attractivity, the understandability, the wealth of information and the ability to tackle risks are presented. In the next section, Process 1 (P1) will represent the unified problem-driven biomimetic design process (Fayemi et al. 2017), Process 2 (P2) will represent the process presented in the ISO norm (ISO/TC266 2015) and Process 3 (P3) will represent the TPIB process (Fig. 7).

7.2 Evaluation results

The first evaluated aspect was the overall aspect of the process, its aesthetic, graphic ergonomics and so its ability to be considered appealing at first sight (Table 6).

Where our new process appears significantly better rated than the ISO process, the unified process appears as much better rated. Even if those results do not appear strictly significant, the results show a clear tendency that will have to be considered for further graphical optimizations.

The second elements that were tested are the logic of the new axis structuring the process (Table 7).

Based on the results, both the vertical and horizontal axes have been given the higher rate of positive answer on the logic of their structure. Combined these results support the idea that the restructuring of the axes was a relevant lever to improve the readability of the process.

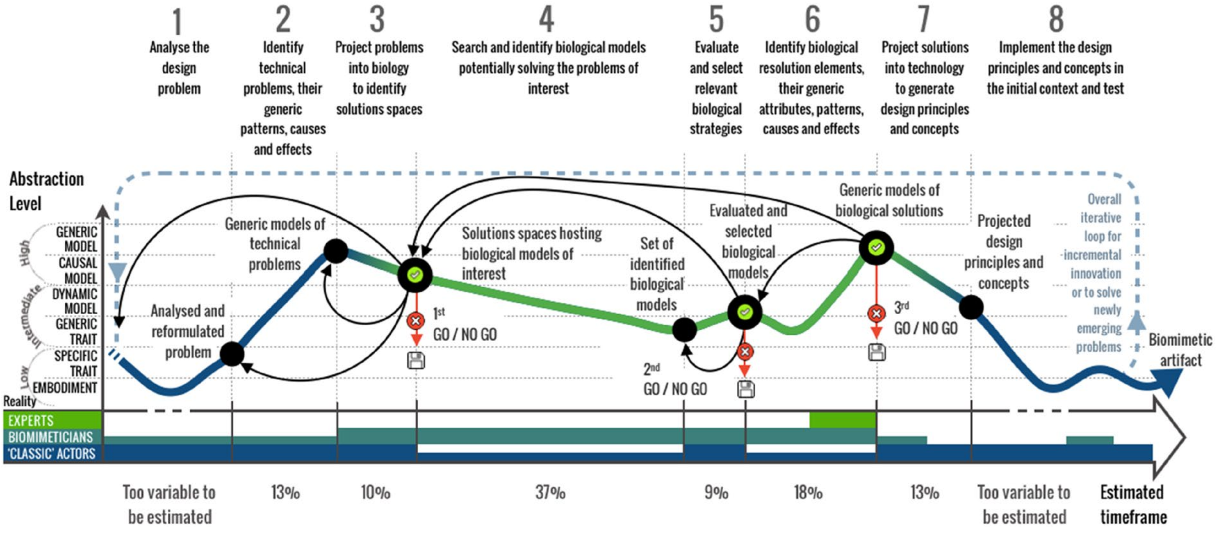

Fig. 10 The Technology Pull Interdisciplinary Biomimetic process

Table 6 Comparison of three biomimetic design processes on their visual aspects ($n=32$)

Process	Identified as the more appealing
Process 1 (unified problem-driven)	74.2%
Process 2 (ISO)	12.9%
Process 3 (TPIB process)	48.4%
p value (Fisher test) P1 vs P3	0.06•
p value (Fisher test) P2 vs P3	5.1e−3**

p value: '***' < 0.001; '**' < 0.01; '*' < 0.05; '.' < 0.1

We also evaluated the axes' semantics, but the results showed no significant differences and so underline a way for improvement.

A previous version of the semantics associated with the steps was also tested and reported to be significantly more confusing than the initial step's names [mean number of misunderstood steps P1 = 0.71 vs P3 = 1.4 *p* value (*t* test) = 0.02]. The semantics presented in this article are then already considering the feedback obtained on this aspect and will be tested again in coming studies.

The last aspect on which we wanted to focus our evaluation was the fear of risk and the guidance brought by the newly integrated Go/No Go steps and iterative loops (Table 8).

On both the ability of the process to integrate risk management as part of the process thanks to Go/No Go steps and at reducing those risk through iterative loops, our contributions have been identified as significantly relevant.

