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Linkage, an Online Tool to Support Interdisciplinary Biomimetic Design Teams

Implementation of biomimetics in practical innovation strategies still faces various impediments. Multidisciplinary communication is one of the most recognized one. Enabling teammates having various cognitive and conceptual frameworks to properly exchange information is a key lever for optimization. In a previous study, we performed a comparative analysis of biologists' and engineers' cognitive and conceptual frameworks in order to support the establishment of a shared framework of reference within biomimetic teams. This theoretical work led us to consider various guidelines, embodied in a tool, LINKAGE, guiding the team along the biomimetic process, and more specifically during analysis and abstraction steps. This article presents a first version of this free access digital tool, LINKAGE 1.2. After the description and positioning of LINKAGE, comparing with other existing tools, a testing phase involving 19 professionals divided into five interdisciplinary teams is presented. The results of this evaluation lead to the validation of some of the tool's objectives while underlining some lines of improvements. Various perspectives on the tool's development are also presented. [DOI: 10.1115/1.4049969]

Keywords: cognitive-based design, collaborative design, computer-aided design, conceptual design, design teams, multidisciplinary design and optimization, biomimetics

1 Introduction

This article presents the second part of a study on the development of LINKAGE, a tool which aims at supporting interdisciplinary biomimetic teamwork during the analysis and abstraction of technological problems and biological solutions. Designed to assist communication between teammates with a background in engineering and in biology, the tool is structured to embody a shared cognitive framework of reference defined in the first and theoretical part of this study [1] and presented in Sec. 1.2. After the presentation of the online collaborative platform LINKAGE,[2] the results of the evaluation of some of the tool's features, specifically its perceived contributions and its ergonomics, by professional users are presented.

Sections 1.1–1.3 present a synthesis of the extensive theoretical work performed in the first part of this study [1].

1.1 Biomimetic Practice and the Communication Impediment. From Leonardo Da Vinci, to Otto Schmitt, to Benyus [2], *bio-inspiration*, or looking at living organisms for inspiration, has been an approach of increasing interest in the scientific community. Biomimetics, as the technical prism focusing on bio-inspiration, is a crucial element in the spread and implementation of these new practices. 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*" [3].

If the potential of biomimetics has been proven over the past decades [4,5], it struggles to become an innovation strategy of reference. Where the need to further integrate biologists is underlined in the literature [6,7], the methodological framework (processes and tools), hasn't been originally designed to include these unusual profiles. Specifically, scientific literature underlines interdisciplinary communication as one of biomimetics' main challenges [8–12]. Helms et al. explain these obstacles as follows "*biologists and engineers typically speak a very different language, creating communication challenges*," "*they typically use different methods of investigation and often have different perspectives on design"* [13]. Fayemi et al. also identify three explanations "*Their different backgrounds lead to divergent disciplinary or functional understanding of a concept, whether due to perception, languages, or 'thought styles'*" [14]. These elements can be associated with various "communication noises" from communication sciences among which *cognitive dissonance*, *encoding* format, and *decoding* process [1].

In the context of our study, we chose to focus on *cognitive dissonance,* leaving aside the issue of field-specific vocabulary, already discussed in the literature [15]. To address this impediment, we established a shared cognitive framework of reference as a lever for optimization and a foundation to build on [1].

1.2 A Shared Framework of Reference, a First Step Toward Synergetic Interdisciplinary Teamwork. By looking at both design or biological processes and graphic representations, we extracted various concepts and cognitive shifts that were turned into nine guidelines structuring a cognitive framework of reference common for both biologists integrated within biomimetic design teams and classic design team members [1]:

- *Guideline A: Consider subjective elements as embedded in external constraints.*
- *Guideline B: Combine prescriptive and descriptive approaches.*
- *Guideline C: Expose cognitive links to bridge functional, structural, material, and behavioral abstracted concepts.*
- *Guideline D: Present problems and solutions within their spatiotemporal contexts.*
- *Guideline E: Dedicate spaces for both product design and knowledge gathering while supporting their synergetic contributions.*

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- *Guideline F: Consider problem/solution dynamics through a state-based evolution*.
- *Guideline G: Model systems through nested structures*.
- *Guideline H: Be specific on forms*.
- *Guideline I: Support a systemic standpoint*.

For it to be used and impactful, this framework needed to be easily available. Since this list appears obscure in practice, we decided to embody these guidelines into a digital tool, leading to LINKAGE (Fig. 1).

Without getting into details on the tool itself yet, which will be extensively presented in Sec. 3, the positioning of LINKAGE compared to other biomimetic tools appears as a key contextual element.

1.3 The Positioning of LINKAGE. Compared with existing free access online tools, LINKAGE appears highly singular since it does not aim for the same objective as most of them (AskNature, DANE, BIOPS, etc.): the identification of biological models of interest (step 4). Indeed, the tool focuses on the analysis and abstraction steps of the biomimetic design process [16], and so the gathering, structuring, sorting, and understanding of key information to be turned into generic design guidelines to be transferred across scientific fields for analogical purposes.

On these specific steps, some tools have also been published in the literature, notably to model biological system. Among them we can mention, the SAPPhIRE model [17], the FBS model [18], flow-based models [19], or the "What-Why-How" template [8]. If these templates have proven their interest from a research standpoint, they often remain underused by biomimetic practitioners [20]. They appear to need substantial training and lack numeric support, like with the "What-Why-How" template [8], or to simply not being accessible in an online free access user-friendly form, like with SAPPhIRE.

In a 2007 study investigating the use of biomimetic tools, Appio underlined that AskNature is, by far, the best known and most used biomimetic tool. One of the key explanation is "*its accessibility via a user-friendly Web interface*" [20]. In other words, it is a tool that is not made for research purposes, but which transfers research findings through an interface fitting the needs of design teams. Doing so, it manages to reach practitioners and currently have a remarkable impact on the spreading of biomimetics.

Based on this key factor, LINKAGE aims at answering the need for a user-friendly tool, guiding the teams during the complex analysis and abstraction steps of the biomimetic design process while supporting the communication between teammates. Within this context, the cognitive framework of reference previously established (Sec. 1.2) is used to design the graphical representation and structuring of the tool. On the process itself, since abstraction has been widely studied in the literature, the tool is based on existing theoretical foundations, combining and reformulating concepts when it appeared relevant (Sec. 3.2).

Based on this positioning, LINKAGE's aim is to support the bridging of gaps between biologists and biomimetic design teams, and between research and practice.

1.4 Research Question and Hypothesis. Our overall research axis investigates the integration of actors trained in biology within biomimetic design teams. As previously presented, such dynamics is limited by several challenges among which communication is recognized as a key issue. This article thus deals with the following research question: "How to support the practical analysis and abstraction of information within interdisciplinary biomimetic design teams?" and introduces a hypothesis in the form of LINKAGE.

This article thus presents LINKAGE and offers an initial test on its acceptability and contributions.

