# An approach for exploring non-technical complexity in engineering design processes

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**Abstract** Engineering practitioners consider non-technical complexity, related to systems under design, to be uneasy to address, due to perceiving it to be outside their expertise. Tackling non-technical complexity requires practitioners to see connections between the complexity and themselves, then be motivated enough to act. Motivation, however, is challenging because complexities must be sufficiently articulated and the practitioners should feel confident to address them. We propose an approach, called 3U, to support engineering practitioners to better perceive and express non-technical complexity problems, reduce cognitive constraints and begin initial solution ideation to become stimulated to address the problems. The approach consists of complexity mapping, relay ideation and bio-inspired analogy creation. We preliminarily evaluate the approach through a workshop and interviews. Workshop participants found the approach particularly valuable in the early period of projects but identified the complicatedness of using bio-inspired analogies. We consider our approach can contribute to enhancing multidisciplinary team collaboration.

*"The way we see the problem is the problem." - Stephen R. Covey*

## 1 Introduction

Engineering practitioners encounter non-technical complexity while designing complex systems, such as uncertainties in design-procedural, political, economic, market and societal factors (Keating et al., 2019; Pereira Pessôa, M.V. & Gonzaga Trabasso, 2017; Schijf et al, 2022; Sonnetti et al., 2020). Non-technical complexity problems should be addressed, as the system under design (SUD) is not isolated from its design environment (Earl et al., 2004).

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Non-technical complexity problems are present in the communication and collaboration of multidisciplinary design teams. The activity of design is a collaborative problem-solving activity, in which engineering practitioners experience, recognize and handle non-technical complexity problems (Lumsdaine, Shelnutt, & Solar, 1999). As for collaborative problem-solving, the following three variables contribute to transitioning the state from perceiving problems to entering the solution exploration, according to Kim and Grunig (2011): perceptual, cognitive, and motivational precedents. Perceptual variables refer to perceiving missing points between expected and experienced circumstances, connections of perceivers themselves to the problematic circumstances, and constraints restricting perceiver's capabilities for dealing with the problematic circumstances. Cognitive variables cover encountering deficiencies in immediately applicable solutions to the problematic situations and remembering relevant and useful knowledge or experience. The perceptual and cognitive factors stimulate problem perceivers to become motivated enough to take communicative actions (e.g., information transferring) for solving problems. Those perceptual, cognitive, motivational, and communicative elements are interrelated and form a mechanism of problem solving in multidisciplinary design teams. (Fig 1).

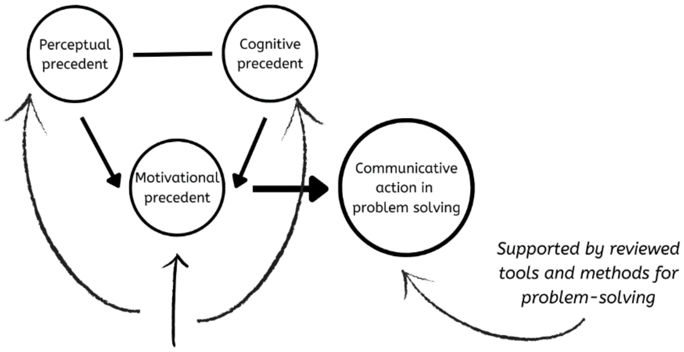


**Fig. 1** Knowledge gap in problem solving tools and methods, considering situational factors contributing to problem-solving, adapted from Kim & Grunig (2011)

Facilitating collaborative problem-solving of non-technical complexity in multidisciplinary design teams, however, is not as simple due to the following reasons. Firstly, explicitly delineating non-technical complexity problems is challenging, especially if they are ill-defined problems (Bruner & Pomazal, 1988; Dutta, 2018; Helmold, 2021; Wang & Chiew, 2010). Secondly, engineering practitioners have been mainly trained for dealing with technical complexity like fits, forms and functions of designed artefacts (Baligar et al., 2022). The resulting lack of resources (e.g., knowledge and self-competence) might cause them to feel overwhelmed or restricted, even if non-technical complexity is expressed (Aldoory et al., 2018; Grunig & Ipes, 1983). Additionally, engineering practitioners will less relate to non-technical complexity problems when regarding them unmanageable with their fields of expertise. Consequently, in reality, non-technical complexity will remain a limitation.

