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Bio-inspired design: Ideation in collaboration between mechanical engineers and biologists

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PRIOR PUBLICATIONS

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1. Introduction

"I think the biggest innovations of the twenty-first century will be the intersection of biology and technology. A new era is beginning just like the digital one when I was his age"

Steve Jobs referring to his son (Isaacson, 2011, p. 539)

Bio-inspired design is a technical product development or engineering design approach at the intersection of biology and technology. Bio-inspired design (also called biomimetics, biomimetic design or biomimicry) is the application of knowledge of "*living systems*" in research and development to solve technical problems and develop technical inventions and innovations (VDI, 2012).

Why is bio-inspired design interesting for technical product development?

Biology offers a large and mostly unexplored pool of biological systems. The solutions of these systems to problems and challenges encountered in the natural world have been tested by millions of years of evolution: biological species unfit to tackle the challenges have died out; the surviving biological species have adapted and optimized their strategies. (Benyus, 2014; Nachtigall, 2010, pp. 121–130; VDI, 2012).

For the development of innovative technical products, designers require novel solution ideas. Using bio-inspired design approaches, they can "tap" the biological pool of solutions.

What are challenges of bio-inspired design?

Biological solutions can rarely be used in the technical domain directly: bio-inspired design usually entails a step of abstraction and analogical transfer (Lindemann & Gramann, 2004). Abstraction and analogical transfer require knowledge. As bio-inspired design is a transdisciplinary approach, knowledge is required in both the biological and the technical domain (Hashemi Farzaneh, Kaiser, & Lindemann, 2016). Designers in technical product development usually have an educational background in engineering, but no higher education in biology. Therefore, if the knowledge gap of designers cannot be bridged, bio-inspired design "*will remain the domain of a few innovators skilled and interested enough to decipher the primary biological literature*" (Benyus, 2014). Methods and tools have been developed to support engineering designers using bio-inspired design despite a lack of knowledge. However, they cannot replace personal knowledge which provides the cross-links to information (Probst, Raub, & Romhardt, 2012, p. 16) that enable a better analogical transfer. Moreover, they mostly provide pre-processed information in catalogues and databases (e.g. Deldin & Schuknecht, 2014, Hill, 1997, pp. 107–221, Löffler, 2009, pp. 87–95). Consequently these methods and tools do not give access to biological systems that have not been explored for bio-inspired design previously. On the other hand, information on a large number of biological systems is accessible (e.g. via biological research publications) – but biological knowledge is necessary to understand the information. To gather knowledge of the technical and the biological domain, collaboration between engineers and biologists has been proposed (e.g. by Helten, Schenkl, & Lindemann, 2011; Jordan, 2008). However, few empirical studies have examined collaboration between biologists and engineers in detail (see section 2.4.2, page 29). The focus of this work is therefore this promising but mostly unexplored approach to bio-inspired design: engineers and biologists collaborating in pairs to solve a technical task.

In which phase of technical product development is the application of bio-inspired design most effective?

As stated above, designers require solution ideas as a basis for developing innovative products. Ideation – the generation of new, unknown solution ideas is a central element of the product development process (Lindemann, 2009, pp. 137–156; Pahl, Beitz, Feldhusen, & Grote, 2007, pp. 121–162). The generation of alternative solution ideas is crucial, since companies under time pressure tend to implement single solution ideas hastily instead of developing alternative solution ideas to select the most adequate (Lindemann, 2009, p. 137). The generation of solution ideas based on analogies is the core of bio-inspired design making it a well-suited method for creative ideation (Lindemann, 2009, pp. 146–147; Pahl, Beitz, Feldhusen, & Grote, 2007, pp. 122–124). This work therefore focusses on bio-inspired ideation in the early phases of product development. The aim of ideation in the early phases is the generation of first solution ideas which will evolve throughout the product development process to a technical product.

To sum up, the aim of this thesis is to develop an understanding of the influences of bi-disciplinary collaboration between biologists and engineers on the development of solution ideas in an ideation phase. An additional aim is to support collaborating biologists and engineers in developing solution ideas with a higher potential for innovation.

For this purpose, two descriptive experimental studies with graduated biologists and engineers are conducted. In short ideation phases, the participants collaborate in pairs on a technical task. They receive information from biology to develop bio-inspired solution ideas. Bi-disciplinary pairs are compared to uni-disciplinary pairs of biologists and engineers.

The first descriptive study serves to develop an initial understanding of the influence of the pair composition on the solution ideas. The results are used for a prescriptive study in which *BioId*, a support for **bio**-inspired **id**eation, is developed. The second study reassesses the influence of the pair composition with data from additional pairs and evaluates the influence of *BioId*.

The thesis is structured as described in the following:

Section 2 introduces the scientific background of this thesis. To start with, the broad term *innovation* is defined and traced back to solution ideas developed in the ideation phase. By this means, two factors present in solution ideas are deduced which are crucial for the later innovation of a product: quality and novelty (2.1). Then, the situation of ideation within the product development process is explained and the ideation activities *exploration*, *generation*, *evaluation* and *communication* are explained (2.2). The next sub-section introduces analogies as an ideation mechanism and bio-inspired design as an approach to the deliberate use of analogies from nature (2.3). Methods, tools and collaboration to tackle a main challenge of bio-inspired design – the knowledge gap between the disciplines biology and engineering – are discussed in the last sub-section (2.4).

Section 3 presents the research approach of this thesis: the research gap is described and research questions are developed (3.1). Then, the research methodology is explained (3.2): this includes the experimental methodology with detailed information on participants, experimental procedure, and materials. Moreover, the analysis methodology is presented, i.e. the transcription and coding of the design experiments, the quantitative analysis, the qualitative analysis, and the verification of the results.

The results of the first descriptive study are shown in section 4. Quantitative (4.1) and qualitative results (4.2) are reported to develop an initial understanding of the influence of the bi-disciplinary collaboration. The quantitative results focus on the outcomes of ideation – the solution ideas. The qualitative results explain these outcomes and provide starting point for the development of *BioId*. The section closes with a conclusion and the implications of the results for the development of *BioId* (4.3).

The development of *BioId* is detailed in section 5: the development starts with a task clarification (5.1). Then, *BioId* is conceptualized (5.2) and elaborated by analysing existing support models for bio-inspired design and extracting useful aspects from these supports (5.3). The realisation of BioId is explained (5.4) and a study for the support evaluation is presented (5.5). Based on the support evaluation, *BioId* is improved (5.6). Moreover, an example of the use of *BioId* is explained (5.7).

The results of the second descriptive study are reported in section 6 with regards to the influence of the bi-disciplinary collaboration and of *BioId*. Consistent with section 4, the quantitative results are described first (6.1), followed by the qualitative results (6.2). The conclusion provides an overview on the reassessed influence of the pair composition on solution ideas and the evaluation of *BioId* (6.3).

Section 7 presents the verification of the results. Two factors are assessed: order effects during the experiment (7.1) and possible influences of the three different design tasks on the results (7.2).

A discussion of the results is provided in section 8: the limitations of this work are summarized (8.1) and the results are compared to similar studies (8.2). Section 9 presents a conclusion of the thesis (9.1) and starting points for future research (9.2) and the application of bio-inspired design for industrial practice (9.3).

2. Background

This section constitutes an overview on existing research relevant for this work. Figure 2-1 shows the allocation of the topics with regards to the general procedural model of product development and design proposed in the VDI 2221 guidelines (VDI, 1993). An overall goal of new product development is innovation (2.1) which makes companies successful in competition with other companies (Lindemann, 2009, p. 139). Innovation is achieved if an invention commercially succeeds on the market. Innovations can therefore only be observed after the completion of the product development process when the final product is on the market (Trott, 2008, p. 14). However, there is a direct link to ideation in the early phases of product development: ideation results in the initial generation of solution ideas (2.2) which evolve throughout the later phases of the product development process to a technical product.

One mechanism for ideation is the transfer of analogies (2.3). Analogies can be transferred from nearer domains (e.g. existing technical products) or far domains (e.g. biology). Bio-inspired design focusses on the deliberate transfer of analogies: it implies the transfer of analogies from biology to the technical domain. For bio-inspired design, disciplinary knowledge and information play an important role. However, in technical product development, designers do not necessarily possess biological knowledge. This knowledge gap therefore poses a challenge for bio-inspired design. One possibility to tackle this challenge are methods and tools designed to close the knowledge gap, another possibility is collaboration of biologists and engineers (2.4).

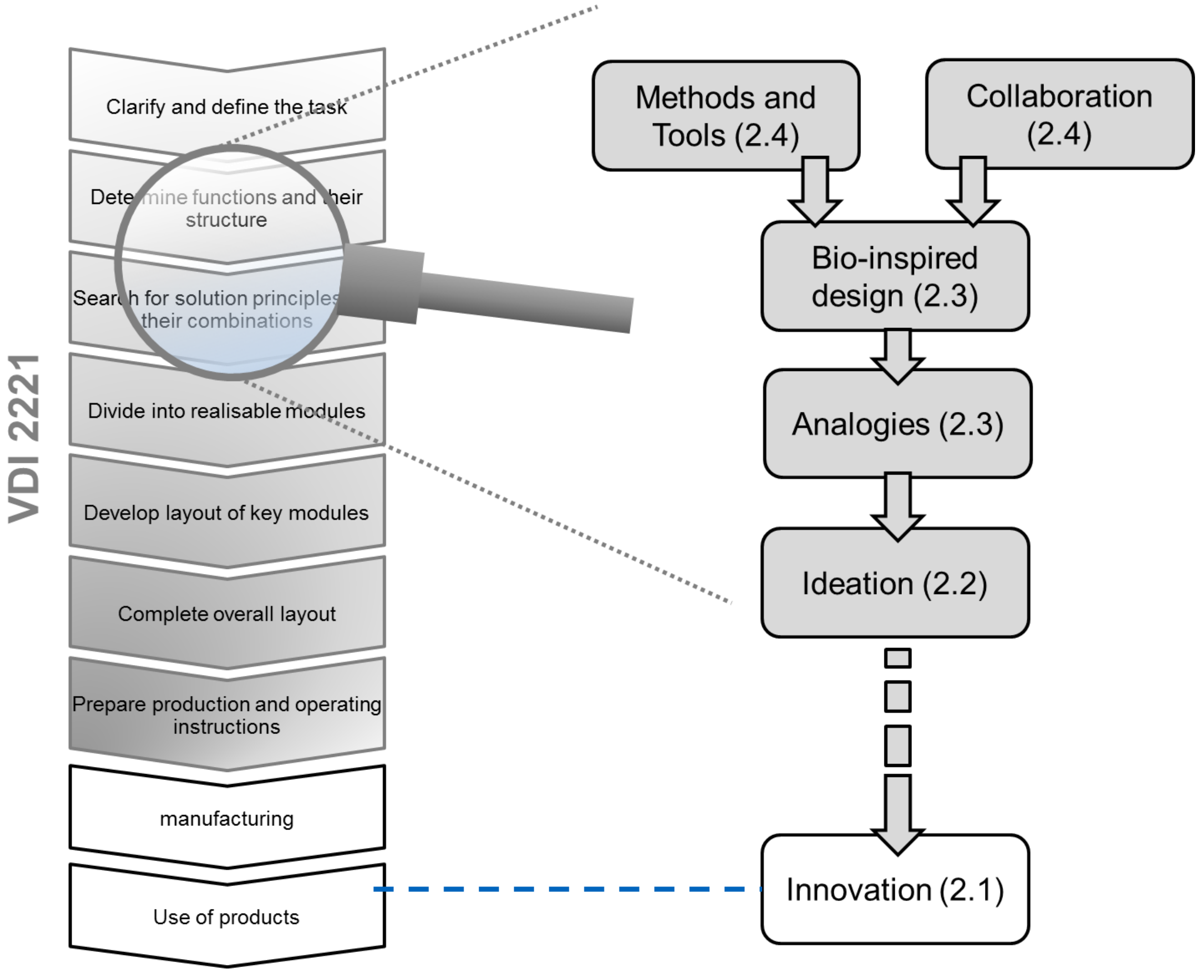


Figure 2-1: Background topics of this work (VDI 2221 procedural model from VDI, 1993)

2.1 Tracing innovation back to solution ideas

"Today, the idea of innovation is widely accepted. It has become part of our culture – so much so that it verges on becoming a cliché" (Trott, 2008, p. 4)

This citation shows that the term *innovation* is widely spread and familiar, in fact, it is used for a number of different processes and products (Hauschildt & Gemünden, 2011). This work focusses on *product innovation*.

To understand the relation between product innovation and initial solution ideas, the definition by Trott (2008, p. 14) can be used: he defines three components of innovation: *new ideas* ("*theoretical conception*"), *technical invention* and *commercial exploitation*. New ideas serve as a starting point. Developed into a product or process, new ideas become technical inventions. Technical inventions have to be commercially exploited to complete the innovation. Similarly, Reichle (2006, p. 20) defines a product innovation as the successful implementation of a creative novel idea or invention with a benefit for company and customer. Consequently, two factors determine the innovativeness of a technical product: novelty and (market) success (Binz & Reichle, 2005; Reichle, 2006, p. 19).

In addition to an invention's potential for market success, patentability is relevant for many companies to protect their intellectual property: according to the European Patent Office (2013, p. 110), inventions are patentable if they *"are new, involve an inventive step and are susceptible of industrial application".*

To sum up, for innovation and patentability, novelty and the market success of a product are crucial factors. Both aspects, commercial success and novelty are rooted in the early phases of product development: if solution ideas do not have the quality to enable the target achievement of the final product, the probability of commercial success is low. If solution ideas are imitations of existing products and no novel solution ideas are developed, the final product probably has a low degree of novelty. In the following sub-sections, both aspects - quality and novelty - are further explored.

2.1.1 Quality

Quality on the level of products implies that an innovative product has to be commercially exploitable, i.e. it has to be successful on the market. In technical product development, a common approach for ensuring the success of the product on the market is to define requirements. Requirements are based on an analysis of external demands such as the customer and market and internal demands, such as competencies and technologies within the company. Requirements are used to evaluate the technical solution throughout the product development process and to ensure the target achievement. (Lindemann, 2009, pp. 84–85; Pahl, Beitz, Feldhusen, & Grote, 2007, pp. 213–215).

Requirements can be defined by using checklists (e.g. (Ehrlenspiel, Kiewert, Lindemann, & Mörtl, 2013, p. 59; Pahl, Beitz, Feldhusen, & Grote, 2007, p. 220). Moreover, requirements are used in quality management: in DIN Deutsches Institut für Normung e.V., 2005, quality is defined as the "degree to which a set of inherent characteristics" of a product, process or system "fulfils requirements".

However, for the evaluation on the level of solution ideas, researchers have defined quality criteria based on requirements which are adapted to the preliminary character of solution ideas: a number of aspects of the technical solution have not been defined yet, therefore an evaluation of the fulfilment of all detailed requirements is challenging (Lindemann, 2009, pp. 180–181).

The developed quality criteria depend on the nature of the solution ideas at stake: Girotra, Terwiesch, and Ulrich (2010) evaluate non-technical solution ideas from a company perspective (*business value*) and customer perspective (*purchase intent*). Similar perspectives are proposed by Binz and Reichle (2005) for technical solution ideas (*manufacturer* and *customer benefit*). These perspectives are further detailed by Messerle, Binz, H., and Roth (2013) who propose a number of evaluation criteria. They assign the criteria to two categories: the evaluation of the *potential* and the *mastering* of solution ideas. This view is shared by Reinig and Briggs (2008) who evaluate if a solution idea is *easy to implement* and if it *solves the problem*. Accordingly, Shah and Vargas-Hernandez (2003) evaluate *technical feasibility* and *performance*.

Feasibility is a task-independent general aspect. For example, Messerle et al. (2013) consider criteria for *technical feasibility*. Shah and Vargas-Hernandez (2003) consider *manufacturability*.

In contrast to task-independent feasibility criteria, the *potential of solution ideas* (Messerle et al., 2013), *solving the problem* (Reinig & Briggs, 2008) and *technical performance* (Shah & Vargas-Hernandez, 2003) are task-specific quality criteria.

2.1.2 Novelty

To start at the level of products, novelty can be analysed with regards to different reference frames: for example, Srinivasan and Chakrabarti (2010) consider a product or solution idea *novel* if it is *historically* or *globally* novel, i.e. new to mankind. Shah and Vargas-Hernandez (2003) additionally discuss *societal* (new to a certain society) and *personal* novelty (new to a person). For patentability, *historical* or *global* novelty is required. In other words, an invention is novel and patentable if no information about the invention has ever been published before (European Patent Office, 2013, pp. 112–114). Historical novelty can only be evaluated with reference to existing products which have been sold on a market or inventions which have been published in a patent, research publication or other form.

On the level of solution ideas, evaluating novelty poses a challenge because solution ideas are still undefined with regards to a number of aspects. Researchers have used different approaches to tackle this challenge, e.g. by using experts to rate novelty (Sarkar & Chakrabarti, 2011) or by substituting the direct measurement of novelty. As a substitute for novelty, Shah and Vargas-Hernandez (2003) assign novelty values depending on the *unexpectedness* of a solution idea. They rate the use of common, familiar technologies for a certain technical problem as *expected*. Lopez-Mesa and Vidal (2006) measure the *non-obviousness* of solution ideas. To measure *non-obviousness*, they compare all *solution ideas* generated by several individuals or groups to solve a certain technical problem. A solution idea is more non-obvious if few teams generate the solution idea.

Measuring *variety* provides another substitute for evaluating novelty directly: Srinivasan and Chakrabarti (2010) found a correlation between the variety of concepts on the solution idea level and the novelty of the concepts. Variety is a variable which has to be assessed for sets of ideas, for example the set of ideas of one designer or of a design team (Shah & Vargas-Hernandez, 2003; Srinivasan & Chakrabarti, 2010).

To assess variety for a set of ideas, Shah and Vargas-Hernandez (2003) count the number of ideas on the levels of *physical effect*, *working principle*, *embodiment* and *detail* and multiply them with a weighting. They predefine the functions necessary to fulfil the given task and attribute a weighting depending on the importance of the function. To calculate a normalized variety of a set of ideas, the resulting sum is divided by the total number of ideas.

Nelson and Yen (2009) propose to count the number of differentiations between ideas instead of counting the number of ideas on each level. The number of differentiations is one less than the number of ideas. Consequently, a single idea on each level of abstraction leads to a variety score of zero. Moreover, Nelson and Yen (2009) show that normalizing the variety score is inadequate under certain circumstances: this is the case for two sets of ideas where the first set does not include ideas on the lower levels of abstraction. If the second set of ideas has the same number of ideas on high levels of abstraction but additionally ideas on lower levels of abstraction, its normalized variety score is lower than the variety score of the first set of ideas. Therefore, Nelson and Yen (2009) propose to dismiss the normalizing of variety scores. Dismissing the normalizing of variety scores leads to a combined measure for variety and quantity of ideas (Nelson & Yen, 2009).

A different approach is proposed by Srinivasan and Chakrabarti (2010): they use the seven constructs of the *SAPPhIRE* model to subdivide overall solution ideas. They then compare the solution ideas to each other in a sequential manner: the first solution idea has a variety of zero. The second solution idea is compared to the first one on the different SAPPhIRE levels. Its variety value depends on the highest level of abstraction on which the solution ideas differ: the higher it is; the higher is the calculated value. All subsequent solution ideas are compared to the previous ones and an overall variety for the set of solution ideas is calculated.

2.1.3 Conclusion

Figure 2-2 shows an overview on the factors influencing innovativeness and patentability of technical products. These factors emanate from the ideation phase and the resulting solution ideas. On the one hand, quality measures play a role – general criteria are used to determine the feasibility of solution ideas. Moreover task-specific quality criteria are used to evaluate the potential of the solution ideas for solving a technical task. On the other hand, novelty is related to variety, unexpectedness or non-obviousness on solution idea level.

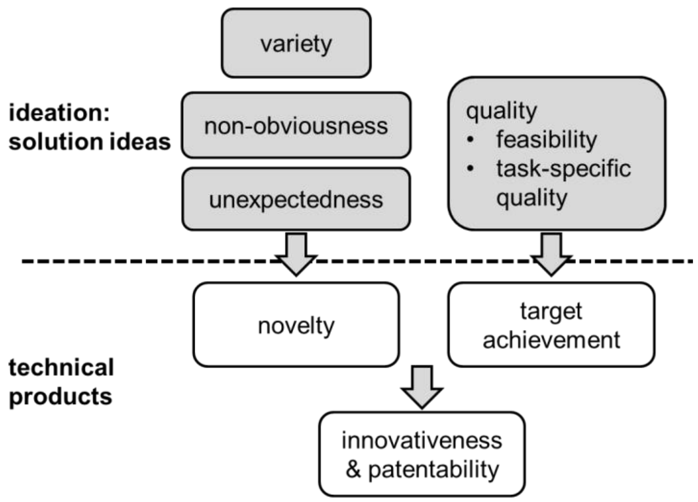


Figure 2-2: Influencing factors on solution idea level for innovativeness and patentability of technical products

2.2 Ideation

As described in the previous section, the generation of novel solution ideas with high quality is crucial for the development of innovative products. In stage gate models such as the VDI 2221 procedural model (VDI, 1993) shown in Figure 2-1(page 10), ideation is the focus of the early phases of product development or engineering design.

In the following, ideation is placed into the context of the product development or engineering design process (2.2.1). Moreover, cognitive aspects of ideation activities are discussed with regards to exploration (2.2.2), generation (2.2.3) and evaluation and documentation (2.2.4). To illustrate the activities with a simple example, a design task used in previous work is applied: the development of a technical solution (or product) to prevent bike theft (Hashemi Farzaneh, Kaiser, & Lindemann, 2012a; Hashemi Farzaneh, Kaiser, Schröer, Srinivasan, & Lindemann, 2012).

2.2.1 Ideation in the context of product development processes

The observation of Blessing (1996) for stages and activities delivers the framework to explain the relation between the overall product development or engineering design process and ideation: On the macro-level of a product development or engineering design process, stages are passed through in a sequential way as described in the VDI 2221 procedural model (VDI, 1993) (still, a number of models allow for iterations). The micro level of each stage involves cyclic activities. In consequence, the overall design or product development process can be seen as a spiral (Blessing, 1996).

Adopting this perspective, ideation comprises activities which are repeated several times throughout the product development process. Researchers have developed a number of models to explain the product development process and the involved ideation activities. The level of granularity changes from model to model. Lindemann (2009, p. 41) emphasizes this by pointing out that the elements of the Munich procedural model can be used both on the macro-level of the product development process and on the micro-level of single stages.

Table 2-1 shows examples for ideation activities from literature. The activities can be assigned to three common categories: *exploration*, *generation* and *evaluation*. A fourth category, *communication* is not explicitly addressed by all the listed researchers. Cross (2008, p. 30) uses these categories in his *simple four-stage model of the design process*. Figure 2-3 places the activity categories in the context of stage gate and spiral models used to describe product development, engineering design and ideation processes.

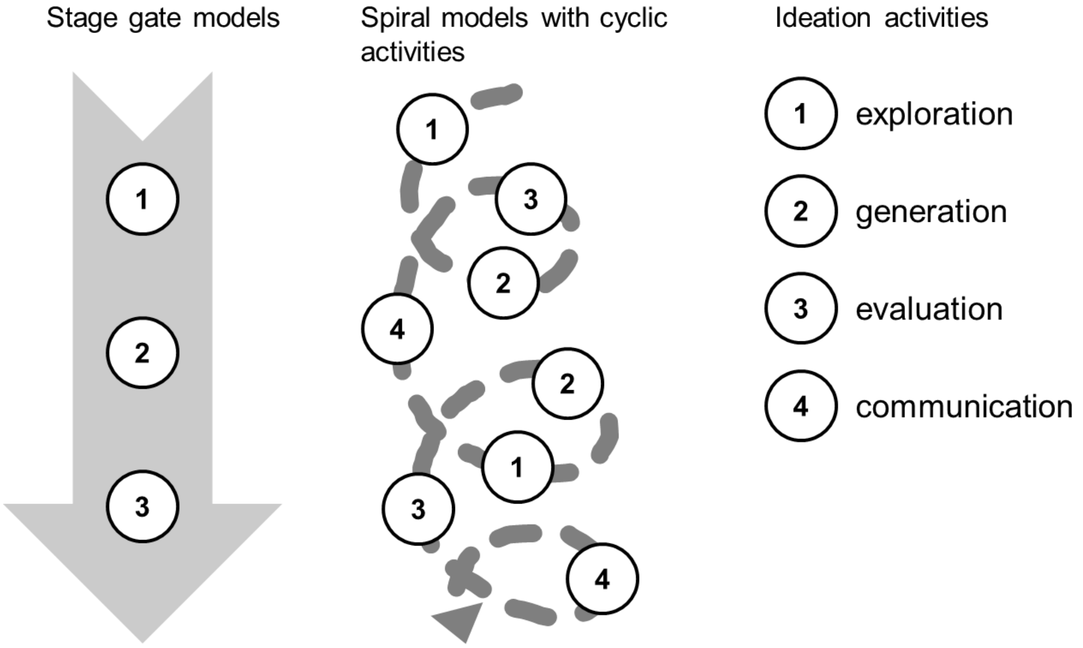


Figure 2-3: Situation of activities and stages in product development, engineering design and ideation models

Within *exploration*, Gero (1990) names both the activities of *formulation* and a later *reformulation* which underlines the cyclic nature of ideation in design. Eder and Hosnedl (2008, p. 64) describe the operations *state the problem* and *prepare information*. Lindemann (2009, p. 40) even describes three activities: goal planning, goal analysis and task structuring. To conclude, exploration comprises the assembling of information on a problem, task or goal. The designer uses this information to structure and focus on a specific ideation task or goal.

As to *generation*, Dörner (1998) and Eder and Hosnedl (2008, p. 64) include a search activity. Gero (1990) underlines a *synthesis* activity. Hatchuel and Weil (2009) focus on the iterative character of generation: One mental concept (e.g. an ideation task) is developed into another concept (e.g. an initial solution idea). To conclude, several researchers focus on different aspects of generation: the search for existing solutions, the generation of new solutions and the iterative character of generation.

Regarding *evaluation*, Gero (1990) and Lindemann (2009, p. 40) include a preceding step before the actual evaluation: analysis or properties assessment of the generated solution ideas. Eder and Hosnedl (2008, p. 64) and Lindemann (2009, p. 40) underline the aspect of selecting or deciding for a solution. Lindemann (2009, p. 40) additionally addresses *ensuring goal achievement*. To conclude, for evaluation, the solution ideas are analysed with regards to the fulfilment of the initially specified task or goal.

Communication is only addressed by Gero (1990) who emphasizes the *design description* and by Eder and Hosnedl (2008, p. 64) who additionally name *communication*.

Table 2-1: Ideation activities of the design/ product development process

reference	**ideation activities**			
Categories based on Cross (2008, p. 30)	exploration	generation	evaluation	communication
Gero (1990)	formulation reformulation	synthesis	analysis evaluation	production of design description
Dörner (1998)	definition	search generation	check	
Eder and Hosnedl (2008, p. 64): basic operations for problem solving	state the problem prepare information	search for solutions	evaluate, decide check, verify, reflect	communicate solution represent
Hatchuel and Weil (2009)		a concept is expanded into other concepts (C-C)	a concept is expanded into new knowledge (C-K)	
Lindemann (2009, p. 40): Munich procedural model	goal planning goal analysis task structuring	generate solution ideas	properties assessment decision making ensuring goal achievement	

In the following subsections, cognitive processes and strategies which play a role for ideation activities are presented with regards to the four categories exploration (2.2.2), generation (2.2.3) and evaluation and communication (2.2.4).

2.2.2 Exploration

In stage gate processes such as the VDI 2221, task clarification is one of the first stages – theoretically a clarified task description has to be the input for most ideation activities. Still, the exploration of the task or goal is a frequent activity during the ideation phase: Cross (2001) reviewed empirical studies of design and identified *problem framing* as a central activity. This is in accordance with Schön's (1983, p. 287) postulation of the idea of reflection-in-action. Regarding design, he observes this reflection-in-action in the discussion of two architects which focusses on the critical review and reframing of a design task (Schön, 1983, p. 102).

Adopting the example of the bike theft task from previous work, a number of *problem frames* are possible. The designer can for example focus on the mechanism of a bike lock or on different options of activating and deactivating the lock. If he or she adopts a broader problem frame, the designer can address infrastructural solutions that provide space for leaving bikes securely. From an even broader perspective, the designer can address the motivation for bike theft.

Empirical studies indicate that an explicit exploration of task and goals influence idea generation positively: Dylla (1990, p. 148) analysed design experiments with six single designers and found that the successful designers conducted a detailed goal and task analysis. Valkenburg and Dorst (1998) analysed the procedure of two design teams in a competition and observed that the winning team had identified one aspect of the task and focussed on this aspect. In contrast, the loosing team had attempted to focus on all aspects (Valkenburg & Dorst, 1998).

The exploration of task and goals is not restricted to the beginning of the ideation phase: Cross (2001) describe the concept of *co-evolution* of the task and solution ideas during ideation: Designers jump between the clarification of the task and the generation of solution ideas. This behaviour has been observed by Kolodner and Wills (1996) who found that a design team refined problem formulations in the process of designing and testing the designed prototypes. Fricke (1996) analysed the procedure of 13 designers and deduced that most successful designers used a flexible exploration strategy, i.e. they switched between solution-neutral task descriptions and sketches of solution ideas.

To conclude, the detailed exploration of the goal and task is a relevant factor for a successful idea generation. Moreover, during ideation, designers switch between exploration and generation and improve their understanding of task and goal. This supports the cyclic perspective on ideation activities depicted in Figure 2-3 (page 15).

2.2.3 Generation

The actual generation of solution ideas – the core of the ideation phase – can be regarded as a process of problem solving. Dörner (1987, p. 14) differentiates between four types of problem solving depending on the clarity of the goal and the familiarity of the means to reach the goal. Adopting his definition, ideation is the "most difficult" type of problem solving: both the goal is not clearly defined (therefore the *exploration* activity is necessary) and the means to reach the goal are unknown.

To tackle this type of challenging problems, general problem solving procedures have been identified in cognitive psychology: Anderson (2009, pp. 209–241) names the cognitive procedures *difference reduction* and *means-end analysis*: *Difference reduction* presumes the identification of the difference between the current state of a situation and the desired state. For example, as to the bike theft task, the difference between the current and the desired state is the movability or portability of a bike. A solution to reduce the movability is to lock it to a bike shed for example. For less obvious solutions, *means-end analysis* plays a role: Instead of regarding only the overall goal – the desired state – subgoals are added. For example, if the problem to "prevent the stealing of a bike" is complicated by the fact that the thief has a bolt cutter, a possible subgoal is to equip the bike with a GPS tracker so that it can be located if it is stolen.

The breaking down of an overall goal into subgoals is a commonly postulated strategy for technical product development or engineering design (e.g. Pahl et al., 2007, p. 243) The idea is to generate partial solutions to each sub-goal separately. Methods and supports such as the Zwicky box explicitly support the combination of these sub-solutions to an overall solution (Ponn & Lindemann, 2011, pp. 116–117). In addition to simplifying the achievement of the overall goal, this is supposed to lead to more solutions. There are different forms of this strategy regarding the level of detail: In design experiments, Dylla (1990, p. 139) observed two different types of designers: The first type broke down the goal to subgoals and generated and detailed one partial solution after the other. The second type generated all partial solutions on a rather abstract level to design an overall concept and then detailed the overall concept.

Even if the overall goal is divided into sub-goals, the generation of partial solutions remains a challenge: Where can solution ideas be found if the means to reach the goals are unknown?

Dörner (1987, p. 77) states for this type of problem solving that individuals often search in a *search space* which is smaller than the *solution space* where the solution can be found. This can be illustrated by the nine-points-problem depicted in Figure 2-4: The points have to be connected by four lines in one stroke. Most individuals restrict their search of the solution to lines between the nine points and not beyond the points.

This observation can be transferred to technical product development and engineering design: If designers try to develop solution ideas, their *search space* is restricted to familiar solutions that they deem adequate for the technical task. However, in the *solution space* there are a number of unknown solutions and solutions that the designers know, but fail to recognize their relevance for the task.

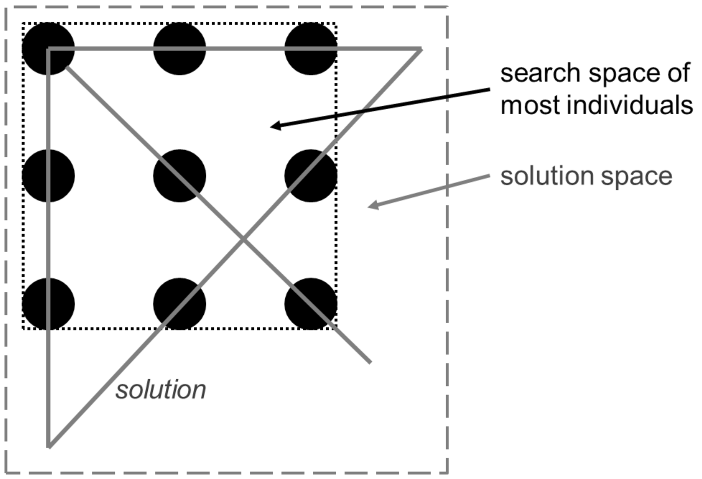


Figure 2-4:Nine-points problem: The search space is smaller than the solution space (Dörner, 1987, p. 77)

In order to enhance the search space of designers, a number of methods have been proposed: To access existing products, inventions and technologies, methods and catalogues have been developed. An example are catalogues of solution principles as proposed by Koller (2011, pp. 465–564) and Roth (2000, pp. 10–211).

Other methods and approaches go beyond the space of existing technical products and inventions: the search space can be further enlarged by drawing on analogies, additionally from non-technical domains: An example is the synectics method proposed by Gordon (1961, pp. 3-7): in a group, a number of *irrational* analogies are generated and explored to solve technical problems.

Analogies and bio-inspired design as an approach to design-by-analogy will be further explored in the following sub-sections.

To sum-up, cognitive approaches to the generation of solution ideas include the breaking up of the task or goal into sub-goals and the generation of partial solutions. These partial solutions are then combined to an overall solution. Solutions are searched for in a search space which is not congruent with the solution space. Using analogies can enlarge the search space and enable the detection of non-obvious solutions which enable the designer to solve the task and reach the goal of ideation.

2.2.4 Evaluation and Communication

In comparison to the divergent activities *exploration* and *generation* which result in a pool of solution ideas, *evaluation* and *communication* are convergent activities: They serve to select a smaller number of solution ideas to be further developed.

On the macro level of the product development and engineering design process, formal methods are proposed for evaluating solution ideas and more detailed designs. Examples are the use of a cost-benefit analysis with weighted points (Pahl & Beitz, 2013, p. 112) or an evaluation algorithm based on the *Quality Function Deployment* method (Binz & Reichle, 2005).

On the micro level of ideation, the evaluation of solution ideas precedes their communication to others including the documentation of solution ideas. However, designers do not necessarily use formal methods to decide whether they want to communicate and document a solution idea or not. If formal evaluation methods are used, they are rather simple. For example, Lindemann (2009, p. 165) proposes the use of simple criteria for exclusion to pre-select of a number of solution ideas from a high quantity of solution ideas.

Consequently, the rather implicit evaluation of solution ideas is subject to heuristics. Heuristics in a cognitive sense are mental simplifications that unconsciously influence judgement and decisions (Hallihan, Cheong, & Shu, 2012). They mentally enable humans to take quick decisions (Gilovich, Griffin, & Kahneman, 2002, p. xv)

Hallihan et al. (2012) have identified eleven heuristics or biases they consider *relevant* for technical product development or engineering design. They conducted a study on the influence of *confirmation bias* described as the tendency to interpret information in a way that it confirms existing beliefs and to disregard information inconsistent with these beliefs. There are several other heuristics leading to the misjudgement of information (e.g. r*epresentativeness*, *anchoring*). Other heuristics are related to the effort that has been put for a solution idea (e.g. *effort*, *sunk cost*) and the time or sequence of the presentation of information (e.g. *primacy and recency*, *mere exposure*) (Hallihan et al., 2012). The bike theft example shows how heuristics can push designers to concentrate on single aspects of a problem: nowadays, individuals are exposed to mobile phones and mobile applications very frequently. The frequent exposure to this stimulus can cause the *mere exposure* effect: A designer possibly concentrates on the use of mobile applications for actuating the bike lock neglecting other aspects of the design task (such as the locking mechanism).

If ideation is conducted in pairs or groups, additional cognitive effects play a role and can lead to the quick abandonment of solution ideas. An example is *distraction conflict* – participants of a pair or group are distracted by the communication and the solution ideas generated by other participants. They therefore do not communicate solution ideas or abandon communicated solution ideas (Baron, 1986).

In previous work, design experiments with groups of mechanics, industrial design students and mechanical engineering students were conducted and analysed with regards to cognitive effect and biases. It was observed that a number of solution ideas were not documented by the groups even though the instructions stated that all solution ideas had to be documented by means of annotated sketches. The abandonment of solution ideas was often not based on an extended discussion or evaluation. Several cognitive effects were identified in the transcriptions of the videos from the design experiments Therefore, an influence of heuristics and other cognitive effects on the decision was assumed (Hashemi Farzaneh, Kaiser, & Lindemann, 2012; Hashemi Farzaneh, Kaiser, & Lindemann, 2013).

To conclude, heuristics and other cognitive effects in pairs or groups can lead to the abandonment of solution ideas during ideation. Consequently, a number of generated solution ideas are not documented. To take this into account, in this work, all generated solution ideas are analysed, not only the documented solution ideas.

2.2.5 Conclusion

Figure 2-5 summarizes the discussed cognitive aspects of ideation activities. When developing a solution idea, designers run through a micro-cycle of exploration, generation, evaluation and communication activities. The explicit exploration of the ideation task positively impacts on solution ideas. For the generation of a solution idea, an overall ideation task is commonly broken down to sub-tasks and partial solutions are generated. The terms *search* and *solution space* play an important role in design research: Analogies enlarge the search space so that parts of the solution space otherwise ignored by the designers are accessed. For the evaluation and communication of solution ideas, heuristics and team or pair effects play a role: They can lead to the ad-hoc abandonment of solution ideas.

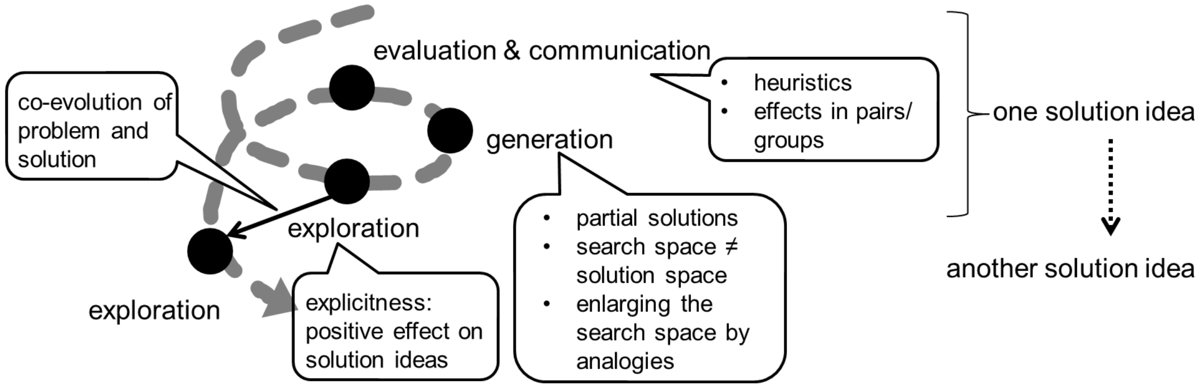


Figure 2-5: Cognitive aspects of ideation activities

2.3 Analogies and bio-inspired design

The Oxford Dictionary (2013) defines the term analogy as a “comparison between one thing and another [two “analogues”], typically for the purpose of explanation or clarification.” In the following sub-sections, the transfer of analogies (2.3.1) and dimensions of analogies (2.3.2) are explained. Then an introduction to bio-inspired design is given: an approach that entails the deliberate transfer of analogies from the biological to the technical domain (2.3.3)

2.3.1 Transfer of analogies

The process of analogical transfer has been studied in cognitive psychology from a general perspective. Researchers have emphasized the aspect of mapping: a knowledge transfer from one familiar situation – the base or source domain – to an unfamiliar situation – the target domain (Gentner, 1983; Gick & Holyoak, 1983). The aims of this knowledge transfer can be multiple: examples are the understanding of unfamiliar situations or the solving of unfamiliar problems. To enable a mapping between two analogues, in particular syntactic, relational properties play a role: Gentner (1983) argues that analogies can be distinguished from other types of similarities and comparisons by their purely syntactic rules. According to Hesse (1970, p.59), analogues possess “horizontal” (i.e. “similarity”) relationships between the two analogues and “vertical” (i.e. “causal”) relationships between two aspects of one of the analogues.

This view can be adopted for ideation in engineering design as shown in Figure 2-6: To solve a new problem in one domain A, one strategy is to identify a similar problem in another domain B with an existing solution via a “horizontal” relation. The “vertical” problem-solution relation in domain B can serve as an analogy, i.e. knowledge about this relation can be transferred to develop a solution in domain A.

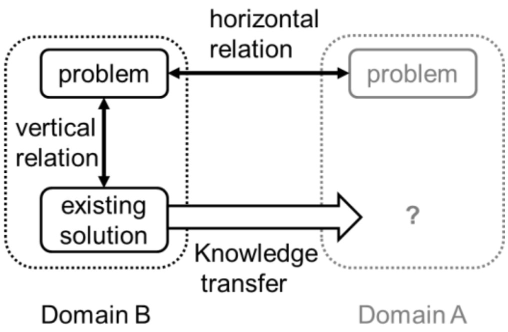


Figure 2-6: Analogical transfer for ideation

Goel (1997) states that analogical design implies “reminding and transferring knowledge about one design situation to another” for different design tasks in the new situation. A number of studies have focused on analogical transfer for ideation (e.g. Chan et al., 2011; Dahl & Moreau, 2002; Srinivasan, Chakrabarti, & Lindemann, 2013). The studies took into account different dimensions of analogies explained in the next sub-section.

2.3.2 Dimensions of analogies

A number of parameters have been established and examined in empirical studies to differentiate between several dimensions of analogies. An overview is depicted in Figure 2-7.

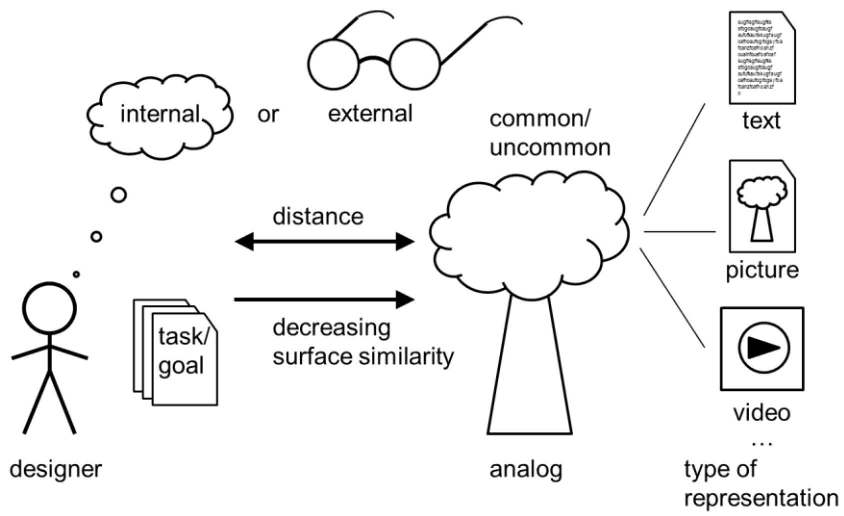


Figure 2-7: Dimensions of analogies

Analogies can have different sources: They can be internal – the designer retrieves them from personal knowledge acquired due to past experiences – or external – there is a source of knowledge or inspiration which acts as a stimuli or trigger (Srinivasan et al., 2013). If the source of analogy is external, different types of representation can be used, for example pictorial or textual representations (Chan et al., 2011).

In addition, analogies can be differentiated by the commonness of the presented information – if it is likely that the designer has encountered it before, it is considered common (Chan et al., 2011).

Another aspect is the distance of the analogue: It can be from more or less distant domains or fields, e.g. patents of technical systems can have a more or less similar purpose compared to the design task (Chan et al., 2011). Analogues from more distant domains are less surface-similar, so that the designer has to rely on the relational (structural) similarities (Chan et al., 2011; Gentner, 1983; Wilson, Rosen, Nelson, & Yen, 2010) Moreover, the verbal formulation of the analogues can be regarded and a semantic distance deduced, e.g. "food peelers" are more similar to "nutcrackers" than "depilators" (Lopez, Linsey, & Smith, 2011). Similarly, entire textual descriptions, such as patents, can be analysed and compared by means of computational tools to calculate their distance (Fu et al., 2012).

In the following sub-section, an approach to analogical transfer using distant analogies is presented: bio-inspired design.

2.3.3 Bio-Inspired Design

Nature offers countless biological solutions tested by evolution (VDI, 2012) – accessing these solutions can considerably enlarge the search space for designers. Therefore, bio-inspired design aims at the *abstraction, transfer, and application of knowledge gained from biological models* (VDI, 2012). In other words, bio-inspired design implies the transfer of analogies from the natural domain to the technical domain (Vattam, Wiltgen, Helms, Goel, & Yen, 2011). In this regards, bio-inspired design is an approach to design-by-analogy using distant analogues (see Figure 2-6, page 22).

Researchers have developed and applied a number of procedures for bio-inspired design. On the one hand, there are technology-pull (also called top-down or problem-driven) approaches which start with a technical task for which a biological analogue has to be found. On the other hand, there are biology-push (also called bottom-up or solution-driven) approaches. They originate in knowledge about biological solutions which is used to develop a technical application (Helms, Vattam, & Goel, 2009; Schenkl, Kissel, Hepperle, & Lindemann, 2010; VDI, 2012).

As the starting point for ideation in this work is a technical task, the technology-pull approach is relevant. Technology-pull approaches are described by a number of researchers. An overview is given in Table 2-2. The described steps of bio-inspired design can be assigned to the ideation activities *exploration* and *generation* (compare Table 2-1).

Table 2-2: Exemplary technology-pull procedures for bio-inspired design

	Exploration	**Generation**		
		Search	**Analysis**	**Transfer**
Lindemann and Gramann (2004)	1) Formulate the intention/ the target	2) Correlate biological systems	3) Analyse the correlated systems	4a) Is it possible to deduce a technical analogy? 4b) Realise the technical solution* 5) Is the degree of abstraction adequate? 6) Is the intention realistic?
Lenau, Dentel, Ingvarsdóttir, and Gudlaugsson (2010)	1) Problem definition phase	2) Search phase	3) Analysis phase	4) Principle phase 5) Design phase*
VDI (2012)	1) Analysis			2) Analogy/ abstraction 3) Project/ design of experiments* 4) Experiments/calculations* 5)Prototype construction/ manufacturing* 6)Application tests* 7) Overall evaluation*

*subsequent steps of the product development process

Specific to bio-inspired design is the search for biological systems to be used as analogues, the analysis of these analogues and the transfer of a bio-inspired analogy. These activities can be integrated into the analogical transfer process depicted in Figure 2-6 (page 22). The result is shown in Figure 2-8. For the further development of the bio-inspired solution idea, the technology-pull procedures refer to subsequent steps of the product development process which are not specific to bio-inspired design. Hereby, the VDI (2012) emphasizes the importance of experiments and further tests of the bio-inspired solution.

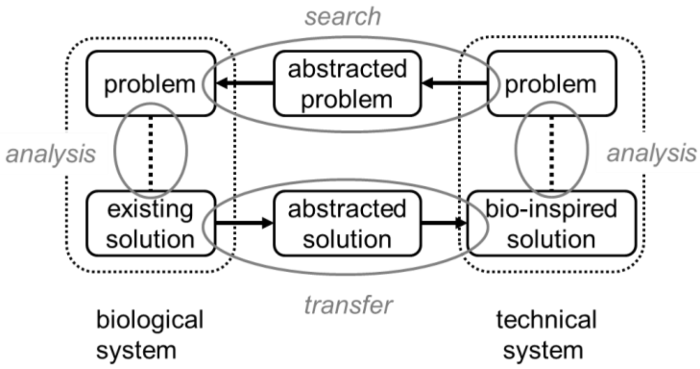


Figure 2-8: Search and analogical transfer in bio-inspired design

The *search* activity aims at identifying a biological system in the biological domain. The biological system has to address a similar problem as the technical problem and "solves" this problem with a solution. The challenge of the *search* activity is the identification of the similar problem in biology: Designers have to abstract technical tasks or problems and to formulate them in a more general way to enable the search for a similar problem in biology (Lindemann & Gramann, 2004). The *analysis* activity implies the examination of the existing biological solution and the addressed problem. The *transfer* activity implies the actual transfer of the existing solution to the engineering domain and to generate a technical solution. Again, a step of abstraction is required, as the biological system with its solution often cannot be used in the technical domain directly.

The importance of the adequate abstraction level has been emphasized by a number of researchers (Lindemann & Gramann, 2004; Mak & Shu, 2004a) Based on an abstracted solution, a concrete technical solution can be developed. To analyse bio-inspired solution ideas and their abstraction level, researchers have therefore developed different measures:

Mak and Shu (2004b) and Vakili, Chiu, Shu, McAdams, and Stone (2007) define four categories for the ***accuracy*** of bio-inspired physical effects and working principles ("strategies"): *Unrelated* strategies have no link to the biological system. *Incorrect* strategies are inspired by the biological system, but the designers misinterpret the strategy. *Incomplete* strategies use a "general principle" behind the biological strategy, but not the concrete strategy (Vakili et al., 2007). *Correct* strategies consist of "similar elements" compared to the biological strategy (Mak & Shu, 2004b).