Fig. 1 LINKAGE's logo

2 Materials and Methods

2.1 Materials

2.1.1 Digital Version of LINKAGE 1.2. Following its initial design, LINKAGE 1.0 was updated after initial internal tests in November 2019 into 1.1. LINKAGE V.1.1 was itself updated after a series of tests with students in December 2019, leading to the V.1.2 of the tool. LINKAGE 1.2 (January 2020) is the version evaluated in this article, the tool is currently available at the following address[3] (Fig. 2).

Significative improvements or developments of the tool will occur in the future. The tool's available version will be specified on the following page.[4]

2.1.2 Experimental Sample. The test of LINKAGE was carried out with interdisciplinary teams of professionals (all graduates of a master's degree or more, and currently employees in different companies) as part of the Specialized Master's Innovation Management and Business Development of the Arts et Métiers Institute of Technology.

The experimental sample consisted of 19 participants divided into five teams. Each team was composed of at least one graduate engineer with professional experience. Furthermore, since training in biology varied from general interest to PhD graduate, we asked participants to self-evaluate their biological knowledge to compose teams with the best possible balance of skills considering the given sample (Table 1).

On the 19 participants to the workshop, only 12 of them fully filled the questionnaire evaluating the tool.

2.1.3 Evaluation Survey. The results are collected through a questionnaire of 26 questions designed on Typeform,[5] presenting questions evaluated through 5-point Likert scales (0 = negative to 4 = positive inclination) and targeting three key points:

- 6 questions allowing an overall evaluation of the tool, based on Nielsen's usability criteria [21] on satisfaction, ease of handling, risk of errors, interest in reasoning (derived from the efficiency criterion) and model accuracy (derived from the efficiency criterion). For example: "Were you satisfied by the tool?".
- 6 questions focusing on the tool's ergonomics. For example: "Are help buttons and pop-ups sufficient to guide the user?".
- 14 questions focusing on the validation of the different objectives pursued by the tool (structuring the team's reasoning, communicating, common understanding of concepts, etc.). For example: "Does the tool support the communication between teammates?".

The questionnaire ended by asking respondents if they "would recommend LINKAGE to other biomimetic design teams?".

2.2 Methods. The experimental protocol was composed of three mains parts as follows:

- Introduction to biomimetics, and of the experimental protocol (45 min). If the tool is presented from an overall standpoint (objectives and main steps), no demonstrations or detailed guiding are described before its first use. Thus, its autonomous use and ergonomics are specifically tested.

[3]See Note 2.
[4]https://linkage-lcpi.com/presentation
[5]https://www.typeform.com/

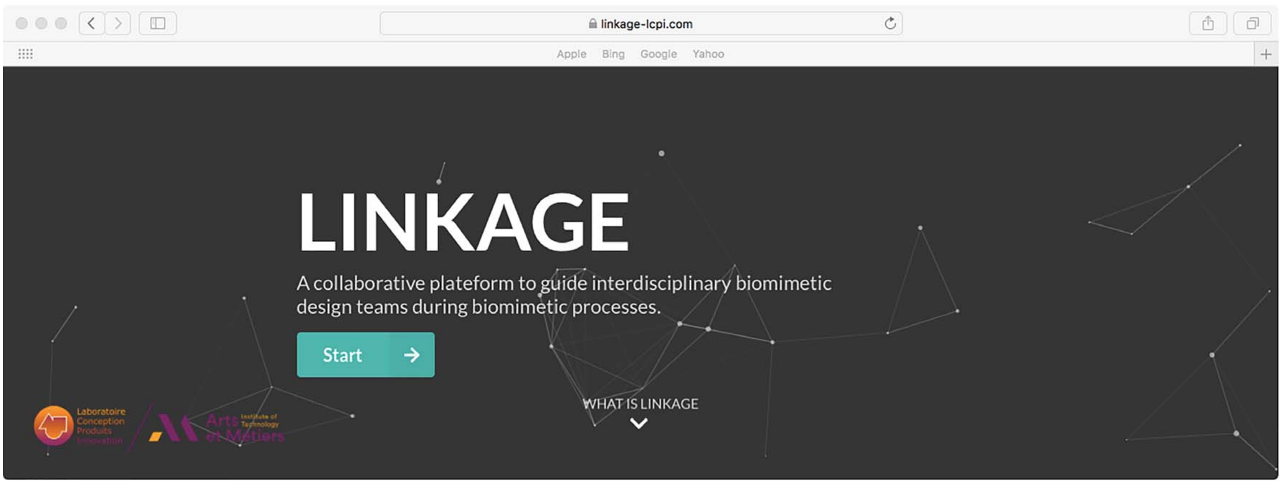

Fig. 2 LINKAGE's welcome page

Table 1 Presentation of the experimental sample

$N = 19$ (during the experiment) $N' = 12$ (responses to the survey)	Maximum score of the personal biological knowledge auto-evaluated in each team (0–4)	Expertise in engineering design
Team 1 ($n = 4$) ($n' = 4$)	2	At least one engineering graduate professional working in the field of design (innovation, aeronautics, automotive, etc.)
Team 2 ($n = 4$) ($n' = 2$)	4	
Team 3 ($n = 4$) ($n' = 2$)	3	
Team 4 ($n = 3$) ($n' = 1$)	1	
Team 5 ($n = 4$) ($n' = 3$)	3	

- Questions which emerged during the workshop were answered and used to identify key levers for improvement, except that and our role of timekeepers, teams worked in total autonomy.
- Adapted biomimetic design process based on [16] (Fig. 3): Step 2 (1 h), Step 3 (30 min), Step 4 (2 h), Step 5 (30 min), Step 6 (1 h), Step 7 (1 h). In the case of the experiment, the first step had already been performed in previous sessions. Moreover, because of the experiment's time limit, we stopped the process after the seventh step, and the generation of solving concepts.
- Feedback and discussion, the evaluation questionnaire is sent to each participant (15 min).

Each team worked on a specific subject previously imposed by the context of our experiment, as a result, we were not able to choose those subjects. Because of the variability of the targeted fields, from medical devices to material sustainability (Table 2), we could not evaluate the impact of the tool on the results of the process. Thus, we focused on the individual evaluation of the tool given by participants.

In order to solve the research problem, Sec. 3 presents LINKAGE V.1.2 (objective, design, structure, information flow, etc.) before Sec. 4 describes the results of the tool's evaluation.

3 LINKAGE V.1.2

LINKAGE V.1.2 is a digital tool which embodies the nine structuring axes previously established (Sec. 1.3) to support interdisciplinary biomimetic design teams' communication and practice during analysis and abstraction steps of the biomimetic process.

3.1 Objectives. LINKAGE is a tool designed to be user-friendly and accessible even for teams having limited knowledge on biomimetics.

Its first objective is to support communication within biomimetic interdisciplinary teams, more specifically between practitioners having a background in biology and those having a background in product design. To this end, the tool is designed as an online collaborative work platform and allows the setting up of teams by bringing together a set of users.

Its second objective is to support biomimetic practice by guiding the reasoning of these interdisciplinary teams. To do so, users are guided while being on the platform through a structured environment, an interactive interface and help buttons presenting instructions or pieces of advice.