## *1.1 Knowledge gap and research aim*

Understanding the essential elements for problem-solving and the interconnection between them, we reviewed problem-solving approaches to see to what extent the tools can support engineering practitioners dealing with non-technical complexity problems. Heuristics, analogy, algorithmic deduction, exhaustive search, and others have been used for problem-solving in many disciplines (Wang & Chiew, 2010). Two philosophy of thought processes, design thinking and system thinking, have been highlighted as complex problem-solving methods for recent decades (Arnold & Wade, 2015; Buchanan, 2019). These thought processes were modified as tools and methods for the design environment (Wynn & Clarkson, 2018). Complex system modelling methods like system dynamics and agent-based modelling, support analytical activities (Abar et al., 2017; Currie et al., 2018; Nabavi et al., 2017; Namany et al., 2020). A3-architecture overview, analytical hierarchy process, and architecture frameworks facilitated abstracting ideas and communicating them with stakeholders (Borches, 2010; Hafsi & Assar, 2016; Kalutara et al., 2018).

The reviewed approaches, however, are primarily used for understanding big pictures of design processes and predicting outcomes of interactions amongst the elements of SUDs. Because non-technical problems are not explicitly supported, the application of the approaches to such problems may depend on the experience, training and motivation of the practitioners. Therefore, we identify a gap in the problem-solving approaches, as they do not explicitly support to better perceive, express, nor address the non-technical complexity problems that design teams experience.

We undertake the identified gap by providing a three-step approach, named *3U Approach: **U**npacking, **U**nblocking, and **U**nraveling*, to support engineering practitioners in perceiving and expressing non-technical complexity problems, as well as generating initial ideas to address those problems. For the approach, we adapted the creative problem-solving framework (CPS) consisting of the following three stages: understanding the challenge, generating ideas, and preparing for action (Isaksen & Treffinger, 2004). We applied mind-mapping, brainstorming, and analogical thinking, tools for both problem finding and ideation of creative problem solving process, to fulfill each of the stages (Vernon et al., 2016). To preliminarily evaluate the 3U approach we conducted a workshop and interviews.

The paper is structured as follows. Section 2 presents the 3U Approach including the selected tools for each of the three steps. Section 3 describes the methods we used to preliminarily evaluate the 3U approach. The results are discussed in Section 4. Finally, the paper's discussion and conclusion are presented in Sections 5 and 6, respectively.

## 2 3U Approach: Unpacking, Unblocking, and Unraveling perceived non-technical complexities in an integrative way

This section illustrates our proposed approach supporting engineering practitioners to better perceive, express and generate initial ideas to address non-technical complexity problems (Fig. 1). The approach, inspired by CPS, consists of three steps: i) **U**npacking non-technical complexity with a complexity mapping, ii) **U**nblocking the externalized complexity problems by brainstorming in pairs (consecutively that is referred to as relay ideation), and iii) **U**nraveling the complexity problems by creating bio-inspired analogies.