Mak and Shu (2004a) define two dimensions to evaluate ***similarity***: The *strategic accuracy* and the *abstraction of biological entities*. The four resulting values are illustrated in Figure 2-9: An analogy is regarded as *strategically accurate* if the biological strategy to solve the addressed problem is transferred to the technical solution idea. The biological entities are considered *abstracted* if no elements from the biological inspiration are directly used in the technical solution idea.

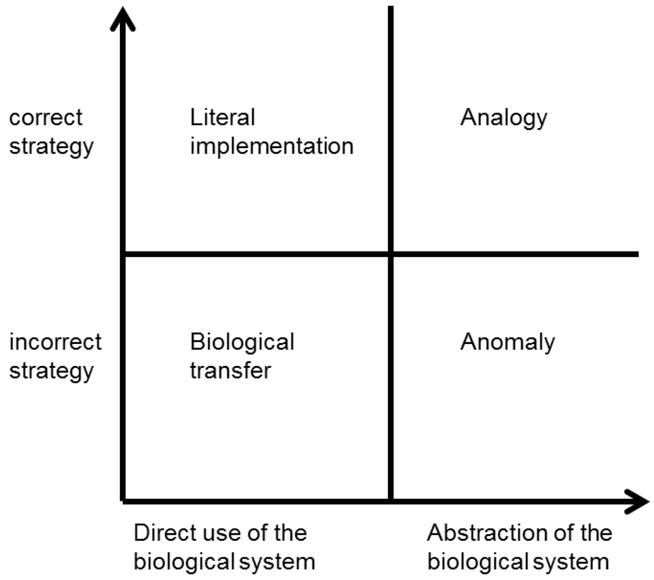


Figure 2-9: Analogy types: Dimensions of similarity

Another measure are the ***elements of transfer*** as defined by Sartori, Pal, and Chakrabarti (2010). They regard analogies using the SAPPhIRE model (Chakrabarti, Sarkar, Leelavathamma, & Nataraju, 2005) and identify five abstraction levels on which bio-inspired analogies are transferred: *Copy parts* is the use of the biological material and structure for the technical solution. *Transfer organs* implies transferring properties or conditions that are necessary for solving the problem. *Transfer attributes* entails the transfer of properties, but it is unclear if they contribute to solving the addressed problem. *Transfer state change* describes a more abstract analogical transfer, i.e. the technical system solves a similar problem as the biological system, but not with the same means. *Resulting transfer* implies an unintended transfer of analogies or similarities from the biological system.

To conclude, both the search and transfer activity require the understanding of the biological and technical system. This is a challenge for designers, as they are mostly educated in the technical domain, but do not possess sufficient biological knowledge to understand the biological system. Approaches to tackle this challenge are presented in the next sub-section.

2.3.4 Conclusion

Analogical transfer is a mechanism of idea generation that enlarges the search space for designers. There are different dimensions of analogies. Bio-inspired design is an approach for the use of distant analogies from the biological domain. Researchers have developed different procedures for exploration and generation activities. The generation activities include search and analysis of biological systems and the transfer of an analogy. To analyse bio-inspired solution ideas, different analogy types have been defined.

2.4 Tackling the challenges of bio-inspired design

As shown in Figure 2-8, bio-inspired design and its activities of search and transfer require the understanding of both disciplines. For understanding, knowledge is required. Probst et al. (2012, p. 16) define *knowledge* as cross-linked *information*. *Information* is defined as *data* set into context. From this perspective, the technical task description or articles or books on biological systems can be considered as information. To understand the relations (cross-links) of these pieces of information, knowledge is required in both the mechanical engineering and biological discipline. Disciplines have “a specific body of teachable knowledge with their own background of education, training, procedures, methods and content areas” (Apostel, 1972). Designers are often mechanical engineers who have no education in biology. This results in a lack of knowledge for bio-inspired design. Researchers have proposed a number of methods and tools or suggest the collaboration between biologists and mechanical engineers to tackle the knowledge gap. Both approaches are discussed in the following sub-sections.

2.4.1 Methods and tools

This sub-section gives an overview on existing methods and tools for bio-inspired design, assigned to the activities of *search*, *analysis* and *transfer* illustrated in Figure 2-8 (page 25).

Search

A number of methods and tools have been proposed to support the search activity in bio-inspired design:

One approach is the presentation of pre-processed information on biological systems in **catalogues and databases**. Similar to the catalogues of existing technical solution principles (Koller, 2011, pp. 465–564; Roth, 2000, pp. 10–211), these catalogues and databases support the search of biological systems via functions. The term *function* is a technical concept which describes the purpose of a technical system (Ponn & Lindemann, 2011, p. 434). Hill (1997, pp. 107–221) and Löffler (2009, pp. 87–95) use basic functions similar to Koller (2011, pp. 465–564) and Roth (2000, pp. 10–211) for accessing a catalogue of biological systems. Hill (1997, pp. 107–221) describes the basic functions with combinations of five verbs *transfer, hold, connect/ separate, store/ block* and *form* with the three objects energy, material and information. Lindemann and Gramann (2004) use a taxonomy of less abstract functions described by verbs for an association list. The Biomimicry Institute (Deldin & Schuknecht, 2014) developed a taxonomy of verbs and objects for accessing an online database of biological phenomena and systems. Chakrabarti et al. (2005) includes further technical constructs in addition to *function* (called *action*) in the SAPPhIRE model which can be used to map technical and biological system in the IDEA-INSPIRE database.

The type of information presented in catalogues and databases differs: Hill (1997, pp. 107–221), Lindemann and Gramann (2004) and Löffler (2009, pp. 87–95) present abstracted biological principles, Chakrabarti et al. (2005) model biological systems with the technical constructs of the SAPPhIRE model. The Biomimicry Institute’s *asknature* database (Deldin

& Schuknecht, 2014) gives access to textual descriptions, pictures and links to further information.

However, all catalogues and databases have in common that they present pre-processed information on biological systems which often have already been explored for bio-inspired design (Kaiser, Hashemi Farzaneh, & Lindemann, 2012, 2014). This decreases the chance of finding biological analogues that inspire novel solution principles which have not been used for existing bio-inspired products.

An approach to find biological systems with unknown solutions is the search in **biological publications** which have not been pre-processed for bio-inspired design. Researchers have developed a number of strategies for formulating search terms to search for biological publications, e.g. in internet databases. They are based on the reformulation of abstract technical functions to search terms common in biology: Hacco and Shu (2002) use synonyms and other variations of search terms. Chiu and Shu (2007) propose the use of biological meaningful keywords they identified in biological textbooks. Nagel, Stone, and McAdams (2010) developed an engineering-to-biology thesaurus. Kaiser et al. (2014) propose to use search terms for properties and environmental influences in addition to functions.

Analysis and Transfer

Researchers have developed models to represent biological information for the purpose of analysis and a subsequent analogical transfer. According to Stachowiak (1973, p. 157), models can be defined by three distinctive features: Firstly, they have a representative feature, i.e. a model is a representation of an original. Secondly, models have a reduction feature: As a result of abstraction, they do not represent all attributes of the original. Thirdly, the pragmatic feature underlines that a model is used for a specific purpose at a specific time (Stachowiak, 1973, p. 157).

Accordingly, Nachtigall (2010, pp. 79–85) defines models as abstracted representations of biological systems (representative and reduction feature) which facilitate their explanation and can be used to develop a technical system (pragmatic feature).

For analysis and transfer in bio-inspired design, the use of the SAPPhIRE model (Chakrabarti et al., 2005), the DANE model (Vattam et al., 2011) and the inspiration cards (also called Biocards) (Lenau, Helten, Hepperle, Schenkl, & Lindemann, 2011; Lenau, Keshwani, Chakrabarti, & Ahmed-Kristensen, 2015)) have been described (e.g. by Keshwani, Lenau, Kristensen, & Chakrabarti, 2013, Lenau et al., 2015, Chakrabarti, 2014).

The SAPPhIRE model includes seven constructs to describe biological and technical systems, i.e. *state change*, *action*, *part*, *physical phenomenon*, *input*, *organ* and *physical effect*. The models allows also to *"structure information in a database of systems from both domains"* (Chakrabarti et al., 2005). The DANE model focusses on input-output relationships and includes descriptions of structure, behaviour and function of the described biological and technical systems (Vattam et al., 2011). The inspiration cards include sketches and a description of the biological system and its abstracted solution principle formulated in technical terms for functions (Lenau et al., 2011).

Independent of the concrete modelling approach for the abstracted representation of a biological system, knowledge is required. A lack of knowledge can lead to a misunderstanding of the biological system. If designers are mechanical engineers, collaboration with biologists can be a solution.

Despite their differences, the models described above are based on concepts of function, behaviour and structure which have been used in particular for the abstraction of technical systems. In biological research, different models are used for describing biological systems (Hashemi Farzaneh et al., 2016).

2.4.2 Collaboration between mechanical engineers and biologists

Collaboration between mechanical engineers and biologists was observed by several researchers (Helten, Schenkl, & Lindemann, 2011; Vattam, Helms, & Goel, 2008, 2009, 2010) They studied teams of undergraduate students of biology and engineering. The teams ran through an entire engineering design process over an extended period of time. From the studies, mainly positive results were reported: for example, Helten et al. (2011)found that the collaboration led to a better an quicker understanding and evaluation of biological systems. However, the studies' explanatory power is limited by three factors: Firstly, the observed teams consisted of undergraduate students – It is not clear if they can be transferred to collaboration between graduated mechanical engineers and biologists. Secondly, due to the extended period of the projects, not every design stage was observed closely, in particular there are no detailed results on ideation activities. Thirdly, the studies do not include a comparison to teams of one of the disciplines. Therefore, they do not enable a direct comparison regarding the effect of the bi-disciplinarity of the teams.

In comparison, research on collaborations between professionals from different disciplines results in both negative and positive results: Mannix and Neale (2005) reviewed psychological research on diversity in teams and found that the negative effects prevail in the majority of research contributions. They conclude that self-and social categorization plays a role: individuals categorize others and have expectations based on this categorization. Based on these expectations, they develop stereotypes about individuals belonging to a different "category" (Mannix & Neale, 2005).

However, conflicts and confrontation can positively influence ideation: Stempfle and Badke-Schaub (2002) discuss cognitive confrontation as a necessary component of creativity. Kurtzberg (2005) reported that even though individuals in diverse teams feel less creative, they develop a higher number of ideas.

With regards to the goal of collaboration between biologists and engineers – the improved understanding of biological and technical system - a knowledge transfer is required. This knowledge transfer can be hindered by different manners of presenting information and terminology (Helten, Schenkl, & Lindemann, 2011; Jordan, 2008, p. 107).

2.4.3 Conclusion

There are two approaches to tackle the challenges of search, analysis and transfer activities in bio-inspired design: The use of methods and tools as supports and collaboration between engineers and biologists. All activities require knowledge of biology and mechanical engineering. Most designers are engineers and therefore do not possess enough knowledge in biology.

On the one hand, pre-processed information on biological systems can be searched for in catalogues or databases. The disadvantage of this approach is the limitation to already explored biological systems.

On the other hand, designers can search for biological publications. There are a number of approaches to support this search, but the transfer of analogies from biological publications again requires knowledge of both disciplines. This is still a requirement, even if modelling approaches such as *SAPPhIRE*, *DANE* or *inspiration cards* are used. A possibility to solve this problem is collaboration between engineers and biologists. However, interdisciplinary collaborations in general are not always successful. No studies specifically compare ideation in bi-disciplinary pairs or teams of biologists and engineers to uni-disciplinary pairs or teams. No supports that especially focus on these collaborations have been developed for bio-inspired design.

3. Research approach

Innovative and patentable products are the overall goals of new product development. As explained in the previous section, patentability requires the novelty of the developed technical solution: It has to be unique and novel so that no other patent or product using this technical solution exists. Innovativeness requires novelty and additionally the success of the product on the market. This target achievement of the product benefits both customer and company.

How can bio-inspired design contribute to this goal?

Figure 3-1 illustrates the train of thought of this work similar to a reference or impact model as proposed by Blessing and Chakrabarti (2009, pp. 20–25): It depicts factors on the product or technical solution level, the level of solution ideas and the level of designers who develop the ideas. The expected positive relations of the factors are shown as arrows.

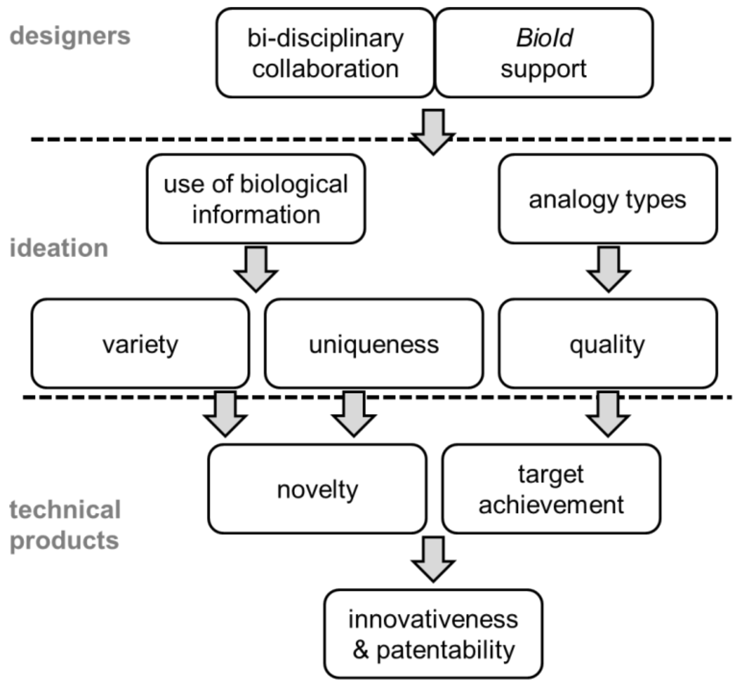


Figure 3-1: Model to illustrate the train of thought of this research

In a product development project, the final technical solution and product is developed out of a number of solution ideas. There are many development steps between the first solution ideas and the final technical solution and product. Nevertheless, this work is based on the assumption that the novelty of a solution idea positively influences the novelty of the final product. Moreover, it is expected that the quality of a solution idea positively impacts on the target achievement of the final technical solution and product. As bio-inspiration plays its major role in the ideation phase, the influences of the development steps following ideation are not regarded in this work.

Novelty is not measured directly in this work, because it is not possible to verify the global novelty of a preliminary solution idea. However, focusing on the ideation phase, the novelty of a solution idea can be influenced by several factors: Srinivasan and Chakrabarti (2010) found a correlation between the variety of concepts on the solution idea level and the novelty of the concepts. In addition to variety, the uniqueness of solution ideas is regarded as a factor influencing novelty. In this work, uniqueness implies that a solution idea is only generated based on one inspiration. The underlying assumption is that uniqueness on the inspiration level increases the probability of novelty on a global level. Similar assumptions have been made for the measures *unexpectedness* (Shah & Vargas-Hernandez, 2003) and *non-obviousness* (Lopez-Mesa & Vidal, 2006). Here, it is expected that the use of several, different biological information sources impacts on variety and uniqueness of solution ideas: This relation will therefore be measured.

Regarding quality, it is expected that different analogy types describing the correctness of analogical transfer (accuracy) and the level of abstraction (similarity, elements of transfer) have an impact. In this work, the influence of different analogy types on the quality is therefore analysed.

In the previous section, a number of approaches to bio-inspired analogical transfer have been presented: The challenge of bio-inspired analogical transfer is to extract the adequate analogy from biological systems. In product development, the designers searching for solution ideas traditionally have a technical education which did not include the teaching of biological knowledge. This challenge can be faced by preparing information about specific biological systems for the designers. Moreover, databases of prepared information on biological systems have been developed (see section 2.4.1, p. 27). The limitation of this approach is that only selected and prepared biological systems are accessible to designers. Another approach is the collaboration with biologists. This approach does not limit the number of biological systems to a database, but opens the access to biological systems which have not been explored for bio-inspired design. This creates possibilities for finding unknown solutions in nature increasing the potential for novel solution ideas.

So far, the collaboration of biologists and engineers in the ideation phase has not been researched in an experimental setting. The aim of this work is to close this gap and address the influence of bi-disciplinary collaboration on the quality, variety and uniqueness of solution ideas developed in an ideation phase with biological information. For this purpose, an embedded mixed methods approach according to Creswell (2014, pp. 215–240) is used: Quantitative data is collected in design experiments to test the influence of pairs of biologists and engineers on the solution ideas. Qualitative data from observations in the experiments is explored to explain the influences. Based on the findings and related research, the *BioId* support for these bi-disciplinary pairs is developed and evaluated in the same experimental setting.

The following sub-sections present the research questions (3.1) and the research methodology (3.2) in detail.

3.1 Research questions

As shown in Figure 3-1, the goal of this work is to analyse the influence of bi-disciplinary collaboration in an ideation phase with biological information on the innovativeness of technical solutions. As the focus of the study is the ideation phase, quality, variety and uniqueness of solution ideas are analysed as measures for innovativeness. In a first study, bi-disciplinary pairs (one biologist and one engineer) are compared to uni-disciplinary pairs (two biologists or two engineers). Based on the results, the *BioId* support is developed. In a second study, the influence of bi-disciplinary pairs working with the *BioId* support (support pairs) is examined in addition to the influence of the pair composition. The following research questions guide the studies:

1. How do the **pair composition** and the ***BioId* support** influence the **quality** of solution ideas developed in an ideation phase with biological information?
2. How do the **pair composition** and the ***BioId*** support influence the **variety** and **uniqueness** of solution ideas developed in an ideation phase with biological information?

The following sub-questions will be regarded to answer the two research questions:

A quantitative approach is used for examining the relations depicted in Figure 3-1:

1. **Quality** of solution ideas
   1.1. How do the pair composition and the support influence the analogy types transferred from biology to develop technical solution ideas?
   1.2. How do the analogy types influence the quality of solution ideas?

2. **Variety/uniqueness** of solution ideas
   2.1. How do the pair composition and the support influence the use of biological information sources in ideation?
   2.2. How does the use of biological information sources influence the variety of solution ideas?
   2.3. How do the pair composition and the support influence the variety of solution ideas?
   2.4. How does the use of biological information sources influence the uniqueness of solution ideas?
   2.5. How do the pair composition and the support influence the uniqueness of solution ideas?

A qualitative approach is used to explain the relations:

3. How does the participants' view explain differences in the use of biological information sources, the analogical transfer and the developed solution ideas during ideation?
4. How do the procedures of the pairs explain differences in the use of biological information sources, the analogical transfer and the developed solution ideas during ideation?

3.2 Research methodology

The Research methodology is based on the *Design Research Methodology* developed by Blessing and Chakrabarti (2009): In a first descriptive study, bi-disciplinary pairs of one biologist and one mechanical engineer are compared to uni-disciplinary pairs of biologists and engineers working on a bio-inspired design task. Based on this descriptive study, a prescriptive study is conducted to develop a support for bi-disciplinary pairs. A second descriptive study with the same experimental set-up is used to analyse the influence of the *BioId* support and to reassess the influence of the bi-disciplinary collaboration with additional pairs.

In the following, the experimental methodology (3.2.1) and the analysis methodology (3.2.2) are described.

3.2.1 Experimental methodology

Participants

For this work, design experiments with ten biologists (of which four had graduated in bio-physics, bio-chemistry, bio-informatics or biogeography) and ten mechanical engineers were conducted. The participants were research assistants at several institutes from different areas of biology and mechanical engineering of the Technical University of Munich. Since each participant had a different research topic for his or her doctoral thesis, it is assumed that each participant had a different area of expertise. A list of the research areas and topics of the participants is shown in the appendix (11.1). The participants volunteered for participating in the study.

A total number of eight individuals (four biologists, four mechanical engineers) participated in the study in the year 2013. Twelve individuals participated in the study in the year 2015 (six biologists, six mechanical engineers). The assignment to pairs was adapted in the second study to have the same number of biologist pairs, engineer pairs, bi-disciplinary pairs without support and bi-disciplinary pairs with support (five each).

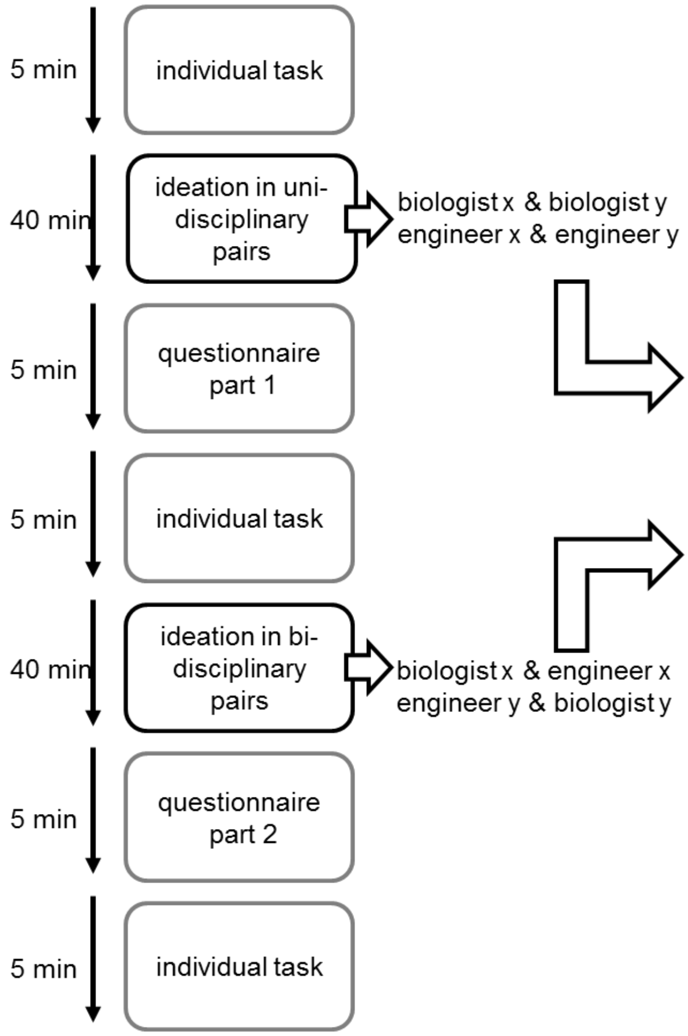
Experimental procedure

Figure 3-2 shows the experimental procedure: The participants took part in two design experiments, answered questionnaires and solved individual tasks.

All design experiments were conducted with pairs of two participants. The experimental procedure is shown in Figure 3-2. The same experimental procedure was conducted in both studies (2013 and 2015). Each participant first collaborated with another participant from the same discipline working on one design task. Subsequently, each participant collaborated with one participant from the other discipline working on another design task. This experimental procedure deviates from classical experimental design, because all participants participated in the control (uni-disciplinary pairs) and the experimental group (bi-disciplinary/ support pairs).

To implement the experimental procedure, pairs of two biologists (termed biologist “x” and “y” in Figure 3-2) and two engineers (termed engineer “x” and “y” in Figure 3-2) were formed considering their availability at the dates of experiments. After the ideation in uni-disciplinary pairs, the participants were assigned to a bi-disciplinary pair by drawing lots.

For the experiments conducted in 2013, there were eight participants, resulting in two biologist pairs, two engineer pairs and four bi-disciplinary pairs working without a support. Based on the analysis of these experiments (first descriptive study), the *BioId* support was developed. For the experiments conducted in 2015, there were twelve participants. For the second descriptive study, the data from both rows of experiments (2013 and 2015) was analysed. One aim of the second descriptive study was the evaluation of the *BioId* support. Moreover, the results of the first descriptive study regarding the influence of the pair composition were reassessed with the data from the additional pairs. Therefore, in the planning of the experiments for 2015, the numbers of pairs were counterbalanced to have five pairs of each category. Consequently, one bi-disciplinary pair in the second study worked without support (see Figure 3-2).



	2013	2015
participants	8	12
biologist pairs	2	3
engineer pairs	2	3
bi-disciplinary pairs (no support)	4	1
bi-disciplinary pairs with support	-	5

first descriptive study (2013)

second descriptive study (2013 and 2015)

Figure 3-2: Experimental procedure

The order of participation (first a uni-, then a bi-disciplinary pair) was chosen to exclude a possible influence of learning: the participants might learn something from the other discipline in the bi-disciplinary pair and use it afterwards. Apart from a positive influence of learning, negative effects due to fatigue are possible. Therefore, both negative and positive order effects were tested by three individual tests as shown in Figure 3-2: before the first design experiment, between the experiments and after the second design experiment. The design experiments had duration of 40 minutes both for uni- and bi-disciplinary pairs. The duration was announced to the participants and after 30 minutes, they were reminded that they had ten minutes left for their task. The participants had a couple of minutes to fill out a questionnaire after both design experiments. The individual tasks had to be completed in approximately five minutes, after which all task sheets were collected from the participants. There were no breaks between design experiments, filling of questionnaires and individual tasks – just a couple of minutes were necessary to change the rooms.

The experiment design results in five uni-disciplinary pairs of biologists, five uni-disciplinary pairs of mechanical engineers, five bi-disciplinary pairs (one biologist, one mechanical engineer) working without a support and five bi-disciplinary pairs working with the *BioId* support developed in the prescriptive study (support pairs). The detailed assignment of participants to pairs and design tasks is shown in the appendix (11.3).

For the analysis of the first study, the first row of experiments with 8 participants was regarded. For the second study, the data from both rows of experiments was regarded. This resulted in a total number of 20 participants.

Materials

Design experiments in uni-/ bi-disciplinary pairs

At the beginning of the design experiments in uni- and bi-disciplinary pairs, all pairs received a design task and three information sources providing biological information: a video, a Wikipedia[1] article and a research publication.

The **design task** included a textual description, in two cases an illustrative figure, and the task itself. The task was described by a sentence of the form “develop a solution to …” It was followed by the instructions to develop as many solutions as possible and to document them by annotated sketches. Two or three requirements were given. The participants were not explicitly told to develop bio-inspired solution ideas, but received the video, Wikipedia article and research publication as “information from biology”. Therefore, they inferred to use this information for their solution ideas. The participants were not given instructions on bio-inspired design or design-by-analogy. The design tasks are included in the appendix (11.2).

Using different **information sources** allows for comparing the use of the information source by uni- and bi-disciplinary pairs. Video, Wikipedia article and research publication were used to replicate realistic sources of information in bio-inspired design and creative ideation in

[1] The term “Wikipedia articles” refers to selected articles published online by Wikimedia Deutschland - Gesellschaft zur Förderung Freien Wissens e.V./ Wikimedia Foundation Inc. (see appendix 11.2)

general: In an internet search, a designer can encounter and access these biological information sources. Moreover, they vary regarding the type of representation, i.e. the amount of text and pictures: The selected videos consist of moving pictures and in some cases verbal comments. The Wikipedia articles and research publications include both pictures and text. In addition, the amount of textual information is low in the selected videos, higher in the Wikipedia articles and highest in the research publications. Inversely, the videos contain few technical terms, the Wikipedia articles more and the research publications most. Moreover, the videos contain more pictorial information.

Three comparable design tasks and selected biological information for each task (video, Wikipedia article and research publication) were used in the design experiments. Each participant worked on a different design task in each design experiment. The design tasks and biological information sources are summarized in Table 3-1. The design task, the video and the Wikipedia article were German as all participants spoke German fluently. However, they had the option to switch to the English version of the Wikipedia article. The publication was written in English. As the participants are confronted with English publications during their daily work, they were supposed to understand the publications in English. The participants were given paper and pens to document their ideas. The support pairs (bi-disciplinary pairs working with a support) were additionally given the *BioId* support – it is described in section 5.

Table 3-1: Design tasks and biological information sources (details in the appendix 11.2)

Design task	Task description (German)	Biological information		
		Publication	**Wikipedia article**	**video**
I – water pump	"Develop a solution for lowering a water pump with hose and supply cables down a well."	fish parasite	byssus	praying mantis
II – sun protection	"Develop a solution to prevent the heating of rooms due to solar radiation."	wasp	iris (eye)	sun flower
III - aquaplaning	"Develop a solution to prevent aquaplaning."	beetle	leaf	spider net

Questionnaires

After each design experiment, the participants filled out a questionnaire. It included questions the following variables:

1. Number of different solution ideas (few…many)
2. Further development of the solution ideas (badly… well)

3. Inspiration by biology (no inspiration…very inspiring)
4. Complete documentation of solution ideas (no documentation… all solution ideas documented)
5. Quality of solution ideas (low… high)

The participants had to rate the variables with the range indicated in brackets[2]. Additionally the questionnaire provides space to explain the reason for the rating of the variables 1 to 4. After the rating of quality, the participants were asked to name their best solution.

On the questionnaire filled out after the second design experiment (in the bi-disciplinary pair), the participants were asked for additional comments on the entire workshop.

The questionnaire filled out by the participants of the support pairs included additional questions on the use of the *BioId* support. They were asked to rate:

6a. The facilitation of understanding of the technical information due to the support (no facilitation… considerable facilitation)

6b. The facilitation of understanding of the biological information due to the support (no facilitation… considerable facilitation)

7. The facilitation of bio-inspired ideation due to the support (no facilitation… considerable facilitation)

The questionnaire provides space to explain the reason for the rating of these variables. Moreover, the participants were asked how they could transfer the biological "solution" to the technical domain most easily (variable 8). They could choose the options "inspiration by sketch", "inspiration by model" and "other idea". This question aims at the structure of the support which is explained in section 5.

The original questionnaire is included in the appendix (11.6).

Individual tasks

The three individual tasks aimed at testing the participants' previous individual disciplinary knowledge and capability of transferring bio-inspired analogies and possible order effects due to the procedure of the design experiments. The task consists of two parts:

- Part 1: Which aspects of (a given biological system) are interesting for a technical application?
- Part 2: Which aspects of (a given technical system) could be improved by bio-inspired design? Name a possible biological model!

Three different biological and technical systems were given: elephant and ship, dolphin and robot, bat and airplane. The participants were given a form for each part of the task with columns for the aspects of the biological/ technical systems and the designated technical/ biological system. Part 1 had to be done in five minutes before the participants were given the

[2] Due to a mistake in the template, the range the participants could choose from varied from four options to five options. For the analysis of the results, the range was transformed to percentages 0… 100%.

forms for part 2 for which they had five minutes as well. The sequence of the three individual tasks was varied (see appendix 11.3).

3.2.2 Analysis methodology

The analysis approach is based on a preliminary analysis of the collected data which was necessary to ensure the applicability of the measures. For the analysis, the data collected in the studies was regarded. This includes the data collected from the design experiments with uni- and bi-disciplinary pairs, the individual tasks and the questionnaires. An overview is shown in Figure 3-3.

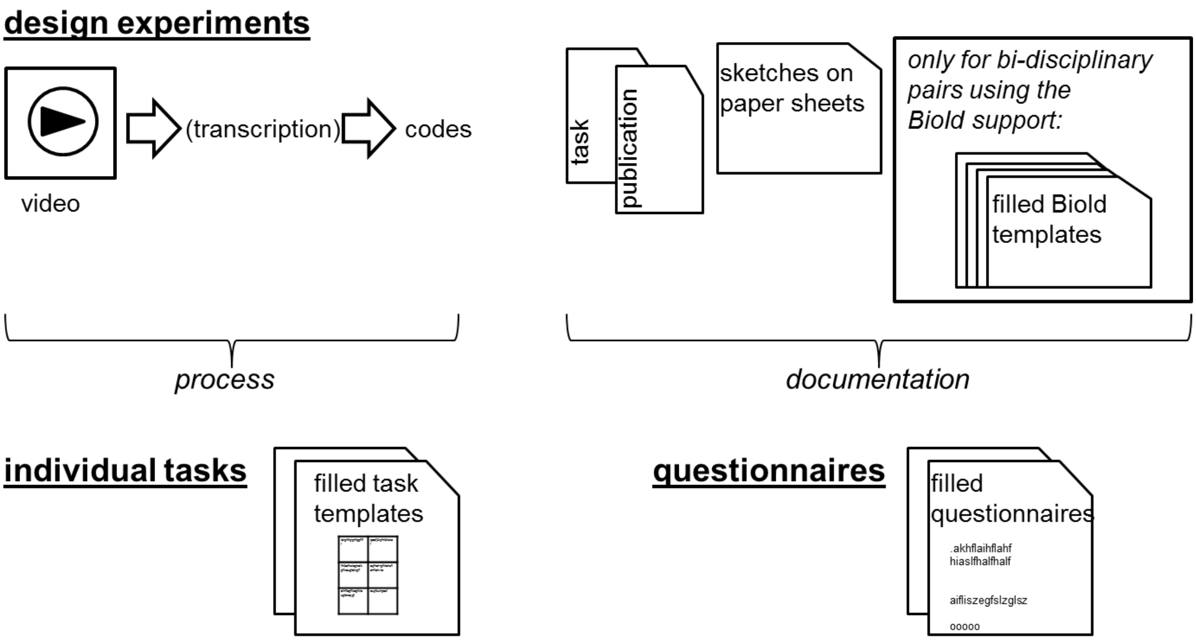


Figure 3-3: Data collected in the studies

As depicted in Figure 3-3, the design experiments were recorded on video. The videos of the study in 2013 were transcribed in detail and then coded. The videos of the second study in 2015 were coded directly – this was possible, because sufficient experience with the coding had been gained to directly identify the codes in the video. At the end of the experiment, the design task, the printed publication, the previously blank paper sheets and, in case of a support pair, the *BioId* templates were collected. Notes and documented solution ideas were identified on the collected documents. The documented solution ideas are included in the appendix (11.4). Lists of the solution ideas and their analysis are shown in appendix 11.5.

Regarding the individual tasks, the filled task templates were directly collected after the five minutes the participants had for the task. The questionnaires were collected when the participants had filled them after each design experiment.

The following sub-sections explain the transcription and coding of the design experiments, the quantitative analysis, the qualitative analysis and the verification of results. A quantitative approach was used to analyse the effects of the bi-disciplinary collaboration and the support (research questions 1 and 2). A qualitative approach served to explain these effects (research question 3).

Transcription and Coding of the design experiments

To analyse the design experiments, all analogies and solution ideas developed by each pair had to be identified. Moreover, the communication related to the task and biological information and knowledge are relevant for the analysis. In previous work, it was observed that during the ideation phase, groups did not document a considerable portion of solution ideas (Hashemi Farzaneh, Kaiser, Schröer, Srinivasan, & Lindemann, 2012). Consequently, in this work, both all generated and documented solution ideas were considered separately. All generated solution ideas were identified in the video recordings of the design experiments. A solution idea was additionally considered *documented* if the participants had retained it by a textual note or a sketch.

To identify all generated solution ideas, a coding scheme was used. It is based on a coding scheme developed in previous work (Hashemi Farzaneh, Kaiser, & Lindemann, 2012; Hashemi Farzaneh, Kaiser, & Lindemann, 2013) which assigns all pieces of communication to a category. For this work, not all codes are relevant, e.g. the assessment of the solution ideas' properties is not regarded.

Therefore, the following codes are used:

- Goal planning and analysis: discussing the task and requirements
- Biological information and knowledge: discussing publication/ Wikipedia article/ video/ further biological knowledge
- Analogical transfer: relating biological information and knowledge to the task
- Solution idea:

  The generation of a new solution idea is indicated by:

  - new category: generating a new solution idea of another semantic category than the previous solution idea (e.g. based on another biological inspiration)
  - expansion of the scope: generalizing or abstracting a solution idea
  - variation: generating a new solution idea which is semantically related to the previous solution idea, but aspects of the idea are changed

  No new solution idea is indicated by:

  - concretization: detailing of a solution idea
  - repetition: repeating a previously generated solution idea without changes

An example for the use of the coding scheme is shown in Table 3-2: It lists a part of the transcribed communication from one of the design experiments (biologist pair 1) and the assignment of the communication to codes. This excerpt includes the generation of two solution ideas which can be identified by the codes *solution idea: new category* (time: 22:50) and *solution idea: variation* (time: 23:40). Before generating the solution ideas, one of the participants speaks about the praying mantis presented in the video. An analogical transfer can be identified and therefore both solution ideas are considered to be based on a bio-inspired analogy from the video. The two solution ideas were sketched. The sketches are shown in appendix 11.4.

Table 3-2: Verbal communication (excerpt) from the ideation in biologist pair 1 and identification of the codes (b1 and b2: participating biologists)

Time [min:sec]	communication	code	Identified solution idea
22:30	b1: If you look at the leg of the praying mantis, it has…	biological information: video	
22:40	b1: …well it sometimes closes its arms like this [sketching] It has these spikes; that means…	biological information: video; analogical transfer	
22:50	b1: …you could also have the hose here. Then you would have – let's do this here:	solution idea: new category	Solution idea n°5 (clamp with spikes)
23:00	b1: [sketching]		
23:10	b1: Then you would have something with a joint and a big gap...	solution idea: concretization	
23:20	b1: …it's not quite like this… then here is the water hose…	solution idea: concretization	
	b2: yes		
23:30	b1: …then you would have gaps of different sizes for the small hoses*	solution idea: concretization	
23:40	b2: You can also do something like a cable strap, but with spikes. Spikes that can be shifted.	solution idea: variation	Solution idea n°6 (cable strap with shiftable spikes)
23:50	b2: According to the distance between the spikes, there is more space for the hose. Also for hoses of different sizes*.	solution idea: concretization	

**Note: The task is to fix a hose and several cables of different diameters to the rope that holds the water pump. The two participants refer to the cables by the term "small hoses".*

In a next step, the solution ideas for each of the three tasks were analysed and compared. In this work, "solution idea" is defined as a communicated thought that proposes a (partial) fulfilment of a given design task. This definition is based on Feldhusen and Grote (2013) who define a solution idea as a *new solution to a known problem*. Moreover it relates to Lindemann (2009) who distinguishes between solution ideas whose applicability for the fulfilment of requirements has not been tested and evaluated solution alternatives. It has to be noted that solution ideas do not necessarily propose a complete solution or overall concept for the given task. As examined in previous work, a solution idea can be a thought for a partial solution which only fulfils a portion of the given task. Moreover, these partial solutions cannot always be combined to fulfil an overall solution. Instead, they often show alternative strategies for fulfilling a task (Hashemi Farzaneh et al., 2012).

For each solution idea, the following information was documented and is listed in the appendix (11.5.1) for each task:

- Inspiration: publication, Wikipedia article, video, further biological knowledge, unclear or other (e.g. technical) knowledge
- Documentation (none, documented (text/ sketch etc.))
- Short description (emphasising differences to the previous idea)

The solution ideas were regarded on four abstraction levels (definitions based on Ponn & Lindemann, 2011, pp. 427–460):

- Function: the purpose of a technical solution (idea) and its elements
- Physical effect: physical law that supports the function
- Working principle: combination of geometric and material properties that enable the physical effect
- Embodiment: detailed design of the components of a technical solution (idea)

The function level is the most abstract level; the embodiment level is the least abstract level. All solution ideas differed on the embodiment level, but similar working principles, physical effects and functions could be identified. Each solution idea can include one or several working principles, physical effects and functions. Therefore, in appendix 11.5.1 all solution ideas on embodiment level are assigned to one or several working principles. In appendix 11.5.2, the working principles are assigned to physical effects and functions.

As an example, the assignment of the solution ideas extracted from the communication excerpt above to working principles, physical effects and functions is shown in Table 3-3.

Table 3-3: Assignment of solution idea n°6 to working principles, physical effects and functions

embodiment	working principle	physical effect	function
Solution idea n°5 (clamp with spikes)	clamp	static friction	hold
	Spikes between cables/ hose/ rope	form closure	adapt to diameter of cables/ hose (discrete steps)
Solution idea n°6 (cable strap with shiftable spikes)	enlacement by one part	static friction	hold
	cable strap	form closure	tighten
	Shiftable spikes between cables/ hose/rope	form closure	adapt to diameter of cables/hose (continuously)

It can be seen that both solution ideas present a solution to the partial function *hold* and *adapt to the diameter of cables/ hose*. However, solution idea n°5 adapts to different diameters in discrete steps, i.e. the spikes are fixed, whereas solution idea n°6 allows for continuous adaptation with shiftable spikes. Moreover, solution idea n°6 provides a solution to the partial function *tighten*. For solution idea n°5, the participants did not define a tightening mechanism for the clamp (such as a spring, a snapping mechanism etc.).

This example shows that the approach to partition the solution ideas with regards to working principles, physical effects and functions allows comparing them in a coherent manner. Comparing solution idea n° 5 and 6, for example, shows that both ideas include similar physical effects. Moreover, solution idea n°6 presents a more complete solution to the task because it addresses the function *tighten*. The following sub-section describes the use of the partitioned solution ideas to analyse the analogy type, quality, uniqueness and variety of solution ideas.

Based on the described analysis of the solution ideas on embodiment, working principle, physical effect and function level, a number of ideas were excluded from the further analysis (they are also excluded from appendix 11.5):

- ideas that were generated to apply an analogy from one of the biological sources, but have no relation to the task (for example task III (aquaplaning): *safety mechanism similar to a spider net*).
- ideas that were based on a misinterpretation of the task (for example task I (water pump): *spikes at the walls of the water hole prevent objects in water from clogging the pump*)
- ideas that only specify a function, but no physical or working principle or embodiment were too vague to be evaluated (for example: task III (aquaplaning)*: something is applied on the tire so that the tire "connects" to the water*)

Quantitative Analysis

The quantitative analysis is used to examine the relations depicted in Figure 3-1. This view focusses on the results of the ideation: the generated and documented solution ideas. For the quantitative research questions, the independent and dependent variables are listed in Table 3-4.

Table 3-4: Research questions (RQ) - Independent and dependent variables

RQ	Independent variable	Dependent variable
1.1	pair composition and support	analogy type: accuracy, similarity, elements of transfer
1.2	analogy type: accuracy, similarity, elements of transfer	quality of solution idea
2.1	pair composition and support	use of biological information sources
2.2	use of biological information sources	variety of solution ideas
2.3	pair composition and support	variety of solution ideas
2.4	use of biological information sources	uniqueness of solution ideas
2.5	pair composition and support	uniqueness of solution ideas

Two variables are measured on the level of pairs:

The variable *pair composition and support* has four *values*:

- uni-disciplinary pair of engineers (engineer pair)
- uni-disciplinary pair of biologists (biologist pair)
- bi-disciplinary pair of one biologist and one engineer (bi-disciplinary pair)
- bi-disciplinary pair of one biologist and one engineer working with the *BioId* support (support pair)

For the variable *use of biological information sources*, pairs using all three given biological information sources are distinguished from pairs using less (none, one or two) biological information sources:

- pairs using analogies from the three biological information sources, i.e. the publication, the Wikipedia article and the video for generating/ documenting solution ideas
- pairs using analogies from two or less biological information sources for generating/ documenting solution ideas

The measures for the variables on solution idea level (analogy type, quality, variety, uniqueness) are described in the following sub-sections.

Analogy type: accuracy, similarity and elements of transfer

To analyse the analogy type of each solution idea, the inspiration of each solution idea was documented (see appendix 11.5). On the videos and transcription from the design experiments, the elements of communication related to knowledge were identified. This communication of knowledge can be followed by communication about the generation of a solution idea based on an analogy. The analogy is therefore a theoretical concept: it is always related to a specific solution idea. Even though the analogy is generated before the solution idea in a cognitive process; when it is communicated, it is inseparable from the solution idea. This can be seen in the communication excerpt shown in Table 3-2: The participant says: "It has these spikes [biological information], **that means** you could also have the hose here [solution idea: new category]." Here, the connection of biological information and a new solution idea by the term *that means* indicates the analogy.

Using videos and transcription, the analogies were therefore associated with preceding communication of knowledge. If the communicated knowledge was related to the publication, the Wikipedia article, the video or further biological knowledge the analogies were considered *bio-inspired*. There were also analogies based on other knowledge, e.g. knowledge about existing products: For this work, these analogies were not considered.

The three definitions explained in section 2.3.3 (page 23) are used to analyse the analogy type of the bio-inspired solution ideas: *accuracy* (Mak & Shu, 2004b; Vakili, Chiu, Shu, McAdams, & Stone, 2007), *similarity* (Mak & Shu, 2004a) and *elements of transfer* (Sartori et al., 2010). These three definitions have been used to analyse analogies by the cited researchers. Table 3-5 shows the interpretation of these variables for this work, Table 3-6 lists examples for each analogy type for the sun protection design task used in the descriptive studies.

Table 3-5: Measures for the analogy type (measured on solution idea level)

variable	values	Comparison to the biological inspiration (x: different, o:different or similar, ✓: similar)			
		embo-diment	working principle	physical effect	function
Accuracy based on Mak and Shu (2004b) and Vakili et al. (2007)	unrelated	x	x	x	x
	incorrect	o	✓	x	o
	incomplete	x	x	x	✓
	correct	o	o	✓	✓
Similarity based on Mak and Shu (2004a) (see Figure 2-9)	biological transfer	✓	✓	x	x
	literal implementation	✓	✓	✓	✓
	analogy	x	o	o	✓
	anomaly	x	o	x	o
elements of transfer based on Sartori et al. (2010)	copy parts	✓	✓	o	o
	transfer organs	x	o	✓	✓
	transfer attributes	x	✓	x	o
	transfer state change	x	x	x	✓
	no transfer	x	x	x	x

For the analysis in this work, the definition of ***accuracy*** is interpreted as follows: An *incorrect* analogy does not implement a physical effect similar to the biological inspiration, but similar geometric or material properties on the working principle level. Regarding the sun protection examples in Table 3-6, *small tubes reflecting specific wave-lengths of light* inspired by polar bear fur is based on an incorrect analogy: the solution idea implements neither a similar function nor a similar physical principle (see Koon, 1998). However, it imitates the hollow hairs of the polar bear (working principle level). Analogies are considered *correct* if the solution idea implements a function and its associated physical effect of the biological inspiration. They can also implement the working principle and embodiment of the biological inspiration. For example, this is the case if *sun flowers adapting to the sun position* are planted in front of the window (see Table 3-6): the sun flowers fulfil the intended technical function (*adapt to sun position*) using the *phototropism*. For this solution idea, the biological system sun flower is used directly; therefore the solution idea uses the biological system's embodiment and working principle as well. Analogies are considered *incomplete* if they implement only a function similar to the biological inspiration, but have a different physical effect. This is the case for the solution idea to *rotate of a sun-shading device* adapting it to the sun position. The solution idea has a similar function as the biological system *sun flower* (it adapts to the sun position), but no (similar) physical principle is defined. An *unrelated* analogy is generated in relation to the discussion of the biological system, but there is no similarity on any of the abstraction levels. Using *photochromic glass adapting to insolation* for sun shading is an example. This solution idea was generated by one pair in conjunction with the discussion of the Wikipedia article. However, no common working principle, physical effect and function can be identified. Instead, this solution idea had a second technical inspiration - the existing technical product *photochromic sun glasses*.

Concerning ***similarity***, *biological transfer* and *literal implementation* both refer to the transfer of the biological system (or parts of it). In case of the sun protection task, the use of *heat-absorbing bacteria* to absorb the heat in window panes is an example for biological transfer: The solution idea refers to the bacteria in the cuticle of wasps described in the given research publication. However, these bacteria do not directly absorb heat, but the heat energy is converted into electric energy by the wasp's cuticle. The bacteria's cell walls are then charged with electric energy. To conclude, this analogy is not similar in terms of physical effect or function. In difference to biological transfer, literal implementation additionally requires a similar physical effect and function. This is implemented for the example of *sun flowers adapting to the sun position*. An analogy of the type *analogy* is transferred if there is no similarity on embodiment level, but at least on function level and possibly on working principle and physical effect level. An example is the solution idea *to use a lens to redirect sun light* listed in Table 3-6. In case of this solution idea, working principle, physical effect and function are similar to the eye contraction described in the Wikipedia article. Another example is the use of *black elements expanding and shrinking due to insolation*. In this case, the function (expand and shrink) and the working principle (black element) are similar to the iris. However, no similar physical effect is defined, the iris contracts and widens due to muscle actuation. An *anomaly* requests that there is no similarity or a similarity exclusively on working principle or function level. Regarding the sun protection task, the two solution ideas *photochromic glass* (no similarity) and *small tubes reflecting specific wave-lengths of light* (similarity on working principle level) are both anomalies.

In this work, the definition of ***elements of transfer*** is defined as follows: *Transfer organs* is interpreted as the transfer of at least the physical effect and the function of the biological system. For the sun protection task, the *use of a lens to redirect sun light* is an example. *Transfer attributes* refers to the transfer of a set of properties and conditions of the biological inspiration (working principle) – but the physical principle which implements the function is unclear or not similar to the biological system. An example is the *black elements expanding and shrinking due to insolation*. *Transfer state change* is interpreted as the use of a function of a biological system. This is the case for the *rotation of a sun-shading device*. Sartori et al. (2010) further define a fifth category, the *resulting transfer*. It occurs if the transferred elements are already present in the solution idea. This category is not used in this work, as it cannot be identified unambiguously. Instead a category *no transfer* is introduced because in case that there are no similarities on any of the abstraction levels, the solution idea cannot be categorized otherwise. An example is the solution idea *photochromic glass* described above.

Table 3-6: Analogy types: examples for possible combinations between accuracy, similarity and elements of transfer

accuracy	**similarity**	**elements of transfer**	**example**	**biological inspiration**
unrelated	anomaly	no transfer	photochromic glass adapting to insolation	iris (Wikipedia)
incorrect	anomaly	attributes	small tubes reflecting specific wave-lengths of light	polar bear (further biological knowledge)
	biological transfer	parts	heat-absorbing bacteria	wasp (publication)
incomplete	**analogy**	attributes	black elements expanding and shrinking due to insolation	iris (Wikipedia)
		state change	rotation of a sun-shading device	sun flowers (video)
correct	literal implementation	parts	sun flowers adapting to the sun position	sun flowers (video)
	analogy	**organs**	use of a lens to redirect sun light	iris (Wikipedia)

The descriptions of the analogy types and examples show that the concepts of *accuracy*, *similarity* and *elements of transfer* are not independent, but they are related. Table 3-6 shows all possible combinations of analogy types. For example, the solution idea *photochromic glass that adapts to insolation* has no similar embodiment, working principle, physical effect or function compared to the biological system *iris*. Therefore, the analogy type is categorized as unrelated, as an anomaly and has no elements of transfer.