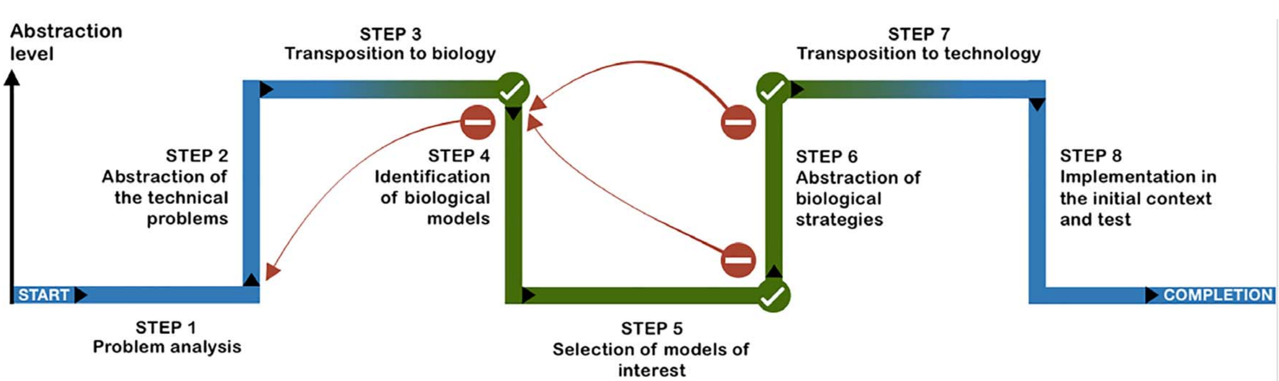

Fig. 3 Biomimetic design process from Ref. [16]

Table 2 Additional information on the workshop's subjects

Team	Field	Subject	Expected result
No. 1	Health	Discrete insulin injection system for diabetics	Product
No. 2	Health	Improve population's diet habits	Product
No. 3	Material	Alternative for plastic bags	Product
No. 4	Social	Support product sharing to limit pollution	Service (web)
No. 5	Chemistry	Support the use of sustainable cleaning product	Service (app)

Finally, LINKAGE provides teams with a way to store structured information (detailed models, environmental context, association between problems and solutions, etc.) and thus to capitalize on biomimetic studies to maximize the cost-effectiveness of these resource-intensive approaches. Moreover, it also leads the team to recognize the increase in knowledge as a goal, a relevant investment, as advocated in the pre-established cognitive framework (Sec. 1.2, Guideline E).

The long-term aim of this tool is to increase the practical efficiency of biomimetic design teams, to contribute to the implementation and spread of biomimetic innovation strategies.

3.2 Choices Made on the Theoretical Foundations. Two main theoretical fields composed our starting point: our previous work on communication [1] and a synthesis of the main academic literature dealing with abstraction steps in biomimetics [17–19,22–25]. These academic foundations are not questioned in this article. However, choices have been made to make these concepts easily available and to turn these findings into an operational tool.

3.2.1 Choices Made on the Presentation of Abstraction. Performing abstraction is a key step in biomimetics. At an overall scale, it can be presented as a know-how which leads to the extraction of generic principles from specific information. In biomimetics, this approach is mostly applied to functional design problem to generate generic design problems or to biological functional traits in order to extract generic functional solutions. Abstraction allows teams to avoid literal transfer which are hard to perform, are often irrelevant, limit creativity, and can lead to poorly efficient solutions [26]. As described in the literature, this analogical thinking is based on relations rather than features which then appear as intermediary information [27]. From this well-recognized starting point, several prisms have been described in the literature to guide abstraction, and so to identify from a set of information, systems of interest, and their key relations.

In the context of LINKAGE's design, we had to choose a given set of prisms to use. We chose to use the "What-Why-How" approach [8], that we extended to include a "Where & when" prism, to consider the various prisms described in the literature and to reason on interconnected systems rather than isolated ones [22].

In her work, Yen et al. underlined that students had difficulties to properly use this approach [8] and it is our hope that the tool will give a proper guidance to make this method efficient. Our approach differs from the presented by Yen et al. [28] on several aspects.

First, using What-Why-How can rise numerous potential questions. For example, asking "what are the required structures of the system?" or "what are the traits making a given structure relevant?" lead to deeply different answers, and similarly for "how" and "why". Our work thus differs from Yen's in the structuring of the questions that are used.

Second, we would like to underline that the two steps of abstractions (steps 2 and 6) are fundamentally different as they deal with either a technological problem or a biological solution. Therefore, if the abstraction reasoning appears similar, the form of the questions in the tool and the focus of intention will differ.

Finally, if we focus specifically on the "why", various interpretations can appear for practitioners. Thus, "why does the apple fall from the tree?" has at least two answers depending if we consider a "why" of causality, with the answer "because of gravity", or a "why" of intent, with the answer "for the tree to spread its seeds". To address this specificity, we will use "what natural principles cause…" as a "why" of causality and "for what purpose do…" as a "why" of intention.

Table 3 presents some of the main prisms existing in the literature, their gathering through the "What-Why-How-Where and When" approach and finally the actions they are associated with in LINKAGE (Table 3). We can underline the co-existence of the "why" of "intention" (function) and of "causality" (principle, action, physical law, energy, and information) in previously published classifications.

Taking these variations into account, LINKAGE is designed to allow users to combine and confront identified information to easily structure a model encompassing their system of interest whether it is representing a technological problem or a biological solution.

After the construction of the model, a specific part of the tool guides the rise of abstraction to formalize the specific observations into generic design problems or solving guidelines. During this phase, various instructions and tips are presented in help buttons allowing practitioners to have access to more detailed information if they need to. The information flows and resulting model are presented in Sec. 3.3.1.

As previously presented, one of LINKAGE main objective is to support communication within biomimetic design teams during the analysis and abstraction steps. Section 3.3.2 thus focuses on the

Table 3 Abstraction prisms used within LINKAGE

Reference	What?	How?	Why?	Where and When?
Gero and Kannengiesser [29], Goel et al. [30]	Structure	Behavior	Function	–
Mak and Shu [26]	Form		Principle	
Bhasin and McAdams [25]	Material and structure	Mechanisms, process		
Nagel et al. [31]	Form, surface, architecture, material	Process	System, function	
Chakrabarti et al. [17]	Part, organ	State, resources (inputs), physical phenomenon	Action, physical law	
Vincent et al. [32]	Substance and structure	Energy and information		Space and time
Action in LINKAGE	Description of the elements composing the system at several systemic level	Establishment of dynamic interactions between the various elements	Identification of natural principles explaining causal relations	Description of the system's environment at each previously defined state

embodiment of the theoretical findings on communication previously presented (Sec. 1.2).

3.2.2 Choices Made on the Communication. First, we chose to design a free online tool to make it easily available to the largest number of practitioners regardless of their expertise. Then, we worked at applying the various guidelines of the cognitive framework of reference previously presented (Sec. 1.2) during the tool's designing phase. Table 4 presents the embodiment of the axes composing the preconized cognitive framework through LINKAGE features (Table 4) adapted from our previous theoretical recommendations [1].

Most guidelines are embedded within the tool's structure and so are not consciously followed by the users. The main idea is to support and guide interdisciplinary teamwork during the formalization of models for teams to better understand the structured information and generate a shared conceptual framework of reference associated with the project.