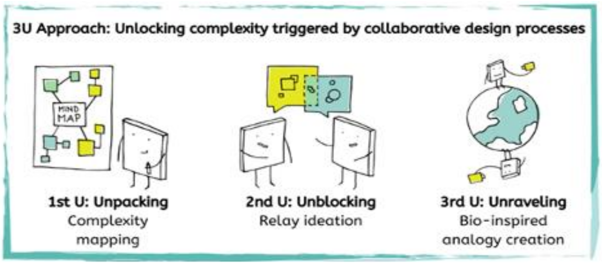


**Fig. 1** 3U Approach for the exploration of non-technical complexity by engineers

***Unpacking the non-technical complexity problems with a complexity map***

The first step of our approach focused on perception of non-technical complexity problems by using a tool we refer to as *complexity map* (Fig. 2). The tool adapted mind mapping to facilitate the process of spotting roughly perceived non-technical complexity scattered in mental spaces (Davies, 2011; Hocking & Vernon, 2017; Wang & Chiew, 2010). As mind mapping is initiated by situating central subjects in the middle of a blank page, complexity mapping is started by looking at visualized models of collaborative design processes in canvas. Map users can put sticky notes or any signs on the elements of design process models relevant to the complexity to be mapped. We considered that *getting to see* the models of collaborative design processes and their influencing factors could better provoke the thought process of engineering practitioners.

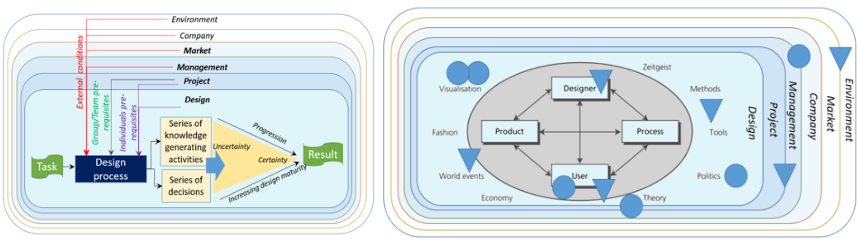


**Fig. 2** Examples of the complexity map developed by adapting mind maps and combining it with the work of Earl et al., (2004); Hales and Gooch (2004); and Maier et al. (2014)

***Unblocking the non-technical complexity problems by having relay ideation***
The relay ideation technique, presented by Slegers et al. (2013), is an design-support approach that distributes the problem-solving responsibility by passing it on (relay) from one group to another, after one single step of the problem-solving process.

We adapted the relay ideation technique to consolidate the fluid understanding of the non-technical complexity mapped in the first step, so it can be addressed (Runco & Chand, 1995). The practitioner can solidify their problem understanding by expressing it to a teammate. Once the teammate has sufficient information, they will work on the next problem-solving step. Relay ideation can help addressing non-technical complexities in three ways: i) to encourage talking to others about the non-technical problems to reduce cognitive burden, ii) to prevent possible counterproductive social side effects of some group ideation techniques and iii) to increase the feeling of shared ownership, involvement, and motivation (Lepore et al., 2000; Slegers et al., 2013; Warr & O'Neill, 2005).

***Unraveling the non-technical complexity problems with bio-inspired analogies***
Non-technical complexity problems are often closely attached to human behavior and to the environment where we live our daily lives and perform our professional tasks. This causes our perceived reality to be intertwined with how we perceive opportunities, interpret information, make choices and establish preferences (Pigram, 1993). As a result, the non-technical complexity problems tend to be subjectively contextualized based on diverse human behavior aspects.

Due to this subjective contextualization, it can be challenging to generate ideas to tackle non-technical complexity problems; we become inclined towards the details, our own interests and preferences. Consequently, we need extensive time to actually abstract the problem to a set of essential logics and elements, which we can later systematize to then start formulating solutions (Ghom, 2017).

Bio-inspired analogies have been applied both for abstraction and solution generation of technical design problems such as materials and functions (Nagel et al., 2018). This technique consists on drawing on analogies from nature and getting inspired by solutions developed to cope with natural problems and tested by millions of years of evolution (Hashemi Farzaneh, 2020). As a third step in our 3U approach, we proposed to use bio-inspired analogies to facilitate both abstraction and initial solution idea generation for the non-technical complexity problems, which have been perceived and expressed in the previous two steps.

We used bio-inspired analogies because we considered that non-technically complex events, behaviors, and network (e.g., loosely coupled cross-sectoral collaboration) can be better objectively situated and described in the context of nature. As a result, we can be inspired by the interactions between animals or plants with high-level perception without specific nuance introduced by human behavior (Chalmers et al., 2007; Mitchell, 2021) (see examples in Section 4.1). In addition, bio-inspired analogies are accessible and probably an easier way to start abstraction rather than a fieldtrip for adopting others' views and practices.