After the analysis of the bio-inspired solution ideas, the number of analogies per pair was counted. The focus was on the categories of accuracy, similarity and elements of transfer that focus on a transfer of the function of the biological system and not on a transfer on the embodiment level. As Table 3-5 shows, these are the categories of *correct* and *incomplete* analogies (accuracy), *analogies* (similarity) and *organs* and *state change* (elements of transfer). They are printed bold in Table 3-6.

A reason for this is given by Mak and Shu (2004a) who state:

"However, the potential of biomimetic design is fully realized when one can abstract a strategy used in biological phenomena and implement this strategy in a way that is not limited to a literal one using the same biological players."

In this sense, it is assumed that transferring the function and at the same time not focussing on the biological system on embodiment level implies an understanding of both the biological system and the technical task. Other analogy types, based on misunderstanding, are possibly more random. They can still lead to solution ideas with high quality, but are less reproducible.

Quality

As explained in section 2.1 (page 10), quality criteria are used to measure the potential of solution ideas for the later target achievement and market success of the product. Quality criteria can be task-specific or general criteria. Feasibility is a commonly used general quality criterion (e.g. Eversheim, 2009; Girotra, Terwiesch, & Ulrich, 2010; Messerle, Binz, H., & Roth, 2013).

Therefore in this work, the general criterion feasibility is used, defined as the estimated probability that the solution idea can be developed to a solution or product. Moreover, task-specific quality criteria are defined based on the design tasks and (partial) functions. As shown in Table 3-7, one criterion is defined for the task aquaplaning. The preliminary analysis of the solution ideas of the other two tasks (sun protection, water pump) showed that several criteria are necessary depending on the partial functions of the solution ideas. In a first step, all criteria are measured on the level of working principles to improve the coherence of the evaluation. Then, an overall value for the solution ideas on embodiment level is calculated using the weighting factor *w* depicted in Table 3-7.

Table 3-7: Task-specific quality criteria

task	**partial function**	**task-specific quality criteria *q***	**weighting factor *w***
Aquaplaning	all partial functions	improve contact (tire/ road)	1
Sun protection	cool the building, redirect sunlight, shield heat, shield sun	prevent heating due to sunlight	0,25
		allow view from inside	0,25
	adapt to insolation, adapt to sun position, adapt to temperature, enable adaptation, store electric energy, transform solar energy to electric energy	autonomous adaptation to weather conditions	0,5

Task	**Partial function**	**Task-specific quality criteria *q***	**weighting factor *w***
Water pump	hold	fixation in wet state	0,33
	adapt to diameter of cables/ hose (discrete steps/ continuously)	fixation of cables with different diameters	0,33
	tighten, loosen, tighten and loosen, lower pump into well	easy assembly (quick, no specific knowledge or tools required, no risk of injury)	0,17
		reusability	0,17

The criteria are rated with points ranging from 0 to 3 corresponding to 0…100%. The assignment of points is defined in Table 3-8. The detailed definitions are used to increase the objectivity of the evaluation. This coarse rating scale is in accordance with Kurtoglu, Campbell, and Linsey (2009) and Linsey, Markman, and Wood (2012): They found that broader scales with undefined interim values led to differences between evaluators.

Table 3-8: Quality: Evaluation of feasibility and task-specific criteria using points 0-3

points	**feasibility**	**task-specific criteria**
3 (100%)	• material/ components available • costs probably within the expected margins • integration to predefined system(s) possible	criterion fulfilled for all application cases
2 (66%)	• material/ components available, but high costs • or: existing system(s) have to be replaced/ adapted	criterion fulfilled with deductions: not for all application cases/ criterion fulfilled less well
1 (33%)	• material/ components not completely defined • unclear if the material/ components can be obtained (because it is not commercially available)	• unclear if the criterion can be fulfilled • or: solution has undesired properties
0	not feasible	• criterion not fulfilled • partial solution not aimed at the function which fulfils the criterion

To calculate an overall value for feasibility on embodiment level, the minimum value of *f* of all working principles is assigned: If one of several working principles of a solution idea is not feasible, the whole solution idea cannot be applied in reality:

$$F = min\{f_1 \dots f_n\} \; with \; n = all \; working \; principles \; of \; the \; solution \; idea$$

Equation 3-1: overall feasibility value F of a solution idea

To calculate an overall value *Q* for the task-specific criteria on embodiment level, all working principle values *q* are summed up, multiplied by the weighting factor *w* (see Table 3-7) and divided by the maximum possible value (3):

$$Q = \sum_{i=1}^{n} \frac{q_i \cdot w_i}{3} \; with \; n = all \; working \; principles \; of \; the \; solution \; idea$$

Equation 3-2: overall task-specific quality value Q

As an example, the evaluation of the two solution ideas for task I (water pump) presented in the last section is shown in Table 3-9. Concerning feasibility, both solution ideas receive the maximum feasibility value *F* (3), as their components are available and not expensive and they can be integrated to the pump system. However, the task-specific quality values of the two solution ideas differ:

Solution idea n°6 includes a solution to one more function (*tighten*). However, this solution on working principle level, a *cable strap*, is rated with zero points for the two applied criteria: The criterion *easy assembly* is rated with zero points because of the risk of injury - the user of a cable strap can cut his or her hand with the strap and with the cutting tool that is used to cut the ends of the strap. The criterion *reusability* is rated with zero points because the cable strap cannot be used more than once. Moreover, solution idea n°6 receives three points for the working principle *shiftable spikes*, solution idea n°5 two points for the working principle *spikes*. *Shiftable spikes* can be adapted to differing cable diameters flexibly whereas fixed *spikes* only provide space for predefined cable diameters. Therefore, the overall task specific quality value *Q* of solution idea n°6 is higher than the quality value *Q* of solution idea n°5.

Table 3-9: Example for the quality evaluation of solution ideas

embodiment	**working principle (function)**	**feasibility value *f***	**addressed task-specific criteria**	**task-specific value *q***	**weighting factor *w***
task I, solution idea n°5 (clamp with spikes)	clamp (hold)	3	fixation in wet state	2	0,33
	spikes between cables/ hose/ rope (adapt to the diameter of cables/hose (discrete steps))	3	fixation of cables with different diameters	2	0,33
	overall feasibility: $F = min\{3; 3\} = 3$		overall task-specific quality: $Q = \frac{2 \cdot 0{,}33}{3} + \frac{2 \cdot 0{,}33}{3} = 44\%$		
task I, solution idea n°6 (cable strap with shiftable spikes)	enlacement by one part (hold)	3	fixation in wet state	2	0,33
	cable strap (tighten)	3	easy assembly	0	0,17
			reusability	0	0,17
	shiftable spikes between cables/ hose/rope (adapt to the diameter of cables/hose (continuously))	3	fixation of cables with different diameters	3	0,33
	overall feasibility: $F = min\{3; 3; 3\} = 3$		overall task-specific quality: $Q = \frac{2 \cdot 0{,}33}{3} + 2 \cdot \frac{0 \cdot 0{,}17}{3} + \frac{3 \cdot 0{,}33}{3} = 55\%$		

Variety

The variable *variety* is evaluated using an approach based on the method of Shah and Vargas-Hernandez (2003). A comparable approach was used in previous work (Hashemi Farzaneh, Helms, & Lindemann, 2015a). Moreover, the revisions proposed by Nelson and Yen (2009) are taken into account, as Nelson and Yen have detected inadequate variety scores when using the original method of Shah and Vargas-Hernandez (2003).

To calculate variety for a set of ideas, the differences between solution ideas on function, physical effect, working principle and embodiment level are counted and multiplied by a weighting. The weighting is used to account for the relevance of the difference: According to Shah and Vargas-Hernandez (2003), differences on the more abstract level of physical principles show *“large distances in design space”.* Solution ideas differing on the more abstract levels are therefore more different than solution ideas differing “*in minor or superficial ways*” (e.g. on embodiment level). In this work, a doubled weighting per abstraction level (1-2-4-8) ensures that at least two ideas on the lower abstraction level equal one idea on a higher abstraction level (as claimed by Nelson & Yen, 2009).

Nelson and Yen (2009) propose to dismiss the normalizing of variety scores as conducted by Shah and Vargas-Hernandez (2003). In case of this work, inadequate variety scores due to normalizing do not occur, as there are no solution ideas that only include ideas on high levels of abstraction. Every solution idea contains a solution on embodiment level and one or several working principles, physical effects and functions.

However, dismissing the normalizing of variety scores leads to a combined measure for variety and quantity of ideas (Nelson & Yen, 2009). We therefore use both approaches and calculate a combined variety and quantity score V and a normalized variety score V* using Equation 3-3.

Combined variety-quantity score $V = (s_e - 1) + (s_w - 1) \cdot 2 + (s_{ph} - 1) \cdot 4 + (s_f - 1) \cdot 8$

Normalized variety score: $V^* = \frac{V}{s_e + s_w + s_{ph} + s_f}$

with the number of solution ideas on each level (s_e: embodiment, s_w: working principle, s_{ph}: physical effect, s_f: function)

Equation 3-3: Variety of each pair’s solution ideas

Uniqueness

As Figure 3-1 depicts, the variable *uniqueness* is related to the variable *variety*. In this work, the variable *uniqueness* is introduced because variety cannot be evaluated on the level of single solution ideas. Variety always implies a comparison between several solution ideas. *Uniqueness* is used to evaluate whether a specific solution idea on embodiment/ working principle/ physical effect and function level is bio-inspired and inspired by publication, Wikipedia article or video only. This is regarded across pairs: for example, if one pair developed a solution idea based on an analogy from the given publication and another pair developed a solution idea with the same working principle based on a technical analogy, the two solution ideas are not categorized as *bio-unique* or *source-unique*.

To summarize, all solution ideas on each level of abstraction are categorized according to:

- bio-uniqueness: a solution idea is bio-unique if it only occurs based on a bio-inspired analogy
- source-uniqueness: a solution idea is source-unique regarding publication/ Wikipedia/ video if it only occurs based on this specific information source

Qualitative Analysis

Whereas the quantitative analysis is result-focussed, the qualitative analysis regards the procedures of the uni- and bi-disciplinary pairs and seeks to explore the reasons for the relations established by the quantitative analysis. Therefore, the qualitative analysis focusses on the analysis of the questionnaires and observations on the design procedures.

Questionnaires

The questionnaires are regarded to analyse how the participants describe and explain their performance during ideation (research question 3). The participants' view is compared to the quantitative analysis of the results.

Observations

The procedures of the pairs are analysed to explain differences in the use of biological information sources, the analogical transfer and the developed solution ideas during ideation (research question 4). Both video and transcription are used to examine the pairs' overall procedure with regards to the discussion of task, biological information sources and ideation.

Verification of results

To verify results, Blessing and Chakrabarti (2009, p. 125) propose four different types of validity: statistical conclusion validity, internal validity, construct validity of causes and effects and external validity.

Different measures are taken to ensure the four types of validity: The research design is adapted, statistical tests of the results are conducted and additional verification measures are examined. An overview on the considered aspects is shown in Table 3-10. The results of the statistical tests are shown in section 6 for the second descriptive study. The results of the additional verification measures are presented in section 7.

Table 3-10: Aspects for the verification of results

	Research design	Statistical tests	Additional verification measures
statistical conclusion validity	-	• Wilcoxon rank sum test • Wilcoxon signed-rank test • t-test for two samples with equal variances	-
internal validity	• assignment of participants to pairs • order effect (researcher) • Time order	-	order effect (participants)

	Research design	Statistical tests	Additional verification measures
construct validity of causes and effects	• measures based on existing research • possible bias of the researcher	-	-
external validity	"realistic" tasks and design of the ideation phase	-	influence of three different tasks and information material

Statistical conclusion validity has to be considered to determine covariation between independent and dependent variables (Blessing & Chakrabarti, 2009, p. 125). To ensure statistical conclusion validity in the quantitative analysis, the non-parametric Wilcoxon rank-sum test (also called Mann-Whitney U test or Mann-Whitney-Wilcoxon test) is used for the comparison of pairs. A non-parametric test is used because the analysed data is not normally distributed. For this reason, the Wilcoxon rank-sum test has been used in a number of other publications in design research (e.g. Kurtoglu, Campbell, & Linsey, 2009; Lenau, Keshwani, Chakrabarti, & Ahmed-Kristensen, 2015)

The test allows comparing two populations: In case of this work, the two populations are two different values for the **pair composition and the use of the BioId support**, e.g. uni-disciplinary pairs and support pairs. Moreover, the pairs using all **information sources** and the pairs using less than three information sources are compared using the Wilcoxon rank-sum test. The test calculates if the null hypothesis (there is no difference between the two populations regarding the dependent variable) can be rejected with a specific probability. This rejection of the null hypothesis allows to conclude the alternative hypothesis (the populations differ with regards to the dependent variable) (Rumsey, 2013, pp. 305–314)

The Wilcoxon rank-sum test is based on the following conditions (Rumsey, 2013, p. 306):

- The two populations have the same distribution
- The two population have the same variances
- The samples from the two populations are independent

Exemplary histograms in appendix 11.10 show how the first two conditions can be checked. However, as the size of the compared population is between five and ten, it cannot be ensured that distribution and variances are the same. The third condition is strictly speaking not fulfilled for this work, because the participants took part in both a uni- and a bi-disciplinary pair. As the impact of the pair composition is the focus of this work, the influence of the individual participants is neglected but will be discussed in section 7.

To apply the Wilcoxon rank-sum test, the values of the dependent variable are ranked, the rank sums R_1 and R_2 are built and a test value U is calculated for both populations:

$$U_1 = n_1 \cdot n_2 + \frac{n_1 \cdot (n_1+1)}{2} - R_1 \qquad U_2 = n_1 \cdot n_2 + \frac{n_2 \cdot (n_2+1)}{2} - R_2$$

with n_1= number of values, population 1, n_2= number of values, population 2

Equation 3-4: Test value U (Sachs, 2004, p. 383)

The lower test value is compared to tabulated values for several levels of significance α (probability of error). The values for α (in appendix 11.10) are taken from Sachs (2004, pp. 381–392) who gives more details on the method.

Commonly a maximum value of α =5% (sometimes 10%) is accepted for rejecting the null hypothesis, i.e. the probability that the null hypothesis is correct is 95% (90%). When the null hypothesis can be rejected, the result (the populations differ with regards to the dependent variable) is considered *statistically significant* (Rumsey, 2013, p. 76; Sachs, 2004, p. 185).

To test the significance of **order effects** (section 7.1), a modified version of the Wilcoxon rank-sum test is used: the Wilcoxon signed-rank test: It tests if the tendencies of two populations are similar, i.e. in this work it is used to test for the significance of decreasing/ increasing number of aspects listed by the participants for the individual tasks. The positive/ negative difference in aspects between the individual task before the experiments and after each pair ideation is calculated. They are ranked and the rank sums are built for positive differences and negative differences. The lower rank sum is then compared directly to tabulated values for several levels of significance α (see appendix 11.10).

For testing the statistical significance of the comparison between different groups of solution ideas, in this work the **analogy types**, a parametric statistic test can be used due to the higher amount of data. Here, the t-test for two samples with equal variances is used (for details see Sachs, 2004). It is a commonly applied test for comparing two samples and has also been used in design research (e.g. by Lenau et al., 2015).

Internal validity has to be checked to ascertain that there is not only covariation between independent and dependent variables, but a cause-and effect relationship. For internal validity, a number of potential influences have to be considered, including extrinsic and intrinsic factors. Extrinsic factors are related to the assignment of participants to the experimental and control group. Intrinsic factors concern influences during the experiment and the analysis of the results (Blessing & Chakrabarti, 2009, pp. 125–129; Frankfort-Nachmias & Nachmias, 2008, pp. 95–101; Martin, 2008, p. 155).

For this work, the following factors are considered important:

- Assignment of participants to pairs: The assignment was due to their date of participation and the drawing of a lot. As the participants had different research areas, every pair united different areas of expertise.
- Order effect (participants): The participants could learn from the first experiment in uni-disciplinary pairs and improve their performance in the second experiment. This effect is tested by the individual tasks in between the experiments.

- Order effect (researcher): The analysis the data is conducted differently at different points of time. To reduce this influence, the analysis of the solution ideas of the first study was redone after the conduction of the second study. Then, there was an overview of all solution ideas, so that solution ideas could be evaluated with an increased consistency.
- Time order: It has to be made sure that the independent variable influences the dependent variable and not the other way round. The view on bio-inspired design depicted in builds on Figure 2-8 (p. 25). This view is supported by the analysis of the videos from the design experiments: The conversation of the participants first focusses on biological information, then analogies are suggested and consequently solution ideas are generated and further developed.

Construct validity of causes and effects concerns the adequacy of the measures for the superordinate constructs (Blessing & Chakrabarti, 2009, 2009, pp. 126–127): For this work, measures were therefore developed based on existing research (for example for the variables *variety*, *analogy types* etc.)

Another relevant aspect is the bias of the researcher. To minimize possible effects of bias, the solution ideas were extracted from the single design experiments: The actual analysis and evaluation of solution ideas was conducted using a table of all solution ideas for each task not the single solution ideas of each pair. The aim was to reduce the effect of bias towards a certain pair or pair composition and to increase the consistency of the results.

External validity determines the generalizability of the findings. To be generalizable, the sample of the participants has to be representative for the target group. Moreover, the setting of the study plays a role: an experimental setting is artificial and leads to observations that can be non-transferable to reality.

In this work, the sample of participants is not representative for mechanical engineers or biologists in general. The participants were volunteering doctoral candidates from one university. However, their research areas represented a wide range of possible fields of expertise. The experimental setting certainly also has an influence on the generalizability, but it was designed to resemble a real ideation workshop. Moreover, three different design tasks were used to cover a range of possible task and reduce the impact of a particular task on the results. In addition, the influence of the different tasks is analysed in section 7.2. Due to the sample of participants, the external validity of this study is considered low, but this is in line with the majority of studies in design research, or as Blessing and Chakrabarti (2009, p. 128) state: “In design research, the generalisation to target populations may be rare, in particular where data is collected in an industrial setting”. A reason for this the difficulty to define a representative sample in industry or at university and to motivate this sample to participate in the study.

4. First descriptive study: influence of bi-disciplinary collaboration

As explained in the previous section, the first descriptive study focusses on the analysis of the influence of the pair composition: Two pairs of biologists and two pairs of engineers are compared to four bi-disciplinary pairs of one biologist and one engineer. In total, the regarded pairs generated 81 solution ideas on embodiment level and 104 solution ideas on working principle level[3]. Preliminary answers are given to the research questions stated in section 3.1 with regards to the pair composition. The answers are preliminary, because in the second descriptive study, the pairs will be compared again. Then, the comparison will be based on five pairs of each pair composition and allow for more valid conclusions. The results of the first descriptive study will be used to develop a support (section 5).

To give a first overview on the results, Figure 4-1 shows the average[4] number of solution ideas of the different pair compositions on working principle level. The average number of solution ideas is similar for biologist, engineer and bi-disciplinary pairs: 16.5 solution ideas, of which 9.3 are documented. However, the average numbers of bio-inspired ideas differ: As Figure 4-1 shows, the average portion of bio-inspired ideas is highest for biologists, second highest for bi-disciplinary pairs and lowest for engineers. Comparing the documented solution ideas to all solution ideas, the portion of bio-inspired solution ideas is higher. Apparently, bio-inspired solution ideas were documented more frequently by the pairs.

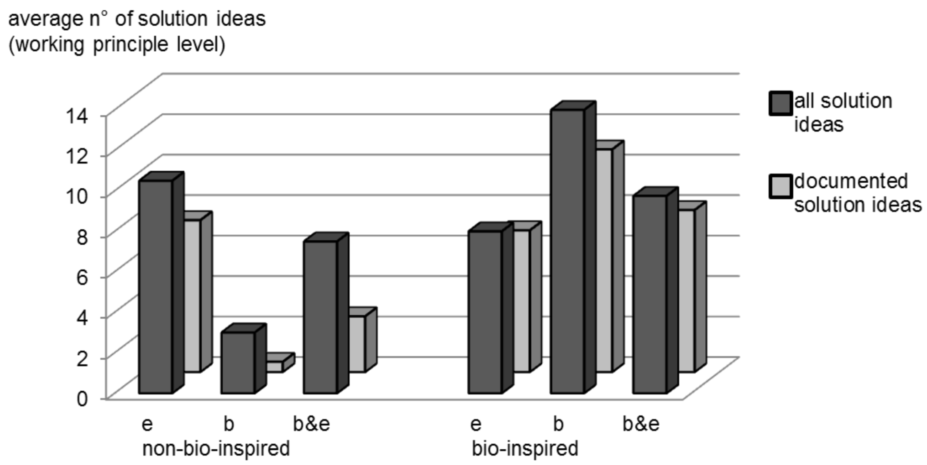


Figure 4-1: Average number of bio-inspired and non-bio-inspired solution ideas per pair (arithmetic mean)

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[3] Similar working principles based on different inspirations are counted separately, e.g. for task I (water pump) *hook and loop fastener* is counted as two solution ideas: 9,3 (inspired by the video) and 9,5 (not bio-inspired) (see appendix 11.5.2)

[4] In this work, the term *average* refers to the arithmetic mean.

The following sub-sections detail the analysis of the solution ideas with regards to the research questions. The results of the quantitative analysis and the qualitative analysis are presented. Then, the measures for the verification of the results are shown. The section closes with a conclusion and the implication of the results for the prescriptive study.

4.1 Results of the quantitative analysis

To start with, the quantitative results for the quality (research question 1) of solution ideas is shown (research question 1). Then, the influences on the variety and uniqueness are examined (research question 2).

4.1.1 Quality of solution ideas (research question 1)

This section focusses on research question 1 with regards to the impact of the pair composition:

How does the pair composition influence the quality of solution ideas developed in an ideation phase with biological information?

First of all, the influence of the pair composition (biologist pair, engineer pair, bi disciplinary pair of one biologist and one engineer) on the analogy types (accuracy, similarity, elements of transfer) is regarded. Then the influence of the analogy types on the quality of solution ideas is examined.

Influence of the pair composition on the analogy types (research question 1.1)

As a basis for the analysis, the types of the analogies for bio-inspired solution ideas are examined. All analogies were classified with regards to accuracy, similarity and the elements of transfer. The categorization is based on a comparison of the working principle, the physical effect and the function of solution idea and biological inspiration as shown in Table 3-5. As explained in section 3.2.2, the analogy types *correct* and *incomplete* analogies (accuracy), *analogies* (similarity) and *organs* and *state change* (elements of transfer) are regarded in the further analysis.

Figure 4-2 shows the average portion of these analogy types for different pair compositions.

With regards to all solution ideas, the engineer pairs transferred the lowest average portion of analogies of all selected analogy types. In comparison, the biologist pairs and bi-disciplinary pairs transferred on average similar portions of the selected analogy types.

Regarding the documented solution ideas, the engineer pairs increased the portion of all regarded analogy types slightly. The biologist pairs' portion of all regarded analogy types remains similar compared to all solution ideas. The bi-disciplinary pairs document a higher portion of all regarded analogy types.

To summarize, the engineer pairs transferred and documented the lowest portion of analogies of the selected analogy categories on average. Biologist and bi-disciplinary pairs transferred a similar portion on average. However, the bi-disciplinary pairs document a higher average portion of solution ideas based on the selected analogy types.

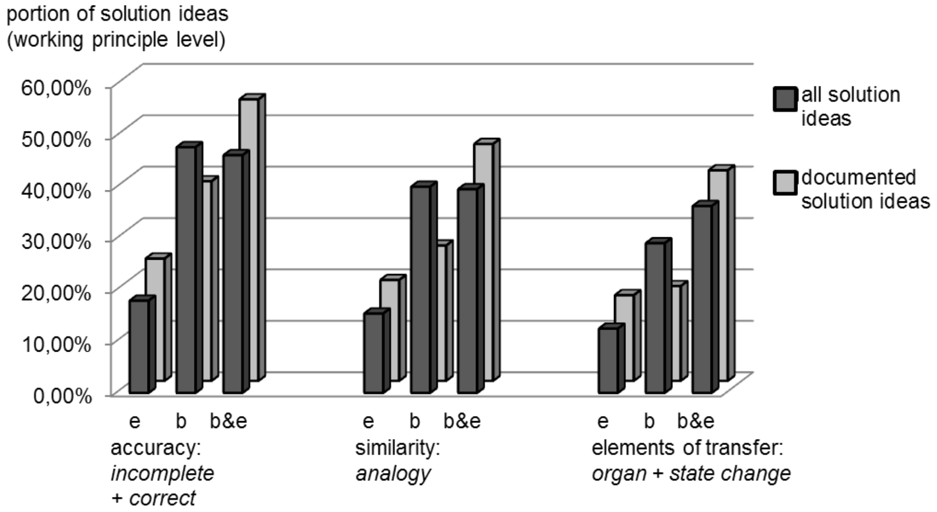

Figure 4-2: Average number of analogy types for different pair compositions (e: engineer pairs, b: biologist pairs, b&e: bi-disciplinary pairs)

Influence of the analogy types on the quality of solution ideas (research question 1.2)

The quality of the solution ideas containing the selected analogy types is compared to the quality of all bio-inspired solution ideas not containing these analogy types. Moreover, a comparison to the non-bio-inspired solution ideas is conducted.

To start with, the task-specific quality Q is regarded:

Figure 4-3 shows the results which are similar for all selected analogy types: The average task-specific quality of the solution ideas containing the selected analogy types is approximately 60%. The average task-specific quality of other bio-inspired solution ideas is lower - approximately 50%. The average task-specific quality of non-bio-inspired solution ideas is lowest with 40%.

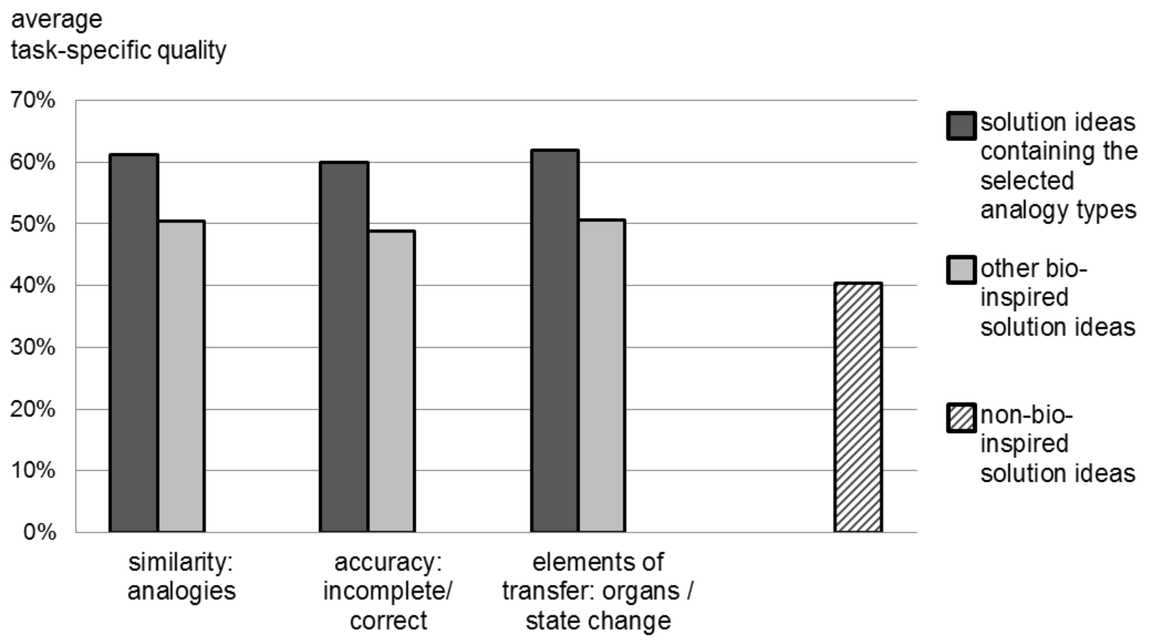

Figure 4-3: Average task-specific quality Q of solution ideas

The significance of the difference between solution ideas containing the selected analogy types and all other solution ideas is tested. A null-hypothesis and an alternative hypothesis are formulated:

- Null hypothesis: Solution ideas containing the selected analogy types have no higher quality Q than (1) other solution ideas / (2) other bio-inspired solution ideas
- Alternative hypothesis: Solution ideas containing the selected analogy types have a higher quality Q than (1) other solution ideas / (2) other bio-inspired solution ideas

Here, the null hypothesis is tested using the t-test for two samples with similar variances presented in section 3.2.2. A normal distribution can be assumed because of the high number of samples (in total: 81 solution ideas on embodiment level).

The results in Table 4-1 show probabilities of error lower than 0.5% for the rejection of the null hypothesis of the comparison between solution ideas containing the selected analogy types and non-bio-inspired solution ideas. It can be concluded that the task-specific quality of the solution ideas containing the selected analogy types is significantly higher than the task-specific quality of non-bio-inspired solution ideas.

For the comparison between solution ideas containing the selected analogy types to other bio-inspired solution ideas, the probabilities are higher than 5%. This can be due to the lower number of samples of bio-inspired solution ideas that did not contain the selected analogy types. The probability of error is higher, but for similarity and elements of transfer it is lower than 10%. For these two analogy types, the difference in task-specific quality can also be considered significant.

Table 4-1: Results of the t- test for comparing the quality of solution ideas containing the selected analogy types to other solution ideas (α: probability of error, one-sided test)

Comparison of solution ideas containing the selected analogy type to:	Accuracy Incomplete or correct analogies	Similarity analogies	Elements of transfer organs or state change
(1) non-bio-inspired solution ideas	α = 0,5%	α = 0,5%	α = 0,5%
(2) other bio-inspired solution ideas	α = 11 %	α = 9%	α = 8 %

In a second step, the feasibility of the solution ideas is regarded. As explained in section 3.2.2, feasibility is evaluated on a scale from 0 to 3 (see Table 3-8). The result is shown in Figure 4-4. The tendencies are similar for all selected analogy types: the average feasibility of solution ideas containing the selected analogy types is higher than the average feasibility of non-bio-inspired solution ideas. The feasibility of other bio-inspired solution ideas is lowest.

To conclude, the higher task-specific quality does not coincide with a decrease in feasibility. This could have been expected, because bio-inspired solution ideas based on distant analogies are expected to be more uncommon and less feasible than non-bio-inspired solutions.

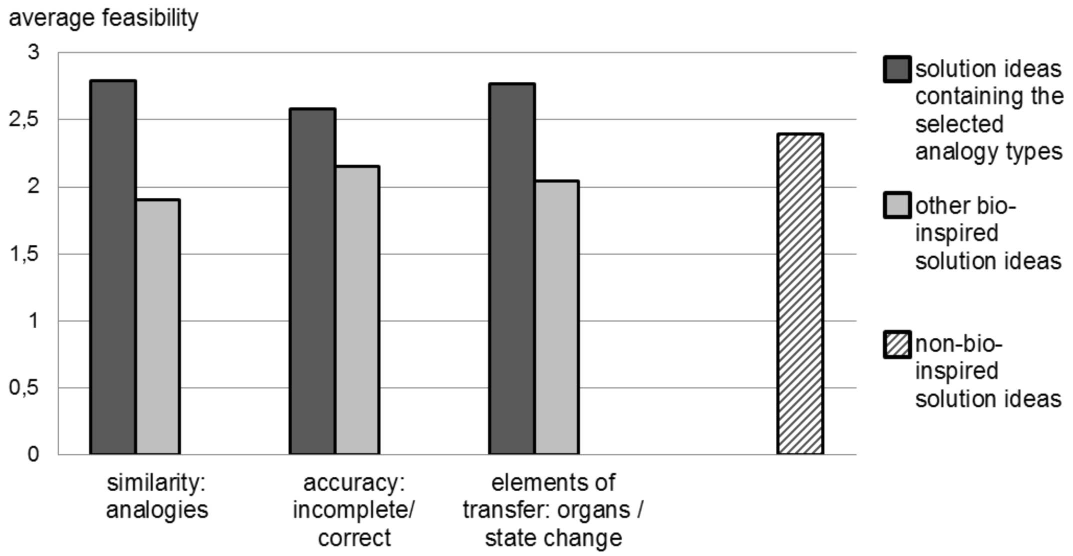

Figure 4-4: Average feasibility F of solution ideas

Conclusion

To conclude, the bi-disciplinary pairs on average documented a higher portion of solution ideas based on the analogy types: *incomplete or incorrect* (accuracy), *analogy* (similarity) and *organs or state change* (elements of transfer). In comparison to non-bio-inspired solution ideas, these analogy types have a positive influence on the task-specific quality of solution ideas and no negative influence on feasibility. One aim of *BioId* is therefore to support the documentation of solution ideas that are based on *incomplete/ correct* (accuracy) *analogies* (similarity) and contain *organ* and *state change* transfer (elements of transfer).

4.1.2 Variety and uniqueness of solution ideas (research question 2)

This section focusses on research question 2 with regards to the impact of the pair composition:

How does the pair composition influence the variety and uniqueness of solution ideas developed in an ideation phase with biological information?

First of all, the influence of the pair composition (biologist pair, engineer pair, bi disciplinary pair of one biologist and one engineer) on the use of biological information sources is regarded (research question 2.1). Then, the influence of the used biological information sources and the pair composition on the variety of solution ideas is analysed (research questions 2.2 and 2.3). Moreover, the influence of the biological information sources and the pair composition on the uniqueness of solution ideas is examined (research questions 2.4 and 2.5).

Influence of the pair composition on the use of biological information sources (research question 2.1)

Table 4-2 shows the number of pairs using analogies from the three given biological information sources (publication, Wikipedia article and video) for generating and documenting solution ideas. As the table shows, three of the four bi-disciplinary pairs used analogies from all three information sources. Only half of the uni-disciplinary pairs used all information sources.

Table 4-2: Number of pairs which used analogies from all three biological information sources

n° of pairs using three information sources for generating and documenting solution ideas	biologist pairs	engineer pairs	bi-disciplinary pairs	sum
	1 (of 2 pairs)	1(of 2 pairs)	3(of 4 pairs)	5

Overall, five pairs used analogies from all three biological information sources for the generation and documentation of solution ideas. Their influence on variety and uniqueness is compared to the three pairs using less information sources in the following subsections.

Influence of the use of biological information sources and the pair composition on the variety of solution ideas (research questions 2.2 and 2.3)

Using the method explained in section 3.2.2 and Equation 3-3 (p. 52) variety *V* and normalized variety *V** were calculated for each pair's set of solution ideas.

Figure 4-5 shows the average variety *V* depending on the use of information sources and the pair composition. The variety *V* combines measuring variety and quantity of solution ideas per pair. For the regarded pairs, variety V ranges from 59 to 129 for all solution ideas and from 31 to 119 for documented solution ideas. The overall average is 105 for all solution ideas and 83 for documented solution ideas. This decrease was expected because all pairs generated more solution ideas than they documented.

Regarding the use of information sources for the generation and documentation of solution ideas, only slight differences can be observed: The average variety *V* of the solution ideas from pairs using all and pairs using less information sources is similar for all generated and the documented solution ideas.

As to the influence of the pair composition, the biologist pairs achieved the highest average variety *V* for all generated solution ideas. The bi-disciplinary pairs generated solution ideas with the lowest average variety. Regarding the documented solution ideas, the engineers achieved the highest average variety *V*, followed by the bi-disciplinary pairs. The biologist pairs documented solution ideas with the lowest average variety *V*.

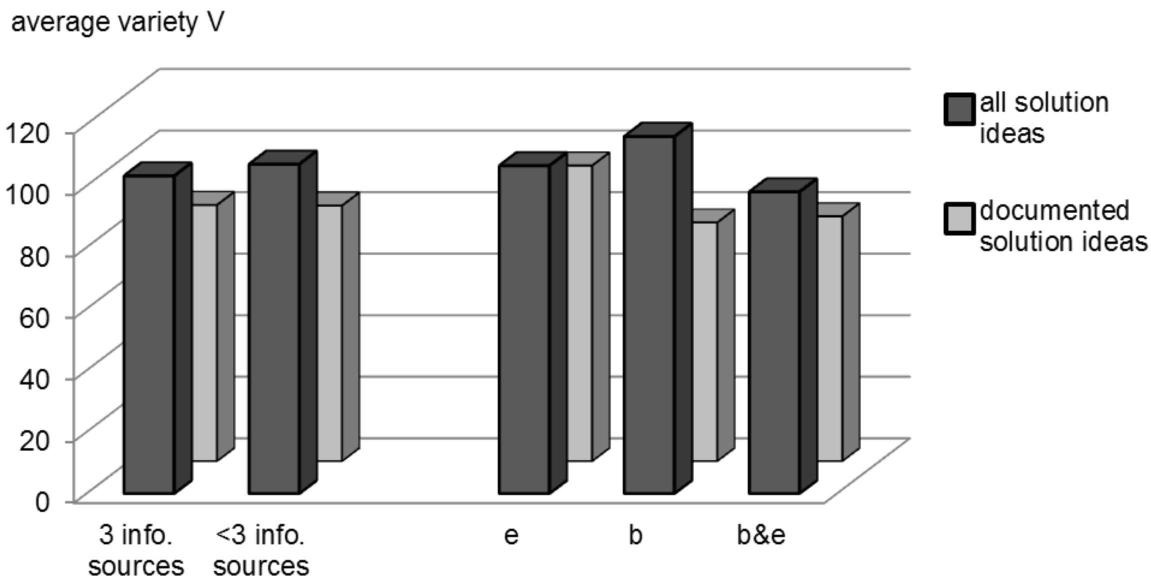

Figure 4-5: Average variety V (e: engineer pairs, b: biologist pairs, b&e: bi-disciplinary pairs)

Figure 4-6 depicts the average normalized variety V*. The normalized variety V* ranges from 2.11 to 2.86 for all solution ideas and from 1.82 to 3.07 for documented solution ideas. The average overall value is similar for all solution ideas (2.70) and documented solution ideas

(2.74). It is concluded that, the normalized variety *V** of the documented solution ideas is not generally lower than the normalized variety *V** of all solution ideas.

With regards to the use of information sources for the generation of solution ideas, the pairs using less than three information sources generated and documented solution ideas with a higher average normalized variety *V**.

As to the pair composition, the average variety *V** of the generated and the documented solution ideas of the bi-disciplinary pairs is lower compared to the uni-disciplinary pairs. On average, the variety *V** of the solution ideas generated by the engineer pairs is higher compared to biologist pairs. However, regarding the documented solution ideas, the average variety *V** of the solution ideas of the biologist pairs is higher.

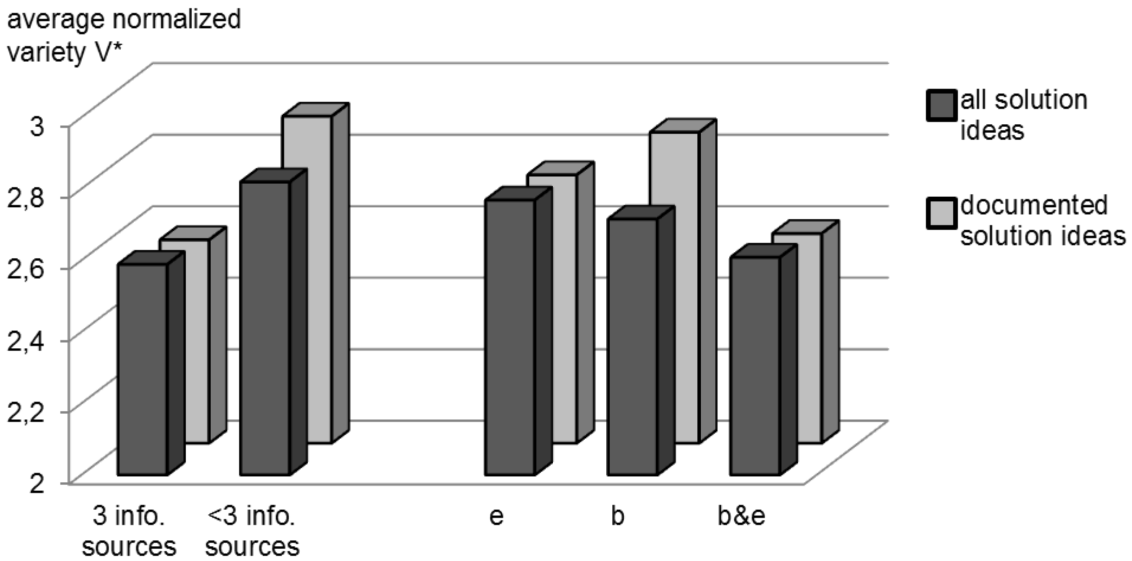

Figure 4-6: Average variety V (e: engineer pairs, b: biologist pairs, b&e: bi-disciplinary pairs)*

Influence of the use of biological information sources and the pair composition on the uniqueness of solution ideas (research questions 2.4 and 2.5)

As explained in section 3.2.2, *uniqueness* is a variable that can be measured for each solution idea, in contrast to *variety* which can only be measured for sets of ideas (for example of each pair). Figure 4-7 and Figure 4-8 show the percentage of *bio-unique* and *source-unique* solution ideas on all levels of abstraction. Figure 4-7 depicts the analysis for all generated solution ideas, Figure 4-8 only for the documented solution ideas.

To start with, all generated solution ideas are regarded:

On the embodiment level, 81 solution ideas were generated by the 8 pairs regarded for the first descriptive study. As Figure 4-7 depicts, more than two thirds of these solution ideas were bio-unique, i.e. they were only generated based on a biological analogy. As all solution ideas differ on embodiment level, two pairs cannot generate the same solution idea based on analogies from two different information sources. Therefore, on the embodiment level, all bio-inspired solution ideas are bio-unique. Moreover, there are almost no bio-inspired solution ideas which are not source-unique, i.e. the solution ideas were only generated based on one information source. The exception is one solution idea which includes analogical transfers from two different information sources. In comparison, most source-unique solution ideas were inspired by the publication, followed by the video and the Wikipedia article. Other biological knowledge inspired less source-unique ideas.

On the level of working principles, 89 solution ideas were generated. As shown in Figure 4-7, more than half of these solution ideas are bio-unique. Most bio-unique solution ideas are also source-unique, less than one tenth of the solution ideas were generated based on analogies from several information sources. In difference to the embodiment level, the portion of source-unique solution ideas based on the publication is only slightly higher than the portion of source-unique solution ideas based on the video and on the Wikipedia article. Least solution ideas were source unique regarding other biological knowledge.

On the level of physical effects, the portion of bio- and source-unique solution ideas decreases: Less than half of the 53 applied physical effects are bio-unique. About one third of the physical effects are source-unique. Here, the four regarded sources (publication, Wikipedia article, video and other biological knowledge) inspire a similar portion of source-unique solution ideas.

On the level of functions, the percentage of bio-unique functions is even lower: Less than one quarter of the 23 functions are bio-unique. There is only one source-unique solution idea which is based on information from the publication.

In a next step, only the documented solution ideas are regarded. As Figure 4-8 shows, in comparison to all generated solution ideas, the portion of bio-unique and source-unique solution ideas change only slightly. Therefore, the same tendencies as for all generated solution ideas are observed for documented solution ideas.

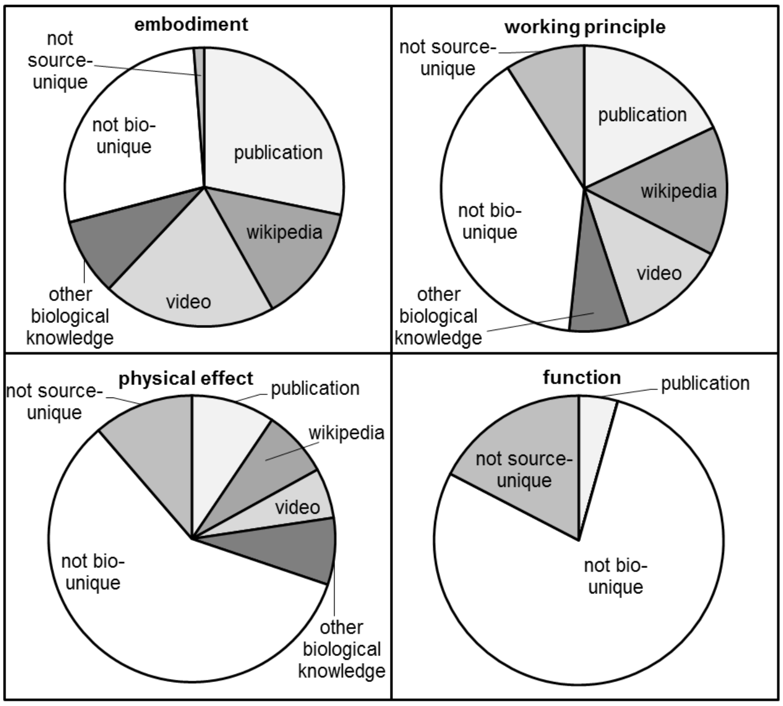

Figure 4-7: Portion of bio-unique and source-unique solution ideas on all levels of abstraction of all generated solution ideas

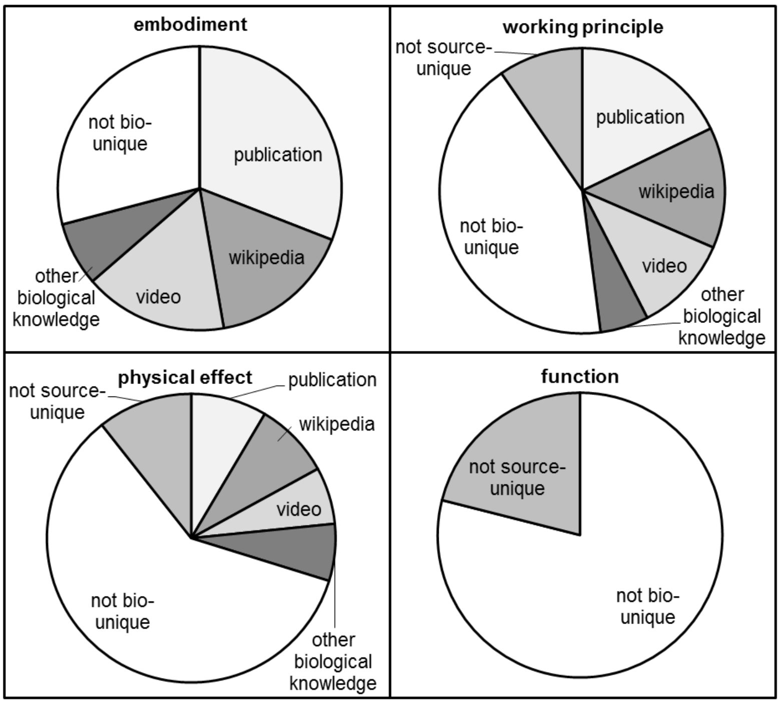

Figure 4-8: Portion of bio-unique and source-unique solution ideas on all levels of abstraction of documented solution ideas

To conclude, on embodiment and working principle level, more than half of the solution ideas were bio-unique. Most of these solution ideas were also source-unique and based on analogies from the three given information sources (publication, Wikipedia article or video). Only a small amount of bio-unique solution ideas on these levels was not source-unique or inspired by other biological knowledge. Comparing the three information sources, the portion of source-unique solution ideas based on information from the publication is highest on embodiment level. Otherwise, the portion of source-unique solution ideas was similar regarding the three given information sources. With increasing level of abstraction, the portion of bio-unique and source-unique solution ideas decreases.

In a next step, the influence of the pair composition is regarded: As bio-uniqueness seems to be more relevant on embodiment and working principle level, only these two levels of abstraction are analysed. Figure 4-9 shows the result for all solution ideas and the documented solution ideas. On working principle level, additionally the portion of source-unique solution ideas is shown. (As explained above, on embodiment level, almost all bio-unique solution ideas are also source-unique.)

The pairs of engineers generated and documented the smallest average portion of bio-unique solution ideas on both levels of abstraction. The biologist pairs generated and documented the highest average portion of bio-unique and source-unique solution ideas. The bi-disciplinary pairs generated and documented a lower average portion of bio-unique and source-unique solution ideas than the biologist pairs

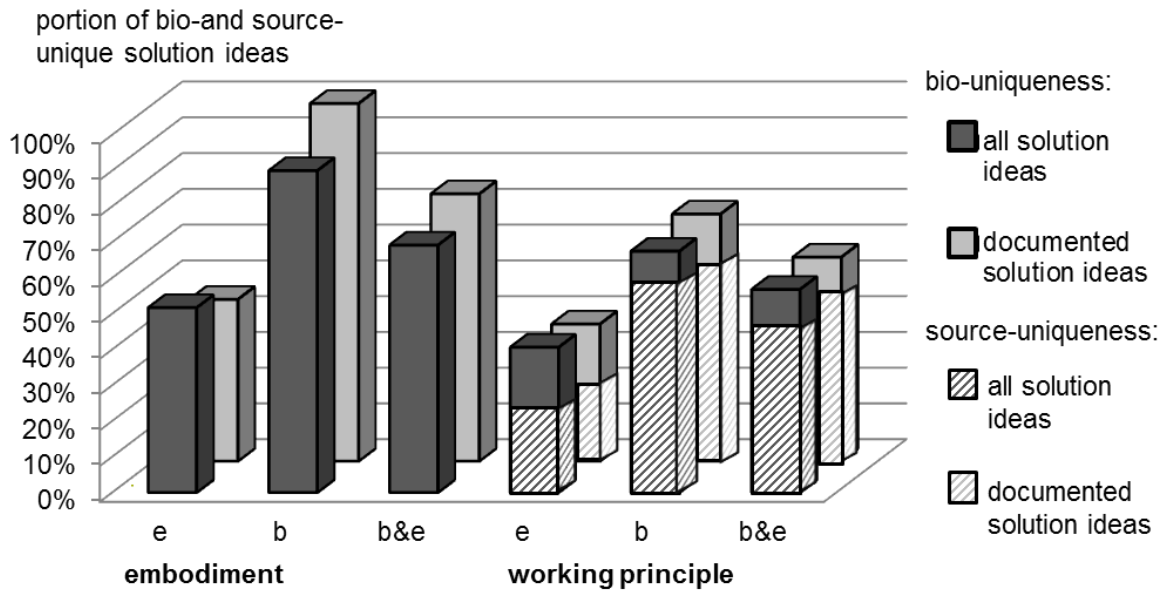

Figure 4-9: Average portion of bio-unique and source-unique solution ideas depending on the pair composition (e: engineer pairs, b: biologist pairs, b&e: bi-disciplinary pairs)

Conclusion

This section focussed on the influence of the pair composition on the use of information sources and their impact on variety and uniqueness of solution ideas.