Through this digital interface, we wish to support communication and to strengthen the team spirit by limiting the following psychological noises:

- Encoding/decoding the signal and the context of interpretation. Through the tool, each member can extract the objectives of the project, the reasons why the different elements are identified, and the reasonings on conceptual links.
- The reasonings generated by the decoded message. The establishment of a shared space for communication should allow the different members of the team to apply approaches specific to their background while understanding the reasoning of the other players. That way, we also want to value the variability of practices through their recognition and their association in the pursuit of a common goal.

Table 4 Guidelines' embodiment within LINKAGE 1.2

Guidelines	Embodiment
Guideline A: Embed subjective elements in external constraints.	Characterization of the super-system and of the system's various states.
Guideline B: Combine prescriptive and descriptive approaches.	Separation in space (embed constraints versus description on multiple levels) and separation in time (help buttons indicating the actors involved).
Guideline C: Expose cognitive links to bridge functional, physicochemical, and behavioral abstracted concepts.	The network of concepts linked through causal interactions, considered at different scales of the model and at various states of the problem/solution.
Guideline D: Present problems and solutions within their spatiotemporal contexts.	Identification of the interaction between the system, its super-system at the system's various states.
Guideline E: Dedicate spaces for both product design and knowledge gathering while supporting their synergetic contributions.	Capitalization of the results through a database of the models formalized with LINKAGE, a search engine allows the search within the database of previous projects performed by the user.
Guideline F: Consider system's evolution through state-based reasoning to represent functions.	Interactive graphical representation of the system's evolution patterns through states.
Guideline G: Model systems through nested structures.	Automated generation of nested subsystems when new interactions are generated (only displayed when involving the system of interest)
Guideline H: Be specific on forms.	A specific space is dedicated for each level to characterize the features of involved elements.
Guideline I: Support a systemic standpoint.	The consideration of various systemic levels, interacting sub-systems and dynamic evolutions should allow teammate to reach a more systemic analysis.

Moreover, from a practical point of view, the synergistic inputs of the prescriptive phases (choice of states and scenarios, choice of elements to be considered, choice of interactions, etc.) and descriptive phases (identification of potential elements, identification of potential interactions, characterization of the elements considered, abstraction of the relevant elements) will be performed by various members of the team and guided by the tool.

Furthermore, since LINKAGE is an online platform, it can support remote work, it should increase the commitment of external experts and to allow physically dispersed team (like international teams) to work together.

Section 3.3 describes the various information flows and specifies how information is displayed throughout the tool.

3.3 Information Flow and Tool's Embodiment. During the implementation of the tool, two key aspects emerged: the overall information flow (from inputs to outputs) and the information embedded within the tool.

3.3.1 Information Flow From User's Inputs to the Tool's Outputs. The main content of the projects is built by the users along their use of the tool. Figure 2 presents the three currently available operational parts proposed by LINKAGE 1.2 and the generic associated information flow (Fig. 4). For clarity purposes, some specificities depending on whether users are performing the second or sixth steps, mainly on the questions' formulation and their order, have not been represented.

The first part of the tool (Fig. 4, Part 1) guides users during information gathering. For example, for each state LINKAGE pushes teams to wonder about the environment of their system and so gathers contextual data (Fig. 4, Part 1). During this first part, the tool thus questions the users for them to consider complementary angles based on the information previously entered. It must be specified that, as displayed by the tool (Fig. 5), users are pushed to consider these other angles to identify key information, not to design the most exhaustive model.

The second part of the tool (Fig. 4, Part 2) extracts information corresponding to the four prisms previously described (Sec. 3.2) to focus the users' attention on several layers of abstraction. Each prism is then presented as a list of combined information. For example, the prism "what" will display a list of each pair of "system: sub-system." Users will then tick a box to indicate which pairs should be considered as key information. This second sorting step, the first being the initial choice of information to build the model, then leads to the rise of the abstraction level. Users are asked to formalize information in a more generic way (Fig. 6), through questions which depend on the nature of the model (design problem versus biological solution). Various guidelines are also offered by the tool to help users during this step (see Sec. 3.3.2).

The last part of the tool (Fig. 4, Part 3) represents a synthesis of the work performed by the team. It gives a graphical overview of the model based on the users' inputs (Fig. 7) and presents all gathered information (participant, entered text and joined images, bibliography or PDF). The level of details increases from the top down, starting by an overview of the abstracted elements (those selected in the second part). The project can then be exported as a PDF report.

Once models are designed, they are stocked within the tool's database and can be accessed from the dashboard of any member having worked on the project, either through the tab "My projects," or through a search engine based on words recognition. From the dashboard screen, users can also access some statistics about their use of the tool (implication on projects, last edited project, number of projects, etc.) (Fig. 8). The tool's ability to guide users' reasoning and structure information was then specifically tested and results are presented in Sec. 4.2.