In the following section, we explain employed methods to preliminarily evaluate the effectiveness of applying the 3U approach in practice.

## 3 Methods

A qualitative research method was employed to preliminarily evaluate the 3U approach presented in Section 2. The method (see Fig. 3) consisted of a workshop and semi-structured interviews. Both sub-methods can foster engagement of research participants and allow participant observation and in-depth description of both the situation in which the 3U approach is applied and the experiences of using it (Ahmed & Asraf, 2018; Tong et al., 2007). The workshop and semi-structured interviews occurred in April and May 2022.

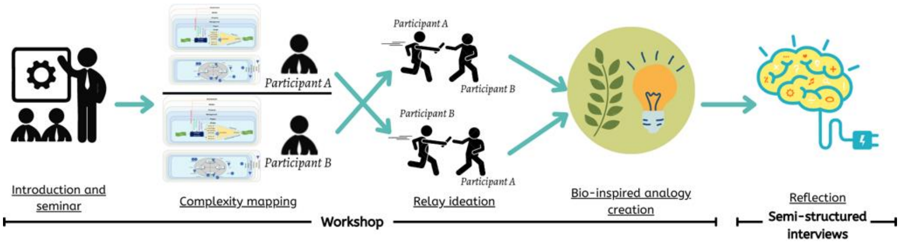


**Fig. 3** Methods for preliminary evaluation of the 3U approach

### *3.1 Workshop organization*

We designed a two-hour workshop where participants applied the 3U approach to their project contexts. The participants were involved in complex manufacturing processes (P1), incorporating systems engineering principles into business practices (P2), public transport systems (P3) and high-tech systems design (P4); all of them were engineering design researchers. None of them disclosed having experience with bio-inspiration solutions.

The workshop consisted of the following three parts: i) participant introduction, ii) a seminar on complex systems design processes and bio-inspired analogy ideas and literature examples, and iii) the 3U approach trial. As for complexity mapping, we provided a complexity map canvas developed based on the work of Hales and Gooch (2004), Maier et al. (2014), and Earl et al. (2004) (Fig. 2). Participants worked on the complexity map individually. Then, they grouped in pairs for relay ideation to express their situational context and non-technical complex problems to their teammate. In the third step, the pairs worked on each other's cases (relay) creating bio-inspired analogies to find solution notions. To exemplify the use of bio-inspired analogy for non-technical complexity, in the seminar we presented natural collaboration phenomena. The examples were an overview of organizational structures of natural collaboration, behavioral archetypes in natural collaboration, mechanisms promoting collaboration, cognitive functions that enhance cooperation of non-human animals, and social morality of animals (Dermody et al., 2011; Duguid & Melis, 2020; Mcauliffe & Thornton, 2015).

### 3.2 Semi-structured interview protocol

We had two sessions of half-hour semi-structured interviews. Each session accommodated one of the pairs that worked together for creating analogies. Interview questions were made to explore their experience in terms of four aspects: i) experience of making complexity maps, ii) experience of creating bio-inspired analogies, iii) applicability of the complexity exploration approach to conducting their design projects, and iv) ways to improve the procedure of the workshop[1].

In Section 4, we illustrate the results of initial evaluation of the 3U approach.

## 4 Results

Subsection 4.1 introduces the workshop results, the mapped complexities and created bio-inspired analogies. Subsection 4.2 explains the interview results.

### 4.1 Identified key non-technical complexity problems and bio-inspired analogies that support tackling the identified problems

Each participant worked on their own complexity map (see Fig. 4). We observed participants started marking elements and factors of design processes illustrated in the provided canvas. They put sticky notes and wrote key terms that helped them to express non-technical complexity problems. Subsequently, two pairs - P1 and P2, and P3 and P4 - were formed for relay ideation and bio-inspired analogy creation. In total, the two pairs perceived and expressed seven non-technical complexity problems for which they developed the respective bio-inspired analogies based on relay ideation format (see Fig. 5).