Finally, we ask the respondents to choose which process would they choose if they were to start a biomimetic project (Table 9). The results show that process 1 and 3 are significantly more selected but, even if process 3 is the process the more selected, selection differences between P1 and P3 are not significant. Interestingly, if we focus on the people that have already used P1 or P2, the proportion of individuals that selected P3 appears higher. The sample is then too little to reach any significant differences in terms of choice.

Feedback on the reason for this final choice underline a trade-off between, on one hand processes' accessibility,

Table 7 Comparison of the perceived axes' logic of three biomimetic design processes ($n=32$)

Process	Yes, the horizontal axis is logic	Yes, the vertical axis is logic
Process 1 (unified problem-driven) (%)	75	84.4
Process 2 (ISO) (%)	87.5	53.1
Process 3 (TPIB process) (%)	96.9	87.5
p value (Fisher test) P1 vs P3	0.02*	1
p value (Fisher test) P2 vs P3	0.35	5.4e−3**

p value: '***' < 0.001; '**' < 0.01; '*' < 0.05; '.' < 0.1

Table 8 Comparison of the perceived risks management of three biomimetic design processes ($n = 32$)

Process	Identified as the best at integrating risks in the process	Identified as the best at reducing risks
Process 1 (unified problem-driven) (%)	53	58
Process 2 (ISO) (%)	3	13
Process 3 (TPIB process) (%)	84	84
p value (Fisher test) P1 vs P3	0.01*	0.04*
p value (Fisher test) P2 vs P3	2.435e−08***	1.158e−11***

p value: '***' < 0.001; '**' < 0.01; '*' < 0.05; '.' < 0.1

Table 9 Comparison of the overall acceptability of three biomimetic design processes

Process	Overall which process would you choose? (total sample, $n = 32$)	Overall which process would you choose? (sample having already use P1 or P2, $n = 10$)
Process 1 (unified problem-driven) (%)	45	36.5
Process 2 (ISO) (%)	6	9
Process 3 (New process) (%)	48	54.5
p value (Fisher test) P1 vs P3	1	0.6699
p value (Fisher test) P2 vs P3	8.4e-04***	0.06347

p value: '***' < 0.001; '**' < 0.01; '*' < 0.05; '.' < 0.1

visual aesthetic and ease of use, and on the other hand, the ability to concretely guide the team, manage risk and allow a better programming of biomimetic projects. Process 1 is then considered "easier to apprehend", "more intuitive", "clear and simple", "representing the circular thinking required in biomimetics" where the process 3 is perceived as "more precise and detailed", "more comprehensive", "less risky", "integrating the planning and project management aspect".

Overall, this evaluation shows that our methodological contributions reached their objectives. Various optimization levers will be presented in the next section that will discuss the findings of this paper and offer perspectives on our study.

8 Discussion and perspectives

Overall, methodological progresses aim at guiding teams during their practice. This guidance is supposed to increase the team's efficiency, reduce the risk, and so the associated fear, to increase biomimetics implementation. Indeed, for the existing companies, a switch towards biomimetics is scary because risky. They lack training, expertise, experience and key skills that they already possess on other problem-solving processes. So, why change? Remains the efficiency parameter. If the results are worth the fear and risks, and so costs, then the change appears legitimate. The strong difficulties that faces biomimetics are associated with the fact that where its potentialities are acknowledged, its efficiency is still to be proven. The paradoxical situation where, in order to reach this efficiency, industrialists must invest in risky projects, which are particularly risky since processes cannot be tested without investment leads us to an increase of the gap between engineering design research and design practice.

This research paper deals with the identification of such risks and the proposition of various levers for improvement through a descriptive phase (Sect. 5) and proposed contributions to both the biomimetic design process and the biomimetic design team (Sect. 6). However, this study has several limitations and so the results are discussed in this section to give the reader a thorough understanding of the contributions.

First, our description phase focused on the conceptual design part of the process and left aside the 8th step and the industrialization phase (not represented on the process). Their huge variability, depending on the targeted field and used technology, have already been pointed out to justify this choice, but these steps remain fundamental difficulties that will have to be properly tackled in future work.