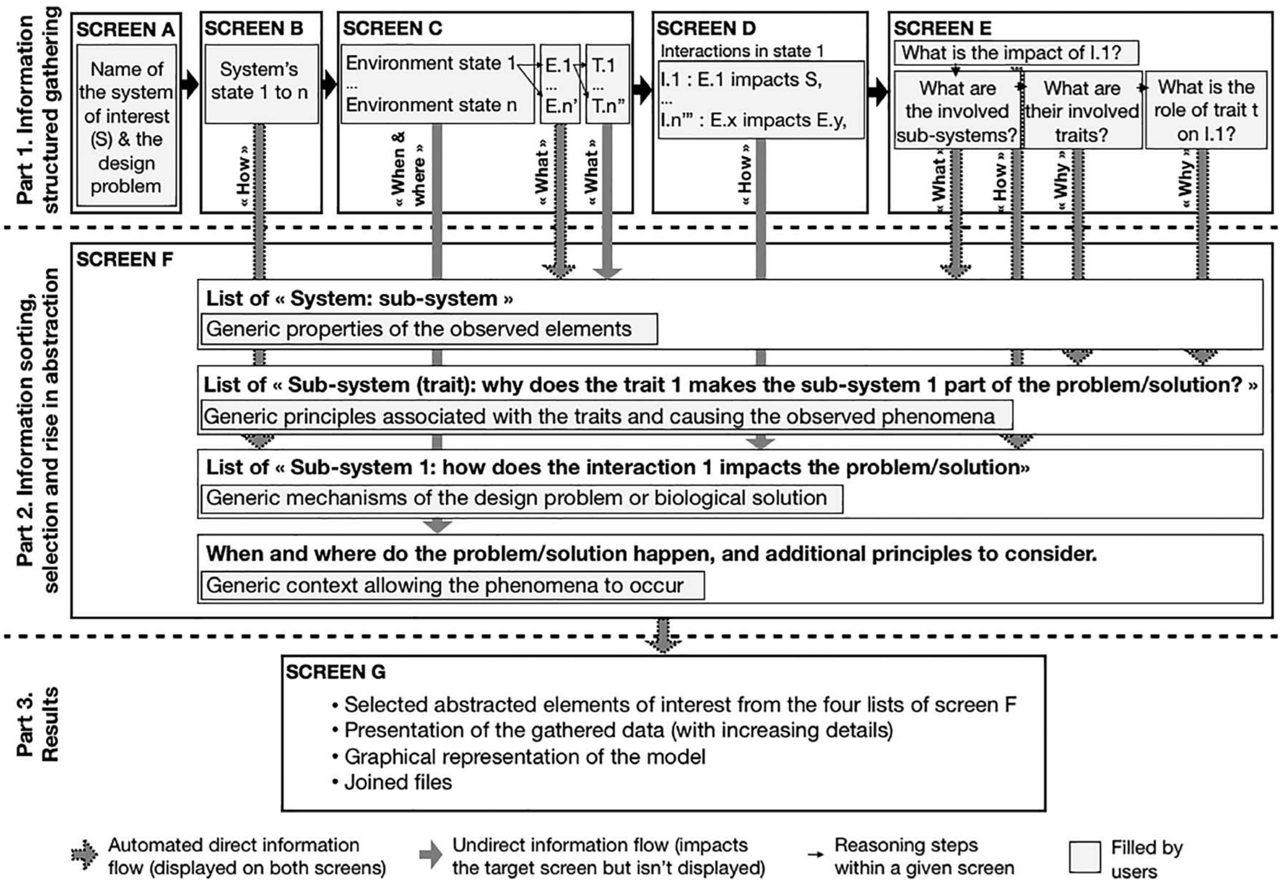

Fig. 4 **Information flows from teams' inputs to LINKAGE outputs, E = Element, T = Trait, I = Interactions, S = System**

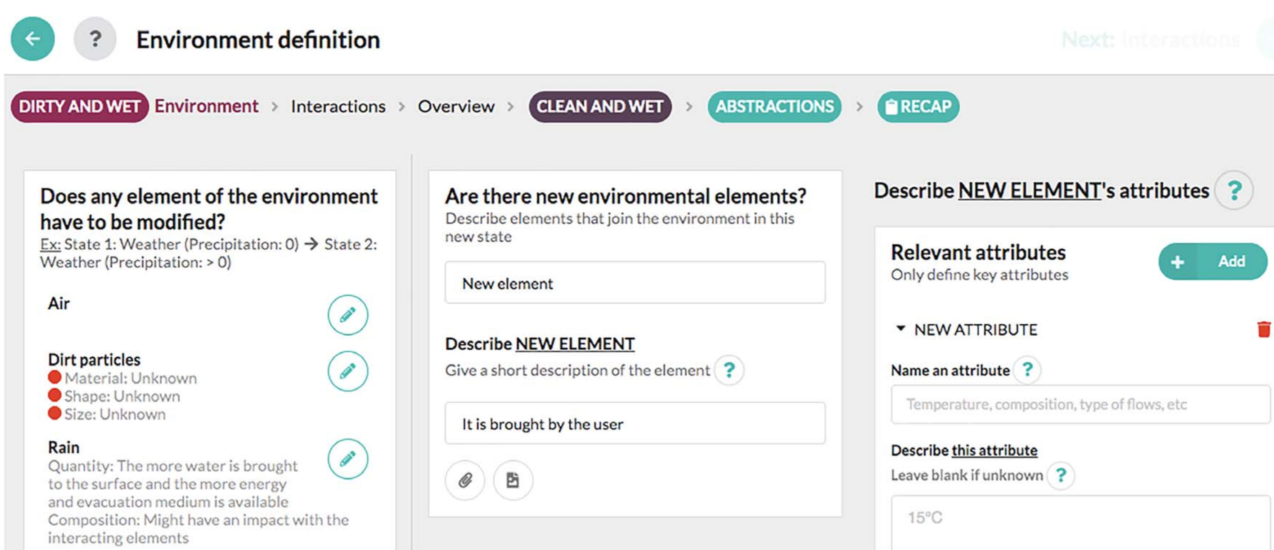

Fig. 5 **Example of a screen C, environment definition for the solving strategy of the lotus leaf super-hydrophobicity (LINKAGE screenshot)**

3.3.2 Information Embedded Within the Tool. Generated models, combining gathered information and abstracted elements, then represent the visible output of the tool. However, the underlying objective of LINKAGE is to support communication between teammates. Thus, another contribution to consider is the support offered by the tool during teamwork and exchanges.

First, as previously presented (Sec. 3.2.2), LINKAGE has been designed following various guidelines to embody a shared cognitive framework of reference for teammates having a background in biology or engineering. The structuring of the tool itself then represents information on the proposed reasoning. This reasoning aims at generating a common conceptual framework within which the system of interest can be modeled. Being able to reason on a common ground, should help teammate build the conceptual framework together and so allow a common understanding of the model.

Second, LINKAGE is equipped with a set of "pop-ups" and "help buttons" advising on various methodological points. Among other things, it offers a distribution of the roles of the members (Fig. 9)

Sub-system: mechanism of the interaction leading to the problem	Formalize associated generic mechanisms to abstract key design problems. ?	Add to recap
User's skin: subject to contamination by the biological wastes	How to limit the toilet contamination? How to limit the survival and proliferation of contaminant? How to limit the transfer of contaminants?	
Surface of the toilet seat: its temperature varies with room temperature	Type here	
Surface of the toilet bowl: Subject to scale deposit	Type here	
Biological wastes: subject to high variability in terms of composition	How to evulate the type of waste? How to properly respond in terms of evacuation system? How to offer different interactions with the bowl?	
Biological wastes' particles: subject to entrapment at the surface of the bowl	How to limit bonds' formation? How to limit contact area? How to ensure a sufficient and properly distributed evacuation force?	
Flushing water: liberated from a tank by the user	How should users trigger the flush? Can users be considered as a resource triggering (intentionaly or not) other mechanisms of interest?	
Flushing water: may leak in case of poor sealing.	How to prevent seal's deterioration through time and use? How to prevent leaking? How to store a fluid temporarly?	
Flushing water: volume may vary depending on the user's choices	How to guide users in their use of the flush? How to allow users to have a fine control of the volume of flushing water? How to prevent mistakes?	

Fig. 6 Example of a screen F: abstraction of guidelines for the design problem of the evacuation of wastes in toilets (LINKAGE screenshot)

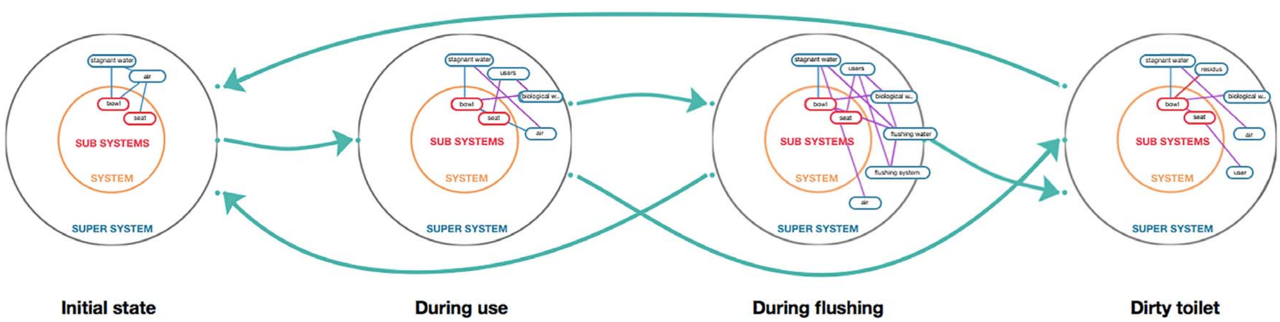

Fig. 7 Example of a graphical overview for the problem of wastes evacuation in toilet (LINKAGE screenshot)