All participants described the processes of making bio-inspired analogies in the order of i) non-technical complexity problems expressed by their peers' through complexity maps and conversations (e.g., *expressed problem:* trade-offs among stakeholders), ii) natural interaction/collaboration phenomena that the non-technical complex problems seemed to resemble (e.g. *similar phenomenon in nature:* pet dogs' trade-off behavior), iii) solutions observed in nature (e.g., *solution in nature:* pet dogs can be motivated to participate in trade-offs if convinced by the reward), and iv) notions for solutions in the human world (e.g., *solution in human world:* highlighting specific rewards to each stakeholder can help them to agree on a common target). One example of the bio-inspired analogy creation processes is illustrated in Fig. 6[2].

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[1] *The semi-structured questionnaire can be provided upon request.*

[2] *All processes can be provided upon request.*

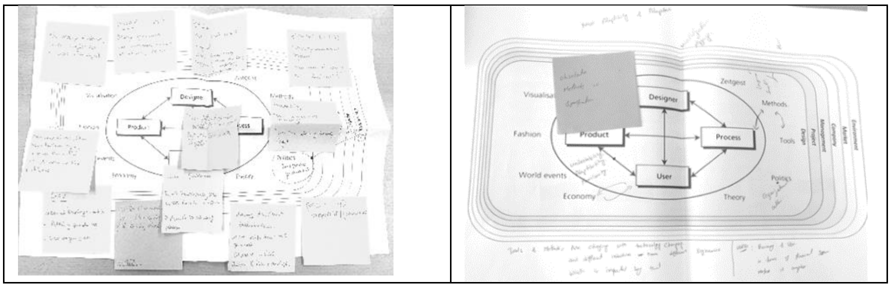

**Fig. 4** Complexity map usage in the workshop

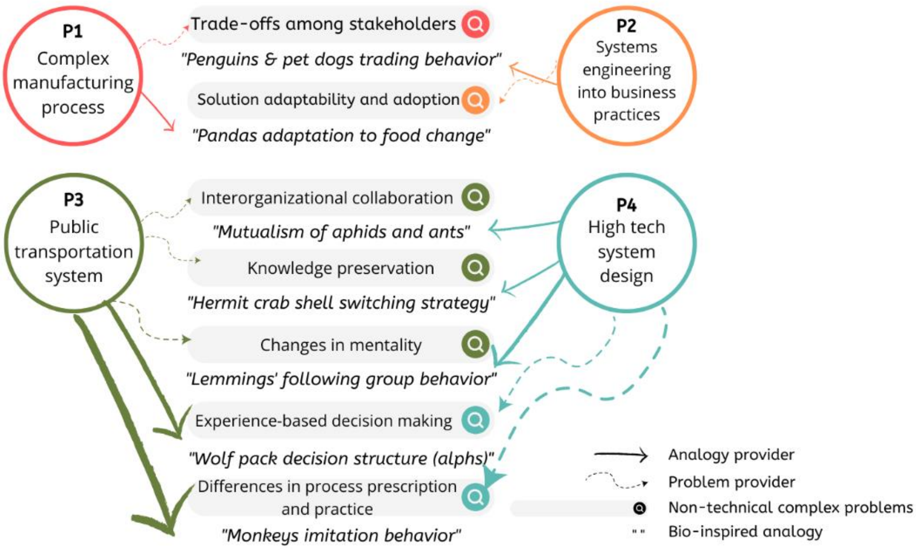


**Fig. 5** Two pair groups defined seven non-technical complex problems from their engineering design projects and created associated bio-inspired analogies.