A higher number of bi-disciplinary pairs used all three given information sources (publication, Wikipedia article and video). However, no positive influence on variety *V* could be found. As to the normalized variety *V**, the pairs that used less than three information sources even generated solution ideas with a higher average variety.

As to the bio- and source-uniqueness of solution ideas, the result was different: More than half of the solution ideas on embodiment and working principle level were bio-unique, i.e. only generated based on a biological analogy. Most of these solution ideas were also source-unique and generated based on an analogy from one of the three information sources exclusively. This shows that the information sources enabled the generation of solution ideas on embodiment and working principle level which were not generated otherwise in this experimental setting. These solution ideas do not necessarily increase variety values, but they are unique for this experiment and can therefore enhance the probability for developing unique and novel products.

Additionally, the influence of the pair composition on variety and uniqueness of solution ideas was regarded directly. On average, the bi-disciplinary pairs generated solution ideas with the lowest variety *V* and *V**. However, the average variety *V* of their documented solution ideas was similar to that of the biologists.

The influence of the pair composition regarding bio- and source-uniqueness was examined on embodiment and working principle level. The biologist pairs generated the highest average portion of bio-unique and source-unique solution ideas. The bi-disciplinary pairs generated and documented less bio-and source-unique solution ideas, but more than the engineer pairs.

4.2 Results of the qualitative analysis

The quantitative analysis provides results regarding the outcomes (generated and documented solution ideas) of the ideation in uni- and bi-disciplinary pairs. However, to improve the outcomes, reasons behind the quantitative results have to be detected. Therefore, a qualitative analysis is conducted focussing on possible improvements of the outcomes of the ideation in bi-disciplinary pairs.

Regarding the quality of solution ideas, the quantitative analysis has shown that the analogy types incomplete and correct (accuracy) analogies (similarity) and the elements of transfer organs and state change have a positive influence on the quality of solution ideas. How can the generation and documentation of these analogy types be improved in bi-disciplinary pairs?

As to the variety and uniqueness of solution ideas, the quantitative analysis has shown that each source of biological information enables the generation of source-unique solution ideas. How can bi-disciplinary pairs be supported to use every given biological information source to generate and document solution ideas?

These two questions are regarded by exploring the participants' view expressed in the questionnaire (research question 3) and the observation of the pairs' procedures during the design experiment (research question 4)

4.2.1 Participants' view (research question 3)

As explained in section 3.2.1 (page 34), the participants filled out a similar questionnaire after each ideation phase in pairs. The questionnaire responses show the participants' view on the ideation in uni-and bi-disciplinary pairs. They were asked to rate several variables and could explain their rating. The rating scales were translated to percentages (0…100%). The complete answers to the questionnaire are listed in the appendix (11.8). Figure 4-10 depicts an overview on the average rating depending on the pair composition: The biologist pairs rated the influence of biology on their solution ideas highest. Several of the biologists attributed this to their professional background and knowledge in biology.

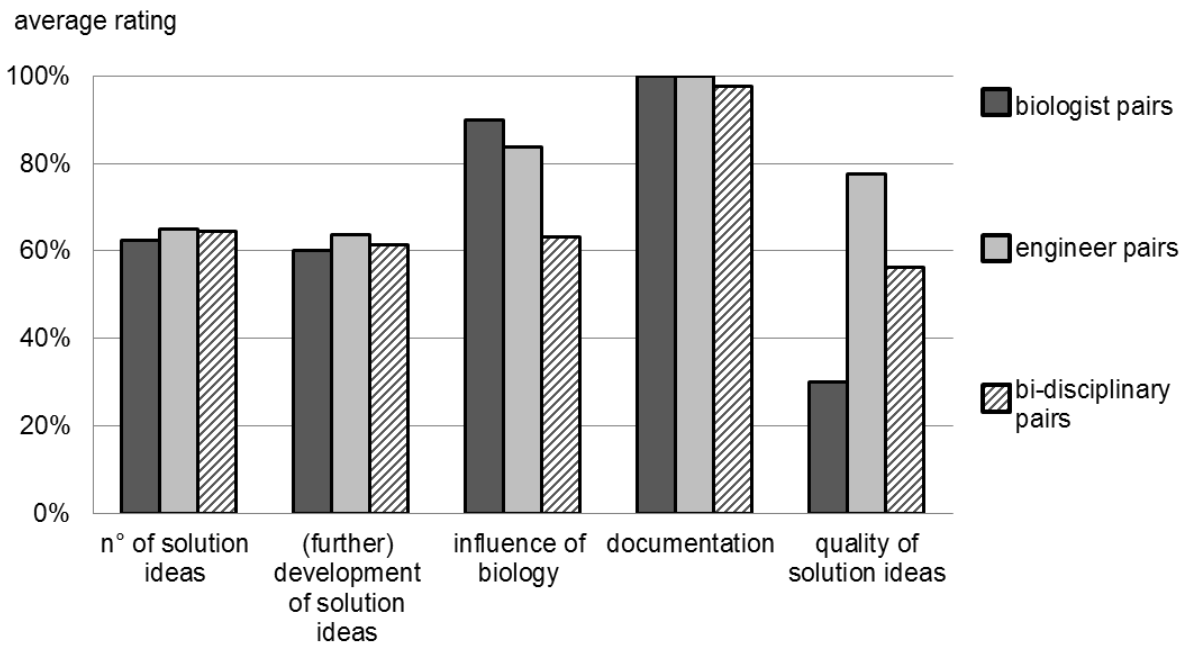

Figure 4-10: Questionnaire: Average rating of different pairs

The ratings regarding the documentation of solution ideas show an evident mismatch to the quantitative analysis: The participants of the biologists and engineer pairs rate the documentation with 100%, i.e. they claim to have documented all solution ideas. The quantitative results are different: The 15 pairs of the first descriptive study generated 81 solution ideas on embodiment level, but documented only 55 of them. As the participants' view regarding documentation is disproportionately positive, the other ratings are also questionable and are not used for developing BioId.

In conclusion, the view of the participants differs from the quantitative results. The participants view on their performance is rather too positive and consequently the comments are not used for the support development.

4.2.2 Ideation procedures (research question 4)

Two observations were made that can be used for the development of the support: general procedures were identified and the role of sketching for the selected analogy types was observed.

General procedures

In the design experiment, the participants were provided with information on the task and with a publication, a Wikipedia article and a video containing information on biological systems. They were told about the duration of the experiment (40 min). Deliberately, they were not given instructions on how to proceed during the experiments, i.e. which information source should be regarded first or how long each information source should be regarded.

In consequence, all pairs followed a different procedure regarding the use of the information sources and the discussion of the task. They are listed in the appendix (11.6). Regarding the different procedures, similarities are identified, so that two general procedures can be deduced (depicted in Figure 4-11):

- **Structured procedure:** A number of pairs regarded each information source once, one after the other (typically for 10 to 15 minutes). Sometimes, an information source was regarded once more in the last couple of minutes of the experiment (e.g. engineer pair 3). This can be interpreted as a "time-filler"- the pairs had still time but already finished using the other information sources for ideation.
- **Jumpy procedure:** A number of pairs regarded information sources several times (typically for a maximum of 10 minutes) "jumping" from source to source. These pairs sometimes left out other information sources (e.g. engineer pair 1).

To assign a pairs' procedure to a general procedure, the frequency and order of regarding information sources was more important than the exact time allocated to each information source. One pair (bi-disciplinary pair 1) cannot be unambiguously assigned – it seemed to follow a mixture of the structured and jumpy procedure.

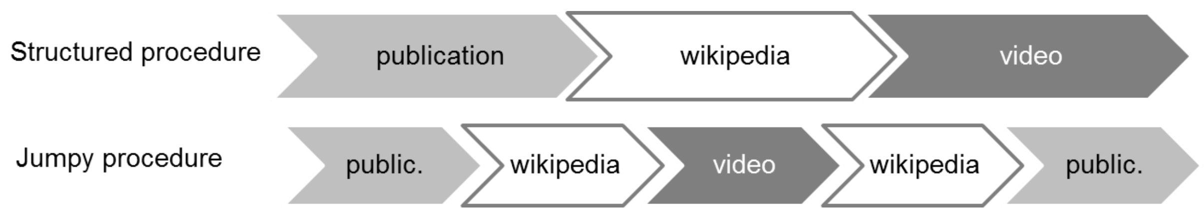

Figure 4-11: Procedure of the different pairs

Regarding the use of information sources, the three pairs who did not use all information sources for the generation of solution ideas followed a jumpy procedure. This means that they discussed all information sources, but did not spend more than a couple of minutes on each information source. It is assumed that these short discussions did not always suffice to understand the biological system and extract an analogy. Instead of concentrating on the biological system in detail, the pair rather swapped to discussing another information source.

Of the five pairs who used all information sources, three followed a structured approach, one pair adopted a mixture and one pair followed a jumpy procedure. Consequently, it is assumed that following a **structured procedure** supports the use of all biological information sources even though it is no prerequisite. The support should therefore encourage the pairs to follow a structured procedure.

Independent of the general procedure followed by the pair, the task was not discussed at the beginning of the design experiment by most of the pairs. Moreover, it was discussed in short time slots (~3 minutes), often several times in-between the discussion of information sources. The support should additionally foster a discussion of the task before the actual start of ideation.

Sketching

Regarding the procedure of the pairs an additional observation was made regarding sketching: The pairs were instructed to document their solution ideas by annotated sketches. However, they frequently discussed biological information, developed and abandoned solution ideas without sketching. In a next step, they sketched one selected solution idea.

Table 4-3 shows which pairs used sketching for discussing biological information: Sketching during the discussion of biological information was used mostly for the information from the publication. One pair (bi-disciplinary pair 2) used sketching to discuss the information from the Wikipedia article.

If sketching was used, all but one pair transferred analogies of the selected analogy types (accuracy: *incomplete/correct*, similarity: *analogy*, elements of transfer: *organ/state change*). The support should therefore foster the use of sketching to support the transfer of the selected analogy types.

Table 4-3: Use of sketching for the discussion of biological information

pair	Use of sketching to discuss information from…	transfer of the selected analogy types
biologist pair 1	publication	yes
biologist pair 3	publication	yes
engineer pair 3	publication	no
bi-disciplinary pair 2	publication	yes
	Wikipedia article	yes

4.3 Conclusion and implications for the prescriptive study

The first descriptive study aimed at analysing the influence of bi-disciplinary collaboration in an ideation phase with biological information on the solution ideas' potential for innovation. Therefore, bi-disciplinary pairs (one biologist and one engineer) were compared to uni-disciplinary pairs (two biologists or two engineers). As measures for innovativeness, firstly the quality and secondly, variety and uniqueness of solution ideas were regarded using a quantitative analysis approach (see Figure 3-1, page 31). Then, a qualitative analysis provided starting points for improving the performance of bi-disciplinary pairs regarding quality and uniqueness of solution ideas.

An overview of the results of the first descriptive study is shown in Table 4-4.

Regarding the quality of solution ideas, selected analogy types resulted in a higher task-specific quality of solution ideas. Sketching to explain biological information supports the transfer of these analogy types. Hence, the support to be developed in the prescriptive study has to foster the use of sketching by bi-disciplinary pairs.

As to variety of solution ideas, no effect of the use of biological information could be found. However, the use of biological information enabled the generation of bio- and source-unique solution ideas. The qualitative analysis showed that a structured procedure during ideation supports the use of all given information sources. A structured procedure therefore has to be a focus of the support.

Table 4-4: Overview on the results of the first descriptive study

Research question			result	Implications for the support
quality	1.1	analogy types	Regarding the selected analogy types, bi-disciplinary pairs transfer a similar portion of analogies for generating solution ideas in comparison to biologist pairs, but document a higher portion on average.	The support should strengthen the transfer of the selected analogy types further.
	1.2	quality	The selected analogy types result in a higher task-specific quality of solution ideas in comparison to non-bio-inspired solution ideas. Transferring the selected analogy types does not negatively influence the solution ideas' feasibility.	

Research question			result	Implications for the support
Variety/uniqueness	2.1	use of biological information	More bi-disciplinary pairs use all information sources	The support should facilitate the use of more information sources to increase the number of bio- and source-unique solution ideas.
	2.2	variety	Pairs using all information sources generate and document more solution ideas, but the normalized variety (*V**) is not higher	
	2.3		Bi-disciplinary pairs do not generate/ document solution ideas with higher variety	
	2.4	uniqueness	Using several information sources leads to bio- and source-unique solution ideas	
	2.5		Bi-disciplinary pairs do not generate/ document more bio- or source-unique solution ideas	
	3	participants' view	The view of the participants on their performance is disproportionally positive, consequently there are no useful comments on how to improve the ideation in pairs	none
	4	procedures	The pairs that followed a structured procedure used all biological information sources.	The support should foster a structured approach, i.e. the biological information sources should be regarded one after another. Moreover, the task should be discussed explicitly, before regarding the biological information.
			Most of the pairs which used sketching to explain a biological information source transferred the selected analogy types.	The support should request the participants to sketch for explaining biological information.

5. Prescriptive Study: Development of the *BioId* support

To develop *BioId*, a support for **bio**-inspired **id**eation, the procedure proposed by Blessing and Chakrabarti (2009, p. 146) is adopted. It includes five steps which are presented in the following sub-sections: task clarification (5.1), conceptualisation (5.2), elaboration (5.3), realisation (5.4) and support evaluation (5.5). The last sub-section (5.6) describes the improvement of *BioId* based on the support evaluation.

5.1 Task clarification

Based on the results of the first descriptive study, a requirements list for *BioId* is formulated. For setting up the requirements list, categories from Blessing and Chakrabarti's checklist for identifying scope and assumptions of design support (Blessing & Chakrabarti, 2009, pp. 302–304) are addressed. The requirements list is shown in Table 5-1.

As to the area of use, the aims of the support were deduced based on the first descriptive study: *BioId* has to support a structured procedure to foster the use of several biological information sources (in case of the design experiments: the use of publication, Wikipedia article and video). The descriptive study has shown that using several biological information sources enables the generation of bio- and source-unique solution ideas. Moreover, *BioId* has to foster the use of sketching for explaining biological information. The first descriptive study has shown that using sketching fosters the transfer of the selected analogy types *incomplete/correct* (accuracy), *analogy* (similarity) and *organs/ state change* (elements of transfer). *BioId* has to support the transfer of several analogies per biological information source. Another aim is to foster the discussion of the task at the beginning of ideation, because it was observed in the first descriptive study that few pairs explicitly discuss the task.

BioId is thought to be used for bio-inspired design in the area of mechanical engineering and for original design (i.e. not for the optimization of existing products).

The users to be supported are mechanical engineers and biologists collaborating in pairs or teams. The task to be supported is an ideation workshop: The input is therefore the task and biological information, the output are solution ideas.

As to the category *effects*, the main need to be addressed is the generation of solution ideas with potential for innovation. *BioId* has to help to overcome difficulties related to the interdisciplinarity of bio-inspired design in pairs or teamsand to facilitate the understanding of representations and terminology of the other discipline. Moreover, *BioId* has to reduce difficulties in identifying and transferring analogies of the selected types. The adopted problem solving method is to regard existing modelling and visualisation approaches and to use adequate elements of these approaches to design *BioId.*

Table 5-1: Requirements list for developing BioId

Area of use	
Aims	• Support the adoption of a structured procedure to use all biological information sources • Support sketching to increase the understanding of biological information sources and the transfer of the selected analogy types • Support the transfer of several analogies of the selected analogy types • Support the discussion of the task at the beginning of ideation
Domain	Mechanical engineering: bio-inspired design
Process type	Original design
Users and tasks	
Tasks to be supported	Ideation workshops with bi-disciplinary pairs of mechanical engineers and biologists
Functions to be fulfilled	Input: technical task, information on biological system(s) Output: bio-inspired solution ideas
N° of users	Bi-disciplinary pairs/ teams of collaborating mechanical engineers and biologists
User description	Experts in mechanical engineering/ biology
Effects	
Needs	Motivation to use the support: Conduct short ideation sessions with experts from biology and engineering, resulting solution ideas have innovation potential
Problems	• Understanding of different representations of unfamiliar discipline • Understanding of terminology from unfamiliar discipline • Difficulty in identifying analogies of the types *incomplete/ correct* (accuracy), *analogy* (similarity) and *organs/ state change* (elements of transfer)
Problem-solving method, approach	Investigate existing modelling approaches for bio-inspired analogical transfer and use elements of these approaches
Expected effect on the work situation and new work situation	• Pushing the users to understand technical and biological system in detail (not only superficially) • More concentration on different analogy types
Potential side effects	• Less creativity in regarding additional biological systems that could serve as a model
validation	• Application evaluation with master students • Success evaluation with doctoral candidates (descriptive study 2)

5.2 Conceptualisation

Based on the findings from the first descriptive study, the intended influence of *BioId* is added to the model of the research approach depicted in Figure 3-1.

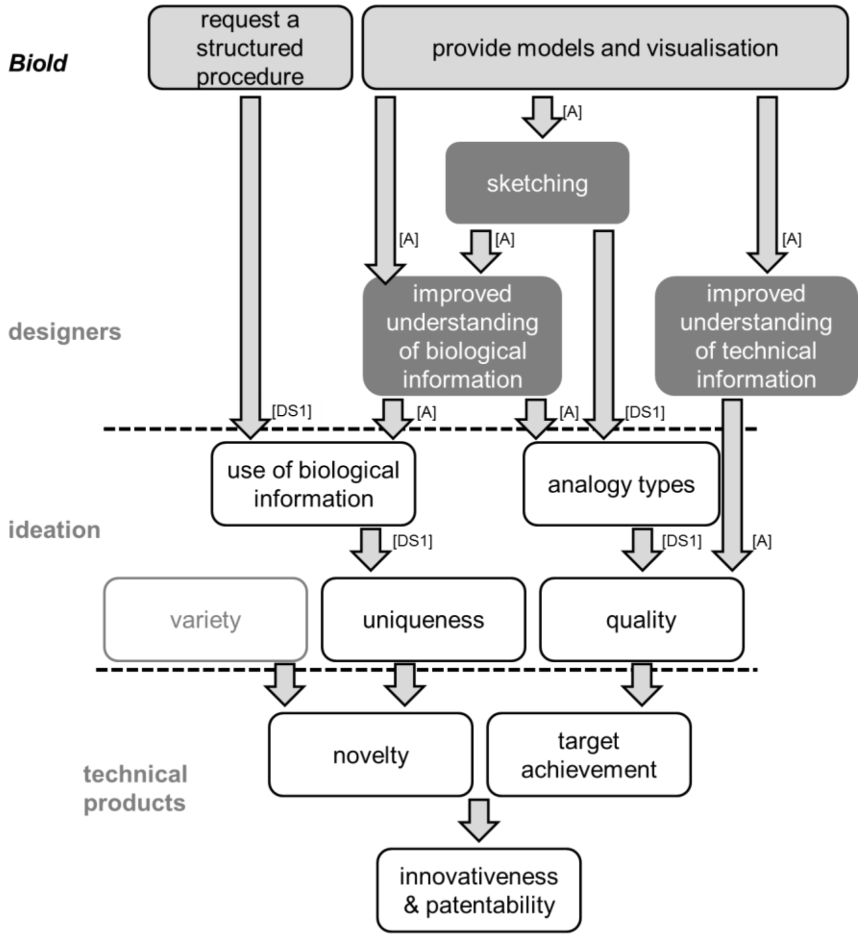

Figure 5-1: Model of the research including the intended influence of the support ([DS1]: indication of the first descriptive study- see section 4, [A]: assumption)

BioId has to support a **structured ideation procedure** to increase the amount of biological information sources a bi-disciplinary pair uses. The first descriptive study showed that this enables the generation of more bio- and source unique solution ideas. A structured procedure can be predefined by the structure of *BioId*.

Moreover, *BioId* has to support the **use of sketching** for the explanation of biological information. The first descriptive study showed that sketching fosters the transfer of the selected analogy types. An explanatory construct is introduced to the model: It is assumed that sketching facilitates the **understanding of biological information** for all participants of a pair or team. Therefore, they can transfer the selected analogy types: They identify *correct* and *incomplete* analogies and not mainly *unrelated* and *incorrect* analogies (accuracy). Moreover, by means of an increased understanding, they are able to abstract the biological systems and consequently transfer the other selected analogy types: *analogies* (similarity) instead of *literal implementations* and *organs* or *state change* instead of *parts* (elements of transfer).

Another aim of *BioId* is to foster the explicit discussion of the task. The underlying assumption is that this improves the **understanding of the technical information** by the pair or team. This can improve the fulfilment of requirements and consequently the quality of solution ideas.

In order to support sketching and understanding of information from both disciplines, *BioId* can provide models and visualisations. These models and visualizations have to be easy to use and to understand for the participating experts from both mechanical engineering and biology.

5.3 Elaboration

As a result of the conceptualisation, *BioId* will build on models and visualisation to improve the understanding of the information from both disciplines, to foster the use of sketching and the transfer of several analogies of the selected analogy types. Existing model and visualisation approaches are analysed with regards to this purpose in sub-section 5.3.1. Then, model aspects which are useful for *BioId* are extracted and combined in sub-section 5.3.2.

5.3.1 Analysis of existing models and visualisations for bio-inspired ideation

As shown in section 2.4, a number of approaches for modelling biological and technical information for bio-inspired design exist. An example is the *SAPPhIRE* model which is used for modelling both technical and biological systems using the same categories (Chakrabarti et al., 2005). Another example is the modelling approach for *DANE* aimed at representing biological systems using an engineering perspective (Vattam et al., 2011). Both modelling approaches are based on concepts of function, behaviour and structure (*SBF* or *FBS*) which have been developed from a technical perspective (e.g. by Gero, 1990). Both approaches enable the modelling of biological information in detail, but request expert knowledge on the categories used. Collections of *SAPPhIRE* and *DANE* models have been stored in databases as sources of inspiration.

However, *BioId* has to be used during short ideation workshops by pairs or teams of mechanical engineers and biologists who are not familiar with concepts of *function*, *behaviour* and *structure*. It is therefore assumed that these bi-disciplinary pairs or teams do not have the time and expertise to use *SAPPhIRE* or *DANE* to model biological and technical information in a short ideation session.

A less detailed modelling approach is used for the *inspiration card* method which was developed to be used by designers themselves after the gathering of information on biological systems (Lenau, Dentel, Ingvarsdóttir, & Gudlaugsson, 2010; Lenau, Helten, Hepperle, Schenkl, & Lindemann, 2011). Both biologists and engineering perspectives are considered by the *KoMBi* approach developed in previous work (Hashemi Farzaneh, Helms, & Lindemann, 2015b). It was designed for biologists and engineers modelling biological/

technical systems to find cooperation partners and to establish a first understanding between the disciplines. In the following, both approaches are analysed and useful aspects for *BioId* are extracted.

Inspiration Cards

The inspiration cards described by Lenau et al. (2011) include five elements:

- Title which describes the biological system and its function
- Figure of the biological system
- Textual description of the *biological mechanism*
- Textual description of an abstracted *functional principle*
- Sketch showing (the stages of) the *functional principle*

The first three elements represent the biological system and its strategy (the *biological mechanism*) to fulfil a certain function. A step of abstraction is conducted to deduce an abstracted *functional principle*. This *functional principle* is described by engineering terminology (Lenau et al., 2011) and is therefore comparable to a bio-inspired solution idea on working principle and physical effect level. The step of describing the abstracted *functional principle* therefore includes the transfer of an analogy from biology to the technical domain.

With regards to the level of abstraction, Lenau et al. (2015) compare *inspiration cards* (called *biocards*) with functional principle descriptions closer to the biological system to more abstract descriptions. They found that the novelty of solution ideas inspired by the more abstract descriptions was rated higher by the designers.

KoMBi (communication model for bio-inspired design)

To develop a modelling approach which builds on familiar models for both biologists and mechanical engineers, six features were identified in both biological and technical models in previous work (Hashemi Farzaneh et al., 2016). Three representations were developed integrating the six features (Hashemi Farzaneh et al., 2015b). An overview is shown in Table 5-2. The three representations are graphs including elements (components) of the biological/technical system and relations between these elements. In difference to the inspiration cards, *KoMBi* does not address the transfer of analogies and the generation of bio-inspired solution ideas.

Table 5-2: KoMBi: Integration of features in three representations

<table>
<tr><th rowspan="2">feature</th><th rowspan="2">definition</th><th colspan="2">KoMBi</th></tr>
<tr><th>representation</th><th>relation type</th></tr>
<tr><td>morphological</td><td>representation of the morphology of a biological/ technical system, i.e. the shape and/ or structural relations of its elements</td><td>system description</td><td>consists of
is connected to</td></tr>
<tr><td>relational</td><td>representation of cause-and-effect relations between several biological/ technical systems or system elements</td><td rowspan="2">system behaviour</td><td>impacts on</td></tr>
<tr><td>change</td><td>representation of the change of a biological/ technical system or system elements</td><td>changes to</td></tr>
<tr><td>data</td><td>representation of quantitative or qualitative data acquired about a biological/ technical system or its elements</td><td rowspan="2">system properties</td><td>attribution of qualitative and quantitative descriptions</td></tr>
<tr><td>mathematic</td><td>mathematic representation of a biological / technical system or its elements</td><td>attribution of mathematical equation</td></tr>
<tr><td>comparative</td><td>representation of a comparison between several variations of biological/ technical systems or its elements</td><td colspan="2">no separate representation, comparison of representations of several systems</td></tr>
</table>

5.3.2 Extraction of aspects which can be used for *BioId*

Comparing the levels of abstraction used for the *Inspiration cards* and the *KoMBi* approaches, different ways of representation are used. For the development of *BioId*, a differentiation between *low* and *high* abstraction levels is made: If only an analogy on embodiment or working principle level is transferred, the abstraction level is considered *low*. If an analogy on physical effect or function level is transferred, the abstraction level is considered *high*. The two approaches *Inspiration cards* and *KoMBi* represent different information with regards to technical, biological and bio-inspired systems. Figure 5-2 depicts the differences:

The inspiration cards do not represent information on a technical system or task. They depict information on a biological system using a sketch or photo on the low abstraction level and text to describe the *biological mechanism* on a higher abstraction level. As explained above, the *functional principle* can be considered a bio-inspired solution idea based on the physical effect and working principle of the biological system. In Figure 5-2 it is therefore assigned to the bio-inspired domain. The *inspiration cards* represent information on the functional principle by textual descriptions and sketches.

KoMBi represents similar information on technical and biological system, but no information on bio-inspired systems. On the low abstraction level, the information is depicted by sketches and graphs. On the high abstraction level, it is depicted by graphs only.

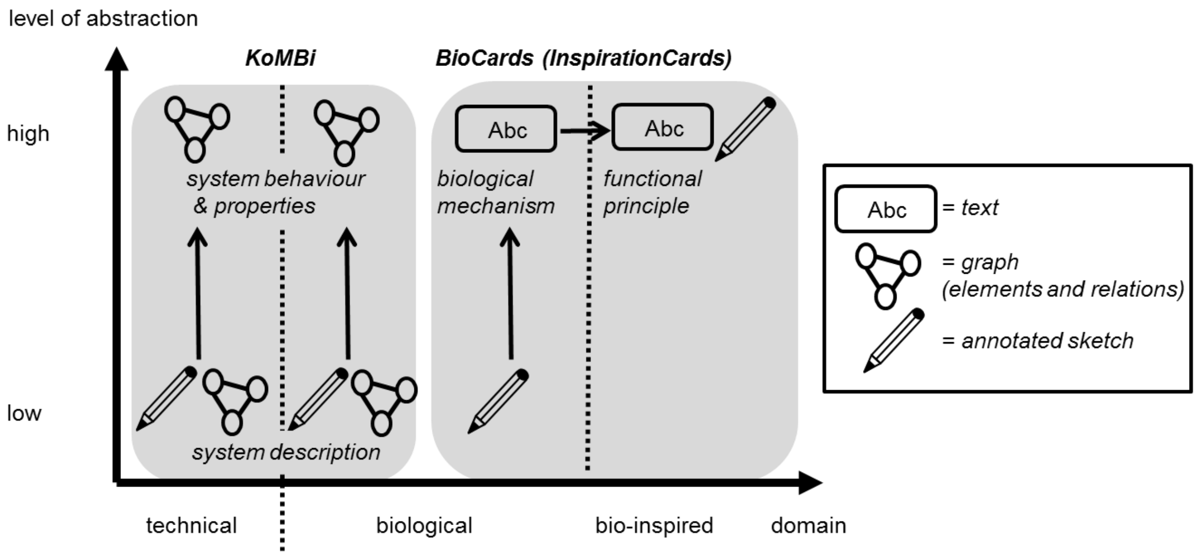

Figure 5-2: Comparison of graphical representations of inspiration cards (Lenau, Dentel, Ingvarsdóttir, & Gudlaugsson, 2010; Lenau, Helten, Hepperle, Schenkl, & Lindemann, 2011) and KoMBi (Hashemi Farzaneh et al., 2015b)

BioId has to enable the representation of information about the technical task (technical system) and the biological information sources (biological system). Moreover, its area of application is ideation, i.e. bio-inspired systems have to be represented as well. This can be achieved by using aspects from *inspiration cards* (biological and bio-inspired system) and *KoMBi* (biological and technical system): The selected means of representation are depicted in Figure 5-3.

On the high level of abstraction, inspiration cards use textual descriptions for the biological system, *KoMBi* applies graph representations. Here, the *KoMBi* approach is used, because graphs are visually easier to grasp than textual descriptions. For the representation of the bio-inspired system, the inspiration cards use textual description and sketching. For *BioId*, this is simplified to the use of sketching only.

On the low level of abstraction, both *ideation cards* and *KoMBi* apply sketching for the representation of information. This approach is adopted for *BioId*. *KoMBi* additionally proposes graph representation linking the elements of the system by relations of the types *consists of* and *is connected to*. As time is limited in ideation workshops, the graph is not used for *BioId*. Regarding the technical system, *BioId* has to support an ideation based on a technical task, therefore no concrete technical system has to be described on a low level of abstraction. The technical task can only be represented on the high level of abstraction.

On the low abstraction level, the existing representations do not represent information on the bio-inspired system. As one aim of *BioId* is to support the transfer of several analogies per biological information source, an analogical transfer to a bio-inspired solution on the low level of abstraction will be included as well. Similar to the high level of abstraction, a sketch will be used for *BioId*.

5.4 Realisation

After defining the means of representation, the procedure to be followed by the pairs has to be defined. As stated in the requirements list (Table 5-1, page 76), *BioId* has to support a structured procedure, i.e. the biological information sources have to be regarded one after the other. Moreover, it has to support the discussion of the task at the beginning of ideation.

The resulting procedure is shown in Figure 5-3: The technical system has to be modelled on a first template. Then, on three separate templates the three biological information sources and the associated bio-inspired solution ideas (systems) are modelled: As the *inspiration cards* and *KoMBi* approaches, the biological system is first modelled on a low and then on a high level of abstraction. For the bio-inspired solution ideas, the same approach is adopted: To start with, the pairs or teams have to transfer analogies and represent bio-inspired solution ideas on a low level of abstraction, then on a high level of abstraction. Here, the models of the biological system serve as inspiration.

A translation of the *BioId* templates is depicted in the appendix (appendix 11.11). An open question is the collaboration mode: either the experts from both disciplines collaborate or they work separately and then discuss and improve the results. Both options will be tested in the support evaluation.

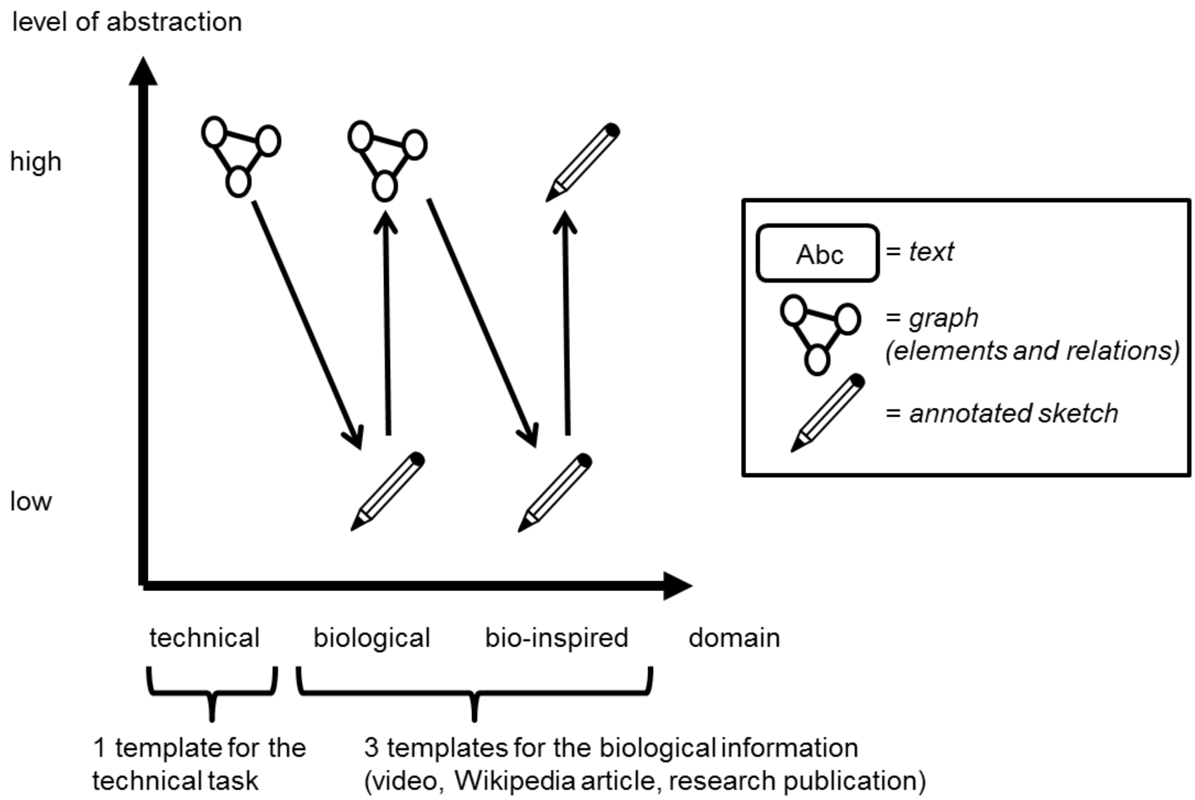

Figure 5-3: Means of representation used for BioId

5.5 Support Evaluation

The support evaluation aims at evaluating the usability of the support. Moreover, the influence of the support on the factors it is expected to affect directly is regarded (Blessing & Chakrabarti, 2009, p. 184). In case of *BioId*, these factors are the use of sketching, the understanding of technical and biological information and the use of the biological information for generating solution ideas (see Figure 5-1, page 77).

In this work, additionally the effect of separate work followed by collaboration in a bi-disciplinary pair is regarded. Therefore, a design experiment with two bi-disciplinary pairs of master students is conducted. In both pairs, a student of biology collaborates with a student of mechanical engineering to solve task I (water pump).

One of the pairs collaborates for the duration of the design experiment. The other pair is asked to work separately for half of the experiment duration. In this pair, both participants are given all four *BioId* templates. The engineering student is instructed to focus on the technical task template, the biology student is asked to focus on the biological information templates, in particular on the description of the biological system.

The material given to the participants and the duration of the experiment (40 min) is equal to the descriptive studies. After the design experiment, the participants are asked several questions in a group interview. Moreover, the outcomes of the ideation, i.e. the filled *BioId* templates are analysed.

The feedback of the students given in the group interview and the *BioId* templates are qualitatively analysed with regards to the modelling of technical task, biological information and bio-inspired solution idea. A summary is shown in Table 5-3.

Regarding the **usability** of *BioId*, both participant feedback and the analysis of the outcomes show difficulties in using the template for modelling the technical task. In contrast, the participants had fewer difficulties to model the biological information. Still, there was a lack of time. This is a possible explanation for the fact that in most cases only one bio-inspired solution idea was developed per biological information source. Moreover, the participants suggested a different procedure regarding the transfer of analogies for the generation of bio-inspired solution ideas: The prescribed procedure requested to model the biological system on low and high abstraction levels and then to develop bio-inspired solution ideas on low and high abstraction levels. Instead, the participants suggest to model the biological system on a low abstraction level and to directly transfer an analogy to generate a solution idea on a low abstraction level. Then, the same procedure should be repeated on the high abstraction level.

As to the **influence on the factors** shown in Figure 5-1 (page 77), the analysis of the outcomes shows that sketching was used to model most biological systems. However, the participants expressed both positive and negative opinions on the use of sketching. The use of biological information for ideation was limited due to the lack of time. The feedback and analysis of the outcomes show no increased understanding of the technical task. However, the developed models of the biological systems show an increased understanding.

With regards to the influence of separate work at the beginning of ideation, the participants' feedback was negative. The analysis of the outcomes also showed less developed biological models in comparison to the pair which collaborated for the entire duration of the workshop.

Table 5-3: Support evaluation: participant feedback and analysis of the outcomes

	Feedback participants	Analysis of the outcomes (*BioId* templates)
Technical task	• difficulties in describing the technical system in a few words • difficulties in selecting one problem of the task description text	template was not understood well, e.g.: • the relations were formulated in passive • the participants failed to differentiate between the technical system and the environment
Biological information	• differing opinions about the sketch of the biological system • time is short	• sketching was used to model most biological systems • the two levels of abstraction were not always completely modelled • the pair collaborating for the entire duration of the experiment modelled the biological system more correctly and completely than the pair of participants who worked separately first
Bio-inspired solution ideas	• The prescribed procedure leads to a step back when the sketch should serve as an inspiration after the biological system has been modelled by a graph. The procedure should be different: 1) low level of abstraction: sketch biological system → bio-inspired idea 2) high level of abstraction: model biological system using a graph → bio-inspired idea • Time is too short	• The participants developed only one idea for most biological information sources.

5.6 Improvement of the support

Based on the results of the support evaluation, several improvements of *BioId* are made. The revised procedure and the means of representation are depicted in Figure 5-4. The revised version of *BioId* is included in the appendix (appendix 11.13, page 276). The following changes are made:

- The graph representation of the technical task is excluded from the template. To simplify the template and to reduce the time-effort for discussing the task, instead of the graph representation, the participants are asked to name sub-tasks and properties of the desired technical solution.
- The sequence of modelling biological system and generating bio-inspired solution ideas is changed as suggested by the participants.
- To enable a more continuous and understandable procedure, the participants have the option of modelling the bio-inspired solution idea on a high abstraction level with a graph representation instead of a sketch.
- The instructions are simplified and focus more on the analogical transfer.

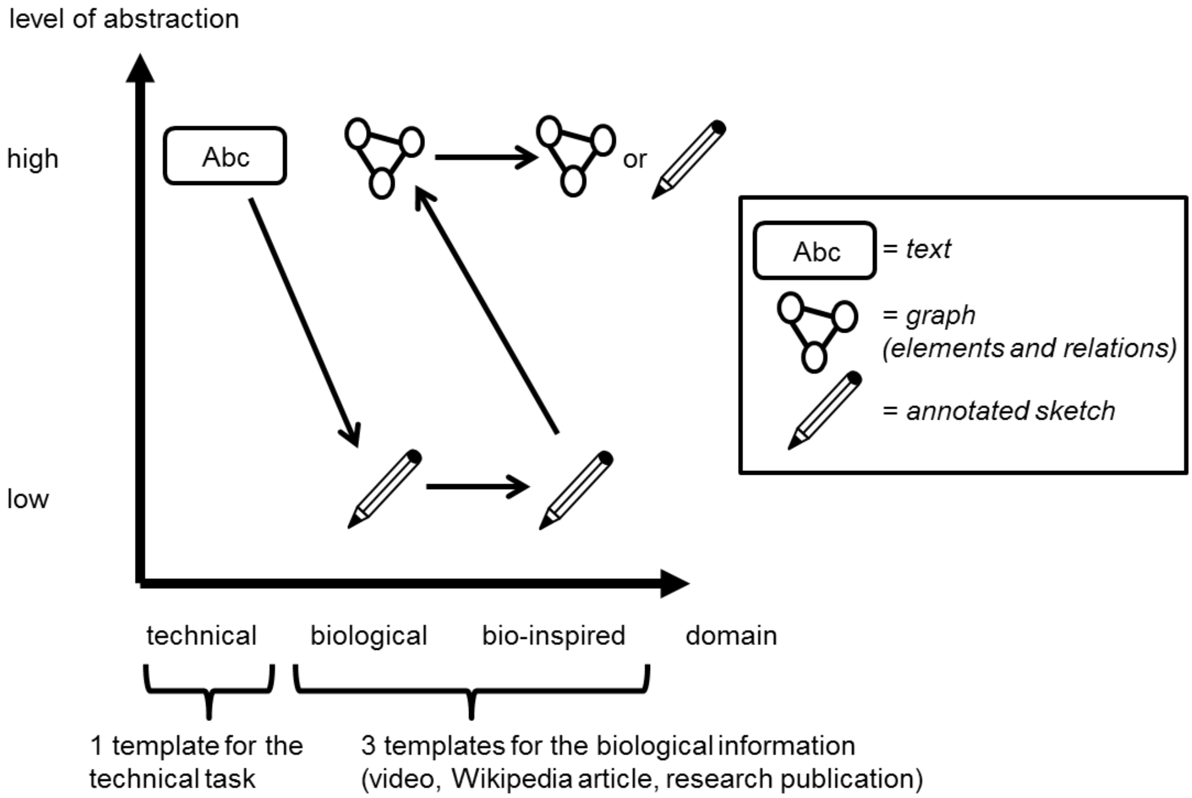

Figure 5-4: Procedure and means of representation used for the revised version of BioId

5.7 Example for the use of *BioId*

Figure 5-5 shows an example for the use of the revised version of the *BioId* support taken from support pair 1. Specifically, it is a simplified translation of the template for modelling the technical task and the biological information. Moreover it shows the text (translated) and the sketches used of support pair 1 to describe the technical task and the biological information (praying mantis) from the video information source.

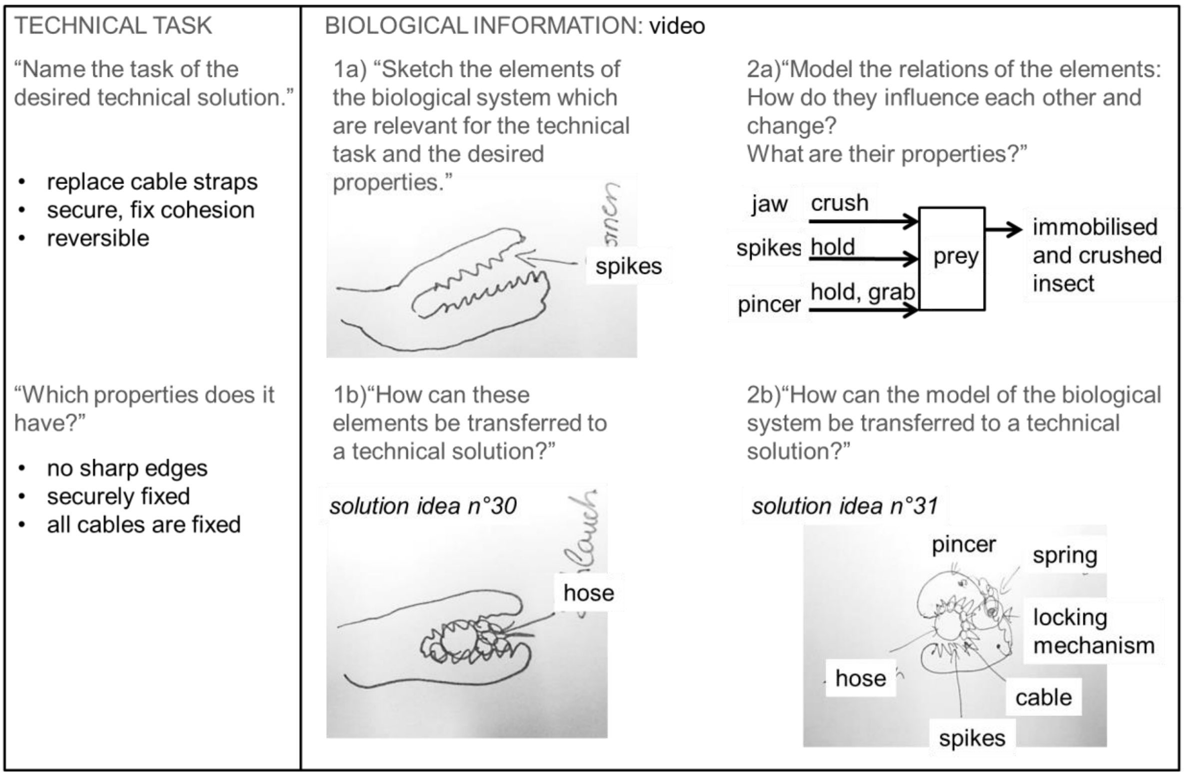

Figure 5-5: Example for the use of BioId (revised version)

Table 5-4 shows the classification of the two solution ideas on embodiment level generated in the example: On working principle level, both solution ideas are composed of a *clamp* (working principle n°13,3) with *barbed hooks* (working principle n°59,3). The *clamp* is categorized as a *correct* (accuracy) *analogy* (similarity) for which *organs* are transferred (elements of transfer). This is due to the similarity to the praying mantis clamp on working principle, physical effect and function level. The barbed hooks of the technical solution are placed with different distances to adapt to the diameter of the cables and hose. In difference, the spikes of the praying mantis penetrate into the body of its prey. Thereby the praying mantis is able to catch prey of different sizes. The solution idea is therefore considered similar on working principle level (*barbed hooks*) and on function level (*adaptation to different sizes/ diameters*). However, it differs on the level of physical effects (*form closure/ penetration*). In consequence it is categorized as an *incomplete* (accuracy) *analogy* (similarity) for which *attributes* are transferred (elements of transfer).

The second solution idea extends the solution by providing a spring that tightens the clamp around hose and cables. This is similar to the praying mantis only on the most abstract level, the function level: The praying mantis can also tighten and loosen its grip, but it does not use elastic deformation or a spring to implement this function. The solution idea is therefore categorized as an *incomplete* (accuracy) *analogy* (similarity) for which a *state change* is transferred (elements of transfer).

Table 5-4: Classification of the example's solution ideas

embodiment (solution idea n°)	working principle	physical effect	function	analogy types
30 31	clamp (13,3)	static friction (FR= μ*FN)	hold	correct analogy organs
30 31	(barbed) hooks (59,3)	form closure	adapt to diameter of cables/ hose (continuously)	incomplete analogy attributes
31	spring (34,3)	elastic deformation	tighten and loosen	incomplete analogy state change

This example shows that the two step approach of *BioId* can enable the further development of a solution idea. In this case, using the second part of the template, the support pair added an additional working principle which completed the solution idea generated with the first part of the template. The added working principle implemented the transfer of an analogy on the most abstract level. This is intended by the template as in the second step, the participants are requested to model the biological system on a more abstract level (physical effects and functions).

6. Second descriptive study: influence of bi-disciplinary collaboration and *BioId*

The second descriptive study reassesses the influence of the pair composition with data from an enhanced number of pairs: Overall, five biologist pairs, five engineer pairs, five bi-disciplinary pairs without support and five bi-disciplinary pairs working with the *BioId* support (*support pairs*) are compared. In total, the regarded pairs generated 196 solution ideas on embodiment level and 187 solution ideas on working principle level. In comparison to the first descriptive study (section 4), there are 105 additional solution ideas on embodiment level and 83 additional solution ideas on working principle level. Using this data, the influence of the bi-disciplinary pair composition is reassessed and the BioId support is evaluated.

An answer is given to all research questions stated in section 3.1.

Figure 6-1 shows the average number of solution ideas of the different pair compositions on working principle level (arithmetic mean). In comparison to the other pairs, the average number of non-bio-inspired solution ideas is lower for the support pairs. The average number of bio-inspired solution ideas is comparable to the bi-disciplinary pairs working without support. Regarding documented solution ideas, the support pairs documented mostly bio-inspired solution ideas. Their total number is on average lower than the number of bio-inspired solution ideas of the other pairs. This decline in the documentation of solution ideas has to be considered in the analysis.

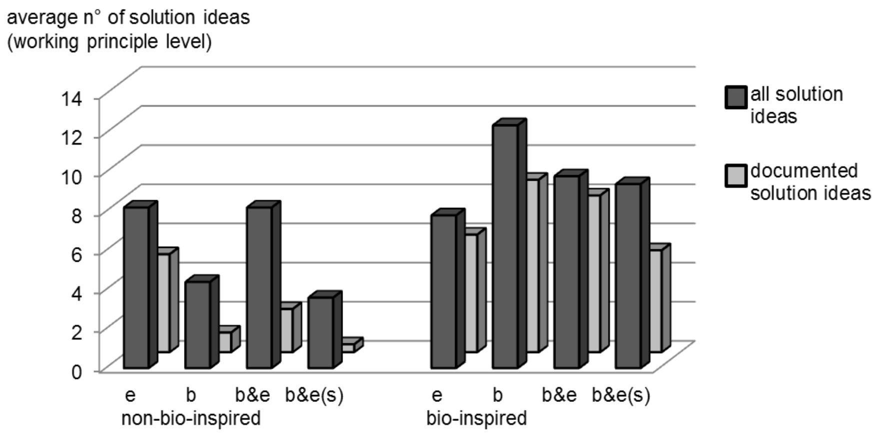

Figure 6-1: Average number of bio-inspired and non-bio-inspired solution ideas per pair (arithmetic mean) (e: engineer pairs, b: biologist pairs, b&e: bi-disciplinary pairs, b&e(s): support pairs)

The following sub-sections detail the analysis of the solution ideas with regards to the research questions. The results of the quantitative analysis and the qualitative analysis are presented. Then, the measures for the verification of the results are shown. The section closes with a conclusion regarding the influence of the pair composition and the evaluation of *BioId*.