Secondly, the estimation of the step's duration implemented on the biomimetic process are extracted from a rather low number of projects, 15, performed by the same team and using each time the same approach. In this context, we underline the variability of biomimetic project in practice. As specified in Sect. 6.1, this axis is not a scientific truth, but represents the experimental feedback obtained in a specific context. However, we still strongly believe that having this information, even if considered as pure estimation, will allow practitioners to better convince decision makers, better prepare biomimetic projects, and better evaluate their own practice. The new structure of the horizontal axis was also designed to allow specific optimization for the teams themselves to develop their own “optimized time distribution” through internal feedbacks, shared good practices in order to improve their expertise in biomimetics.

One of the key aspects of this article was the reflexion surrounding the semantics composing the biomimetic process. We hope that the explanation and conceptual links created on those aspects will lead practitioners to be more confident and efficient when starting a biomimetic project. Our initial attempt to modify the semantics failed as the new terms were considered too academic, too complicated or too restrictive. The update version of these concepts is proposed in this article with the aim of clearly exposing and describing the complexity of terms such as “abstraction” and “transposition”.

This article also introduced the profile of biomimetician, as a new profile, who has been quickly described before her/his integration all along the process was presented. This profile then represents the main perspective of our work. Owing to this suiting process, the proper integration within biomimetic design teams will be made possible through the extensive description of her/his knowledge, know-how and tools. For a few years now, many universities have already been teaching biomimetics leading to a generation of actors trained in biomimetics. If these actors might be considered as a first generation of biomimeticians, several elements must be underlined. First, since these trained actors are not distinguished from untrained engineers/designers in the current biomimetic methodological framework, their specific roles comparing to other team members are not clear in the literature. Secondly, pinning down the concept of biomimetician should calls for a greater specificity of skills, and the formalization of a harmonized set of required actors for a biomimetic team to be efficient. More specifically, we argue for the integration of a greater amount of biological knowledge and know-how since some of the trained practitioners’ main difficulties remain highly related to the biological nature of the information they have to deal with, like the “analysis and understanding of the biology” and the “search for biological models” (Rovalo et al. 2020). Thirdly, biomimetic tools and reasoning were historically designed for the existing practitioners from engineering and design and most existing biological tools are not adapted to biomimetic purposes. There is a need to characterize, design and adapt biological tools and reasonings of interest to a biomimetic purpose. Doing so, biomimeticians should progressively develop true biological skills based on these adapted tools. Combining biological and design practical approaches should bring fundamental skills to design teams wanting to do biomimetics. Finally, considering a specific concept also allows to reason on communication through the interaction between these new actors and engineers, designers or biologists that are not as much trained in biomimetics. To summarize, biomimeticians are though as a synthesis of the current needs. Thus, the adaptation of the existing methodological framework to their integration will be extensively pursued in coming studies. Within this context, educational aspects represent a fundamental axis to explore and previous work on biomimetic pedagogy, a crucial foundation to build on.

Finally, our evaluation phase pointed on the need to work on the ergonomics, visual aesthetics and clarity of our process. Various adjustments have been made in the version published in this article, and we are still currently testing those aspects to allow a more intuitive use of the process we proposed.

9 Conclusion

After a quick state of the art on the current biomimetic processes, tools and team composition, the question of the adequacy between the current engineering design research scope and the practitioners’ real needs emerged as fundamental. In this context, we wondered how can the current theoretical framework be adapted to support the implementation of biomimetics in practice? Our hypothesis was then to focus on perceived and actual risks to be able to identify misunderstanding, required restructuring and practical needs, and so to adapt the theoretical framework. Following the DRM, we performed interviews, FMEA on a biomimetic process of reference and gathered feedback from industrial and student projects to assess practitioners’ perceived risks and needs in a descriptive phase. Based on the obtained results and on research findings, we prescribe methodological changes combining both a research and practical standpoints. We focused our work on two fundamental aspects of this methodological treasure hunt, the map and the team. Through the combined adaptation of the biomimetic process (the map) and the description of the biomimetician, a key actor to be integrated within biomimetic design teams, this article aims at breaking silos between biology and design as well as between research and practice. The article ended with an evaluation of these methodological contributions, underlining their relevance and pointing out some key levers of improvements. This article is built as the foundation stone for our future work on biomimetic design teams and tools. Insofar, biomimeticians compose a rare species, keep on building training programs for passionate people wanting to join the biomimetic adventure then appear as a required step toward the global changes we support through biomimicry. The overall aim of our work is to optimize the methodological framework within a multidisciplinary context in order to guide stakeholders who want to implement biomimetics as an innovation strategy.

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Compliance with ethical standards

Conflict of interest We declare no conflict of interest.

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