## *4.2 Reflections on the workshop*

As a general remark, the participants agreed that the 3U approach can be a good method for understanding and addressing the non-technical complexity problems of their engineering design projects. Particularly, the participants who were in earlier stages of their research found the most tangible potential. A participant, whose study context relied on experienced practitioners for decision-making, realized that he had only a partial view of the solution space. He had only envisioned his design support to reduce dependency on experienced people, whereas, through the analogy from his teammate, he realized that it might not be strictly necessary.

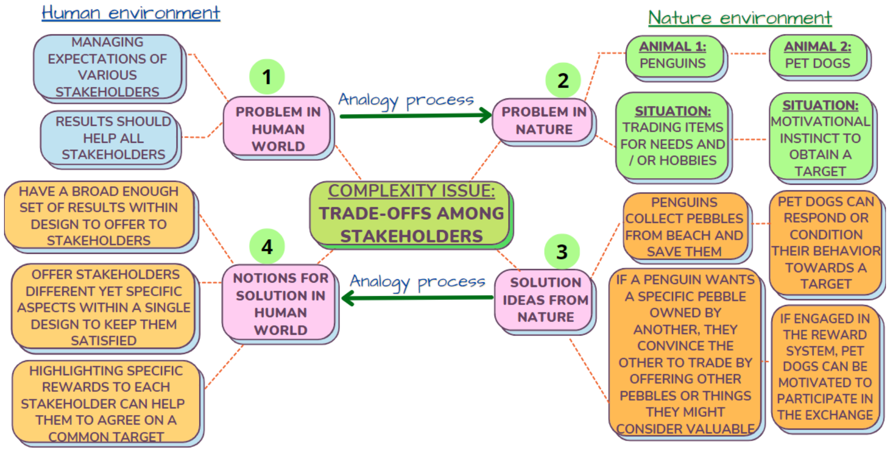


**Fig. 6** An example of the bio-inspired analogy creation processes from the workshop

### *Usefulness of the complexity maps*

The participants positively evaluated the usefulness of the complexity maps. Two benefits were noted: i) explicitly perceiving non-technical complex problems, and ii) expressing and visualizing complexities together with other participants. They recommended using complexity maps in the early stage of a project. As a disadvantage, the complexity maps were not found to be a solution by themselves.

### *Usefulness of relay ideation*

This technique was also regarded positively. The benefits were noted to be improving problem understanding, encouraging peer connection, and gaining other perspectives. The participants gained understanding of their problems by expressing them to others. Connecting to peers and recognizing similarities between their projects was considered as an additional benefit. They referred to having heard ideas that they would not have considered or would have taken longer to come up with themselves. The consensus was these additional benefits were obtained through having someone else working on their problem(s) as opposed to only themselves.

### *Usefulness of applying bio-inspired analogies to tackle complexity problems*

Participants, in general, evaluated making bio-inspired analogies to apply to the non-technical complexity problems as interesting and creative. Some found bio-inspired analogies broadened and shifted their perspectives, while for others using analogies allowed them to understand more, and not to always shift perspectives nor the modes of thinking. Participants also indicated the value of making analogies in the early project stages, similar to the perception of the complexity maps.

Disadvantages of bio-inspired analogies were also discussed. Among the challenges were starting production of examples (they mentioned it gets easier once they get started), tackling multiple complexity issues at once, and directly applying the results in practice. Another limitation was the lack of knowledge in the fields of Biology, Zoology, and other relevant sciences. To cope with this, the participants used nature phenomena they already knew from documentaries and videogames. Furthermore, they noted the restrictions of only using nature as inspiration and of only focusing on improving current situations rather than challenging those situations altogether. Participants also noted three risks: i) misinterpreting nature thereby developing inappropriate solutions, ii) tensions when explaining analogies to stakeholders, and iii) spending excessive amount of time for the analogy creation.

***Feedback for improving the workshop execution***

It was recommended to provide summarized bio-inspiration examples and guidelines for bio-inspired analogy creation. Requesting more than one bio-inspired analogy per case and defining a minimum set of details to be given by the case provider was considered. Combining the complexity mapping with other methods such as the 12 system thinking tracks (Bonnema & Broenink, 2016) and emphasizing sustainability in design as part of using bio-inspiration was mentioned.