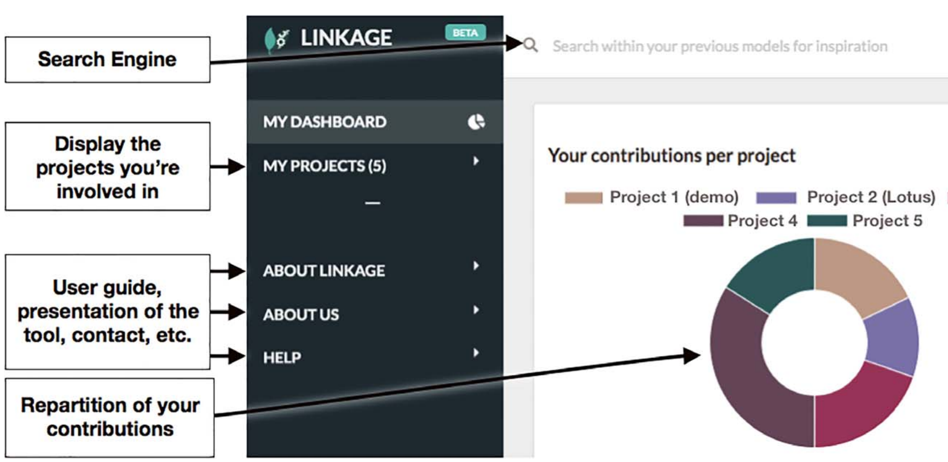

Fig. 8 Example of a dashboard screen (LINKAGE screenshot)

or tips on how to perform a step (e.g., "Hand-drawings are a good way to both communicate on complex concepts and remove unessential elements from the list," help button on abstraction prisms).

These elements should infuse good practices and methodological key points through a user-friendly channel. For example, they might lead to a more patient and deeper exchange of ideas, since seeking for clarifications "is advised by the tool" and so legitimated by a third party.

Last, LINKAGE relies on visual representation to ease information transfer. Previously completed steps are available at all time. Doing so, information is on hand and always contextualized for the teammate to freely reason within their project conceptual

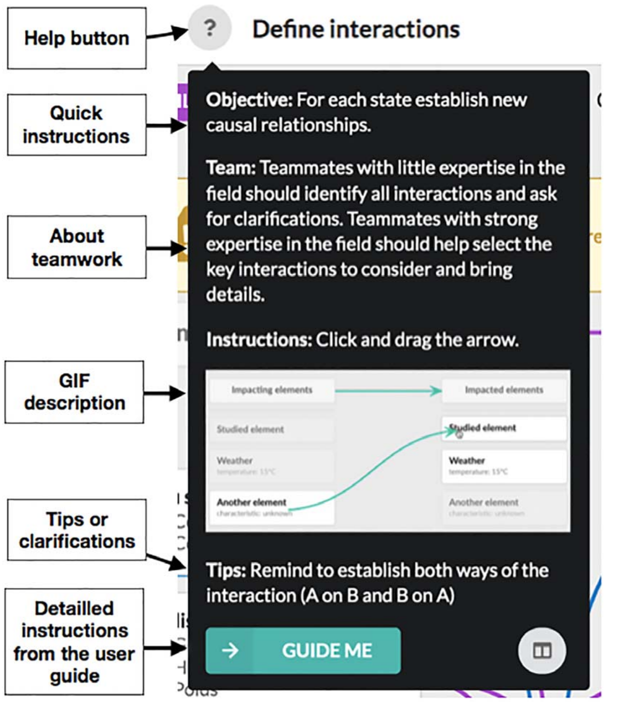

Fig. 9 Example of a help button on interactions (LINKAGE screenshot)

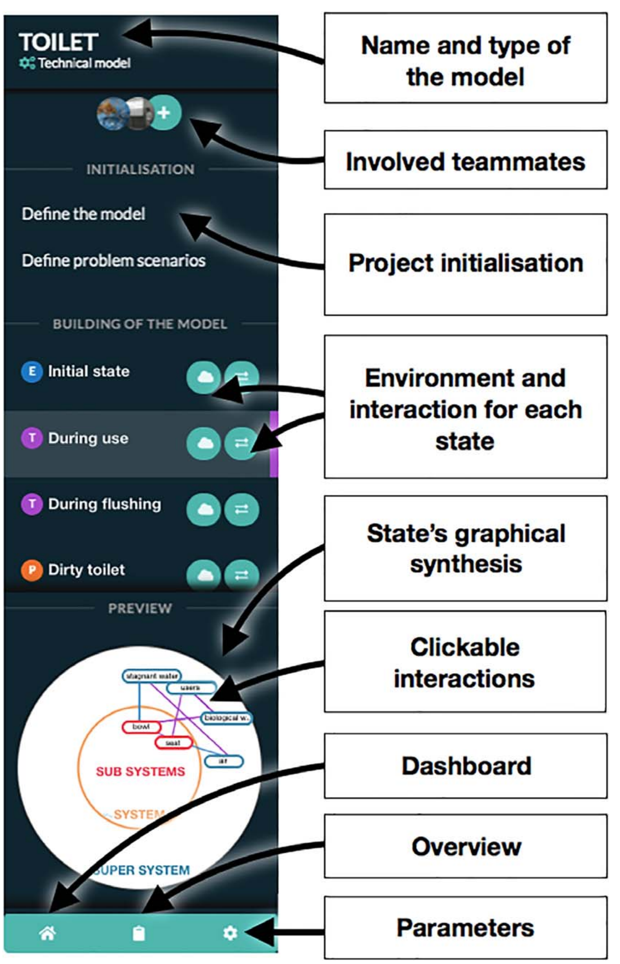

Fig. 10 Menu of LINKAGE operational screens (LINKAGE screenshot)

framework. Moreover, the tool automatically generates an interactive overall graphical synthesis from gathered users' inputs, which can be used during presentation with decision makers to easily show the team's progress (Fig. 10).

Since biomimetic tools appear to be more used if they are user-friendly (Sec. 1), both interdisciplinary teamwork (Sec. 4.2.2) and ergonomics (Sec. 4.2.3) were evaluated during the experimental phase.

4 Results

LINKAGE 1.2 has been tested during a 1 day workshop (Sec. 2.2.1) by five teams of three or four professionals each (Sec. 2.1.2). First, the overall perception is evaluated (Sec. 4.1), before more specific questions are investigated (Sec. 4.2) leading us to underline various limitations and lines of improvement (Sec. 4.3). Considering the sample's size, these results should only be carefully considered as tendencies. They are meant to offer an initial validation of our approach, identify new key parameters to consider and guide further developments of the tool.