6.1 Results of the quantitative analysis

To start with, the quantitative results for the quality (research question 1) of solution ideas is shown (research question 1). Then, the influences on the variety and uniqueness are examined (research question 2).

6.1.1 Quality of solution ideas (research question 1)

This section focusses on research question 1:

How do the pair composition and the support influence the quality of solution ideas developed in an ideation phase with biological information?

First of all, the influence of the pair composition and the *BioId* support on the analogy types (accuracy, similarity, elements of transfer) is regarded. Then the influence of the analogy types on the quality of solution ideas is examined.

Influence of the pair composition and the *BioId* support on the analogy types (research question 1.1)

To start with, the influence of the pair composition and the *BioId* support on the portion of the selected analogy types is regarded: Figure 6-2 depicts the average portion (arithmetic mean) of *correct* and *incomplete* analogies (accuracy), *analogies* (similarity) and *organs* and *state change* (elements of transfer) for the different pairs.

Regarding all solution ideas, the figure depicts that the portion of *correct* and *incomplete* analogies are slightly higher for biologists and bi-disciplinary pairs without support than for engineers. Support pairs transferred the highest average portion of *correct* and *incomplete* analogies. The same result is provided for the number of *analogies* in terms of similarity. Regarding elements of transfer, the highest portion of *organs* and *state change* was transferred by the support pairs, followed by the bi-disciplinary pairs and the engineers. The lowest portion was transferred by the biologists.

As to the documented ideas, the engineer pairs increased the portion of all regarded analogy categories slightly. The biologist pairs' portion of all regarded analogy categories remains similar compared to all solution ideas. In comparison to the uni-disciplinary pairs, the bi-disciplinary pairs without support documented a higher portion of all regarded analogy types. The highest portion of all regarded analogy types was documented by the support pairs.

To summarize, biologist and engineer pairs transfered and documented a similar portion of analogies of the selected analogy types on average. Bi-disciplinary pairs without support transfered a similar portion, but documented a higher portion on average. Support pairs transfered and documented the highest portion of the selected analogy types on average.

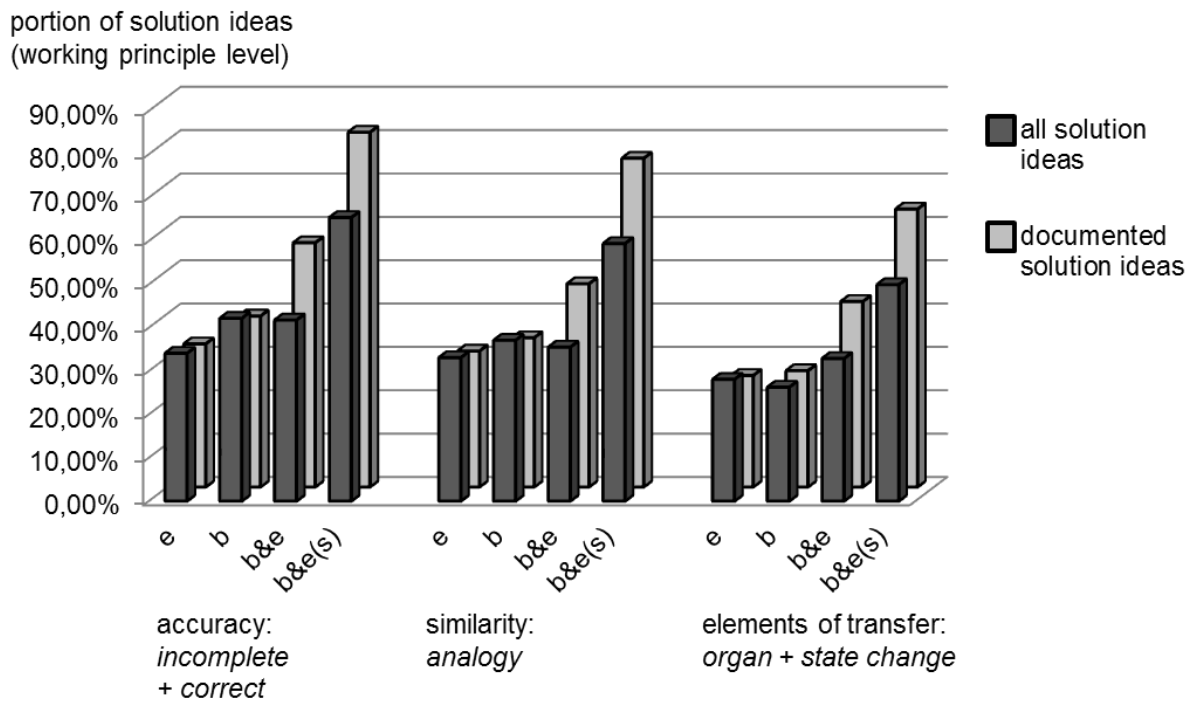

Figure 6-2: Average number of analogy types for different pair compositions (e: engineer pairs, b: biologist pairs, b&e: bi-disciplinary pairs, b&e(s): support pairs)

In a next step, the significance of these average numbers is regarded both for the influence of the pair composition and the influence of the support. Null-hypotheses and alternative hypotheses are formulated:

Influence of the pair composition (Table 6-1):

Comparison of bi-disciplinary pairs without support to uni-disciplinary pairs:

- Null hypothesis: There is no difference between uni- and bi-disciplinary pairs
- Alternative hypothesis: Bi-disciplinary pairs transfer / document a higher portion of the selected analogy types than uni-disciplinary pairs

Influence of the support (Table 6-2):

Comparison of support pairs to uni-disciplinary pairs:

- Null hypothesis: There is no difference between uni-disciplinary pairs and support pairs
- Alternative hypothesis: Support pairs transfer / document a higher portion of the selected analogy categories than uni-disciplinary pairs

The null hypotheses are tested using the Wilcoxon rank sum method presented in section 3.2.2.

Table 6-1 and Table 6-2 show the arithmetic mean and the test value U (calculated by Equation 3-4, page 55) for each analogy category. The last line shows the probability of error α for the rejection of the null hypothesis.

Table 6-1 shows the result of the Wilcoxon rank-sum test for the comparison between uni- and bi-disciplinary pairs without support: Regarding all solution ideas, the probability of error is higher than 10% for all selected analogy types. Despite the different average values, the differences between uni-disciplinary and bi-disciplinary pairs working without support are not distinct enough to be significant. The result of the Wilcoxon rank-sum test is different for the documented solution ideas: Regarding *organs* and *state change* (elements of transfer) and *incomplete* and *correct* analogies (accuracy), the probability of error is lower than 10% and 5%. It can be deduced that with a probability higher than 95% the bi-disciplinary pairs documented a higher portion of *correct* or *incomplete* analogies. With a probability higher than 90%, they documented a higher portion of *organs* and *state changes*. Regarding *analogies* (similarity), the test value U_1=13 for documented solutions is lower than U_1=23 for all solutions. Even though the statistical significance cannot be shown, the test values of the documented solutions are therefore more different than the values of all generated solutions.

Table 6-1: Results of the Wilcoxon rank-sum test for comparing uni- and bi-disciplinary pairs with regards to analogy types (m= arithmetic mean, U_1/ U_2= test values)

	Accuracy Percentage of Incomplete+ correct analogies		Similarity Percentage of analogies		Elements of transfer Percentage of organs and state change	
solution ideas	all	doc.	all	doc.	all	doc.
Uni-disciplinary pairs	m=38% U_1=23	m=40,3% U_1=9,5	m=35% U_1=23	m=36% U_1=13	m=26% U_1=20	m=28% U_1=11,5
Bi-disciplinary pairs (no support)	m=42% U_2=27	m=60% U_2=40,5	m=36% U_2=27	m=53% U_2=37	m=34% U_2=30	m=49% U_2=38,5
probability of error (one-sided test)	$\alpha > 10\%$	$\alpha \leq 5\%$	$\alpha > 10\%$	$\alpha > 10\%$	$\alpha > 10\%$	$\alpha \leq 10\%$

Table 6-2 shows the result of the Wilcoxon rank-sum test for the comparison between uni-disciplinary and support pairs. Regarding the portion of *incomplete* and *correct* analogies (accuracy), the probability of error is lower than 5% for all solution ideas, lower than 0.1% for documented solution ideas. It can be deduced that support pairs transfer and document significantly more *correct* and *incomplete* analogies than uni-disciplinary pairs. As to the portion of *analogies* (similarity), the probability of error is higher, but lower than 10% for all solution ideas and lower than 0.5% for the documented solution ideas. With regards to *organ* and *state change* transfer (elements of transfer), the probability of error is higher than 10% for all ideas, but lower than 5% for the documented ideas.

Table 6-2: Results of the Wilcoxon rank-sum test for comparing uni- and support pairs regarding analogy types (m= arithmetic mean, U_1/ U_2= test values)

	Accuracy: portion of incomplete and correct analogies		Similarity portion of analogies		Elements of transfer portion of organs and state change	
solution ideas	all	doc.	all	doc.	all	doc.
Uni-disciplinary pairs	m=38% U_1=9,5	m=40,3% U_1=0	m=35% U_1=11	m=36% U_1=1,5	m=26% U_1=14	m=28% U_1=8
Bi-disciplinary pairs with support	m=65% U_2=40	m=86% U_2=50	m=60% U_2=39	m=81% U_2=48,5	m=49% U_2=36	m=42% U_2=36
probability of error (one-sided test)	$\alpha \leq 5\%$	$\alpha \leq 0.1\%$	$\alpha \leq 10\%$	$\alpha \leq 0.5\%$	$\alpha > 10\%$	$\alpha \leq 5\%$

To conclude, the pair composition has a positive influence on the documentation of solution ideas which include analogies of the type *incomplete* or *correct* (accuracy) and *organs* or *state change* (elements of transfer).

The support had a positive influence on the transfer and documentation of the selected analogy types: The support pairs transferred a significantly higher portion of the analogy types *incomplete* or *correct* (accuracy) and *analogies* (similarity). They documented a significantly higher portion of solution ideas based on all selected analogy types than uni-disciplinary pairs.

Comparing the influence of pair composition and support, the observed tendencies for bi-disciplinary pairs become stronger if bi-disciplinary pairs work with a support. Considering the comparatively lower number of documented solution ideas shown in Figure 6-1, the support seems to have a “focussing” effect – the solution ideas based on the regarded analogy types are documented more often than other solution ideas.

Influence of the analogy types on the quality of solution ideas (research question 1.2)

The quality analysis is a replication of the quality analysis described in section 4.1.1 including the additional solution ideas. As, at this stage, the solution ideas are regarded separately from the pairs who generated them, similar results in comparison to the analysis provided in the first descriptive study are expected.

As in the first descriptive study, the solution ideas containing the analogy types *incomplete/ correct* (accuracy), *analogy* (similarity) and *organs/ state change* (elements of transfer) are regarded. They are compared to non-bio-inspired solution ideas and all bio-inspired solution ideas not containing these analogy types.

Firstly, the task-specific quality is regarded. As Figure 6-3 shows, the results have the same tendency as for the analysis of the solution ideas from the first descriptive study: The average task-specific quality *Q* of the solution ideas containing the selected analogy types is highest with approximately 60%. The average task-specific quality *Q* of other bio-inspired solution ideas is approximately 50%. The average task-specific quality Q of non-bio-inspired solution ideas is lowest – approximately 40%.

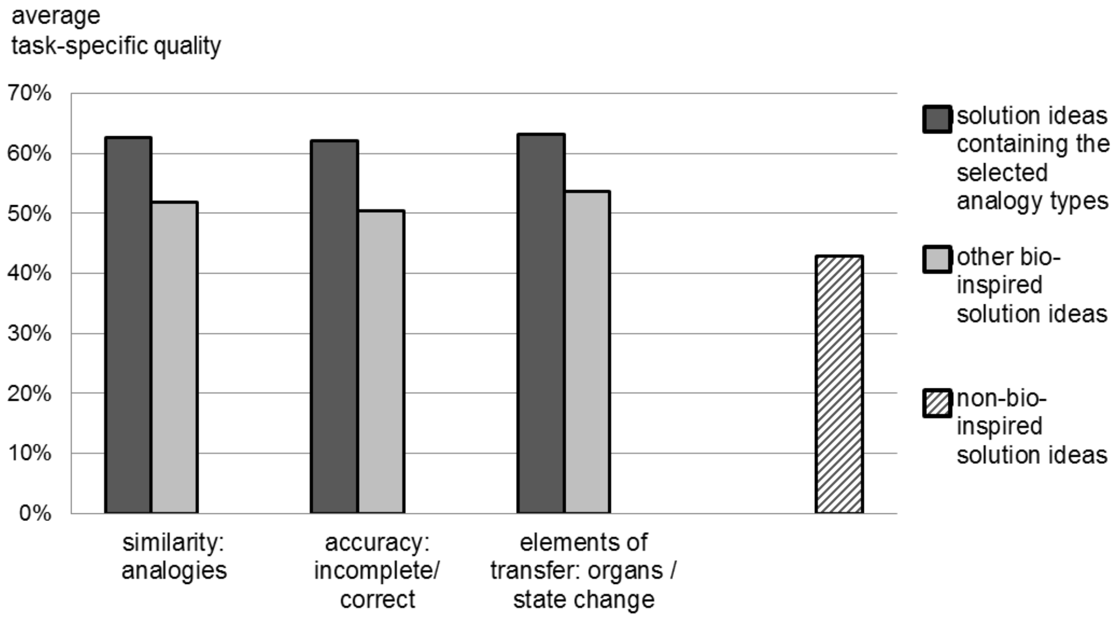

Figure 6-3: Task-specific quality Q of solution ideas

The significance of the difference between solution ideas containing the selected analogy types and other solution ideas is tested with the same null-hypothesis and alternative hypothesis:

- Null hypothesis: Solution ideas containing the selected analogy types have no higher task-specific quality *Q* than (1) non-bio-inspired solution ideas / (2) other bio-inspired solution ideas
- Alternative hypothesis: Solution ideas containing the selected analogy types have a higher task-specific quality *Q* than (1) non-bio-inspired solution ideas / (2) other bio-inspired solution ideas

As in the first descriptive study, the t-test for two samples with similar variances presented in section 3.2.2 is used to test the hypotheses. The results in Table 6-3 show probabilities of error lower than 0.5% for the rejection of the null hypothesis of all tests. In comparison to the analysis of the solution ideas of the first descriptive study, the tendencies are stronger:

Analysing only the solution ideas from the first descriptive study, the probabilities of error for the comparison between solution ideas containing the selected analogy types to other bio-inspired solution ideas are higher than 5%. Including the solution ideas from the second descriptive study, the probabilities of error decrease to under 0.5%.This can be due to the higher number of solution ideas analysed.

In conclusion, the result is as expected: The quality of the solution ideas containing the selected analogy types is significantly higher than (1) the quality of other solution ideas and significantly higher than (2) the quality of other bio-inspired solution ideas.

Table 6-3: Results of the t- test for comparing the task-specific quality Q of solution ideas containing the selected analogy types to other solution ideas (α: probability of error, one-sided test)

Comparison of solution ideas containing the selected analogy type to:	Accuracy Incomplete or correct analogies	Similarity analogies	Elements of transfer organs or state change
(1) non-bio-inspired solution ideas	α = 0.004%	α = 0.004%	α = 0.004%
(2) other bio-inspired solution ideas	α = 0.03 %	α = 0.06%	α = 0.2%

Secondly, the feasibility of the solution ideas is regarded. As explained in section 3.2.2, feasibility is evaluated on a scale from 0 to 3 (see Table 3-8, page 49).

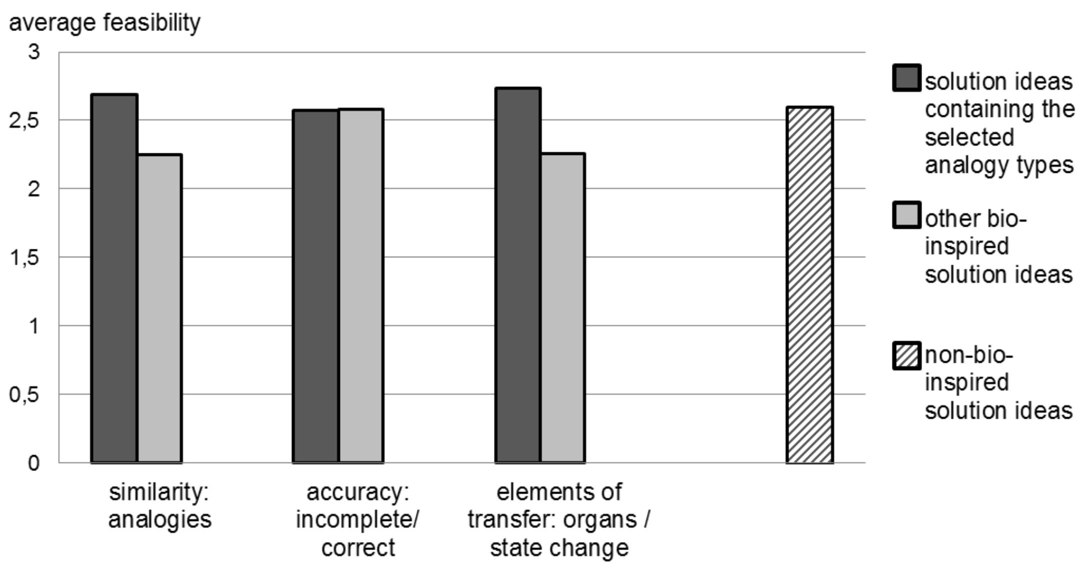

Figure 6-4: Average feasibility F of solution ideas

As Figure 6-4 depicts, the average feasibility of solution ideas containing *analogies* (similarity) and *organs/ state change* (elements of transfer) is higher than the average feasibility of non-bio-inspired solution ideas. The average feasibility of other bio-inspired solution ideas is lowest. Solution ideas containing *incomplete/ correct* (accuracy) analogies have a similar feasibility as non-bio-inspired solution ideas and other bio-inspired solution ideas.

The result is in accordance with the result of the first descriptive study: The higher task-specific quality of solution ideas containing the selected analogy types does not coincide with a decrease in feasibility.

Conclusion

Regarding the influence of the pair composition, the second descriptive study affirms the results of the first descriptive study: In comparison to uni-disciplinary pairs, bi-disciplinary pairs document on average more solution ideas based on *correct* or *incomplete* (accuracy) *analogies* (similarity) and a transfer of *organs* or *state change*. However, not all results are statistically significant.

The influence of the support strengthens the bi-disciplinary pairs: On average they transfer and document the highest portion of the selected analogy types. In comparison to uni-disciplinary pairs, the support pairs document a significantly higher portion of solution ideas based on the selected analogy types.

Solution ideas containing these analogy types have a higher overall task-specific quality value Q than other solution ideas. Using all 207 solution ideas from the first and second descriptive study for the analysis, the statistic test also shows a significantly higher task-specific quality Q than for other bio-inspired solution ideas. Moreover, solution ideas containing the selected analogy types do not have a lower feasibility F than other solution ideas.

6.1.2 Variety and uniqueness of solution ideas (research question 2)

This section focusses on research question 2:

How do the pair composition and the BioId support influence the variety and uniqueness of solution ideas developed in an ideation phase with biological information?

First of all, the influence of the pair composition and the BioId support on the use of biological information sources is regarded (research question 2.1). Then, the influence of the used biological information sources and the pair composition and *BioId* on the variety of solution ideas is analysed (research questions 2.2 and 2.3). Moreover, the influence of the used biological information sources and the pair composition and *BioId* on variety and uniqueness is examined (research questions 2.4 and 2.5).

Influence of the pair composition and use of the *BioId* support on the use of biological information sources (research question 2.1)

Table 6-4 extends Table 4-2 (page 62) and shows the number of pairs using analogies from the three given biological information sources (publication, Wikipedia article and video) for generating and documenting solution ideas. For generating solution ideas, the bi-disciplinary pairs and support pairs used all biological information sources more often than the uni-disciplinary pairs. However, the bi-disciplinary pairs used all information sources more often for documenting solution ideas than the support pairs. Only two support pairs documented solution ideas inspired by all information sources.

Table 6-4: Number of pairs which used analogies from all three biological information sources

N° of pairs	5 Pairs of biologists	5 Pairs of engineers	5 bi-disciplinary pairs	5 support pairs	sum
for generating solution ideas	3	3	4	4	14
for generating and documenting solution ideas	2	2	4	2	10

Overall, 14 pairs used analogies from all three biological information sources for the generation of solution ideas. Ten pairs additionally used analogies from all three biological information sources for the documented solution ideas. Their influence on variety and uniqueness is compared to pairs using less information sources in the following subsections.

Influence of the pair composition/ use of the BioId support and the use of biological information sources on the variety of solution ideas (research questions 2.2 and 2.3)

Using the method explained in section 3.2.2 and Equation 3-3 (p.52), variety V and normalized variety V^* are calculated for the set of solution ideas of each pair.

Figure 6-5 shows the average variety V depending on the use of information sources and the pair composition. The variety V combines measuring variety and quantity of solution ideas per pair. The inclusion of the support pairs in the evaluation does not change the range of the values. The overall average is slightly lower than with data from the first descriptive study (91 for all solution ideas and 62 for documented solution ideas).

Regarding the use of information sources, this analysis is the same as in the first descriptive study, but with the inclusion of more pairs. However, the results are different: In the first descriptive study, the average variety V was similar for pairs using all information sources and pairs using less information sources. With the additional data from the second descriptive study, the average variety V of solution ideas generated by pairs using all three information sources is higher compared to pairs using less information sources. This is also the case for documented solution ideas.

Regarding the influence of the pair composition, the results also differ from the first descriptive study: In the first descriptive study, the bi-disciplinary pairs without support generated solution ideas with a lower average variety V compared to the uni-disciplinary pairs. In the second descriptive study, on average, the bi-disciplinary pairs have the highest average variety *V* both for all generated and documented solution ideas. The biologist pairs have almost the same average variety *V* regarding all solution ideas, but a lower average variety regarding the documented solution ideas. The support pairs generated and documented solution ideas with the lowest average variety *V* compared to the other pairs.

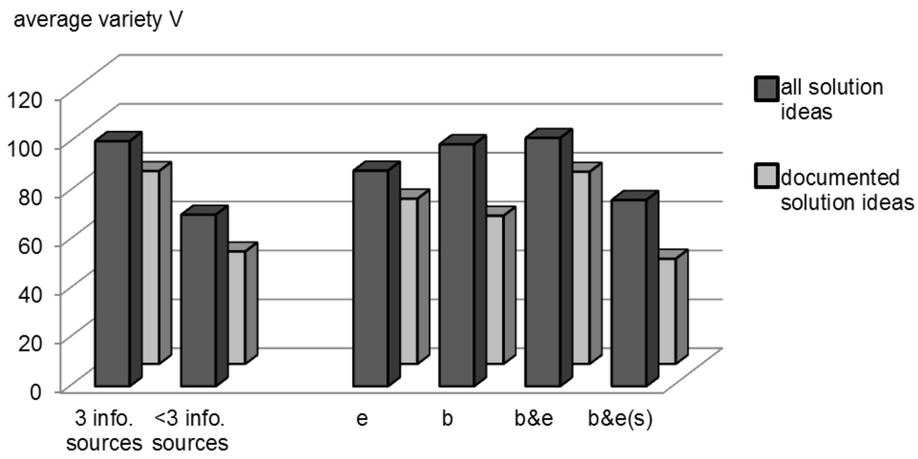

Figure 6-5: Average variety V (e: engineer pairs, b: biologist pairs, b&e: bi-disciplinary pairs, b&e(s): support pairs)

Figure 6-6 depicts the average normalized variety *V**. The range of values is 1.92 to 2.97 for all solution ideas and 1.18 to 3.26 for documented solution ideas. Compared to the first descriptive study, the range of values is higher. The average overall values of *V** are lower compared to the first descriptive study with 2.54 (all solution ideas) and 2.56 (documented solution ideas).

With regards to the use of information sources, different observations compared to the first descriptive study are made: The average normalized variety *V** of the solution ideas generated by the pairs using less than three information sources is higher in comparison to the pairs that used all information sources. On the contrary, for the documented solution ideas, the average normalized variety *V** of the solution ideas generated by the pairs using all three information sources is higher. To conclude, there seems to be no clear tendency.

Regarding the pair composition, the results also differ from the first descriptive study: The bi-disciplinary pairs without support generate and document solution ideas with the highest average normalized variety *V**. The average variety *V** of the generated and the documented solution ideas of the bi-disciplinary pairs working with the support is lower compared to the other pairs.

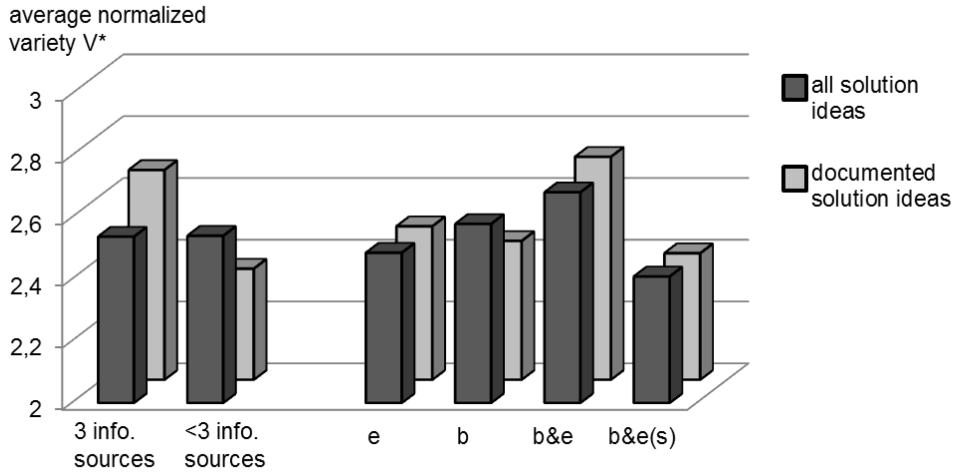

Figure 6-6: Average normalized variety V (e: engineer pairs, b: biologist pairs, b&e: bi-disciplinary pairs, b&e(s): support pairs)*

The significance of the differences in the average variety *V* and *V** is tested using the Wilcoxon rank-sum test. The following null-hypotheses and alternative hypotheses are formulated:

<u>Use of information sources</u> (Table 6-5):

- Null hypothesis: There is no difference between pairs using all or less information sources for generating/ documenting solution ideas
- Alternative hypothesis:
    - Variety *V* is higher for sets of solution ideas generated/ documented by pairs using all three information sources
    - Variety *V** is higher for sets of solution ideas generated by pairs using less than three information sources and sets of solution ideas documented by pairs using all three information sources

<u>Pair composition</u> (Table 6-6):

- Null hypothesis: There is no difference between uni- and bi-disciplinary pairs
- Alternative hypothesis: Bi-disciplinary pairs generate/document sets of solution ideas with a higher variety *V* and *V** than uni-disciplinary pairs

Use of the support (Table 6-7):

- Null hypothesis: There is no difference between support pairs and uni-disciplinary pairs
- Alternative hypothesis: Support pairs generate/document sets of solution ideas with a lower variety *V* and *V** than uni-disciplinary pairs

The null hypotheses are tested using the Wilcoxon rank-sum method presented in section 3.2.2.

Table 6-5 , Table 6-6 and Table 6-7 show the arithmetic mean, the test value U (calculated by Equation 3-4, page 55) and the probability of error α for the rejection of the null hypothesis.

With regards to the use of the information sources, Table 6-5 shows a probability of error for the rejection of the null hypothesis lower than 10% for the variety *V*. For the documented solution ideas, the probability of error is lower than 5%. In comparison to the first descriptive study, the tendencies are strengthened: The variety *V* of the solution ideas generated and documented by pairs using all information sources is significantly higher compared to pairs using less information sources.

As in the first descriptive study, the influence on the normalized variety *V** is different for generated and documented solution ideas and in both cases not significant. As explained in the first descriptive study, variety *V* combines a measure for variety and quantity and therefore, it is concluded from the findings that pairs using all three information sources document a higher quantity of solution ideas. However, there is no relevant influence on the difference (variety) between the ideas.

Table 6-5: Results of the Wilcoxon rank-sum test for comparing pairs using all or less information sources (publication, Wikipedia article, video) regarding variety V and normalized variety V (m= arithmetic mean, U_1/ U_2= test values)*

	Variety *V*		Normalized variety *V**	
solution ideas	all (n_1=14, n_2=6)	doc. (n_1=n_2=10)	all (n_1=14, n_2=6)	doc. (n_1=n_2=10)
pairs using all three information sources	m=100.1 U_1=59.5	m=75.4 U_1=76.5	m=2.54 U_1=37	m=2.66 U_1=62
pairs using one or two information sources	m=70.0 U_2=24.5	m=48.7 U_2=23.5	m=2.55 U_2=47	m=2.45 U_2=38
probability of error (one-sided test)	$\alpha < 10\%$	$\alpha < 5\%$	$\alpha > 10\%$	$\alpha > 10\%$

As to the influence of the pair composition, Table 6-6 shows that the probability of error for the rejection of the null hypothesis is higher than 10% for all comparisons. The observed positive influence of the bi-disciplinary pair composition on variety *V* and *V** is therefore not significant.

Table 6-6: Results of the Wilcoxon rank-sum test for comparing uni- and bi-disciplinary pairs without support with regards to variety V and normalized variety V (m= arithmetic mean, U_1/ U_2= test values)*

	Variety *V*		Normalized variety *V**	
solution ideas	all	doc.	all	doc.
uni-disciplinary pairs	m=93.4 U_1=21	m=65.1 U_1=20	m=2.53 U_1=17	m=2.55 U_1=19
bi-disciplinary pairs (without support)	m=101.4 U_2=29	m=76 U_2=30	m=2.69 U_2=33	m=2.70 U_2=31
probability of error (one-sided test)	$\alpha > 10\%$	$\alpha > 10\%$	$\alpha > 10\%$	$\alpha > 10\%$

As to the influence of the support, Table 6-7 shows that the probability of error for the rejection of the null hypothesis is higher than 10% for all comparisons. The observed negative influence of the use of the support on variety *V* and *V** is therefore not significant when compared to uni-disciplinary pairs.

Table 6-7: Results of the Wilcoxon rank-sum test for comparing uni- and bi-disciplinary pairs with regards to variety V and normalized variety V (m= arithmetic mean, U_1/ U_2= test values)*

	Variety *V*		Normalized variety *V**	
solution ideas	all	doc.	all	doc.
uni-disciplinary pairs	m=93.4 U_1=32.5	m=65.1 U_1=40.5	m=2.53 U_1=35	m=2.55 U_1=29
support pairs	m=76.2 U_2=17.5	m=42 U_2=15.5	m=2.41 U_2=15	m=2.42 U_2=21
probability of error (one-sided test)	$\alpha > 10\%$	$\alpha > 10\%$	$\alpha > 10\%$	$\alpha > 10\%$

Influence of the pair composition/ use of the BioId support and the use of biological information sources on the uniqueness of solution ideas (research questions 2.4 and 2.5)

To start with, the influence of the biological information sources on the uniqueness of solution ideas is regarded. The analysis conducted in the first descriptive study is replicated including the additional solution ideas. The results are shown in Figure 6-7 for all generated solution ideas and in Figure 6-8 only for the documented solution ideas.

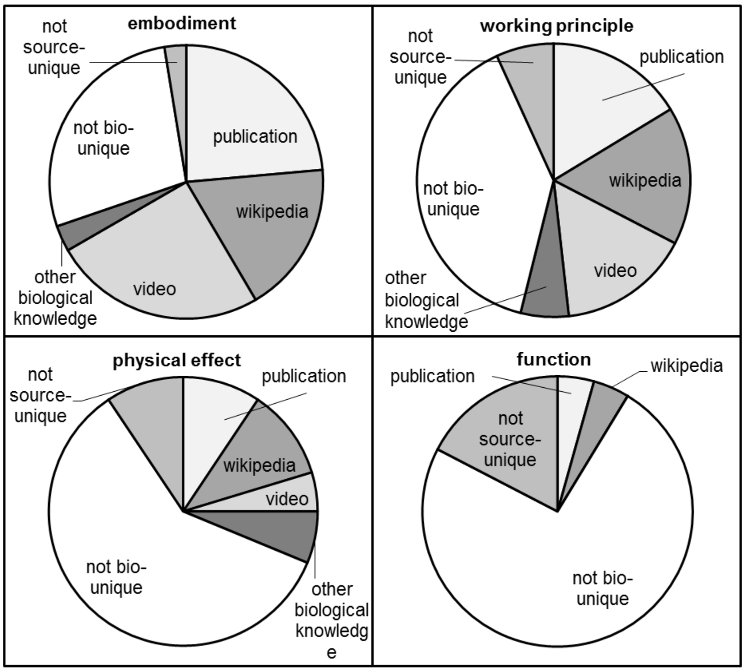

Figure 6-7: Portion of bio-unique and source-unique solution ideas on all levels of abstraction of all generated solution ideas

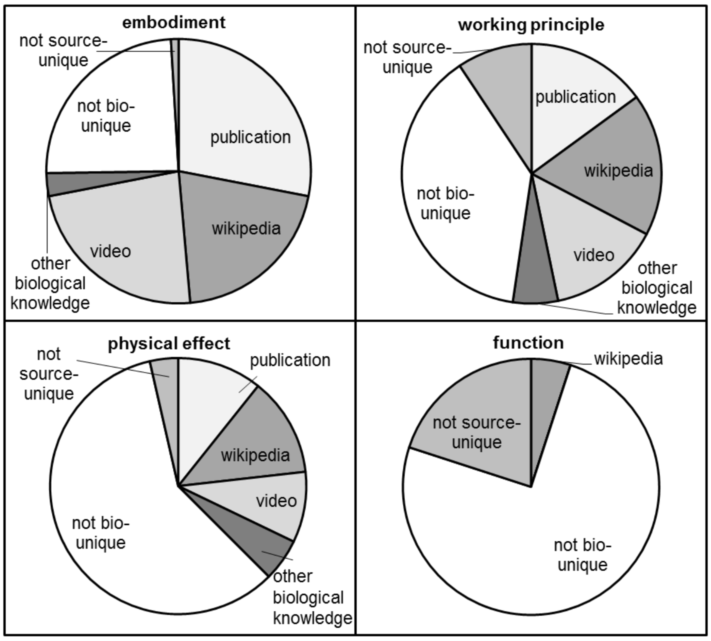

Figure 6-8: Portion of bio-unique and source-unique solution ideas on all levels of abstraction of documented solution ideas

A comparison to the first descriptive study (Figure 4-7 and Figure 4-8) shows almost no difference for all results: The portion of bio-unique solution ideas and source-unique solution ideas regarding all information sources is similar.

In conclusion, the findings of the first descriptive study are confirmed: on embodiment and working principle level, more than half of the solution ideas were bio-unique and source-unique. Only a small amount of bio-unique solution ideas were not source-unique or inspired by other biological knowledge. The portion of source-unique solution ideas is similar with regards to the publication, Wikipedia article and video.

In a next step, the influence of the pair composition and the support is analysed: As in the first descriptive study, only the embodiment and working principle level is regarded, as bio-uniqueness seems to be more relevant on these levels of abstraction. Moreover, on working principle level, additionally the portion of source-unique solution ideas is shown. (On embodiment level, almost all bio-unique solution ideas are also source-unique.) Figure 6-9 depicts the results.

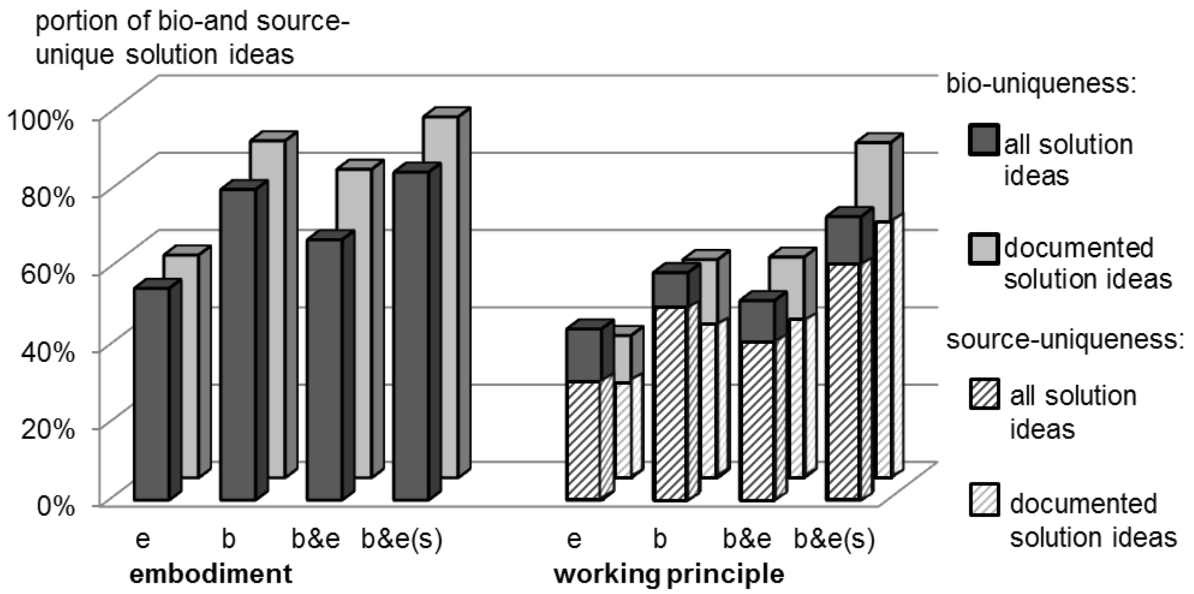

Figure 6-9: Average portion of bio-unique and source-unique solution ideas for different pair compositions and use of the support (e: engineer pairs, b: biologist pairs, b&e: bi-disciplinary pairs, b&e(s): support pairs)

Regarding pair composition, the results confirm the observations of the first descriptive study: The engineer pairs generated and documented the smallest portion of bio-and source-unique solution ideas. The bi-disciplinary pairs without support generated and documented a higher portion of bio- and source unique solution ideas compared to the engineer pairs, but generated a smaller portion than the biologist pairs. However, on working principle level, biologist and bi-disciplinary pairs without support documented a similar portion of bio- and source- unique solution ideas.

In comparison to the other pairs, the support pairs generated and documented the highest average portion of bio-unique solution ideas on both levels of abstraction. They also generated and documented the highest average portion of source-unique solution ideas on the working principle level.

For the influence of the support, the significance of the differences regarding bio- and source-uniqueness is tested using the Wilcoxon rank-sum test. The following null-hypotheses and alternative hypotheses are formulated:

Bio-uniqueness:

- Null hypothesis: There is no difference between support pairs and all other pairs
- Alternative hypothesis: Support pairs generate/document a higher portion of bio-unique solution ideas on embodiment and working principle level

Source-uniqueness:

- Null hypothesis: There is no difference between support pairs and all other pairs
- Alternative hypothesis: Support pairs generate/document a higher portion of source-unique solution ideas on working principle level

The null hypotheses are tested using the Wilcoxon rank sum method presented in section 3.2.2.

Table 6-8 shows the arithmetic mean, the test value U (calculated by Equation 3-4, page 55) and the probability of error α for the rejection of the null hypothesis.

Table 6-8: Results of the Wilcoxon rank-sum test for comparing uni--disciplinary and support pairs with regards to the portion of bio-and source-unique solution ideas (m= arithmetic mean, U_1/ U_2= test values)

	Bio-unique				Source-unique	
abstraction level	embodiment		working principle		working principle	
solution ideas	all	doc.	all	doc.	all	doc.
uni-disciplinary pairs	m=67% U_1=12.5	m=70% U_1=11	m=52% U_1=13	m=47% U_1=4.5	m=40% U_1=16	m=32% U_1=7.5
support pairs	m=85% U_2=37.5	m=93% U_2=39	m=73% U_2=37	m=87% U_2=45.5	m=61% U_2=34	m=68% U_2=42.5
probability of error (one-sided test)	α <10%	α <10%	α >10%	α <2.5%	α >10%	α <2.5%

On embodiment level, the probability of error for the rejection of the null hypothesis is below 10% for all generated and for the documented solution ideas: The support pairs generated and documented a significantly higher portion of bio-unique ideas. Regarding bio- and source-uniqueness on working principle level, this is only the case for documented solution ideas. For all generated solution ideas, the probability of error is slightly above 10%. The comparatively low probability of error (< 2.5%) for the documented solution ideas shows the positive effect of the support regarding documentation.

Conclusion

In this section, the influence of the pair composition and the support on the use of the biological information sources was regarded. As observed in the first descriptive study, the bi-disciplinary pairs without support used all information sources for generating and documenting solution ideas more frequently than the uni-disciplinary pairs. The influence of the support was negative: As the uni-disciplinary pairs, the majority of the support pairs did not use all information sources for their documented solution ideas.

Then, the influence of the use of all three information sources on variety and uniqueness of solution ideas was analysed. Different results than in the first descriptive study were found: using all three information sources had a positive influence on the variety *V*, in particular regarding documented solution ideas. However, no tendency regarding the normalized variety *V** can be identified. It is concluded from this contradictory result that using all three information sources correlates with a higher number of solution ideas, but does not increase the actual difference (variety) between the ideas. A possible reason for the increase of solution ideas is the time needed for understanding the technical task and biological information: Pairs which had more difficulties in understanding needed more time. Consequently, they had not enough time to regard all three information sources and also generated a smaller number of solution ideas.

Regarding bio- and source-uniqueness, the results of the first descriptive study were confirmed: The use of the information sources enabled the generation of bio- and source-unique solution ideas.

Moreover, an analysis of the direct influence of the pair composition and the support on variety and uniqueness of solution ideas was conducted. Regarding variety *V* and normalized variety *V**, the average values differed from the results of the first descriptive study: The bi-disciplinary pairs without support generated and documented solution ideas with the highest average variety *V* and normalized variety *V**. The influence of the support was negative: The support pairs' solution ideas had the lowest average variety *V* and normalized variety *V**. However, the Wilcoxon rank-sum test showed no significance for the comparison of bi-disciplinary pairs without support and support pairs to uni-disciplinary pairs.

As to the bio-and source-uniqueness of solution ideas, the results of the first descriptive study were confirmed: The bi-disciplinary pairs generated less bio- and source-unique solution ideas than the biologist pairs, but more than the engineer pairs. The influence of the support on bio-and source-uniqueness on embodiment and working principle level was positive: The pairs using the support generated and documented the highest average portion of bio- and source unique solution ideas compared to the other pairs. In comparison to uni-disciplinary pairs, significance was shown for the documented solution ideas: The bi-disciplinary pairs using the support documented a significantly higher portion of bio- and source unique solution ideas.

6.2 Results of the qualitative analysis

The quantitative analysis in the previous sub-section has shown a positive influence of the support on the quality of solution ideas. Regarding uniqueness, the support enhanced the portion of bio- and source unique solution ideas. However, a relevant disadvantage was the reduction of the number of generated and documented solution ideas. The support pairs also used less information sources for their documented solution ideas. The aim of the qualitative analysis presented in this section is to explain this reduction of solution ideas and number of used information sources. As in the first descriptive study, the participants' view expressed in the questionnaire (research question 3) and the pairs' procedures during the design experiment (research question 4) are examined.

6.2.1 Participants' view (research question 3)

As in the first descriptive study, the participants' responses to the questionnaire are regarded. Figure 6-10 shows the average ratings of the participants after collaborating in the uni- and bi-disciplinary pairs.

Overall, similar tendencies as in the first descriptive study can be observed: Regarding the rating of the influence of biology, the biologists rate it highest, followed by the engineers. The influence of biology is rated lower by the bi-disciplinary pairs. Only one engineer rated it below 50% and admitted that his pair did not understand the publication. This shows a slight mismatch to the quantitative results: Two of the engineer pairs did not use all three information sources (see section 6.1.2, page 98). Regarding the documentation of solution ideas, the uni-disciplinary pairs and the bi-disciplinary pairs without support rated their documentation of solution ideas by over ninety percent.

Overall, as with the data from the first descriptive study, the results indicate a disproportionally positive view of the results. However, this is not the case for the support pairs:

The average rating of the support pairs is lower than the average rating of all other pairs. Regarding the support pairs, their view is disproportionally negative in comparison to the quantitative results. Still, their negative view on working with the support in comparison to working without the support in the uni-disciplinary pair has to be considered: If the participants do not like working with the support and recognize its positive impact, it is unlikely that mechanical engineers and biologists will use it in a real-world application.

A few positive comments on the support judged it to facilitate a structured approach and to ease the analysis of the biological system in relation to the task. Negative comments stated that the structured approach limited creativity. Moreover, a number of negative comments focus on the task or the inadequacy of the biological information sources to solve the task. This is unexpected, because uni- and bi-disciplinary pairs working without the support did not express this opinion. One possible explanation is that the support made difficulties in understanding task and biological information explicit. It forced the participants to document their understanding – they could not ignore difficulties in understanding as they could without the support. In conclusion, the support has to be improved in a way that it gives the participants a better feeling of their performance.

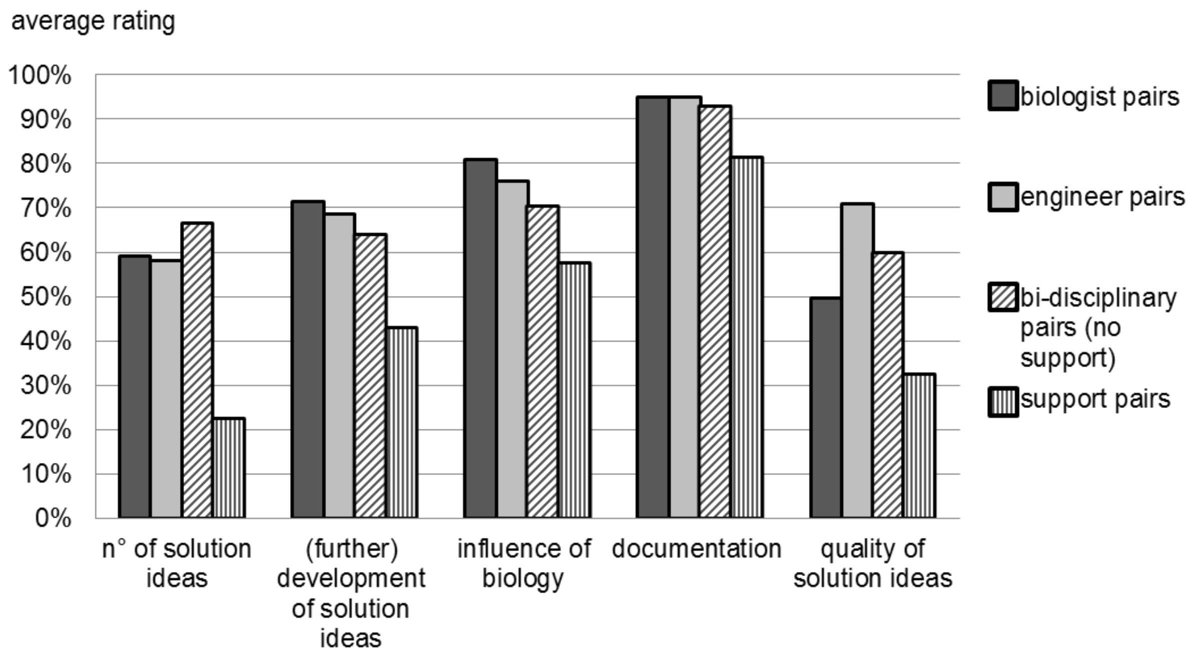

Figure 6-10: Questionnaire: Average rating of different pairs

6.2.2 Ideation procedures (research question 4)

In the first descriptive study, it was observed that a structured procedure during ideation enabled the use of all information sources. Moreover, the use of sketching supported the transfer of the selected analogy types (accuracy: *incomplete/correct*, similarity: *analogy*, elements of transfer: *organ/state change*). This aspect is not examined for the pairs using the support, as the quantitative analysis has shown that they transfer a higher portion of the selected analogy types.

In the following, the support pairs' procedures and their use of the support including sketching, text and diagrams are analysed with regards to the use of biological information sources.

General procedures

Regarding the additional pairs of the second descriptive study, the structured and jumpy procedure could be identified as in the first descriptive study (see appendix 11.6). However, a third procedure emerged which is depicted in Figure 6-11:

- **Fixated procedure:** Two pairs regarded one information source for more than 25 minutes. They either did not regard other information sources (biologist pair 6) or regarded them for a short time (engineer pair 4).

The two pairs following a fixated procedure did not use all information sources for generating solution ideas.

In difference to the uni-disciplinary pairs and the bi-disciplinary pairs working without support, four of the five support pairs proceeded similarly. They followed a **structured procedure** (see first descriptive study, Figure 4-11, page 70) regarding each information source one after the other.

Figure 6-11: Fixated procedure

In consequence, the procedure of the pairs is not the reason for the reduced number of information sources used for ideation. In fact, all pairs regarded all information sources, but not all pairs used all information sources for generating or documenting solution ideas.

As to the discussion of the task, the support did not foster a more structured discussion. Even though the pairs were instructed to work on the task template at the start of the experiment, only one of the pairs (support pair 2) did this.

Use of the support (sketching, text and diagrams)

Figure 6-12 shows the use of the support across pairs and information sources: The templates for the three information sources were evaluated with regards to the four sections *system description* (1a), the *transfer of the system description* (1b), *system behaviour and properties* (2a) and the *transfer of the system behaviour and properties* (2b).