## 5 Discussion

Through the preliminarily evaluation, we investigated the possibilities of the 3U approach to support perception and expression of non-technical complexity, as well as initial idea generation for addressing it. In terms of key findings, the workshop participants found the approach particularly valuable in the early period of projects. Also, they noted the benefits of using both complexity maps and relay ideation to support expressing and visualizing complexities together with others.

As for implications in industry, we consider the 3U approach can bring the following values. Firstly, it can facilitate cross-disciplinary conversation (e.g., communication between project managers and designers). As seen in Section 4.2, the approach could encourage practitioners to change their pre-formulated problem solutions by having a pair conversation. This conversation might help them to speak up and listen more authentically than in a larger groups. Furthermore, linking others' understanding of the human world complex phenomena based on bio-inspired analogies, can be persuasive. Secondly, considering connections of the society context with technical SUDs and creating organizational narratives thereof can contribute to finding business opportunities. Finally, the 3U approach can help to see a more complete big picture of a project (see Section 4.2). Having this big picture with SUDs and societal elements together, could motivate engineers by *seeing* the connection between their tasks and other real-world problems.

As any research, our work also has limitations. Firstly, the theory of situational problem solving, the foundation of this research, assumes that people are generally eager to solve problems, however, in reality, not all engineering practitioners are keen to solving problems (Kim & Grunig, 2011). Additionally, the theory does not specifically focus on non-technical complexity problems. Thus, we assume that non-technical complexity problem solving would involve more motivational variables and relations, such as personal involvement, interests and preferences (Kim & Grunig, 2011). Secondly, we acknowledge that other problem finding and ideation tools such as art practices (e.g., fiction writing and painting) rather than complexity maps, relay ideation and bio-inspired analogy, might be also suitable (Ghom, 2017). Thirdly, the preliminary results of our research are hard to generalize due to the small number of participants and the fact that they perform as researchers in their design teams, which could be different than regular engineering teams. Fourthly, because both understanding and creating bio-inspired analogies for others' complex problems took considerable time, the two-hour workshop setting was found to be too limited. We let the participants work together after the workshop hours and we met them two weeks later to discuss the perceived non-complex problems and created bio-inspired analogies. Due to this, the process conditions could not be completely controlled, which could have affected the results. Lastly, we did not apply quantitative measurements to see to what extent the 3U approach can help designers' non-technical complexity perception and expression, nor to evaluate the quality of the initially generated solution ideas.

Future research could investigate elements that can play crucial roles in engineering practitioners actually addressing non-technical complexity problems and adapting both the theory of situational problem solving and CPS framework. Other future work could involve more diverse disciplines such as Psychology, Cognitive Science, Art, and Ethics, to improve the basic concepts of the approach steps, their order, and the chosen tools. Additionally, we suggest to incorporate company practitioners, not researchers, to examine more the claim of this research (engineering practitioners) and observe the role of communication and organizational culture. We suggest incorporating quantitative measurement for motivation level checking, by using survey or other methods.

## 6 Conclusion

We explored the potentials the 3U approach complexity mapping, relay ideation, and bio-inspired analogy creation to support engineering practitioners to better perceive and express non-technical complexity problems and start to address them by generating initial solution ideas. We evaluated the approach by conducting a workshop and semi-structured interviews. The participants agreed that the 3U approach can support dealing with the complexity problems in their engineering design research processes. In terms of using the 3U approach to discuss with a wider audience or to transform into a tangible solution, we address the following concerns: i) in-depth investigation into crucial elements of engineering practitioners better perceiving and addressing non-technical complex problems, ii) the need to specify and even break down the explanation of the bio-inspired analogy creation process to make it as approachable as possible, and iii) the need to concretize the process of analogy usage for such questions as 'what does this have to do with me?' and 'how does this help me?', all of which can improve exploiting the potential benefits of bio-inspired analogies in design.

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