4.1 Overall Results. As a first step, respondents were asked about Nielsen's usability criteria (Table 5) as described in Sec. 2.1.3.

Participants gave an overall very positive feedback despite a few errors generated during use. Notably, 50% of the users gave the maximum score on the interest of the reasoning proposed by the tool, which "*guides the work,*" "*generates new ideas through a structured approach,*" "*provides a solid basis for reflection.*"

Respondent were also asked to describe what was their opinion on the tool's usefulness. Among other things, they indicated that LINKAGE allows to "easily visualized the interactions," "implement the abstraction reasoning," "consider the environment and various systems of the project," and "help the modeling of the system."

As a synthesis of their evaluation of the tool, participants were asked: "Would you recommend the use of LINKAGE to other biomimetic design teams?". A 7-point Likert scale (0–6) was used in this question to allow a more precise and refine rating. Responses showed a median of 5.5 with 50% of respondents giving the maximum score of 6.

Finally, participants were also asked to underline the tool's weaknesses. Mainly three elements emerged: (1) a need for more examples of use, (2) a variability of the tool's relevancy depending on the project typology, namely, team 4 and 5 worked on the design of service solution and have underlined the tool was made for product design, (3) a need for more time and training (the tool was given with little prior information during the workshops). These limitations will be further study in Sec. 4.3 which elaborates on the weaknesses and limitations identified in both Secs. 4.1 and 4.2.

The two last elements, the typology of project and short timeframe, led teams to mainly design partial models (Table 6) as expressed by a participant "*we had not enough time to complete*

Table 5 LINKAGE's evaluation on Nielsen's usability criteria

5-level Likert scale	0	1	2	3	4	Median
Satisfaction	0%	0%	16.7%	41.7%	**41.7%**	3
Ease of handling	0%	0%	16.7%	41.7%	**41.7%**	3
Risk of errors	0%	0%	**50%**	33.3%	16.7%	2,5
Mistake detection and corrections	0%	8.3%	8.3%	**75%**	8.3%	3
Model accuracy	0%	8.3%	8.3%	**50%**	33.3%	3
Interest of the reasoning	0%	0%	8.3%	41.7%	**50%**	3,5

Note: Maximal value in bold.

Table 6 Status of obtained models

5-level Likert scale	Part 1: Information structured gathering		Part 2: Selection and rise in abstraction
	Partial model	Full model	Abstracted guidelines from the model
Team 1	T: 1	B: 1	B: 1
Team 2	T: 1, B: 1	B: 1	0
Team 3	T: 1, B: 1	B: 1	0
Team 4	T: 1, B: 1	0	0
Team 5	T: 1, B: 2	0	0
Total ($n = 16$)	71.43% (10)	21.43% (3)	7.14% (1)

Note: T = technological model, B = biological model.

each phase." As a result, detailed results (Sec. 4.2) will focus on the first part of the approach proposed by the tool (Sec. 3.4.1, Fig. 3, Part 1).

As presented in Table 6, all generated technological models were only "partial model," whereas 44.4% of the "biological models" were fully completed (end of part 1). One of the main explanations that can be considered is that, since the modeling of technological systems is performed first, users lost a little time during the assimilation of the tool's functioning. For the modeling of biological solutions, teams had more experience and so were more efficient, leading to overall better progresses on biological models. After only 1 hour of practice, and without prior training, one team thus managed to abstract eleven design guidelines, which is rather encouraging.

Overall, these initial results show that LINKAGE was perceived very positively by the considered sample, even if it was not used at its full potential and some weaknesses must be addressed.

4.2 Detailed Results. After these initial questions, the evaluation questions further into details three key aspects of the tool, its impact on teamwork, its impact on information structuring and its ergonomics.

4.2.1 Results on Teamwork and Communication. One of the main objectives of the workshop was to evaluate if the embodiment of the theoretical results obtained on interdisciplinary communication was perceived by users as a support for teamwork (Table 7).

The obtained results offer a first validation of the tool's impact on communication, and specifically on communication between teammates from different disciplines, with 83% of the respondent having given a 3 or higher.

Table 7 also underlined that one participant gave a score of 1 for each criterion, and detailed results show it's the same respondent. One explanation that can be considered is the fact that this respondent was working on the designing of a service, which has been underlined as one of the tool's weaknesses (Sec. 4.1) and will be further discussed in Sec. 4.3.

We also asked the participants if LINKAGE supports the reasoning of the team. This question was considered as a marker of the tool's impact on teamwork, itself impacted by the team's ability to properly exchange information. With a median of 3.5, the positive impact of the tool on team reasoning appears as a clear tendency.

Table 7 Evaluation of LINKAGE on teamwork and communication

5-level Likert scale	0	1	2	3	4	Median
Supports the communication within the team	0%	8.3%	16.6%	**50%**	25%	3
Promotes communication between within interdisciplinary teams	0%	8.3%	8.3%	**50%**	33.3%	3
Supports the reasoning of the team	0%	0%	8.3%	**66.7%**	25%	3,5

Note: Maximal value in bold.

4.2.2 Results on Information Structuring. Additionally to the tool's impact on teamwork, this evaluation phase also aimed at testing the tool's ability to allow information handling and structuring (Table 8) from data found online, on scientific websites or on AskNature.

Table 8 shows similar results for biological or technological information with a median of 3 on both the structuring of information and the tool's ability to highlight missing information. More precisely, it appears that this last contribution is especially recognized on technological information. One explanation can be that the tool supports a systemic approach and so leads users to look for complementary information from those that were initially considered in the technical brief. The team must not only model the expected functions but also the environment within which the system evolves. As stated by one respondent when asked about how did the tool helped her team, the tool "*allowed us to understand the impact of the environment on our system.*"

The results also underlined that all respondents felt both the structuring of the information and the reasoning presented by the tool facilitated their understanding of the studied systems.

These early results present a positive feedback of the users on the tool's ability to allow the structuring of information and to support team's reflection and understanding.

4.2.3 Results on Ergonomics. Facing the observations made in the introduction on the need for more user-friendly biomimetic tools (Sec. 1.3), we designed LINKAGE with the challenging goal of making a tool usable without external training to allow teams to easily implement it in practice. To evaluate this aspect, participants were not previously trained to use the tool. Doing so, the ergonomics and the user-friendly interface were key parameters for participants to use the tool. Table 9 presents the obtained results.

If the tool is mostly recognized as intuitive, logically structured and offering adequate guidance through its pop-ups, ergonomics is also the only section that has received a 0 by a respondent, on intuitiveness.

Moreover, to conclude this section, we directly asked participants "is the tool ergonomic enough?" 66.7% (7 respondents) of respondents considered the tool to be sufficiently ergonomic as it is

Table 8 Evaluation of LINKAGE on information structuring

5-level Likert scale	0	1	2	3	4	Median
Allows teams to structure technological information?	0%	0%	8.3%	**66.7%**	25%	3
Allows teams to identify missing technological information?	0%	0%	16.7%	41.7%	**41.7%**	3
Allows teams to structure biological information?	0%	0%	8.3%	**58.3%**	33.3%	3
Allows teams to identify missing biological information?	0%	0%	8.3%	**66.7%**	25%	3
Facilitates the understanding of the studied system?	0%	0%	0%	**66.7%**	33.3%	3

Note: Maximal value in bold.