For the *system description* (1a), Figure 6-12 depicts that 60% of the 15 requested system descriptions (five pairs, three information sources each) were sketches. This was requested by the instruction of the support. However, 40% of the system descriptions were text only. No system description was “empty”, i.e. all pairs worked on the system descriptions of all three information sources. Regarding the transfer of the system description to a technical solution idea, 60% were documented by sketches. Still, in more than 20% of the cases, there was no transfer of the system description – in the figure this is shown as “empty”. As to the *system behaviour and properties*, the majority was documented as diagrams as requested by the instructions. Again, on 20% of the templates there was no documentation of system behaviour and properties. The last part of the template, the transfer of system behaviour and properties to a technical solution idea was not documented in 60% of the cases.

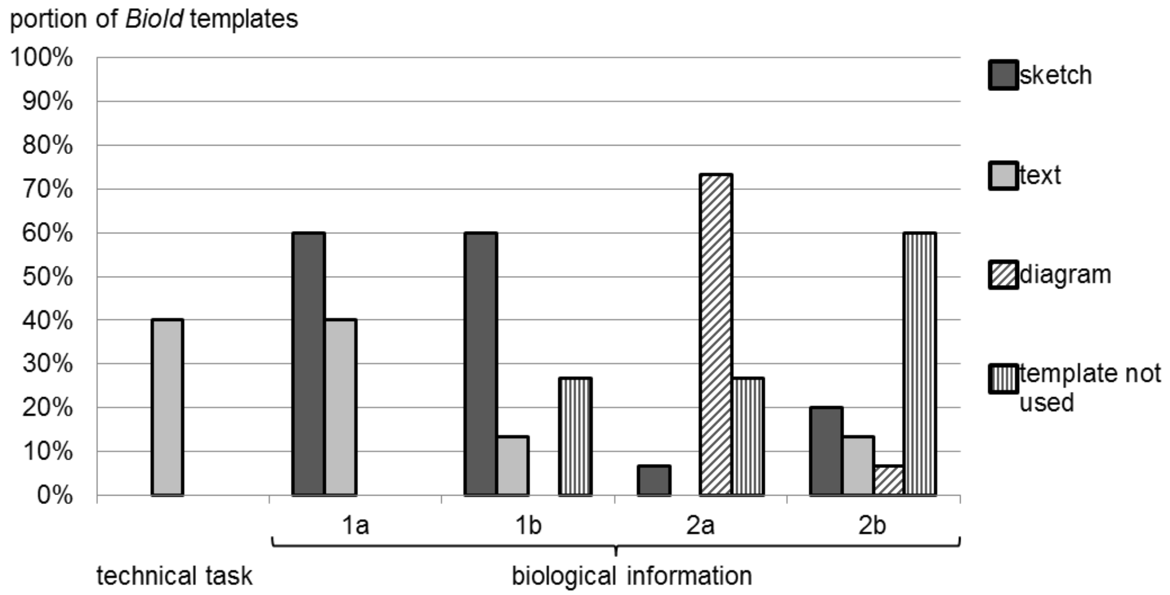

Figure 6-12: Use of the support (sketching, text and diagrams)

To conclude, the pairs mostly used sketching and diagrams as requested. The fact that the first part of the template (1a) was filled out in all cases, but the last part (2b) was filled out in a minority of cases supports the assumption that the pairs suffered from a lack of time. They started all templates, but were unable to finish them due to a lack of time.

6.3 Conclusion

The second descriptive study aimed at reassessing the results of the first descriptive study regarding the influence of bi-disciplinary collaboration. Moreover, it evaluated the developed *BioId* support regarding the innovation potential of technical solution ideas. The support was used by bi-disciplinary pairs (one engineer, one biologist). As measures for innovation potential, firstly the quality and secondly, variety and uniqueness of solution ideas were regarded using a quantitative analysis approach (see Figure 3-1, page 31). Then, a qualitative analysis explained weaknesses of the support.

Table 6-9 shows an overview of the results of the second descriptive study's analysis.

Regarding the influence of the pair composition, most results from the first descriptive study were confirmed.

The *BioId* support enhanced the transfer of the selected analogy types which result in a higher quality of solution ideas.

BioId had a positive influence on the uniqueness of solution ideas: The support pairs transferred and documented a higher portion of bio- and source unique solution ideas. However, on average, they generated and documented a lower number of solution ideas than other pairs. This can be explained by a lack of time: The pairs followed a structured procedure discussing all information sources. Moreover, they mostly used the first part of the support templates and used sketching to discuss biological information. Still, the last part of the template was used in a few cases only. In addition, the participants' perception of the support was disproportionally negative. In consequence, the support has to be improved to facilitate its use and make it more efficient. Moreover, the participants have to enjoy using the support.

Table 6-9: Overview on results of the second descriptive study

	research question		result	evaluation of the support
quality	1.1	analogy types	On average, the bi-disciplinary pairs without support documented a higher portion of solution ideas containing the selected analogy types than uni-disciplinary pairs. This is further supported by *BioId*: For the support pairs, the difference to the uni-disciplinary pairs is statistically significant.	The support strengthens the transfer of the selected analogy types which enhance the task-specific quality of solution ideas.
	1.2	quality	Confirmation of the results from the first descriptive study: The selected analogy types result in a higher task-specific quality of solution ideas and no negative influence on feasibility compared to all other solution ideas and bio-inspired solution ideas only.	
Variety/uniqueness	2.1	use of biological information	Bi-disciplinary pairs without support used all information sources for generating and documenting solution ideas more often than other pairs. Support pairs used all information sources for the generation of solution ideas as the bi-disciplinary pairs without support. However, *BioId* negatively influenced the documentation of these ideas.	The bi-disciplinary pairs without support use all information sources most often for generating and documenting solution ideas. Using all information sources correlated with a higher number of solution ideas. Moreover it enables the generation of bio- and source-unique solution ideas. The support had a negative impact on the number of information
	2.2	variety	Using all three information sources correlated with a higher number of solution ideas.	
	2.3		Despite differences in the average values, no significant positive influence of the bi-disciplinary pair composition or negative influence of	

	research question		result	evaluation of the support
			the support on variety V and normalized variety V^* could be found.	sources used and the number of solution ideas (probable reason: time and effort to use it). However, it increases the portion of bio- and source-unique solution ideas.
	2.4	uniqueness	Confirmation of the results from the first descriptive study: The use of the information sources enabled the generation of bio- and source-unique solution ideas.	
	2.5		Bi-disciplinary pairs without support on average generated less bio- and source unique solution ideas than biologist pairs. *BioId* compensates this weakness: Support pairs documented a higher portion of bio- or source-unique solution ideas than uni-disciplinary pairs	
	3	Participants' view	The participants of the support pairs had a disproportionally negative view on their performance.	The participants' feeling about using the support has to be improved.
	4	procedures	An additional procedure was identified in addition to the structured and jumpy procedure: The fixated procedure adopted by two uni-disciplinary pairs that did not use all information sources. The majority of the support pairs followed a structured approach and discussed all information sources. They mostly did not discuss the task at the beginning of ideation.	The sequence of the template should be prescribed more strictly so that the pairs discuss the task first. The use of the template should be made easier and less time-consuming.
			The majority of the support pairs used the first part of the support template as requested. The last part was used less, probably due to a lack of time. The template for discussing the task was not used by most of the pairs.	

7. Verification of results

In this section, the additional verification measures described in section 3.2.2 are presented (see Table 3-10, p.53). Two measures are described in this section: The results of the descriptive studies are verified with regards to the influence of order effects (7.1). To test for order effects, the participants had to complete three individual tasks during the experiment. Moreover, the influence of the three design tasks *water pump, sun protection* and *aquaplaning* is regarded (7.2).

7.1 Order effects: Analysis of individual tasks

As shown in Figure 3-2 (p. 35), the participants had to work on individual tasks before, between and after the two ideation experiments. Each individual task consisted of two parts as shown in Table 7-1: Firstly, aspects of a biological system and a technical application had to be identified. Secondly, aspects of a technical system that can be improved by bio-inspired design and a possible biological model had to be named.

Table 7-1: Structure of each individual task

Part 1	biological aspect (elephant/ dolphin/ bat)	technical application
Part 2	technical aspect (ship/ robot/ airplane)	biological model

The participants named a total number of 504 biological and technical aspects and corresponding technical applications or biological models. They are listed in the appendix (11.9). The results were analysed to test for possible order effects due to the pair ideation: Did the participants increase their capabilities in bio-inspired design due to the ideation in uni- and bi-disciplinary pairs? Or did their performance decrease as they became tired of the 40 min ideation phases?

The results were analysed quantitatively and qualitatively:

Quantitatively, the number of aspects of biological and technical systems were counted and added for each participant and each individual test. Three aspects were not counted, because no corresponding technical application or biological model was indicated (aspects n°31, 37, 252). Moreover, it was observed that some aspects were re-used by the participants. For example, for the technical system *ship*, the technical aspect *navigation* is identified which can be improved by using *echolocation of whales* (aspect n°23). For the biological system dolphin (a whale!), the same participant names the aspect *echolocation* which can be used for the technical application *navigation at low visibility* (aspect n° 43). The aspect n°43 as well as 19 other aspects were not counted for this reason. However, if a participant listed similar aspects for different biological systems, they were still counted separately. Again, *echolocation* is an example – an aspect often named for both *dolphin* and *bat*. The reason is that even though the aspects are similar, they are not the same, because the different systems implement them in a different manner or in different environments. For example, dolphins and bats both use sound for orientation, but a dolphin uses it underwater and a bat in air.

After counting the number of aspects, for each participant, the proportional increase or decrease of aspects between the different individual tasks was calculated:

Difference between the first post-test (after the ideation in uni-disciplinary pairs) and the pre-test (before ideation in uni-disciplinary pairs):

$$d_1 = \frac{(n^\circ\ of\ biological{+}technical\ aspects)_{post-test\ 1} - (n^\circ\ of\ biological{+}technical\ aspects)_{pre-test}}{(n^\circ\ of\ biological{+}technical\ aspects)_{pre-test}}$$

Difference between the second post-test (after the ideation in bi-disciplinary pairs) and the pre-test (before ideation in uni-disciplinary pairs):

$$d_2 = \frac{(n^\circ\ of\ biological{+}technical\ aspects)_{post-test\ 2} - (n^\circ\ of\ biological{+}technical\ aspects)_{pre-test}}{(n^\circ\ of\ biological{+}technical\ aspects)_{pre-test}}$$

Equation 7-1: Calculation of differences between post-tests and pre-test

The results show an average difference after the ideation in uni-disciplinary pairs of -6%. After the ideation in bi-disciplinary pairs, the average difference is -11% in comparison to the pre-test.

Figure 7-1 shows the frequency distribution of all participants: The distribution is centred around a difference of 0%. However, a majority of participants listed less aspects of biological and technical systems after the ideation in uni-disciplinary pairs (post-test 1) and bi-disciplinary pairs (post-test 2).

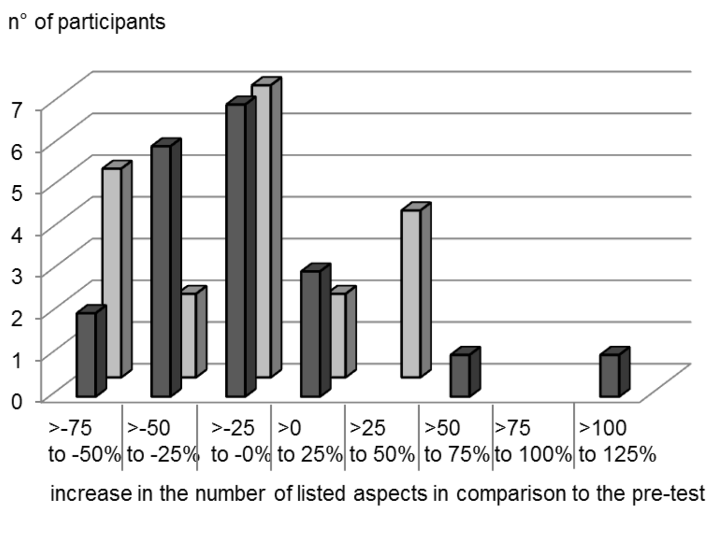

Figure 7-1: Frequency distribution of the increase/decrease of biological and technical aspects after ideation in uni-disciplinary pairs (post-test 1) and bi-disciplinary pairs (post-test 2)in comparison to the pre-test

To test for the significance of this observation, the Wilcoxon signed-rank sum test is used. A null and an alternative hypothesis are formulated:

- Null hypothesis: There is no increase or decrease of the number of listed biological and technical aspects after the uni-disciplinary ideation (post-test 1) / after the bi-disciplinary ideation (post-test 2).
- Alternative hypothesis: Participants list less aspects of biological and technical systems after the uni-disciplinary ideation (post-test 1) / after the bi-disciplinary ideation (post-test 2).

The result of the Wilcoxon signed-rank test is shown in Table 7-2 using the values tabulated in appendix 11.10 for the two-sided test. The two-sided test is used because it is not clear if a decrease (fatigue) or increase (learning) of listed aspects is expected. Table 7-2 shows that the probability of error is higher than 10% for the alternative hypothesis for comparing both post-tests to the pre-test. It can be concluded that the observed decrease in the average number of listed biological and technical aspects is not significant.

Table 7-2: Results of the Wilcoxon signed-rank-sum test
with n: number of participants with a decrease or increase in the number of listed aspects (participants who generated an equal number of aspects are excluded, therefore n<20)

	after uni-disciplinary ideation (post-test 1) n=15	after bi-disciplinary ideation (post-test 2) n=19
Rank sum (participants listing less aspects than in pre-test)	R_1=78	R_1=60,5
Rank sum (participants listing more aspects than in pre-test)	R_2=42	R_2=129,5
probability of error (one-sided test)	$\alpha > 10\%$	$\alpha > 10\%$

Qualitatively, the aspects listed for each biological and technical system are regarded across participants. As the order of biological and technical systems given to the participants was varied, each system was used in pre-test, post-test 1 and post-test 2 for different participants (see appendix 11.3). The quality of the named aspects was in the post-test was compared to the quality of aspects in the pre-tests. As no requirements had been defined for the individual task, the level of detail is regarded as an indicator for quality[5]. The level of detail varied:

If the participants name only components of biological and technical systems, the level of detail is considered low. An example is aspect n°16 (biological system: elephant): As a biological aspect, the participant names *trunk* which he considers a relevant aspect to be

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[5] For the analysis, in most cases, only the aspect is regarded, not the technical application or biological model indicated by the participant. However, in some cases, the participants mixed up biological and technical domain. In these cases, both the aspect and it technical application or biological model is regarded for the analysis.

applied for technical *tubes*. In this case, it remains unclear which aspect of the trunk the participant wants to transfer and why he wants to transfer it.

If the properties or functions of both biological and technical system are detailed, the level of detail is considered high. An example is aspect n°285: As a biological aspect, the participant names *trunk movement, particularly with regards to gripping objects (food etc.)*. On the technical side, he considers this relevant for the *precise steering of robot grippers*. In this case, it is defined that transferring the *trunk gripping movement* is considered interesting for improving the *precision of a robot gripper*.

Regarding the aspects across pairs for each biological and technical system, there are a number of similarities. Both aspects with low and high level of detail occur several times. For example, for the biological system *elephant*, the aspect *trunk* occurs ten times, for the technical system *airplane*, the aspect *wings* or *wing shape* is named four times. The same observation is made for aspects with high level of detail. Table 7-3 lists one example of similar aspects for each technical and biological system.

Table 7-3: Examples of similar aspects of biological/technical systems from individual tasks in brackets: number of aspect (see appendix 11.9)

	examples of similar aspects named by different participants		
biological/technical system	pre-test	post-test 1	post-test 2
elephant	cooling of the blood through large ear surface (2)	ears for cooling → large area for cooling blood in the ear (293)	big ears with large surface to emit heat (223)
dolphin	body-shape: stream-lined shape (136)	streamlined shape (42)	streamlined shape (314)
bat	location by sound waves (260)	echolocation (376)	navigation by sound (482)
ship	driving characteristics with little resistance in water (flow characteristics) (444)	shape of the ship → lowest water resistance (295)	consumption of energy due to ship body design (238)
robot	carrying heavy weights in comparison to own weight, e.g. by means of having several legs (169)	walking on 8 - 4 - 2 legs (70)	ability to carry weights and mobility (328)
airplane	surface texture regarding friction (267)	outer layer, aerodynamics (388)	surface/ wings: low friction (129)

To conclude, no apparent qualitative differences are observed when comparing the pre-test to the post-tests. This is in line with the quantitative result which showed no significant order effects regarding the number of aspects generated at different points of the experiment.

Therefore, it is concluded that no relevant negative or positive order effects occurred due to the experimental procedure. In other words, neither learning nor fatigue seems to have played a considerable role.

7.2 Influence of design tasks

To assess the influence of the three design tasks, both "paths" depicted in Figure 3-1 (page 31) are regarded: Quality measures as indicators for target achievement of the product and measures for uniqueness as indicators for the novelty of a product. Measures for the variety of solution ideas are not regarded because the descriptive studies have not shown statistically significant results for variety.

The results of the single design tasks regarding quality and uniqueness measures are compared to the results of the descriptive studies.

7.2.1 Quality of solution ideas

The descriptive studies showed the results listed in Table 7-4: Regarding task-specific quality, solution ideas containing the analogy types *correct* and *incomplete* (accuracy) *analogies* (similarity) and *organs* or *state change* (elements of transfer) have the highest values. These solution ideas do not have a lower average feasibility. Average task-specific quality and average feasibility are analysed for each task separately in this section. The result is shown in Figure 7-2 to Figure 7-7.

As to task-specific quality, the figures show different values depending on the task: for example, when comparing the sun protection task to the aquaplaning task, the average task-specific quality values of all solution idea categories is higher. A possible explanation is that the aquaplaning task was more difficult to solve for the pairs.

Still, the overall tendencies are the same for all tasks and in accordance with the results from the descriptive study (one exception explained in Table 7-4): The solution ideas containing the selected analogy types have the highest average task-specific quality. Other bio-inspired solution ideas have the second-highest task-specific quality. The task-specific quality of the non-bio-inspired solution ideas is lowest.

Regarding the average feasibility of solution ideas, the results for the single tasks show more variability than the results of the descriptive study. For example for the *water pump* task, the average feasibility of non-bio-inspired solution ideas is highest (2.73). However the difference is to the average feasibility of solution ideas containing organs or state change (2.71) is small. Overall, Figure 7-2 to Figure 7-7 show that the average feasibility of solution ideas containing the selected analogy types is higher or slightly lower than the average feasibility of other solution ideas.

Table 7-4: Separate analysis of each task regarding the average task specific quality and feasibility of solution ideas

Results of the descriptive studies	Separate analysis of each task
Task specific quality: • Highest: solution ideas containing the selected analogy types (approx. 60%) • Second-highest: Other bio-inspired solution ideas (approx. 50%) • Lowest: Non-bio-inspired solution ideas: (approx. 40%)	Values depend on the task, but the general order of the average quality is the same. Exception: For the task water pump, the solution ideas containing *analogies* (similarity) have a slightly lower average task-specific quality than other bio-inspired solution ideas.
Feasibility: The higher task-specific quality of solution ideas containing the selected analogy types does not coincide with a decrease in feasibility.	The average feasibility values vary depending on the tasks. However, they are either higher than the average feasibility of other solution ideas or slightly lower.

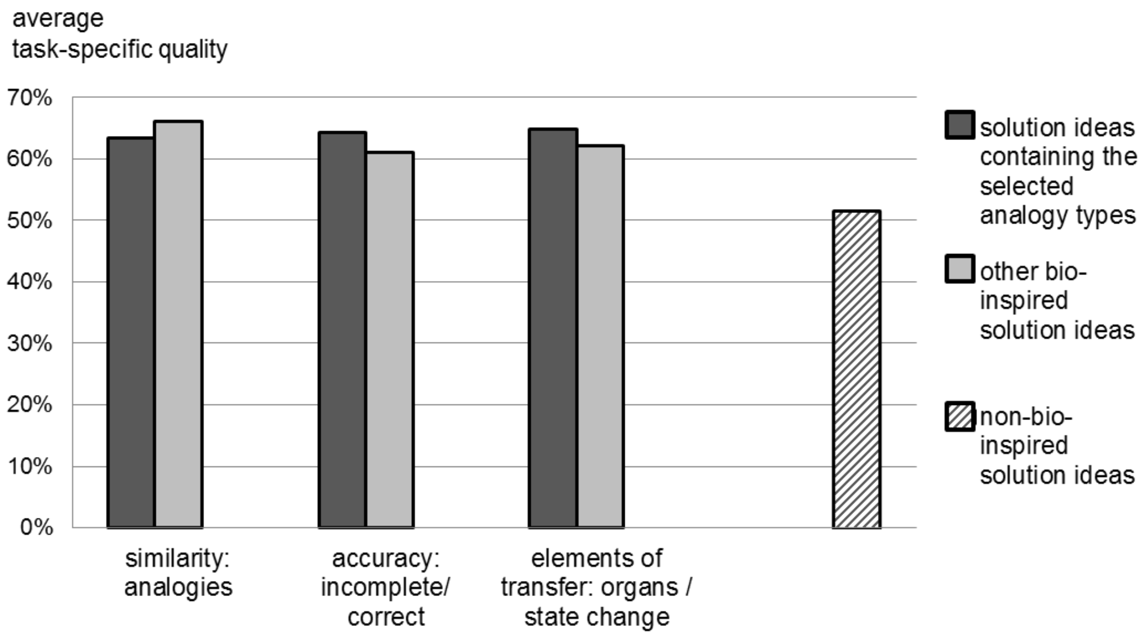

Figure 7-2: Task I (water pump): task-specific quality Q

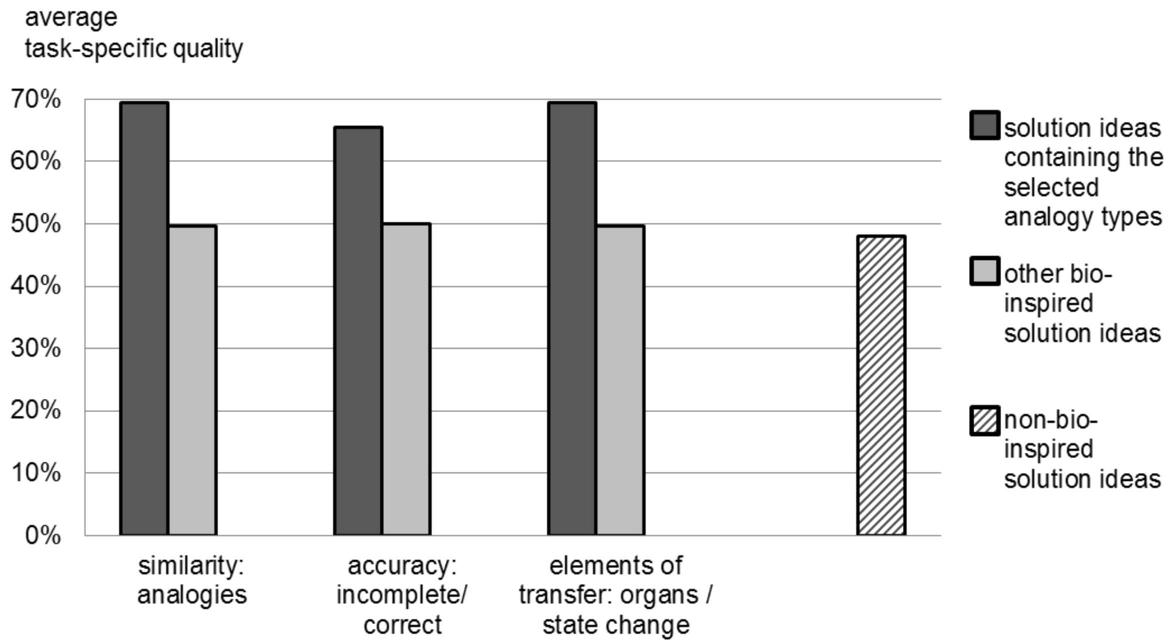

Figure 7-3: Task II (sun protection): task-specific quality Q

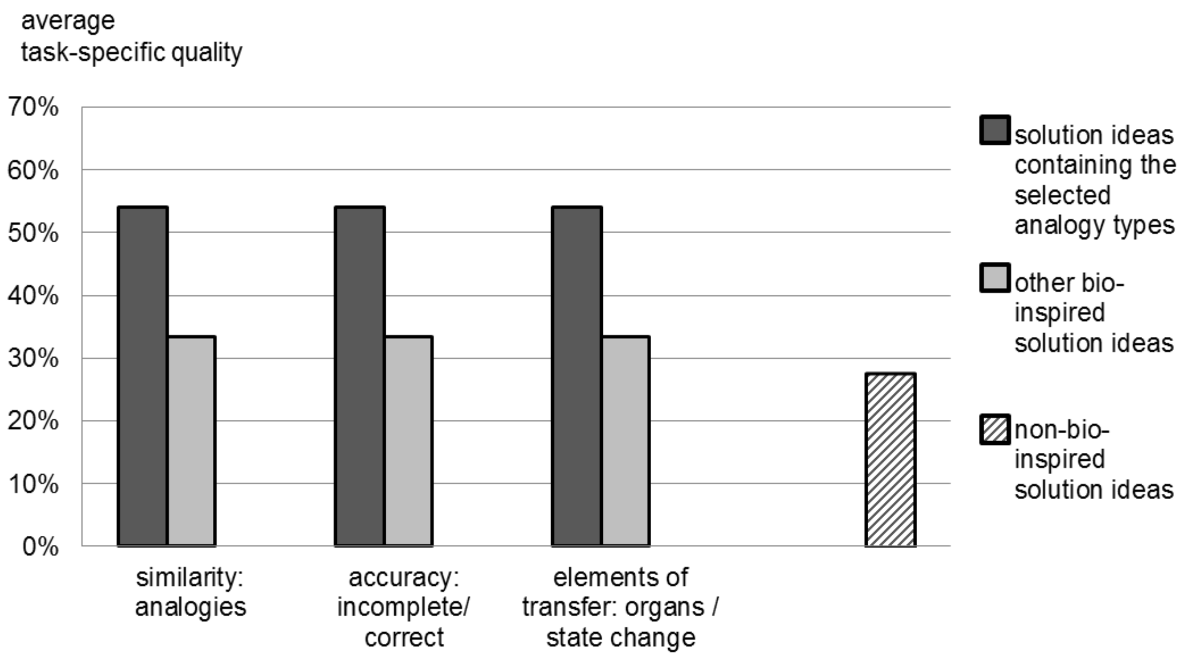

Figure 7-4: Task III (aquaplaning): task-specific quality q

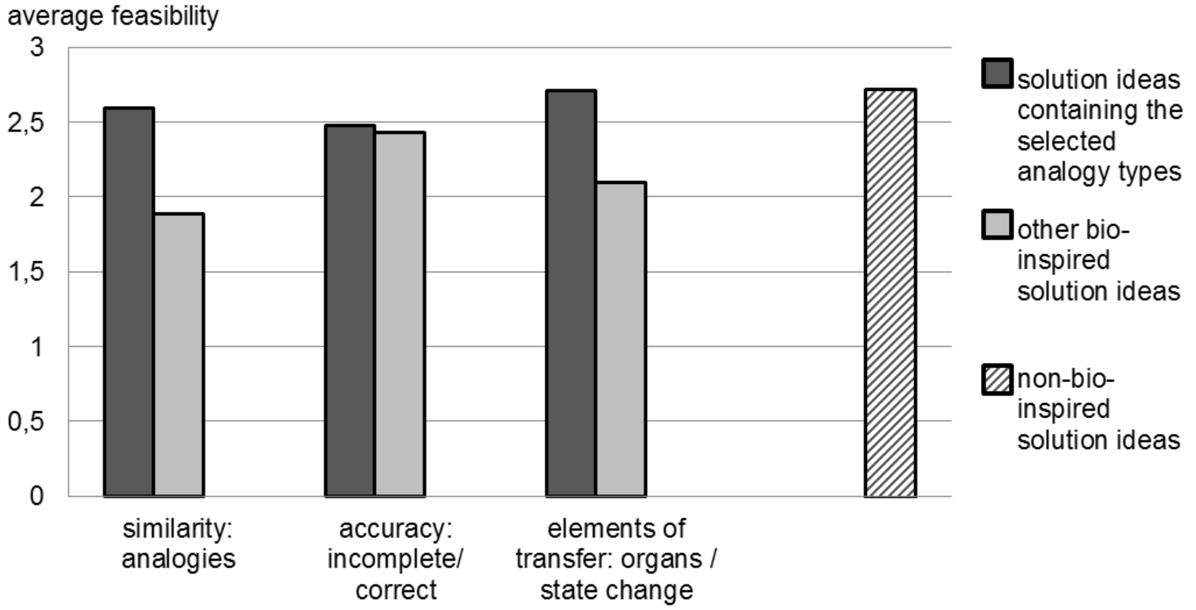

Figure 7-5: Task I (water pump): feasibility F

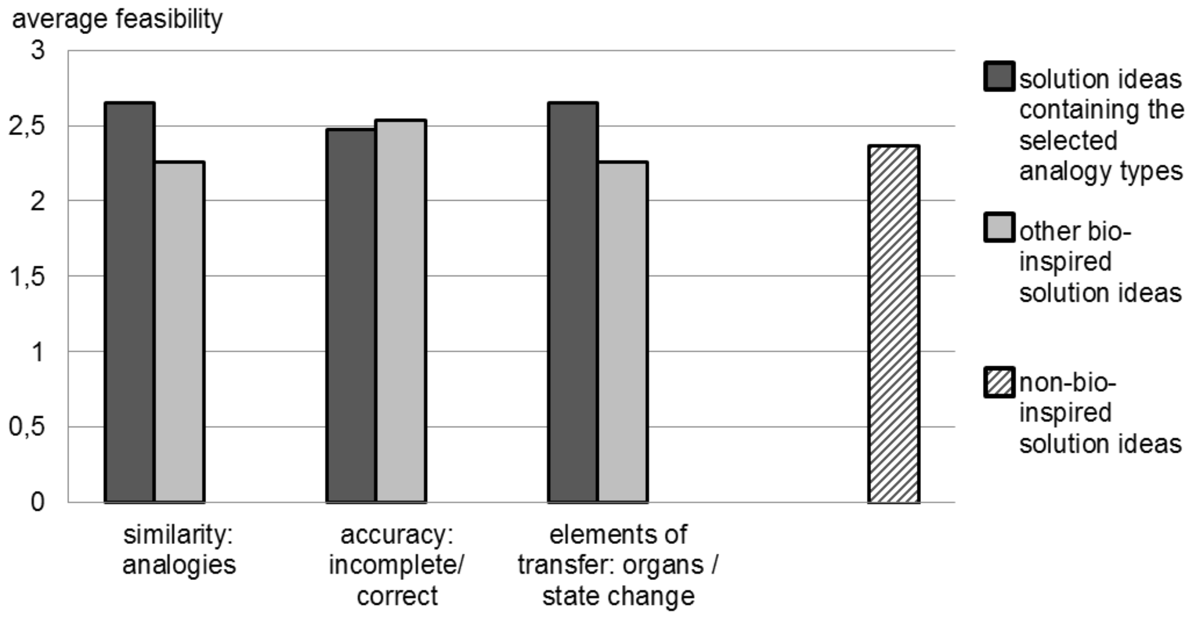

Figure 7-6: Task II (sun protection): feasibility F

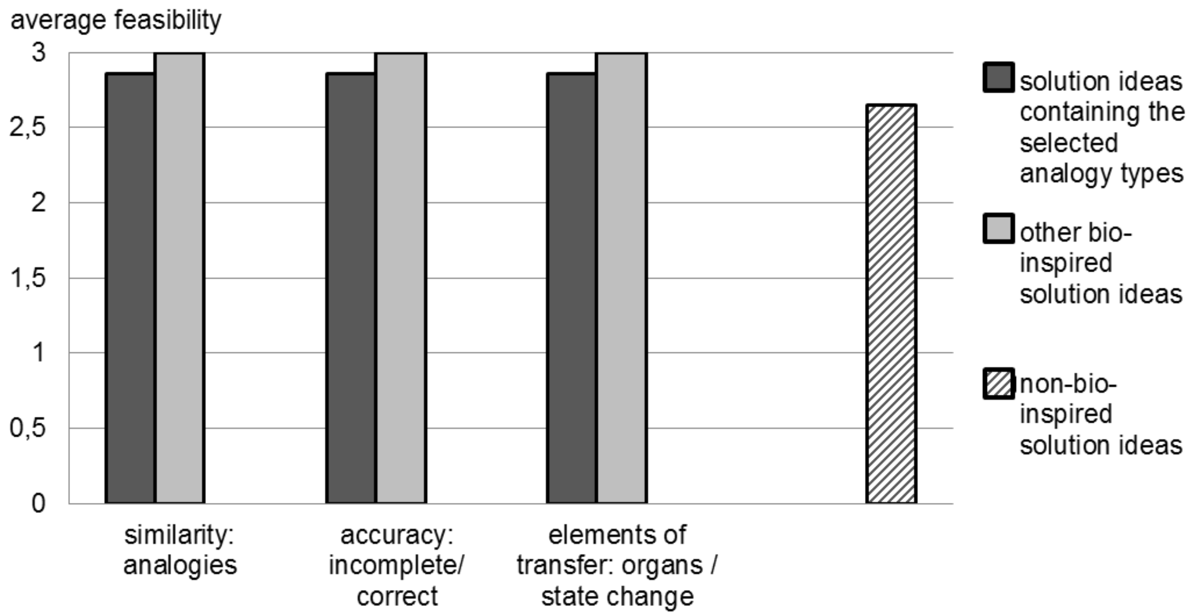

Figure 7-7: Task III (aquaplaning): feasibility F

7.2.2 Uniqueness of solution ideas

Both descriptive studies showed similar results regarding the portion of bio-and source-unique solution ideas (see section 6.1.2, p.98). A summary of the results is listed in Table 7-5. The results were relevant particularly on embodiment and working principle level, as on the higher levels of abstraction the number of different solution ideas was lower. Figure 7-8, Figure 7-9 and Figure 7-10 therefore depict the solution ideas on embodiment and working principle level for each task separately. The results of the descriptive studies listed in Table 7-5 were verified for each task. The first two results can be confirmed for all three tasks – more than half of the solution ideas were bio-unique and most of them were additionally source-unique. However, the information sources *publication*, *Wikipedia article* and *video* play a different role for each task. This can be a result of a different adequacy of the particular biological information chosen for each task: For example, for the task *aquaplaning*, the *beetle* described in the publication seemed to be more useful to the pairs than the *leave* described in the Wikipedia article. This result underlines the importance of using several tasks and corresponding information sources for the experiments: the influence of the specific adequacy or usefulness of a biological system is levelled out. The differences in adequacy or usefulness were not intended when the experiments were designed. However, they were only observed when analysing the results of all pairs.

Table 7-5: Separate analysis of each task regarding bio-and source unique solution ideas

Results of the descriptive studies	Separate analysis of each task
1) On embodiment and working principle level, more than half of the solution ideas were bio-unique and source-unique.	For all tasks, the same result is observed.
2) Only a small amount of bio-unique solution ideas were not source-unique or inspired by other biological knowledge.	For all tasks, the same result is observed.
3) The portion of source-unique solution ideas is similar with regards to the publication, Wikipedia article and video.	The portions differ depending on the task.

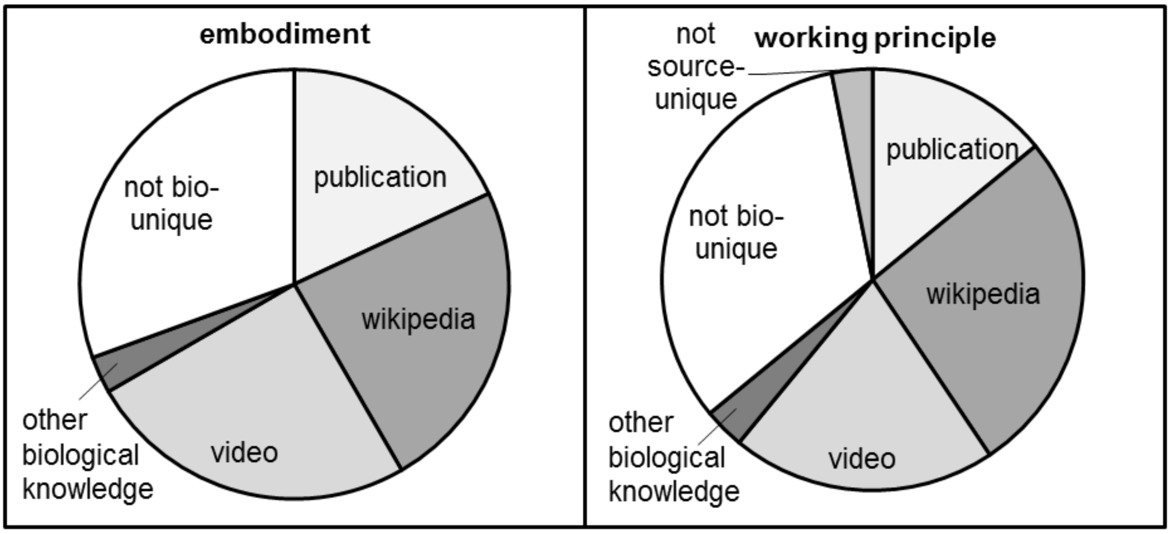

Figure 7-8: Water pump

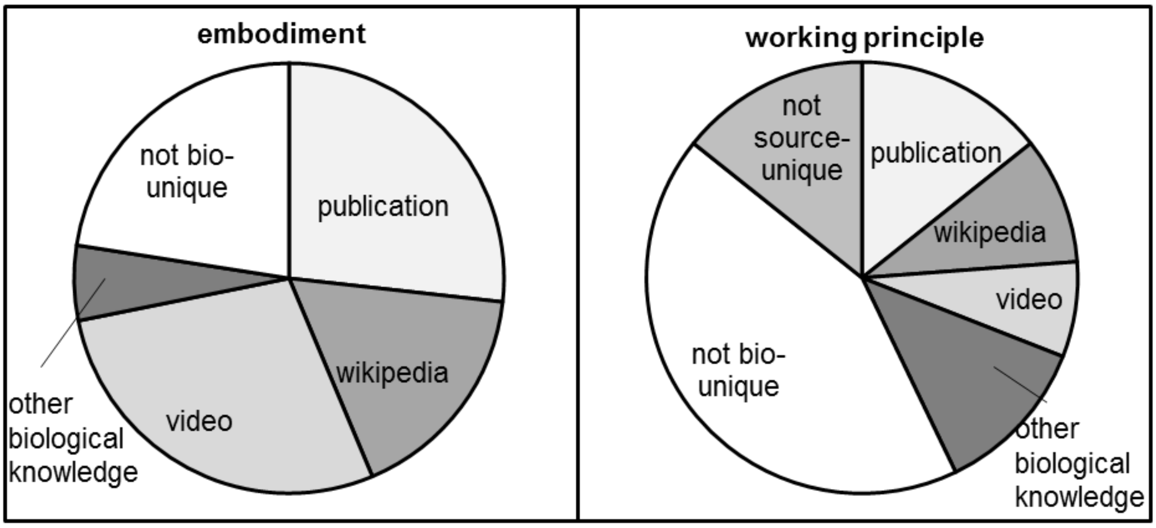

Figure 7-9: Sun protection

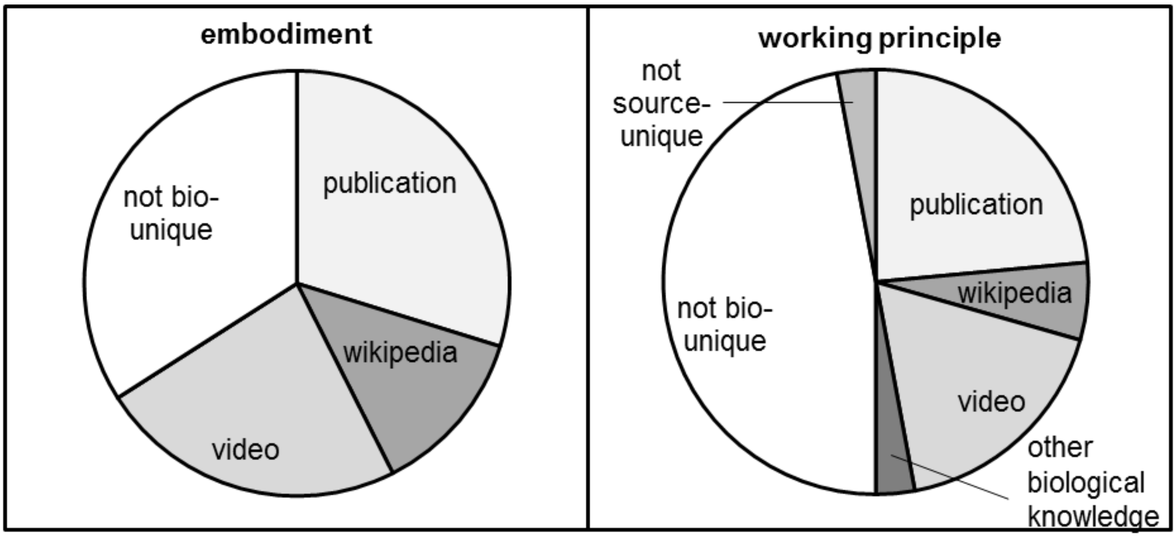

Figure 7-10: Aquaplaning

8. Discussion

In this section, limitations of this work are discussed (8.1). Moreover, the results are discussed in relation to comparable research (8.2).

8.1 Limitations

This thesis describes an experimental study with pairs of graduated engineers and biologists who are doctoral candidates at the Technical University of Munich. Experimental designs in general have the advantage of internal validity because a number of factors relevant during the study can be controlled for. An example is testing for order effects as described in the previous section. However, they have disadvantages with regards to the external validity or generalizability of the results: On the one hand, it remains uncertain whether the observations in the artificial setting of an experiment can be transferred to a real situation. For this work, the experiment was based on a *realistic* task. Moreover, it had a limited duration and effort for the participants as assumed for workshops in real industrial settings. On the other hand, experimental studies regard a sample of participants. It is not sure if the observations made with these participants can be transferred to the general population – in case of this study to mechanical engineers working in industry and biologists available and willing to participate in ideation workshops (Blessing & Chakrabarti, 2009, p. 85).

Other factors not addressed in this study are related to personal influences of the participants. The participants had graduated at a biology faculty or mechanical engineering faculty. Therefore, it was concluded that they were biologists with expert knowledge in biology or mechanical engineers with expert knowledge in mechanical engineering. Moreover, the participants conducted research for their doctoral degree at different institutes or laboratories. It was assumed that thereby the participants had expertise in different areas of biology and mechanical engineering. However, they did not represent the whole range of biological or mechanical engineering areas.

Moreover, personal characteristics can play a role, but it has not been understood how they impact on ideation in bio-inspired design or engineering design in general. For example, there are a number of tests for personal creativity. One of these tests is the remote associate (or in a modified version the compound remote associate) test. It tests verbal-associate abilities as a measure for creativity and a correlation to productivity in brainstorming groups has been found (Forbach & Evans, 1981; Landmann, Kuhn, Marion, Piosczyk, Hannah, Feige, Bernd, Riemann, & Nissen, 2014)

Nevertheless, the variables relevant in ideation for developing technical products are multi-facetted (quality, variety etc.). In contrast, for the measurement of productivity in brainstorming groups, simpler variables such as fluency (quantity of ideas) have been used (e.g. Forbach & Evans, 1981). Therefore, the results cannot be transferred directly to the type of ideation regarded in this thesis.

8.2 Relation to comparable research

In this section, several aspects of this thesis are discussed in relation to comparable research:

Regarding the *BioId* support, the results of the second descriptive study show a reduction in the number of ideas. The quantity of ideas is frequently regarded as a measure for creativity (e.g. by Al-Shorachi, Sasasmit, & Gonçalves, 2015; Shah & Vargas-Hernandez, 2003). However, Reinig and Briggs (2008) found that when a high number of ideas is generated, the quality of the later generated ideas decreases. As the quality of ideas is related to the goal achievement of the final technical product, focusing on the quantity of ideas can be ineffective.

Studies on the inspiration cards (BioCards) have shown a positive influence on novelty, in particular when the descriptions of the biological systems were abstracted (Keshwani, Lenau, Kristensen, & Chakrabarti, 2013; Lenau, Keshwani, Chakrabarti, & Ahmed-Kristensen, 2015). As *BioId* requests an abstraction of the biological system, a similar effect on novelty is possible.

Independent of the BioId support, the verification measures have shown that the different information sources had a different impact on the portion of source-unique solution ideas (see section 7.2.2 (p. 123). This is to a certain extent in line with contradictory results found by Cardoso and Badke-Schaub (2009) and Cardoso, Gonçalves, and Badke-Schaub (2012): Their studies on the influence of using pictures or text as design stimuli showed different results regarding the fixation of designers on single solution ideas.

An aspect which was not in focus of this work, but can be observed in the results is the comparatively low performance of the mechanical engineer pairs: In comparison to biologists and bi-disciplinary pairs, they used less of the selected analogy types and generated less bio- and source-unique solution ideas. Results from a qualitative study on novice designers provided with a bio-inspired design task can provide a possible explanation. If the designers identified similarities to the familiar technical domain on low levels of abstraction (e.g. embodiment), they fixated on these aspects. They then did not identify and transfer analogies on the higher levels of abstraction (Cheong, Hallihan, & Shu, 2012).

9. Conclusion

Bio-inspired design is an approach for developing novel technical solutions inspired by biology with a high potential for innovation. The goal of this thesis was to overcome one main challenge of bio-inspired design - the knowledge gap between the involved disciplines biology and engineering. In this thesis, collaboration between biologists and engineers was regarded – an approach that enables the use of biological knowledge which has not been explored for technical application previously. An adverse approach is the use of catalogues and databases which present biological information pre-processed for a use by engineers. This thesis focussed on ideation in the early phases of product development, as in these phases the development of alternative novel solution ideas with innovative potential provides the basis for the further development steps.

Therefore, the aim of this thesis was to develop an understanding of the influences of bi-disciplinary collaboration between biologists and engineers on the development of solution ideas in an ideation phase. An additional aim was to support collaborating biologists and engineers in developing solution ideas with a higher potential for innovation.

In the following, the results of the thesis are summarized for the single sections and an overall conclusion is given. Then, implications for future research and industrial practice are discussed.

9.1 Results of the thesis

The thesis starts with an overview on the background (section 2). The aim of the background is to trace back the broad term innovation to ideation in the early phases of the product development process. It was shown that the factors *novelty* and *target achievement* which determine the innovativeness of technical products are related to the variables *variety*, *uniqueness* and *quality*. These variables can be measured at the level of solution ideas.

To understand the process of ideation, it was situated within the product development process. The ideation activities *exploration*, *generation*, *evaluation* and *communication* were explained. They were later used to analyse the video data of the experimental studies and to identify the solution ideas.

An ideation mechanism that dominates bio-inspired design is the transfer of analogies from the biological to the technical domain. Therefore a general perspective on the analogical process and dimensions of analogies was given. Bio-inspired design was introduced as an approach to the deliberate use of analogies from nature. Processes describing bio-inspired design were introduced as well as concepts to describe different analogy types occurring in bio-inspired design. These analogy types were then used to analyse the solution ideas developed in the experimental study.

Then, an overview on existing bio-inspired design methods, tools and research on collaboration between engineers and biologists was provided. This overview shows that on the one hand collaboration between engineers and biologists provide high potential for overcoming the knowledge gap hindering successful bio-inspired design. On the other hand, bi-disciplinary collaborations have been little researched so far. In particular, there is a lack of experimental research that can help to understand the influence of bi-disciplinary collaboration on ideation in detail.

Section 3 described the research approach of this thesis: Research questions were developed and the research methodology was described. The research methodology included a first descriptive study which served to develop a preliminary understanding of the influences of bi-disciplinary collaboration between engineers and biologists. The aim was to provide starting points for the development of a support for bi-disciplinary collaboration – the *BioId* support. The influence of *BioId* is evaluated in a second descriptive study. Moreover, the second descriptive study provided additional pairs and therefore increased the amount of data to be analysed. This allowed to reassess the results of the first descriptive study and to use statistical tests for testing the significance of the results.

In both descriptive studies, the same experimental design was used: Participants worked in two different pairs on two different design tasks. The participants were graduated research assistants from the areas of biology or mechanical engineering. First, the participants collaborated in a uni-disciplinary pair with a member of their own discipline. Second, they collaborated in a bi-disciplinary pair with a member of the other discipline. Each ideation in pairs had duration of 40 minutes. The participants were given a design task and selected biological information in the form of three different information sources: a biological research publication, a Wikipedia article and a video. They were instructed to develop solution ideas and to document them by annotated sketches. The experiments were recorded on video. For the analysis, solution ideas were identified regarding the ideation processes (video) and the documented results (sketches). These solution ideas were analysed quantitatively using measures for quality, variety and uniqueness. Qualitatively, questionnaires and the procedures of the participants were analysed to explain the quantitative results.

The results of the first descriptive study were shown in section 4. The quantitative results partly indicated a positive influence of the bi-disciplinary collaboration: Regarding the quality of solution ideas, the transfer of selected analogy types increased the average task-specific quality of solution ideas. Bi-disciplinary pairs did not transfer these analogy types more often than uni-disciplinary biologist pairs, but on average, they documented them more often. With regards to uniqueness, the use of several information sources enabled the development of bio- and source unique solution ideas. The qualitative analysis of the procedures adopted by the pairs allowed for a categorization into different approaches. Adopting a structured approach enabled the participants to use all three information sources.

Based on these results, the following aims of the *BioId* support were defined:

1. Supporting the transfer of the selected analogy types to increase the quality of solution ideas
2. Facilitation of the use of more information sources to increase the number of bio- and source-unique solution ideas
3. Fostering a structured approach (discussion of the task, use of all biological information sources one after the other)
4. Requesting the participants to sketch for transferring the selected analogy types

Section 5 described the development of *BioId*: After a task clarification, *BioId* was conceptualized and elaborated. For the elaboration, existing support models for bio-inspired design were analysed and useful aspects were extracted. Then, *BioId* was realised and tested with four students. Based on this support evaluation, *BioId* was improved. The aims were addressed by the following means:

1. In a two-step approach, *BioId* requests the transfer of more concrete and more abstract analogy types
2. and 3. *BioId* consists of a template for the discussion of the task and three templates for the use of all information sources
4. *BioId* requests sketching or the use of graphical representations at all stages

The results of the second descriptive study are presented in section 6. Figure 9-1 and Figure 9-2 depict the quantitative results regarding all solution ideas and the documented solution ideas.

With regards to the quality of solution ideas, Figure 9-1 shows that the *BioId* support strengthened the positive influence of the bi-disciplinary collaboration: The bi-disciplinary pairs documented a higher average portion of solution ideas using the selected analogy types, but the results were not statistically significant for all analogy types. The bi-disciplinary pairs using the *BioId* support (support pairs) transferred a higher average portion of solution ideas using the selected analogy types. For the documented solution ideas, the positive influence was statistically significant for all selected analogy types. The selected analogy types positively influenced the quality of solution ideas (statistically significant).

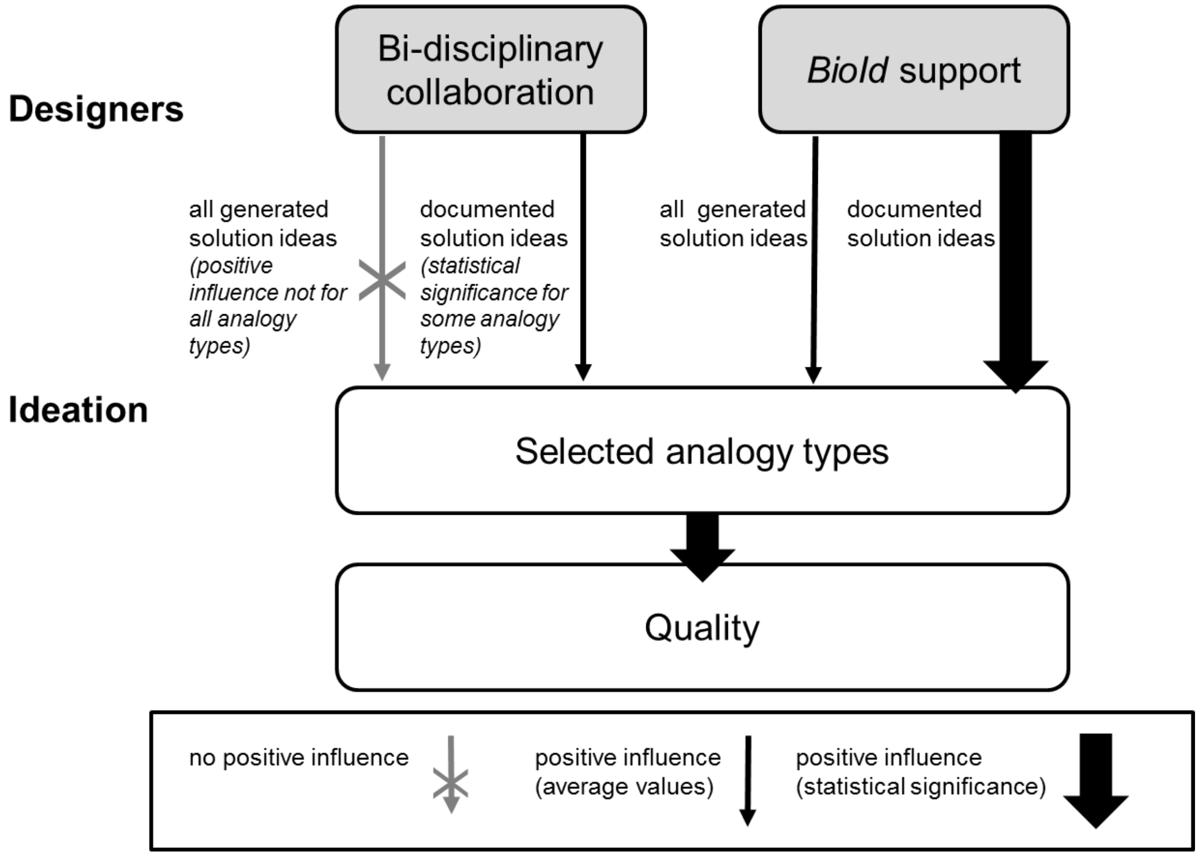

Figure 9-1: Results regarding the quality of solution ideas

For the variety of solution ideas, no results are shown here, as the results were ambiguous. Regarding the uniqueness of solution ideas, the bi-disciplinary pairs used more biological information sources for the generation and documentation of solution ideas than other pairs. In comparison, the pairs using the *BioId* support used less information sources for their documented solution ideas. Using several biological information sources enables the generation of bio- and particularly of source-unique solution ideas. Still, no positive influence of the bi-disciplinary pairs on the generation of bio- and source-unique solution ideas was observed. However, when bi-disciplinary pairs used the *BioId* support, they generated a higher portion of bio- and source-unique solution ideas on average. For the documented solution ideas, statistical significance was shown.

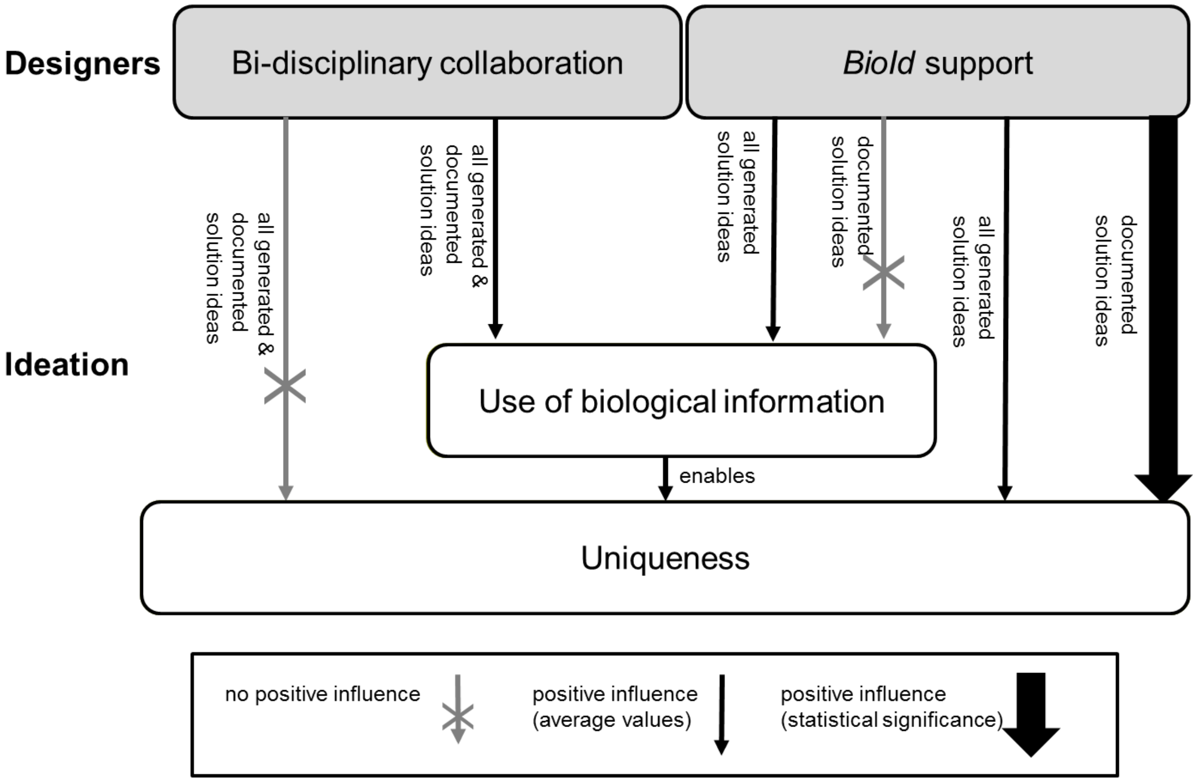

Figure 9-2: Results regarding the uniqueness of solution ideas

Despite its positive influence on quality and uniqueness, the use of *BioId* had two disadvantages: On average, the number of solution ideas decreased in comparison to the other pairs. The qualitative analysis of the ideation procedures showed that the pairs using the support all adopted a structured procedure. It is concluded that even though the participants discussed all biological information sources in a structured manner, they did not have the time to document as many solution ideas as the other pairs. Moreover, the participants provided negative feedback on the usability of the *BioId* templates.

It is concluded that the use of the *BioId* support has an overall positive influence, but it has to be improved to facilitate its use and make it more efficient. Moreover, engineers and biologists have to enjoy using *BioId*.

Section 7 described additional measures for the verification of the results. Two factors are assessed: Order effects during the experiment and possible influences of the three different design tasks on the results. As a result, no order effects due to learning during the experiments or due to fatigue were found. Regarding the three design tasks, they influence the absolute values of quality and portion of bio-and source unique solution ideas. Still the relative tendencies are similar. It is therefore concluded, that using several design tasks has a positive influence on external validity of design experiments, as absolute differences between specific tasks are balanced.

A discussion of the results was provided in section 8: The results were compared to similar studies and the limitations of this work were summarized.

To give an overall conclusion, the results are regarded in relation to the train of thought of this work presented in Figure 3-1(p. 31): As the figure depicts, variety and uniqueness of solution ideas are related to the novelty of the final technical product. The quality of solution ideas is related to the target achievement of the technical product. Both factors, novelty and target achievement are crucial for innovative products. As ideation in bi-disciplinary collaboration supported by BioId positively influences quality and uniqueness of solution ideas, it is concluded that it increases the potential for innovative technical products.

In the following sub-sections, this conclusion is regarded from a research and an industrial perspective and possible future research and development steps are described.

9.2 Implications for future research

The experimental study described in this thesis shows a statistically significant influence of bi-disciplinary collaboration between a mechanical engineer and a biologist supported by *BioId* on two factors: Firstly, the transfer of the selected analogy types and thereby the quality of solution ideas is positively affected. Secondly, the portion of bio- and source-unique solution ideas is increased.

This result has implications for collaboration in bio-inspired design ideation and bio-inspired design in general:

For collaboration, the results show the positive influence of a supported bi-disciplinary composition of the pair, group or team working on the ideation task. “Supported” in this case means the support of the adoption of a structured procedure, the transfer of the intended analogy types and the use of graphical representations and sketching.

For bio-inspired design in general, the positive influence of the selected analogy types on the quality of solution ideas is relevant: Even though different definitions of analogy types and supports for transferring these analogy types have been developed previously, their positive impact on the quality of solution ideas has not been regarded so far.

This work shows multiple possibilities for future research:

The focus of this work is the ideation phase. However in the early phases of product development, the selection of solution ideas and their further development to preliminary prototypes plays a role. Further studies can focus on the impact of the variables regarded in this study on selection and further development activities. For example, this study has shown ambiguous results for the combined variety and quantity measure (V) and the normalized variety measure (V^*). What impact do these types of variety have on the selection from a pool of solution ideas?

If the further development activities are conducted in bi-disciplinary collaboration, an interesting aspect is the role of engineers and biologists: How do they contribute with their knowledge on biology to these product development activities? How does this improve the outcomes?

Moreover, this work focused on a pair perspective, the participants were not regarded individually. To increase the understanding of the effect of the collaboration and the *BioId* support, the data of this study can be reassessed for the individual participants. This can answer questions regarding discipline-specific requirements for using a support for collaboration in more detail.

9.3 Implications for industrial practice

As the design experiments were conducted in a realistic setting, the results of this work can be used for designing ideation workshops in industrial practice: For the composition of a pair, group or team, this work indicates the usefulness of collaboration between mechanical engineers and biologists. Moreover, this works shows the usefulness of templates fostering the adoption of a structured approach and the use of graphical representations and sketching.

In future work, the *BioId* support can be further developed, so that it can be used as a method for bi-disciplinary collaboration in ideation workshops. To achieve this goal, workshops with experts from biology, mechanical engineering and visualization can be conducted. The main aspect to be improved is the time effort needed to understand and use the *BioId* templates. Moreover, aspects regarding satisfaction or fun for the users of *BioId* have to be regarded. In order to achieve these aims, the *BioId* support can be simplified. Moreover its visual appearance can be improved. An additional option is to provide *BioId* as software on a drawing tablet – this opens up additional options for (automated) visualisations and an automated workflow which can increase the participants' interest in the method.

10. References

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Vattam, S. S., Helms, M. E., & Goel, A. (2009). Nature of creative analogies in biologically inspired innovative design. In M. Grimheden, L. Leifer, & M. Norell Bergendahl (Eds.), *Proceedings of the International Conference on Engineering Design (ICED09), Stanford* (pp. 255–264). Glasgow, UK: The Design Society.

Vattam, S. S., Helms, M. E., & Goel, A. (2010). A content account of creative analogies in biologically inspired design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, *24*(4), 467–481.

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VDI. (2012). *VDI 6220: Conception and Strategy - differences between biomimetic and conventional methods/ products*. Berlin: Verein Deutscher Ingenieure, Beuth Verlag.

Wilson, J. O., Rosen, D., Nelson, B. A., & Yen, J. (2010). The effects of biological examples in idea generation. *Design Studies*, *31*(2), 169–186.

11. Appendix

11.1 Descriptive studies: participants

Table 11-1 lists the profession and research institutes of the participants. All ten participants considered as “mechanical engineers” in the studies had a graduate degree (Dipl.-Ing. or MSc.) in mechanical engineering. As to the “biologists”, six of them had a graduate degree in biology (Dipl.-Biol. or MSc.), four of them in a specialised related area (diploma or MSc.).

Table 11-1: profession and research institutes of the participants

profession	**research institutes**
mechanical engineers	Institute of Aerodynamics and Fluid mechanics, Specific field Continuum Mechanics, Institute of Ergonomics, Institute for Machine Tools and Industrial Management, Institute of Materials Science and Mechanics of Materials, Institute of Micro Technology and Medical Device Technology, Institute for Primary Shaping and Metal Forming (2 participants), Institute of Product Development, Institute of Product Development - Virtual Product Development,
biologists	Animal ecology, Animal ecology – Wildlife work group, Chair of Aquatic Systems Biology, Chair for Terrestrial Ecology, Division for Systems Biotechnology, Chair of Zoology
bio-information scientist	Department of Genome-Oriented Bioinformatics
biogeographist	Chair of Soil Science
biochemist	Chair of Biochemistry
biophysicist	Chair of Molecular and Cellular Biophysics

11.2 Descriptive studies: design tasks and biological information

Table 11-2 gives detailed information on the design tasks and the biological information. In the following sub-sections, the slides given to the participants are shown in figures. For task I (water pump) an explanatory sketch is included. For task II (aquaplaning) a figure from *Stumpf, H.(1997): Handbuch der Reifentechnik; Wien: Springer Technik, p. 162* is included in the task.

Table 11-2: Details on design tasks and biological information

design task	**publication (English)**	**Wikipedia article (German or English)**	**video (German)**
I – water pump	Wong, W.-L., Gorb, S.: Attachment ability of a clamp-bearing fish parasite, Diplozoon paradoxum (Unigenea, on gills of the common bream, abramis brama, The Journal of Experimental Biology 216, p. 3008-3014, 2013.	byssus (sea shell) http://de.wikipedia.org/wiki/Byssus	praying mantis: http://www.youtube.com/watch?v=K-RmXhH1gfo&feature=share_email
II – sun protection	Ishay, J.S. et al.: The solar cell in hornet cuticle: nanometer to micrometer scale, Journal of Electron Microscopy: 49 (4), p. 559-568, 2000.	iris (eye) https://de.wikipedia.org/wiki/Iris_%28Auge%29	sunflower: http://www.youtube.com/watch?v=g8mr0R3ibPU
III – aqua-planing	Hosoda, N., Gorb, S.: Underwater locomotion in a terrestrial beetle: combination of surface de-wetting and capillary forces, Proceedings of the Royal Society: 279, 2012.	leaf (plant) http://de.wikipedia.org/wiki/Blatt_%28Pflanze%29	spider net: http://www.youtube.com/watch?v=t2s13frp-Ws

11.2.1 Task I: water pump

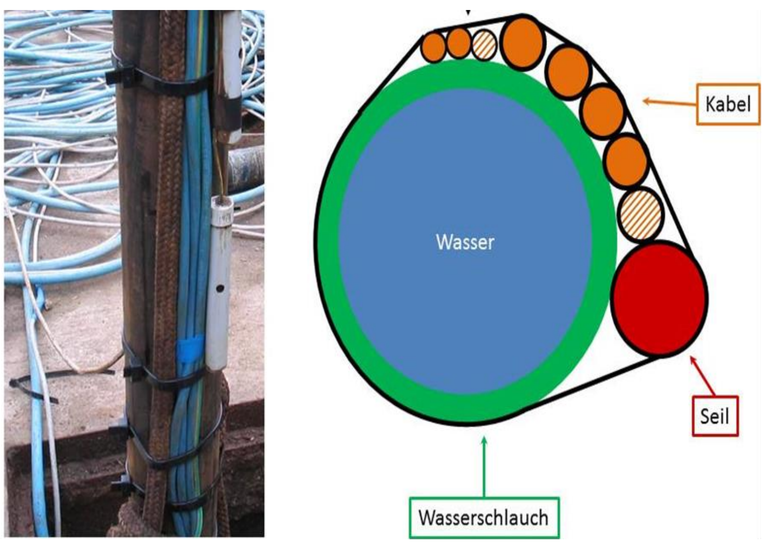
In subtropischen Ländern gefährden regelmäßig Dürreperioden und Wasserknappheit die Landwirtschaft. Zur lokalen Wasserversorgung werden daher in der Landwirtschaft häufig Brunnen eingesetzt. Für kleinere Brunnensysteme werden Pumpen, Wasserschläuche und ihre entsprechenden Versorgungskabel an einem Seil in ihr jeweiliges Bohrloch herabgelassen. Fixiert werden diese Vorrichtungen durch viele, an dem Wasserschlauch angebrachte, Kabelbinder (siehe Abbildung, links).

Diese Konstruktion weist aber einige Nachteile auf. So lassen sich die Kabelbinder beispielsweise nur einmal verwenden. Ist der Verschließmechanismus erst ausgelöst, kann er ausschließlich durch eine Zerstörung wieder geöffnet werden. Gerade für Wartungsarbeiten ist das ungünstig.

Ein weiteres Manko ergibt sich aus der Montage des Verbindungssystems. Um eine ausreichende Kraft aufzubringen, wird bei dem Zusammenbau ein spezielles Werkzeug verwendet. Dieses zieht die Schlaufe des Kabelbinders bis zu einer festgelegten Kraft enger und schneidet dann das Überstehende Ende ab (siehe Abbildung, links). Zum einen ist die Verwendung eines Spezialwerkzeugs nachteilig, da sie zu einem großen Aufwand an Handarbeit führt, zum anderen resultiert aus den abgeschnittenen Endstücken eine zusätzliche Verletzungsgefahr. Wenn das Rohr für Wartungsarbeiten aus seinem Bohrloch gezogen wird, muss es von einem Arbeiter mit den Händen fixiert werden. Die scharfen Kanten der Kabelbinder können zu schweren Schnittwunden an den Händen führen.

Das größte Problem stellt aber die ungleichmäßige Kraftübertragung dar. Wie die Abbildung (rechts) zeigt, wird die Kraft hauptsächlich an markanten Eckpunkten übertragen. Das führt dazu, dass einige Kabel nicht fixiert werden (Schraffierte Kabel im Bild). Damit sind einige Kabel zu stark und andere zu gering belastet. Dieses Hindernis wird durch die Verwendung einer großen Anzahl an Kabelbindern gelöst. Das ist aber keine ressourcen-schonende Vorgehensweise. Des Weiteren kann sich durch das schlammige Wasser an dem Wasserschlauch eine Schicht bilden, die, trotz der großen Menge an Spannsystemen, ein rutschen ermöglicht. Das wiederum hat Auswirkungen auf die Kraftverteilung im gesamten Mechanismus.

Figure 11-1: task I situation description (text adapted from: Spiegel, J. (2013): Analyse der Datenbank PubMed hinsichtlich einer bionischen Lösungssuche anhand eines praktischen Beispiels (unpublished bachelor thesis),Institute of Product Development, Technical University of Munich, Munich(pp. 51-52))



Fixierung der Kabel und des Seils am Wasserschlauch [Spiegel 2013]

Figure 11-2: task I: figure to illustrate the situation (figure from: Spiegel, J.(2013): Analyse der Datenbank PubMed hinsichtlich einer bionischen Lösungssuche anhand eines praktischen Beispiels(unpublished bachelor thesis),Institute of Product Development, Technical University of Munich, Munich(p.51))

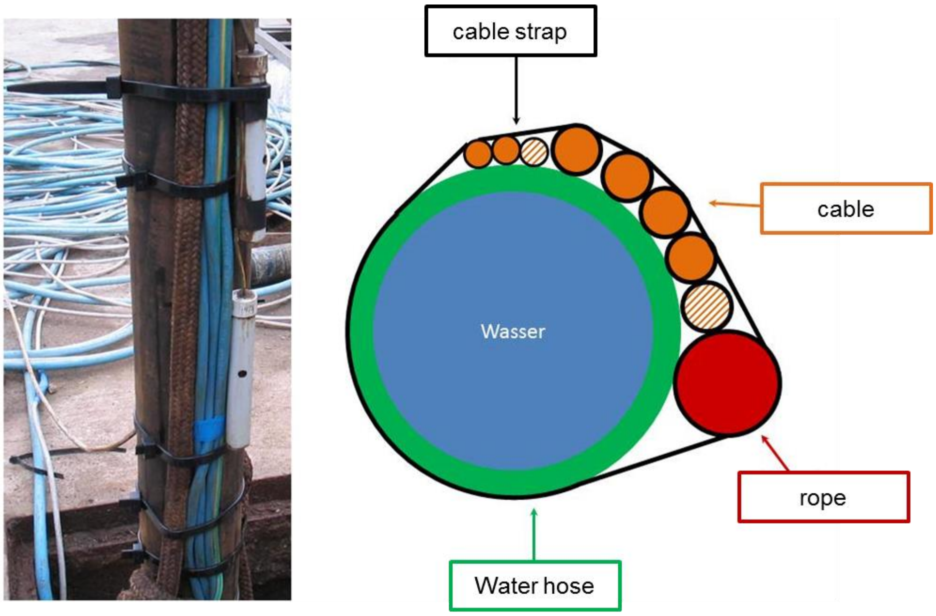


Figure 11-3: task I: figure to illustrate the situation (English translation of figure from: Spiegel, J. (2013): Analyse der Datenbank PubMed hinsichtlich einer bionischen Lösungssuche anhand eines praktischen Beispiels (unpublished bachelor thesis), Institute of Product Development, Technical University of Munich, Munich, (p. 51))

Aufgabe

“Entwickelt eine Lösung, um eine Wasserpumpe mit Schlauch und Versorgungskabeln in einen Brunnen herabzulassen”

> **“Entwickelt so viele Lösungen wie möglich!”**

Beachtet:

- Die Lösung muss **mobil einsetzbar** sein, da die Wasserpumpe im Wechsel in verschiedenen Brunnen genutzt wird.
- Die Lösung muss eine **sichere Fixierung** des Schlauchs und der Versorgungskabel gewährleisten.
- Die Fixierung und das Lösen von Schlauch und Versorgungskabeln sollte möglichst **einfach** sein.

> “Dokumentiert eure Lösungen durch **beschriftete Skizzen**!”
> (**jede** Idee auf einem **neuen** Blatt Papier)

Figure 11-4: task I: task statement and requirements

Task:

"Develop a solution to lower a water pump with hose and cables into a well"

"Develop as many solutions as possible!"

Notice:

- The solution must be **mobile applicable**, as it is used in different wells.
- The solution must ensure a **secure** fixation of cables and hose.
- The fixation and dismounting of cables and hose must be as **easy** as possible.

"Document your solution by **annotated sketches**!"
(**every** idea on a **new** sheet of paper)

Figure 11-5: task I: task statement and requirements (English translation)

11.2.2 Task II: sun protection

Jeder kennt das Problem: Wohnungen und Büroräume mit Fenstern werden durch direkte Sonneneinstrahlung stark erhitzt. Dagegen werden Jalousien, Rollos, Vorhänge eingesetzt, die manuell oder elektrisch geschlossen und geöffnet werden können. Ist der Nutzer des Raums nicht anwesend und schließt den Sonnenschutz, erhitzt sich der Raum. Daher geschieht die Steuerung insbesondere bei Büroräumen häufig zentral, z.B. indem zu einer bestimmten Uhrzeit der Sonnenschutz automatisch herunter- und hochgefahren wird. Für die Nutzer der Räumlichkeiten ist das oftmals ein Ärgernis, da sie bei schlechtem Wetter möglichst viel Licht in die Räume lassen möchten. Ein weiteres Problem stellt die Sichtbehinderung durch den Sonnenschutz dar: Die meisten Sonnenschutzmaßnahmen ermöglichen keine Sicht nach draußen und verdunkeln die Räume zu stark.

Figure 11-6: task II situation description

Aufgabe

"Entwickelt eine Lösung, um die Erhitzung von Räumen bei Sonneneinstrahlung zu verhindern."

"Lasst euch von den biologischen Informationen inspirieren und entwickelt so viele Lösungen wie möglich!"

Beachtet:

- Die Lösung muss den **Einfall von Tageslicht** durch Fenster ermöglichen.
- Die Lösung muss den Raum **ohne aktive Bedienung** des Nutzers vor Erhitzung schützen.
- Die Lösung sollte möglichst **keine elektrische Energie** erfordern.

"Dokumentiert eure Lösungen durch **beschriftete Skizzen**!"
(**jede** Idee auf einem **neuen** Blatt Papier)

Figure 11-7: task II: task statement and requirements

Task

"Develop a solution to prevent the heating of rooms due to insolation."

"Be inspired by the biological information and develop as many solutions as possible!"

Notice:

- The solution has to let **day light** through the windows.
- The solution has to protect the room **without active control** of the user.
- If possible, the solution should work **without electric energy**.

"Document your solution by **annotated sketches**!"
(**every** idea on a **new** sheet of paper)

Figure 11-8: task II: task statement and requirements (English translation)

11.2.3 Task III: aquaplaning

Aquaplaning setzt ein, wenn der Wasserfilm auf der Straße hoch genug ist, sodass die Räder „aufschwimmen“, also der Kontakt zur Fahrbahn abreißt. Befindet sich ein geschlossener Wasserfilm auf der Fahrbahn, bildet sich schon bei geringer Geschwindigkeit ein Wasserkeil vor dem Rad, der es für manche Gummielemente der Reifenprofilierung unmöglich macht, bis zur Straßenoberfläche durchzudringen. Der Wasserkeil wird abhängig von der Wasserableitfähigkeit des Reifenprofils, sowie von seiner Aufstandsdruckverteilung, im Allgemeinen, vorerst in der Mitte der Latsch, das heißt der Kontaktfläche des rollenden Reifens mit der Straße, einwandern (siehe Abbildung). Sobald die verbleibende Fläche nicht mehr ausreicht, die aufgebrachten Kräfte auf die Fahrbahn zu übertragen, entsteht schlagartig Aquaplaning. Wasser ist schwer komprimierbar und besitzt eine vergleichsweise hohe Oberflächenspannung. Bei dem Effekt Aquaplaning sind die atomaren Bindungskräfte des Wassers (Kohäsionskräfte) unter der Aufstandsfläche des Reifens stärker als die zur Fahrbahn gerichteten Kräfte des Reifens. Aufgrund der genannten Eigenschaften muss also das Wasser vom Reifen verdrängt werden, um einen Kontakt mit der Straße herstellen zu können. Bei zunehmender Geschwindigkeit hat die Lauffläche jedoch weniger Zeit das Wasser seitlich abzuleiten. Wird nicht genug Wasser verdrängt, entsteht Aquaplaning, und die Übertragung von Lenk- und Bremskräften auf die Fahrbahn ist dann nicht mehr möglich.

Figure 11-9: task III: situation description

Aufgabe

“Entwickelt eine Lösung, um Aquaplaning bei PKWs zu verhindern.”

“Entwickelt so viele Lösungen wie möglich!”

Beachtet:

- Die Lösung muss dem Autofahrer ermöglichen, bei möglichst “wiedrigen” Bedingungen, (Menge des Wassers auf der Fahrbahn)
  - den PKW zu **bremsen**
  - den PKW zu **lenken**

“Dokumentiert eure Lösungen durch **beschriftete Skizzen**!”
(**jede** Idee auf einem **neuen** Blatt Papier)

Figure 11-10: task III: task statement and requirements

Task

“Develop a solution to prevent aquaplaning”

“Develop as many solutions as possible!”

Notice:

- The solution has to enable the car driver to
  - **break** the car
  - **steer** the car

  under maximum adverse conditions (amount of water on the road)

“Document your solution by **annotated sketches**!”
(**every** idea on a **new** sheet of paper)

Figure 11-11: task III: task statement and requirements (English translation)

11.3 Assignment of participants to pairs and design tasks

Table 11-3 and Table 11-4 show the assignment of the participants to pairs and the sequence of the individual tasks they worked on. Moreover the tables depict the assignment of pairs to tasks.

There is a gap in the numbering, i.e. the participants e3, e4, b3 and b4 are missing. Consequently, there is no biologist/ engineer pair 2 and bi-disciplinary pair 3 and 4. Originally, these participants participated in the study. Due to an organisational problem, the experiments could not be conducted as planned with this group of participants and the results had to be excluded from the analysis.

Table 11-3: Assignment of participants to tasks (first descriptive study, 2013)

sequence of individual tasks:

**elephant + ship, dolphin + robot, bat + airplane*

***dolphin + robot, bat + airplane, elephant + ship*

participant	biologist pair		mechanical engineer pair		bi-disciplinary pair			
	1	3	1	3	1	2	5	6
design task	I	II	I	II	II	III	III	I
e1*			x			x		
e2*			x		x			
e5**				x			x	
e6**				x				x
b1*	x				x			
b2*	x					x		
b5**		x					x	
b6**		x						x

Table 11-4: Assignment of participants to tasks (second descriptive study, 2015)

sequence of individual tasks:

**elephant + ship, dolphin + robot, bat + airplane*

***dolphin + robot, bat + airplane, elephant + ship*

**** bat + airplane, elephant + ship, dolphin + robot*

particip ant	biologist pair			mechanical engineer pair			bi- disc. pair	support pair				
	4	5	6	4	5	6	7	1	2	3	4	5
design task	III	I	II	III	I	II	II	I	III	II	I	III
e7***				x			x					
e8***				x				x				
e9**					x				x			
e10**					x					x		
e11*						x					x	
e12*						x						x
b7***	x						x					
b8***	x							x				
b9**		x							x			
b10**		x								x		
b11*			x								x	
b12*			x									x

11.4 Documented solution ideas (sketches)

This section shows all documented solution ideas listed and numbered according to the task. The lists of numbered solution ideas and the analysis of working principles, physical effects and function level are shown in the following sub-section (11.5).

11.4.1 Task I: water pump

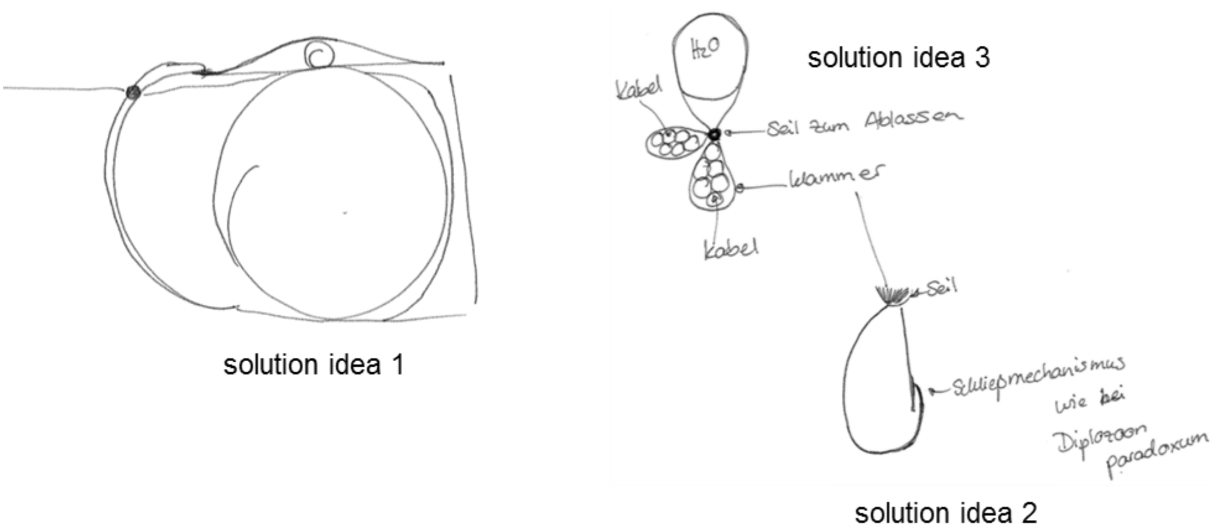


Figure 11-12: Biologist pair 1 – solution ideas 1,2,3

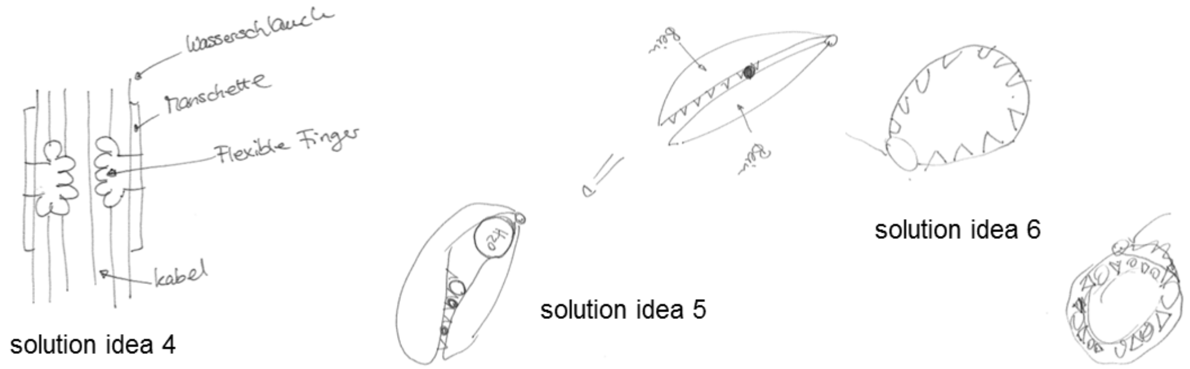


Figure 11-13: Biologist pair 1 – solution ideas 4,5,6

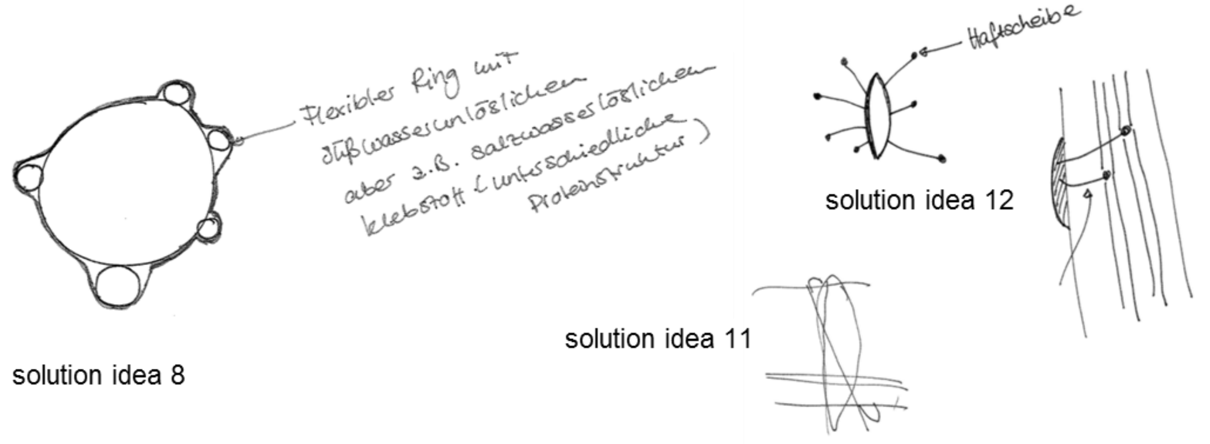


Figure 11-14: Biologist pair 1 – solution ideas 8,11,12

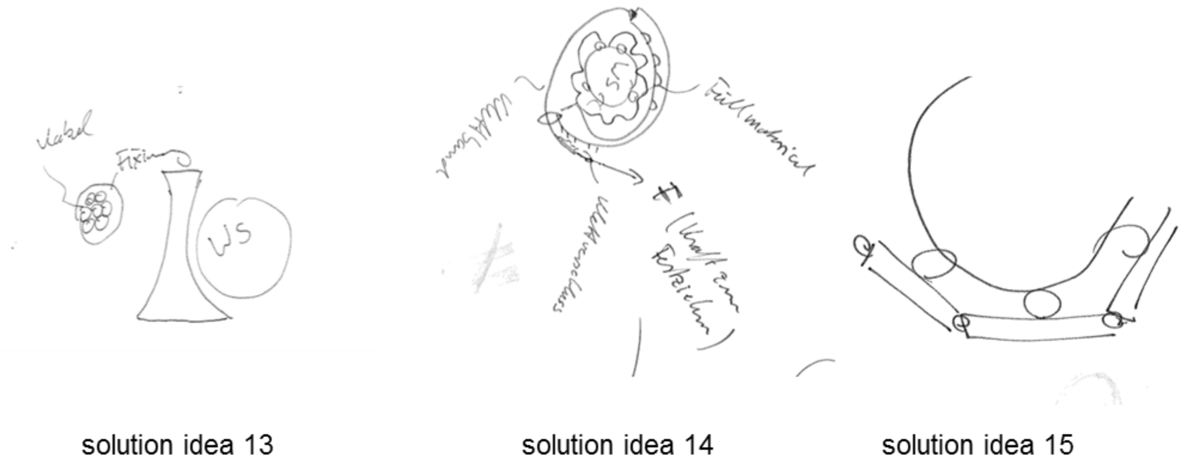


Figure 11-15: Engineer pair 1 – solution ideas 13,14,15

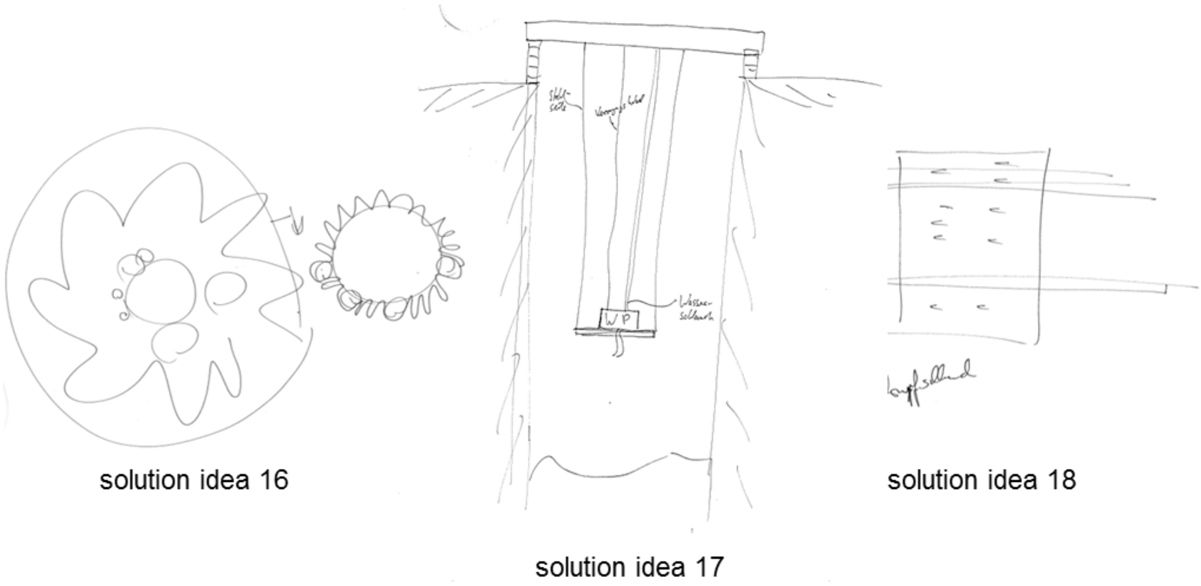


Figure 11-16: Engineer pair 1 – solution ideas 16, 17, 18

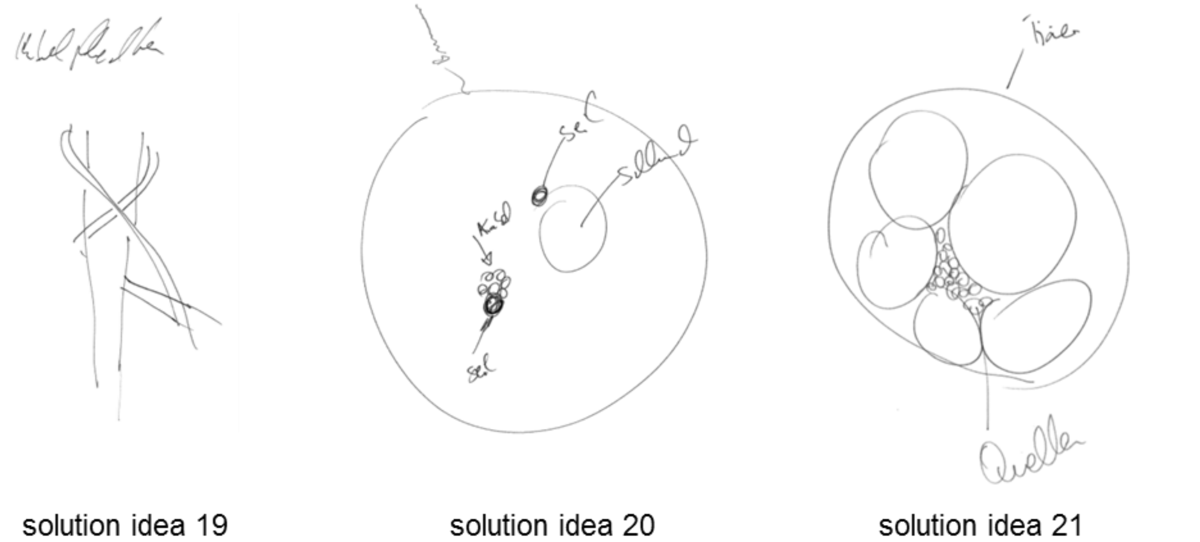


Figure 11-17: Engineer pair 1 – solution ideas 19, 20, 21

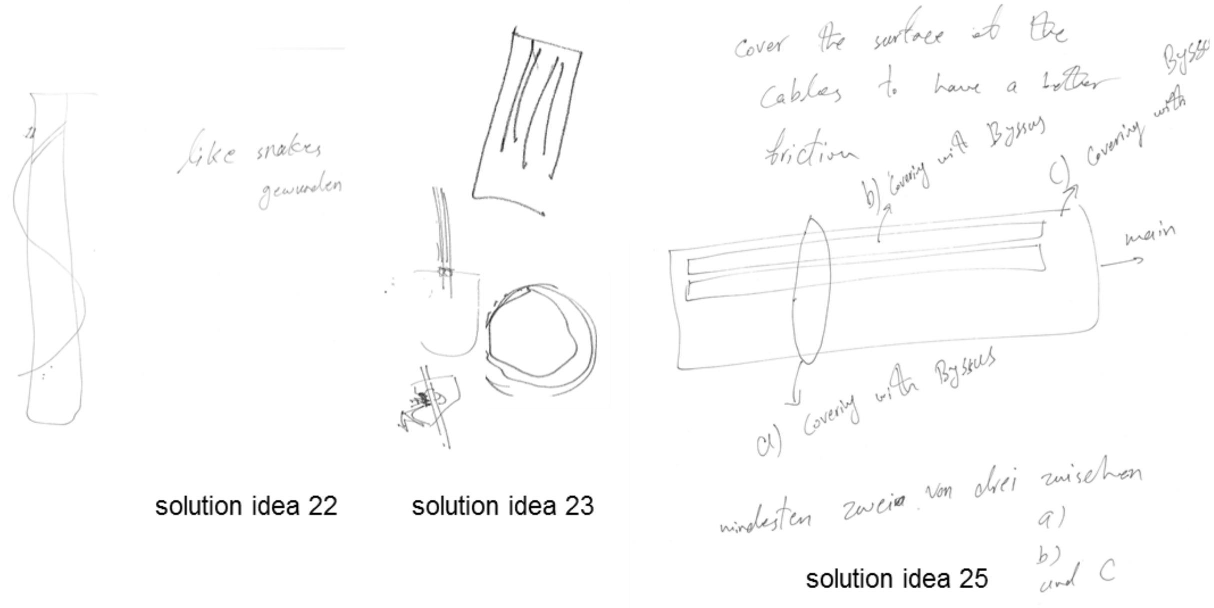


Figure 11-18: Bi-disciplinary pair 6 – solution ideas 22, 23, 25

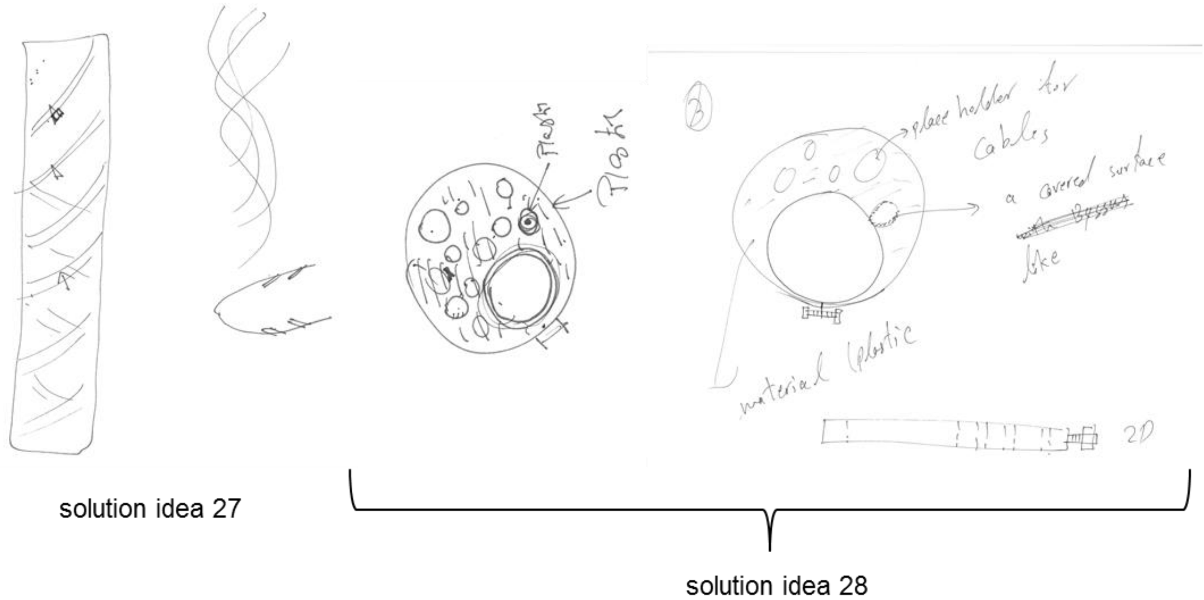


Figure 11-19: Bi-disciplinary pair 6 – solution ideas 27, 28

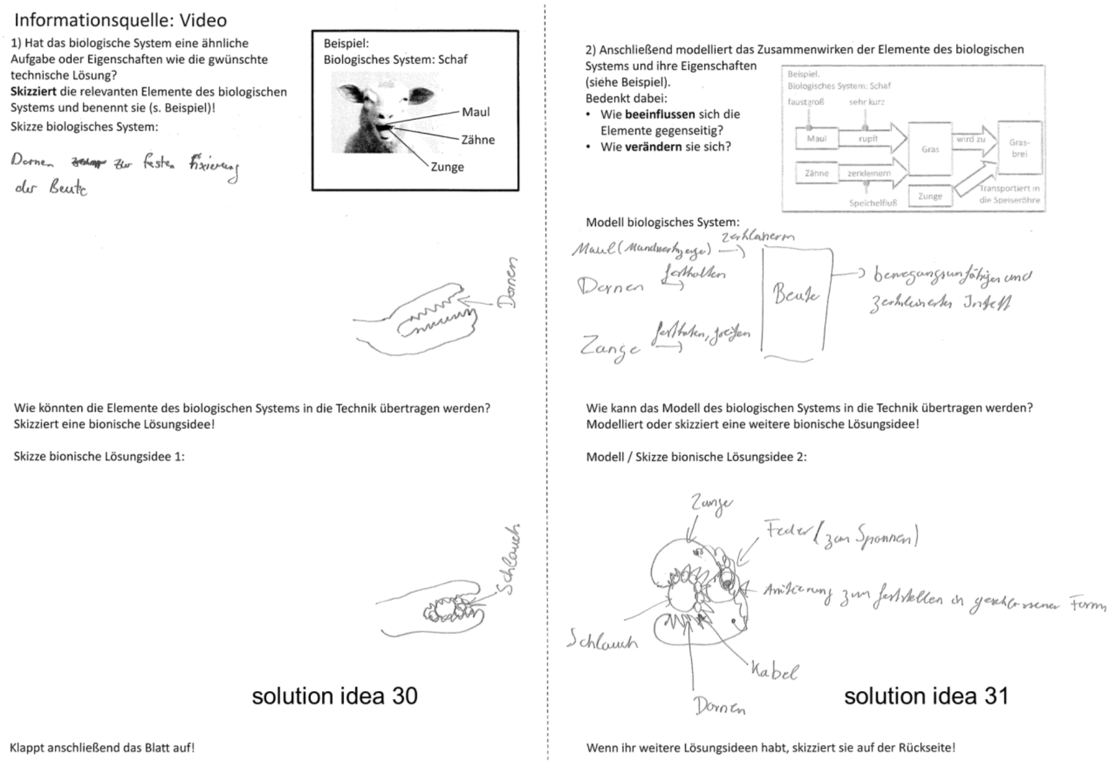


Figure 11-20: Support pair 1-solution idea 30, 31 (BioId template, biological information video)