Table 9 Evaluation of LINKAGE on ergonomics

5-level Likert scale	0	1	2	3	4	Median
Is the tool intuitive?	8.3%	0%	25%	**50%**	16.7%	3
The tool's architecture appears logical?	0%	8.3%	8.3%	33.3%	**50%**	3.5
Do pop-ups and help buttons give enough information?	0%	0%	8.3%	41.7%	**50%**	3.5

Note: Maximal value in bold.

and 33.3% (5 respondents) indicate that ergonomics need to be improved.

Additional work will then be carried out on this specific parameter. However, considering the little training of the users, these early results appear encouraging.

Section 4.3 presents the limitation of the evaluation and combines the various weaknesses underlined in Secs. 4.1 and 4.2 to offer a synthesis of the lines of improvements and present our current work to address these shortcomings.

4.3 Limitations and Lines of Improvement. This section aims at balancing the tendencies presented in the initial results by underlining first the limitation of the evaluation and the second the lines of improvements of the tool.

4.3.1 Limitation of the Evaluation. On the evaluation several limitations must be underlined. First, the sample is too small to be considered significant and the obtained can only be considered as tendencies. To address this limitation, we chose to publish the tool in its first operational version for it to be available to the greatest number. Doing so we want to collect as many feedbacks as possible (through specific forms on the tool) and implement continuous improvements to better support practitioners.

Second, the conditions that were used, a 1 day workshop with only 2 h on the tool, are far from similar than the ones of industrial projects which vary from several weeks to several months. This bias, if it appears inevitable to reach a substantial sample of professional participants in a short time period, limits our findings on several aspects. To begin with, teams only spend one hour on each model (technological step 2 and biological in step 6), without prior knowledge on the tool and with only 45 min of introduction on biomimetics. Thus, we can consider that, on this hour, users took a consequent time to assimilate and explore the tool itself along with the presented instructions. This lack of time may have impacted the results both ways, since users have little time, they donot get the full potential and interest of the tool (impacts the score negatively) but they might also not get the time to perceive the tool's weaknesses (impacts the score positively). To synthesize, tool was evaluated on its ability to deal with the structured gathering of information, leaving aside the part on the rise in abstraction, only reached by one team. This specific contribution of the tool, rise of abstraction, will need to be additionally evaluated through time and usage.

Last, the notion of efficiency has not been studied in this article. The experiment focused on the evaluation of the tool's usability and perceived impact, as a prerequisite for its acceptability. Thus, future work will focus on a proper testing of the tool's efficiency as the final and key parameter. More specifically, two parameters of efficiency will need to be evaluated through comparative studies (with and without LINKAGE), the team's efficiency during abstraction (e.g., quantity and quality of abstracted principles) and the team's ability to communicate efficiently (e.g., quantity and quality of interdisciplinary interactions).

To synthesize, despite an initial evaluation allowing the identification of tendencies validating the interest for the tool and the proposed approach, the efficiency of the tool in an industrial project and on abstraction still need to be further studied.

4.3.2 Lines of Improvement and Current Work. Obtained results have allowed us to identify various weaknesses of the tool. First, even though LINKAGE is perceived as a user-friendly tool by most users despite the absence of prior training, further improvements need to be considered. When asked for specific axes of work, some respondents underlined the need for a more comprehensive "*definition of the different concepts used,*" others explained that "*more examples should be given*" and "*training would be useful.*" Therefore, if our initial observation on the need for a strong ergonomic requirement is confirmed, the tool's interface itself should be further adjusted to ease its implementation. This first line of improvement leaves us to currently work on two aspects:

- the update of the information available on the tool (semantics, help button, user-guide, etc.), to address the need for definitions or example,
- the identification of key required knowledge and know-how for LINKAGE use. The objective is then to make a video tutorial available on LINKAGE, allowing practitioners to implement the tool autonomously.

Second, as previously presented, the notion of projects' typology established itself as a question to address. The two projects that were targeting the design of services, that were imposed by the context, have been underlined by the participants as "*less adapted*" for the tool. Indeed, LINKAGE was built first for product design and the reasoning it supports may need some adjustments for this other typology of project. Moreover, examples proposed displayed by the tool are focusing on products. Thus, the tool's pop-ups and other user-centered supports that were designed to compensate for the little training imposed by the protocol were probably inefficient. This question on the typology of projects was unexpected but appears crucial to properly characterize the prerequisites before using LINKAGE, and overall before considering a biomimetic approach. Facing this feedback, we have decided to put aside projects on services for the time being to focus on improving the tool for product design. In a second time, when the tool will be considered efficient for product, adjustments for services will be further studied.

To conclude Sec. 4.3, the results presented in this article only represent a first step on which to build further studies, specifically on the tool's efficiency. Feedbacks from the participants led us to consider improvements on the information and training required to ensure an easy implementation of LINKAGE.

5 Conclusion and Perspectives

Biomimetics has reached a key step in its development. Research projects on the methodological side of the approach have multiplied and high-potential results have been published. However, these results have a hard time reaching practitioners. Studies have shown that a user-friendly interface, along with an easy access, are among the key parameters to stimulate the appropriation of these results.

For a few years now, we have been working on the integration of teammates having a background in biology within biomimetic design teams. More specifically, this project led us to consider the following research question: How to support the interdisciplinary teamwork within biomimetic design teams? We underlined the issue of the variability of cognitive and conceptual framework within the team leading to distinct, sometimes hardly compatible mental models associated with the project.

To address these communications impediments, we established a shared cognitive framework of reference based on a synthesis of both biologists' and engineering designers' specific cognitive frameworks in biomimetics [1]. Combining this theoretical work with our initial observation on the need for user-friendly tools, we've embodied our theoretical findings into a tool named LINKAGE representing the hypothesis of our approach. This tool specifically targets key steps of the biomimetic process: the analysis and abstraction steps. These steps were chosen since they represent the first step for the understanding and transfer of knowledge, and so the analogical reasoning inherent to biomimetics.

Once LINKAGE was designed (Sec. 3), several initial tests were performed by interdisciplinary teams of professionals (Sec. 4). Overall, the tool is recognized as relevant, useful, and providing a set of contributions. They structure on the one hand the reasoning of the team (cognitive framework) and the information entered by the teams (conceptual framework). Specifically, initial positive tendencies can be underlined on the tool's ability to facilitate communication within interdisciplinary teams. Various experimental limitations have been underlined, notably the tool's efficiency comparing with other approaches has not been evaluated yet. Furthermore, several lines of improvement have been specified.

To conclude, additionally to these limitations which appear as natural perspectives, the version 1.2 of LINKAGE only represents the beginning of our approach on the support of interdisciplinary biomimetic design teams. Our final objective is to make LINKAGE able to guide and assist practitioners through most of the process' steps (steps 1–7). We deeply believe that team's interdisciplinarity and making research results available to practitioners is currently one of the key factors to promote biomimetics spreading in practice.

6 Copyright Reminder

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request. The authors attest that all data for this study are included in the paper.

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