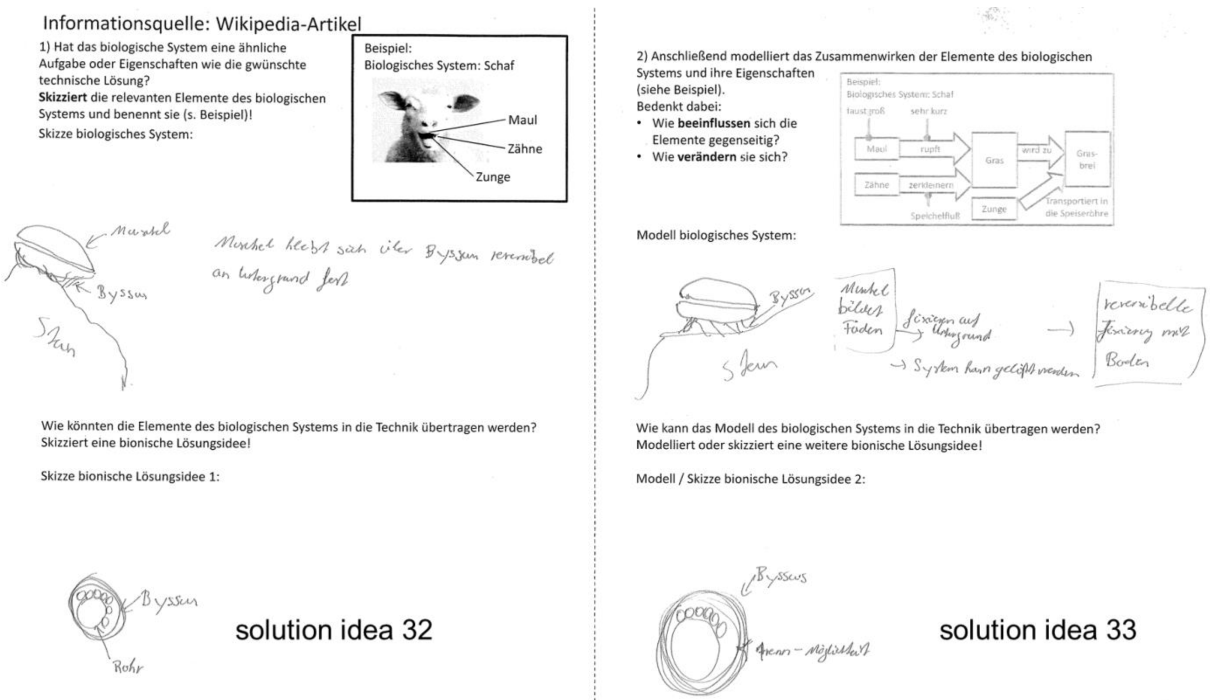


Figure 11-21: Support pair 1-solution idea 32, 33 (BioId template, biological information Wikipedia)

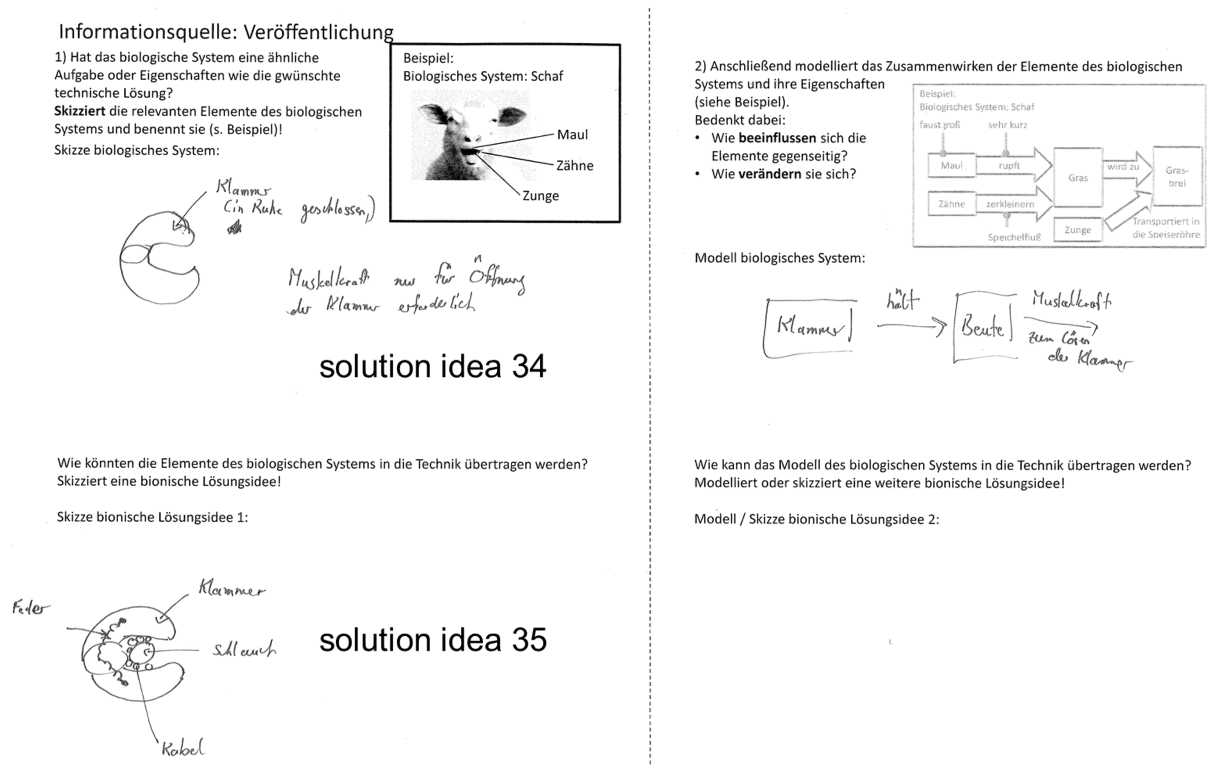
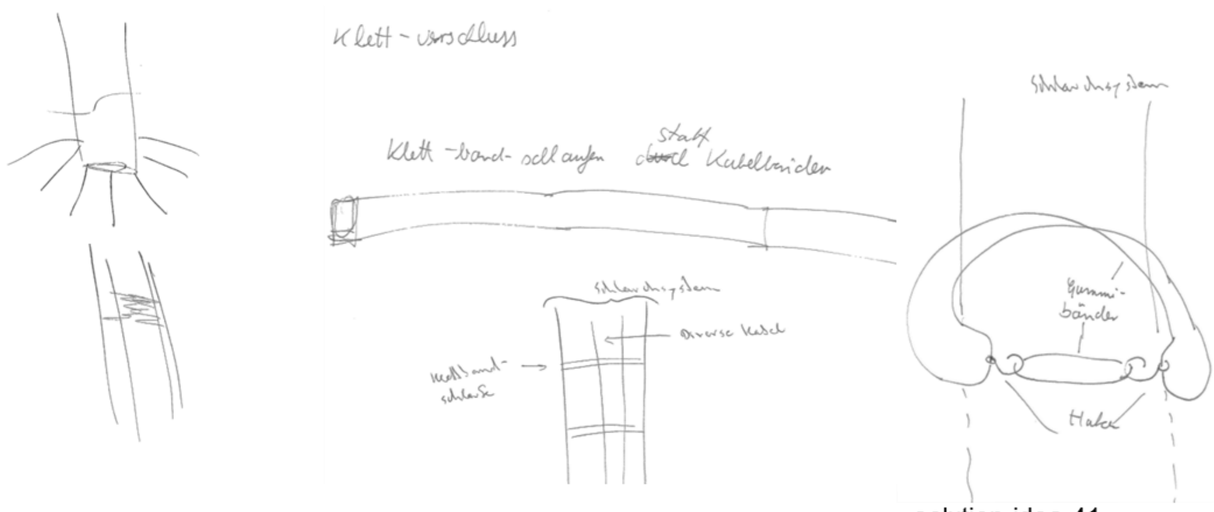
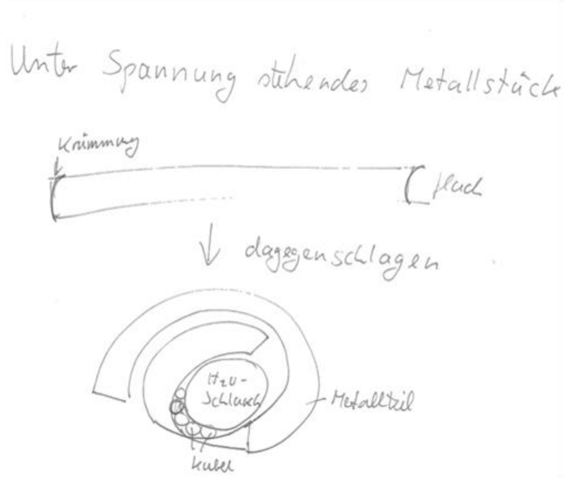


Figure 11-22: Support pair 1-solution idea 34, 35 (BioId template, biological information publication)



solution idea 36 solution idea 38 solution idea 41

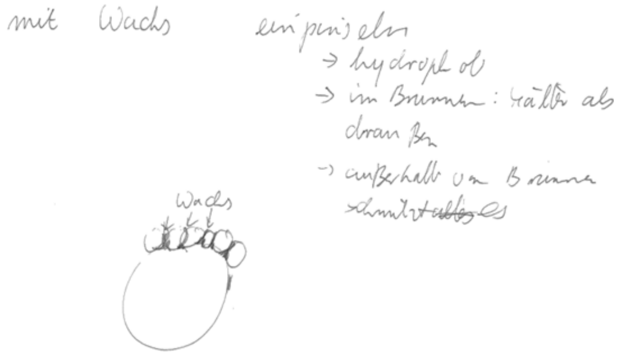
Figure 11-23: Biologist pair 5-solution idea 36, 38, 41



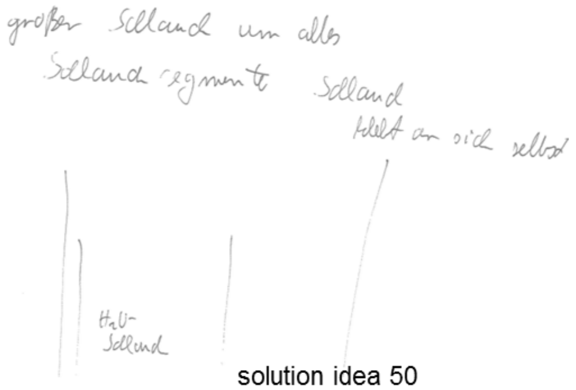
solution idea 46

solution idea 47

Figure 11-24: Biologist pair 5-solution idea 46, 47

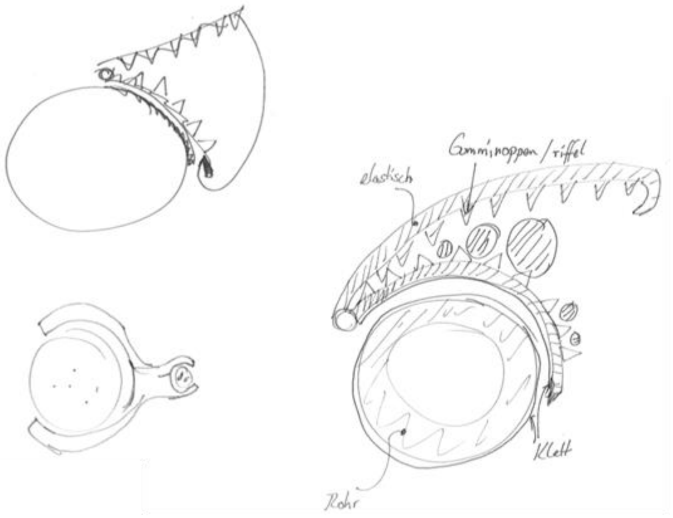


solution idea 48

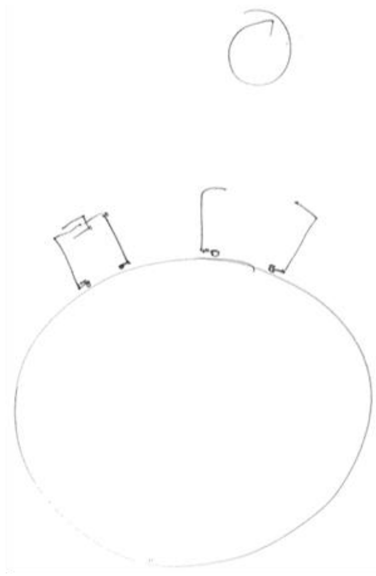


solution idea 50

Figure 11-25: Biologist pair 5-solution idea 48, 50

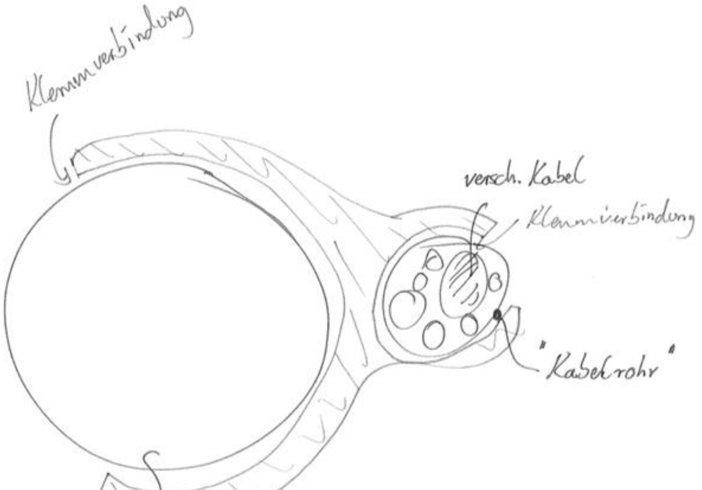


solution idea 53



solution idea 55

Figure 11-26: Engineer pair 5-solution idea 53, 55



solution idea 56

Figure 11-27: Engineer pair 5-solution idea 56

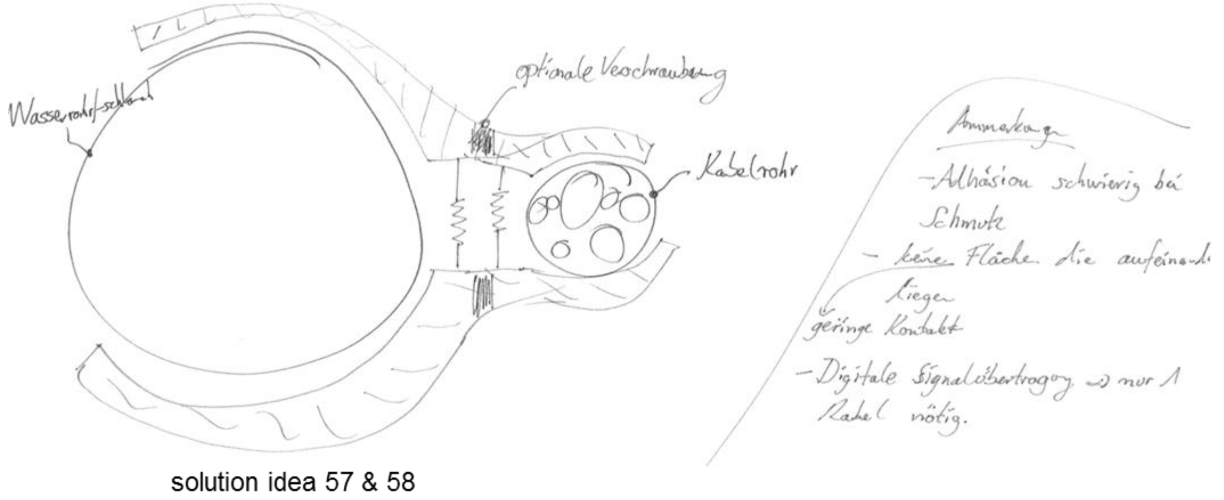


Figure 11-28: Engineer pair 5-solution ideas 57; 58

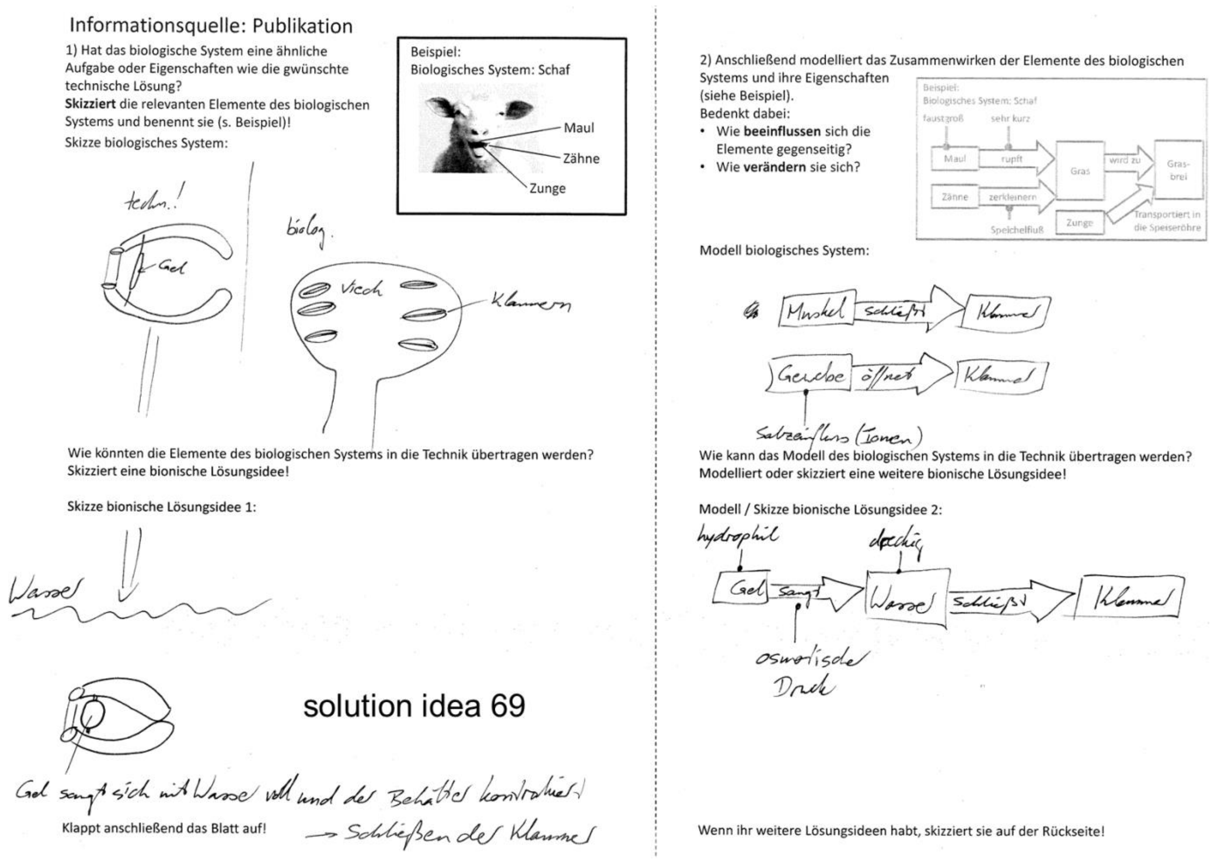


Figure 11-29: Support pair 4-solution idea 69 (BioId template, biological information publication)

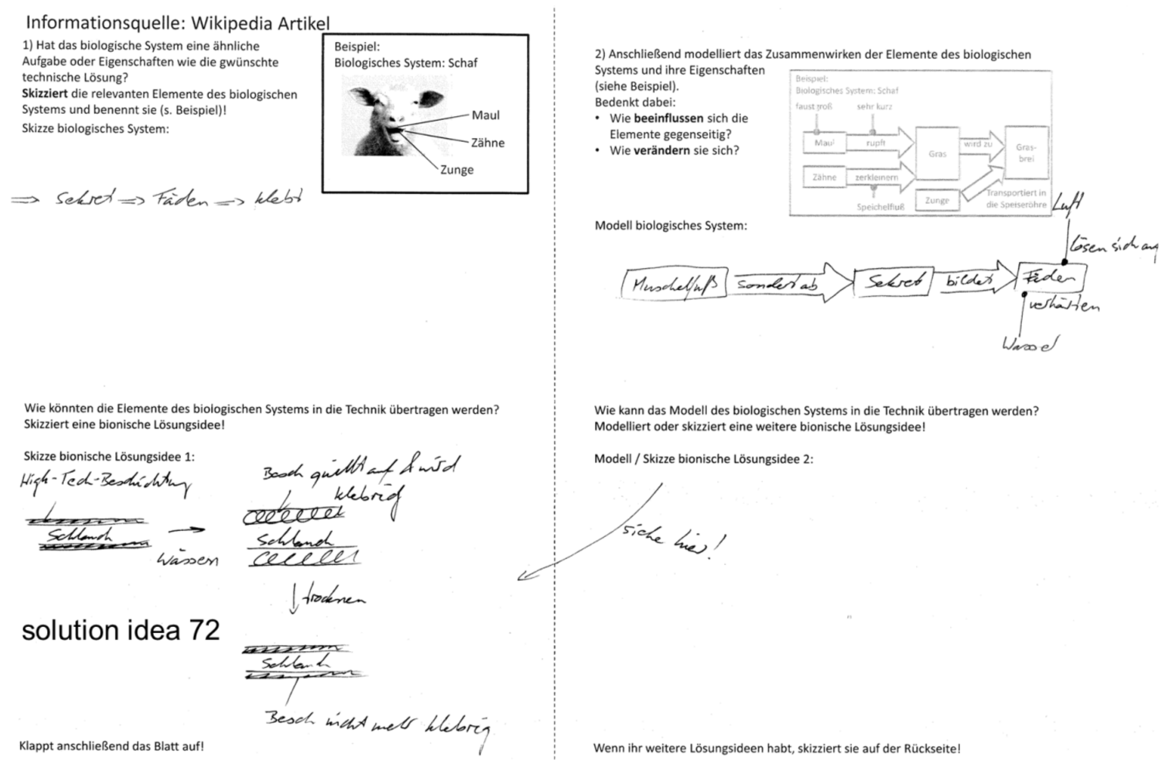


Figure 11-30: Support pair 4-solution idea 72 (BioId template, biological information Wikipedia)

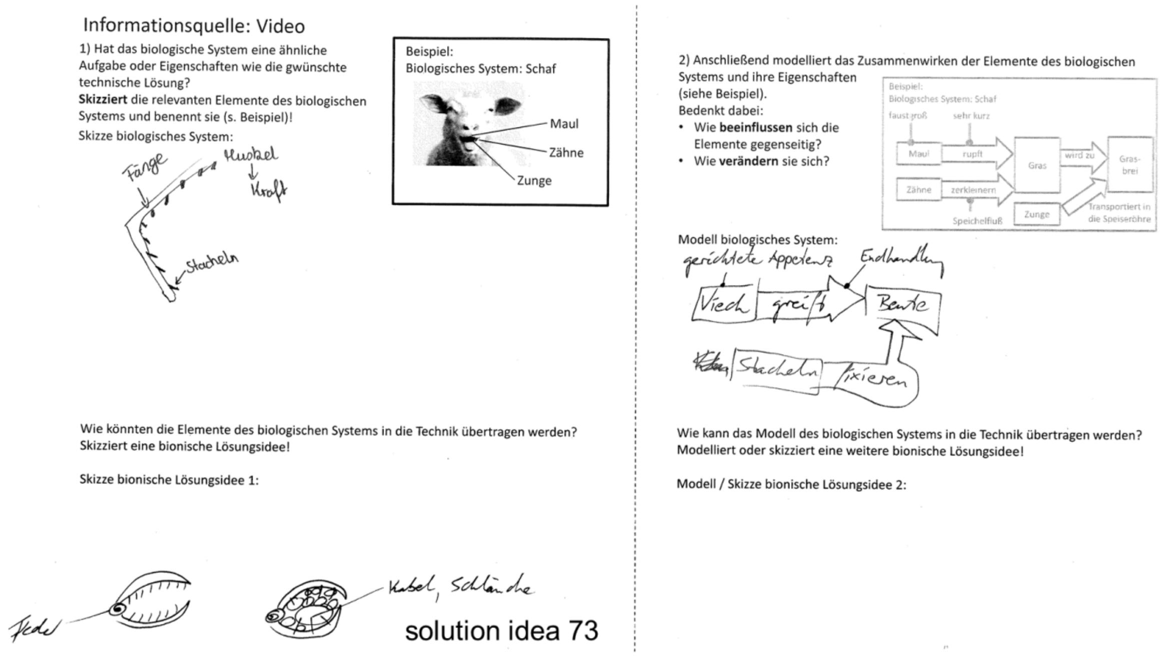


Figure 11-31: Support pair 4-solution idea 73 (BioId template, biological information video)

11.4.2 Task II: sun protection

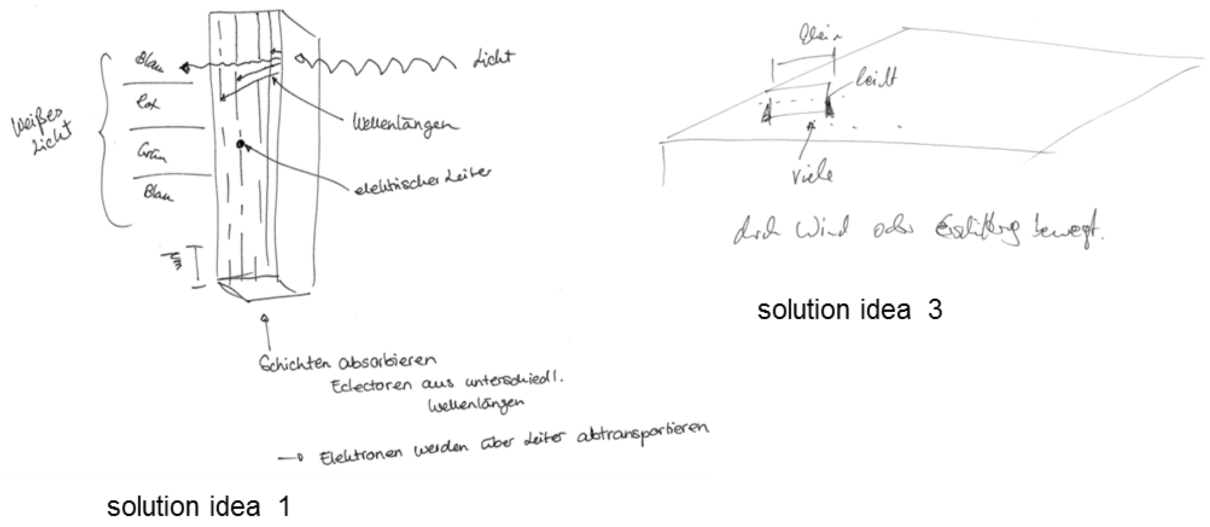


Figure 11-32: Bi-disciplinary pair 1 - solution ideas 1, 2

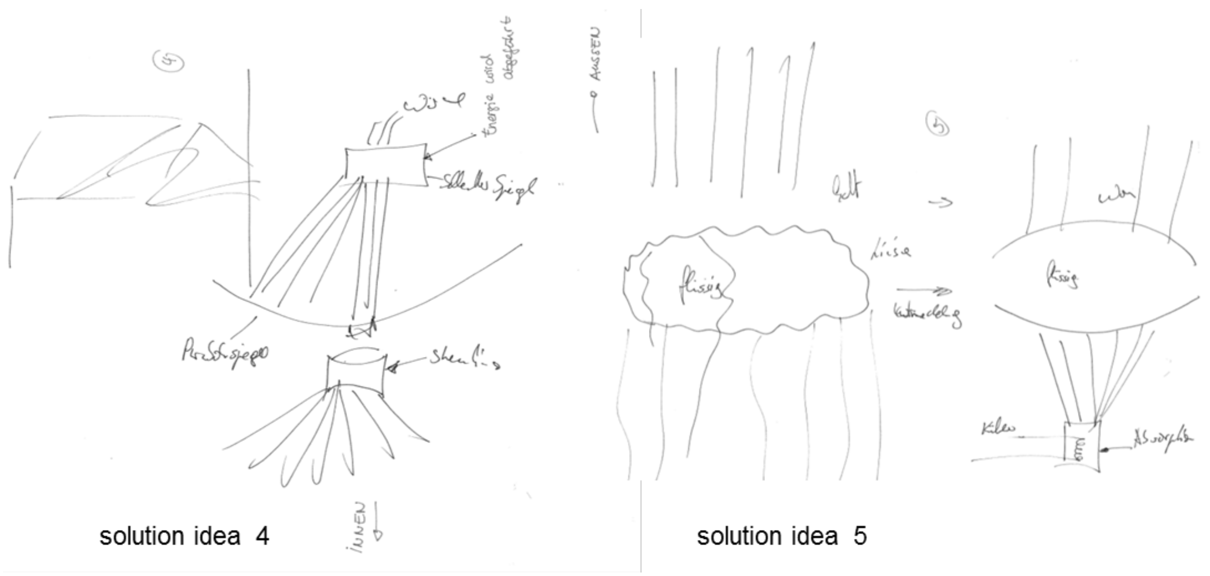
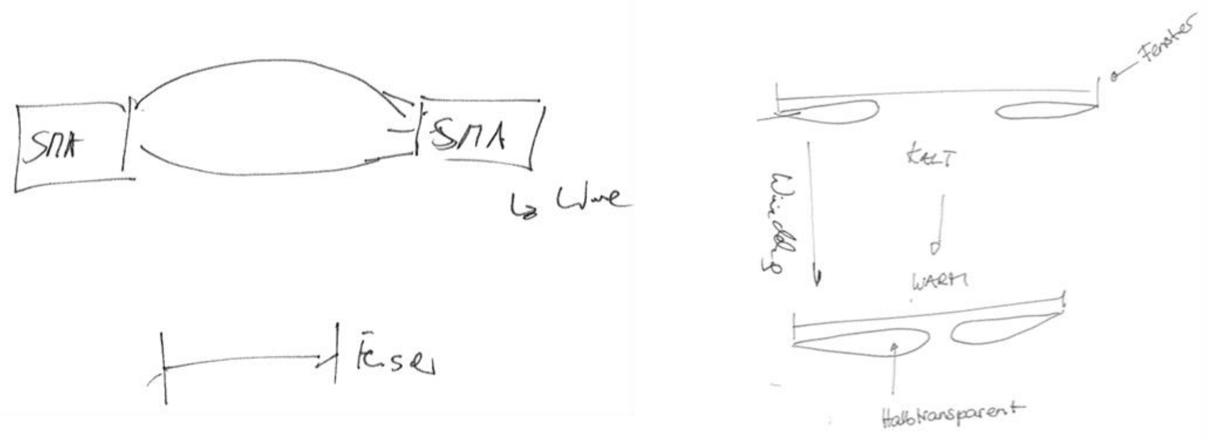


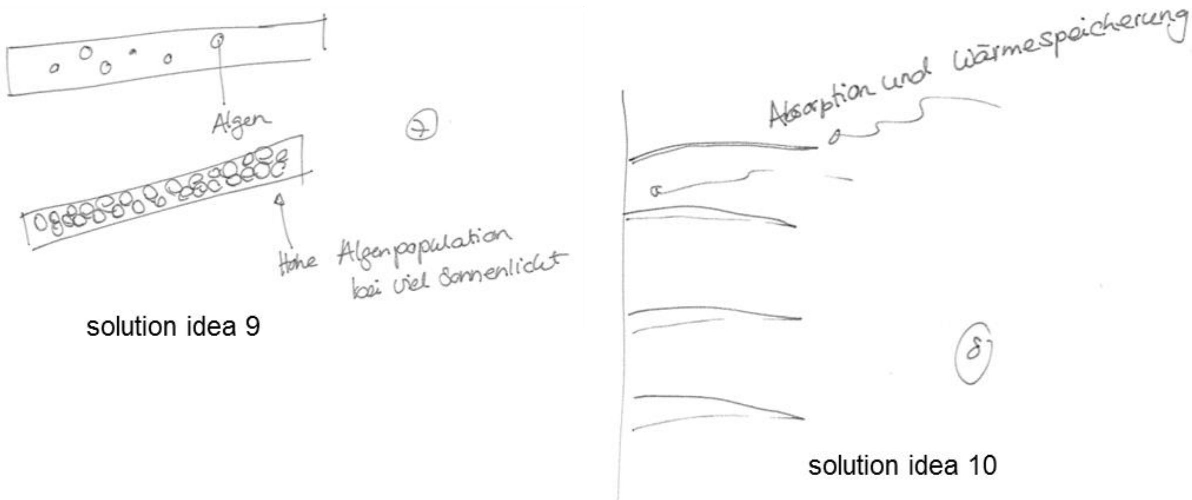
Figure 11-33: Bi-disciplinary pair 1 - solution ideas 4, 5



solution idea 6

solution idea 7

Figure 11-34: Bi-disciplinary pair 1 - solution ideas 6, 7



solution idea 9

solution idea 10

Figure 11-35: Bi-disciplinary pair 1 - solution ideas 9, 10

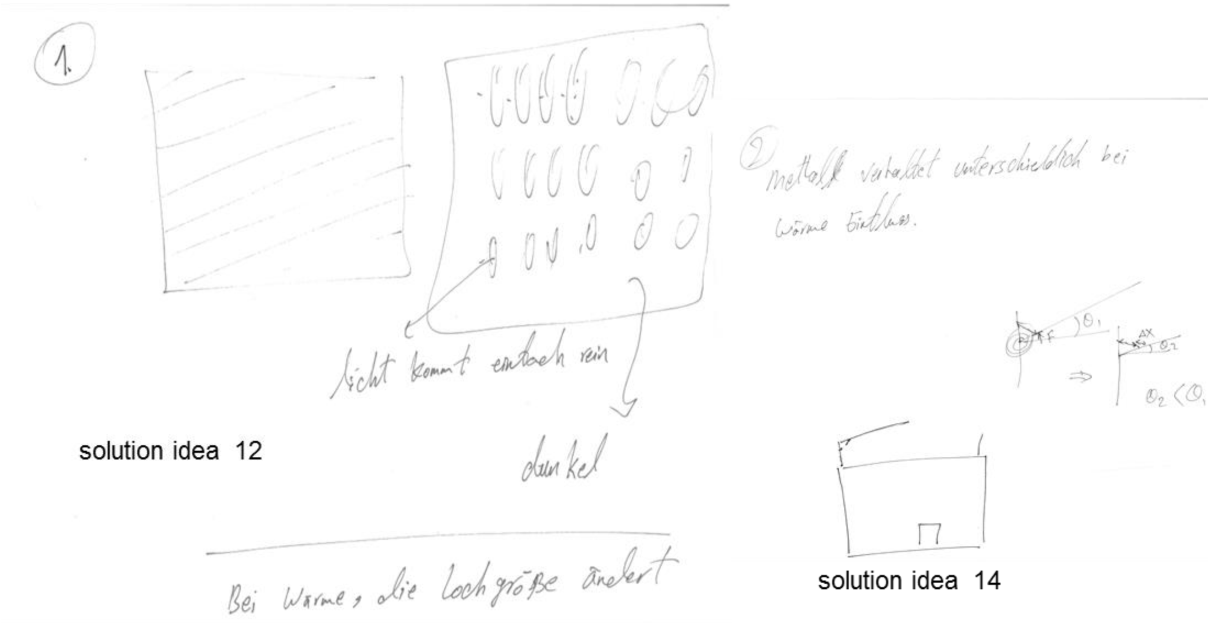


Figure 11-36: Engineer pair 3 – solution ideas 12; 14

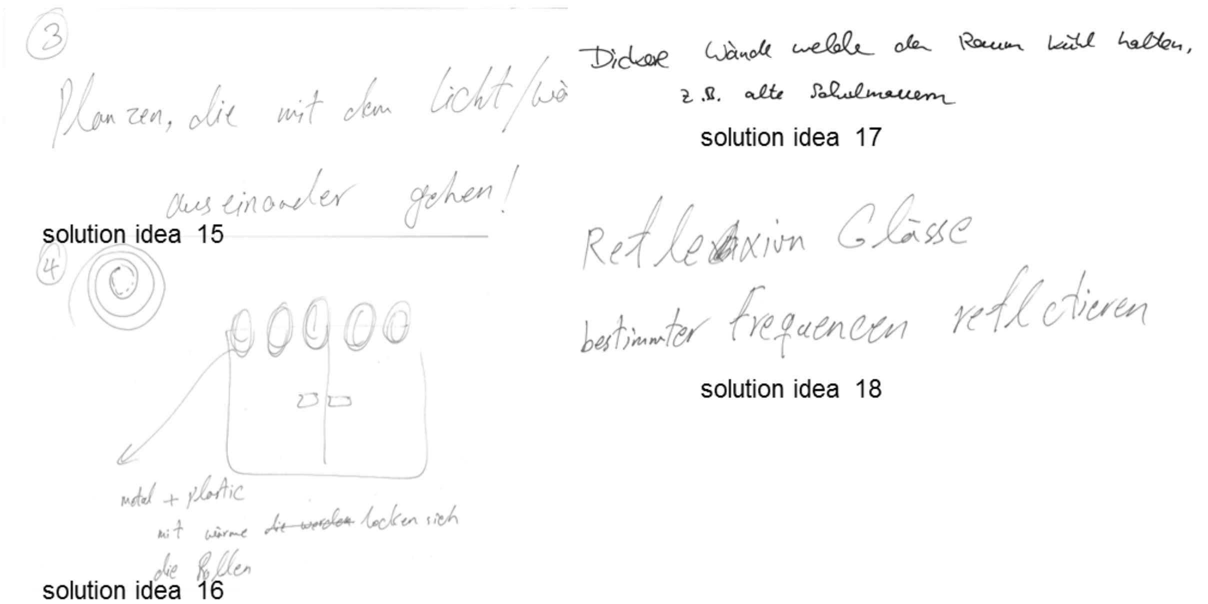
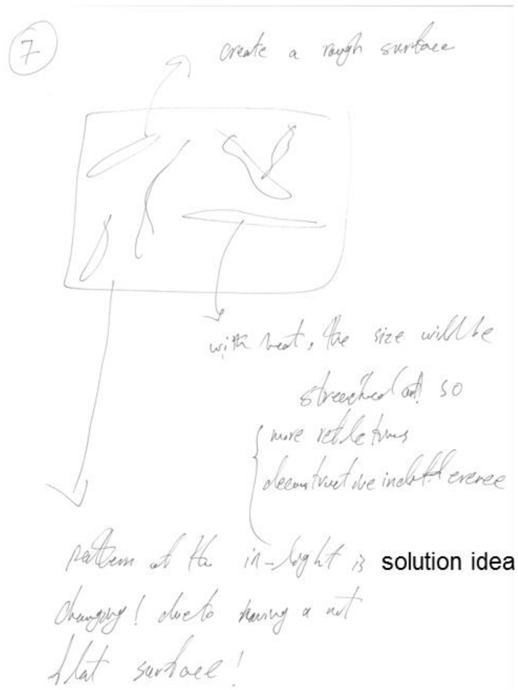
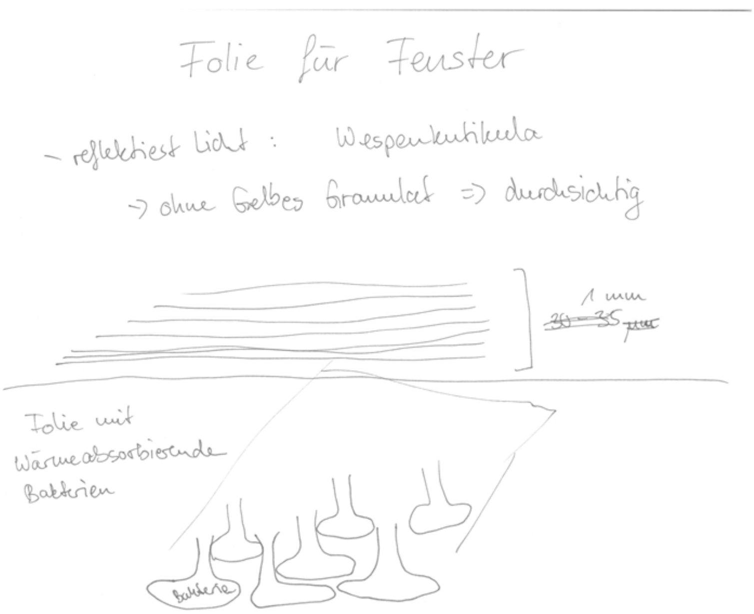


Figure 11-37: Engineer pair 3 – solution ideas 15; 16; 17; 18



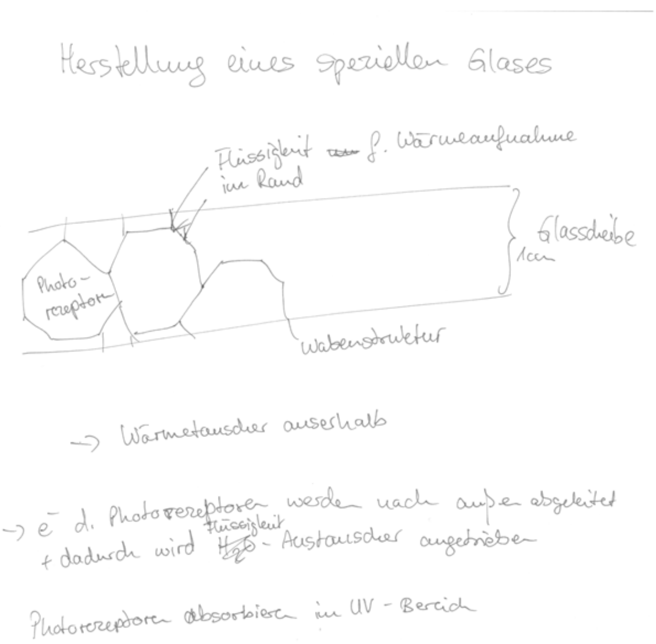
solution idea 20

Figure 11-38: Engineer pair 3 – solution idea 20



solution idea 26

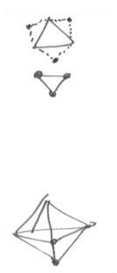
Figure 11-39: Biologist pair 3 - solution idea 26



solution idea 30

Figure 11-40: Biologist pair 3 – solution idea 30

solution idea 31 & 32



solution idea 44

Figure 11-41: Support pair 3 – solution ideas 31; 32; 42 (additional sketches)

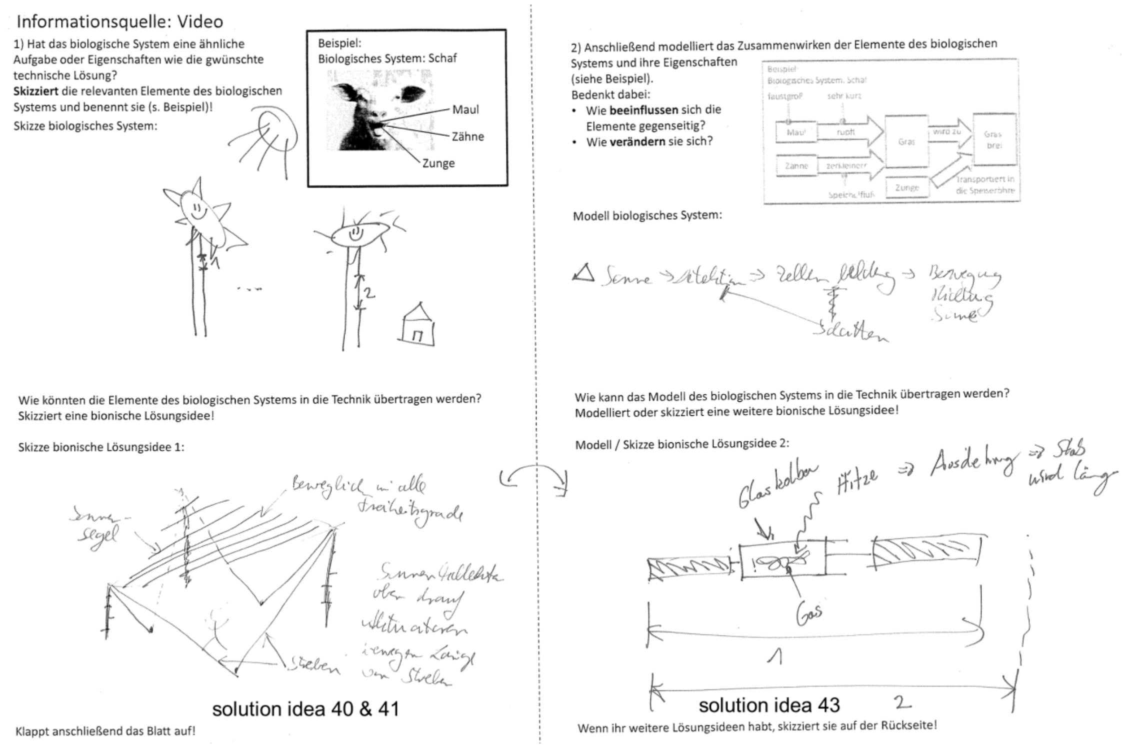


Figure 11-42: Support pair 3-solution ideas 40; 41; 43 (BioId template, biological information video)

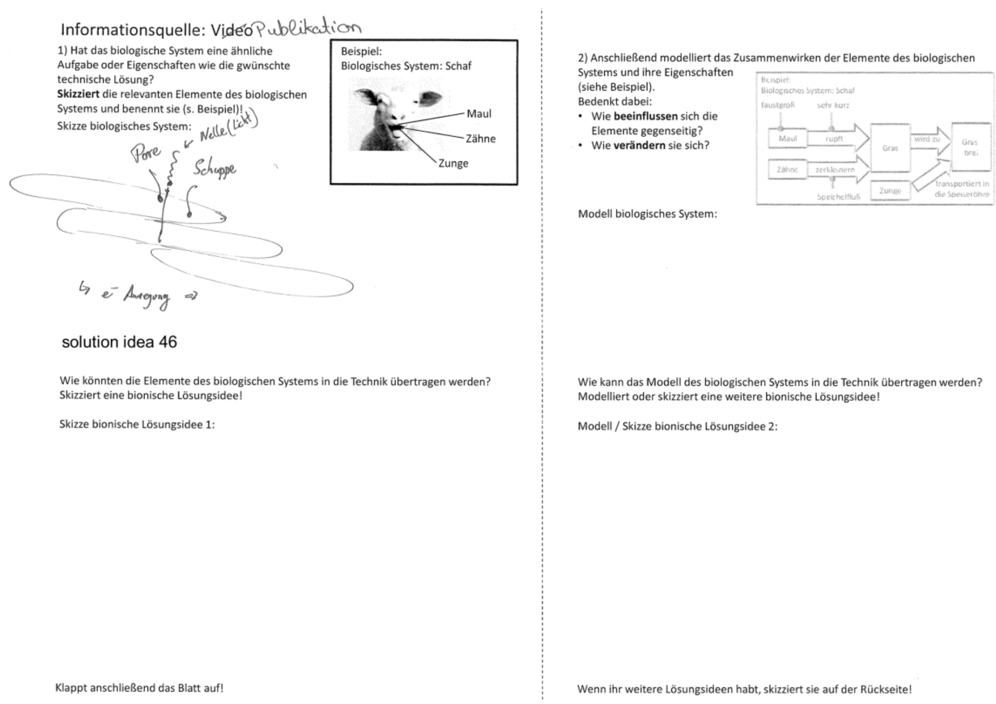


Figure 11-43: Support pair 3-solution idea 46 (BioId template, biological information publication)

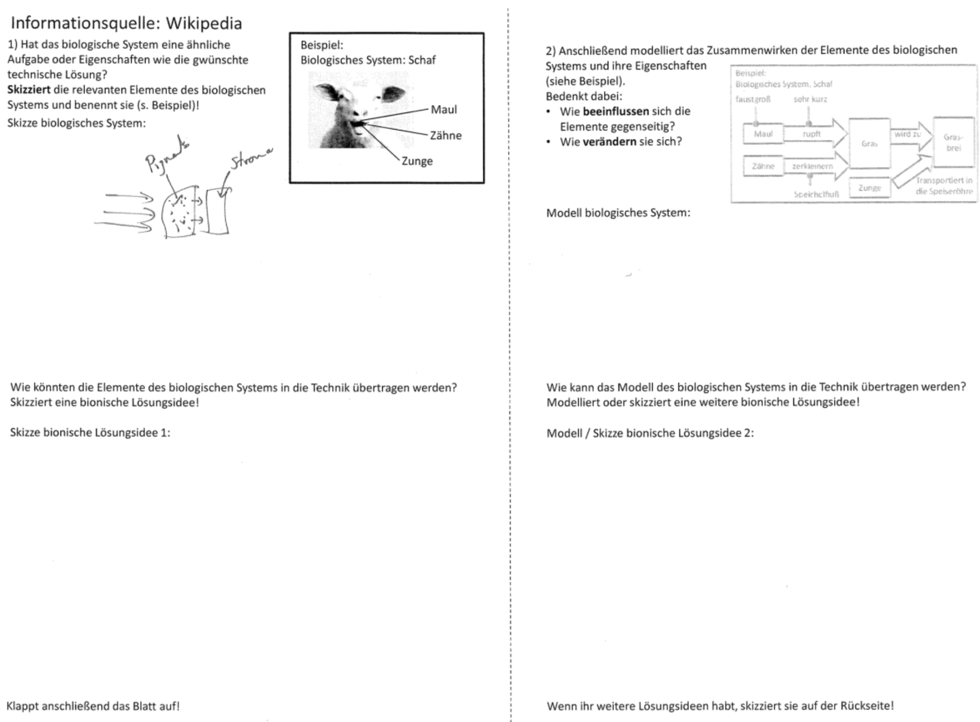


Figure 11-44: Support pair 3-no solution idea (BioId template, biological information Wikipedia)

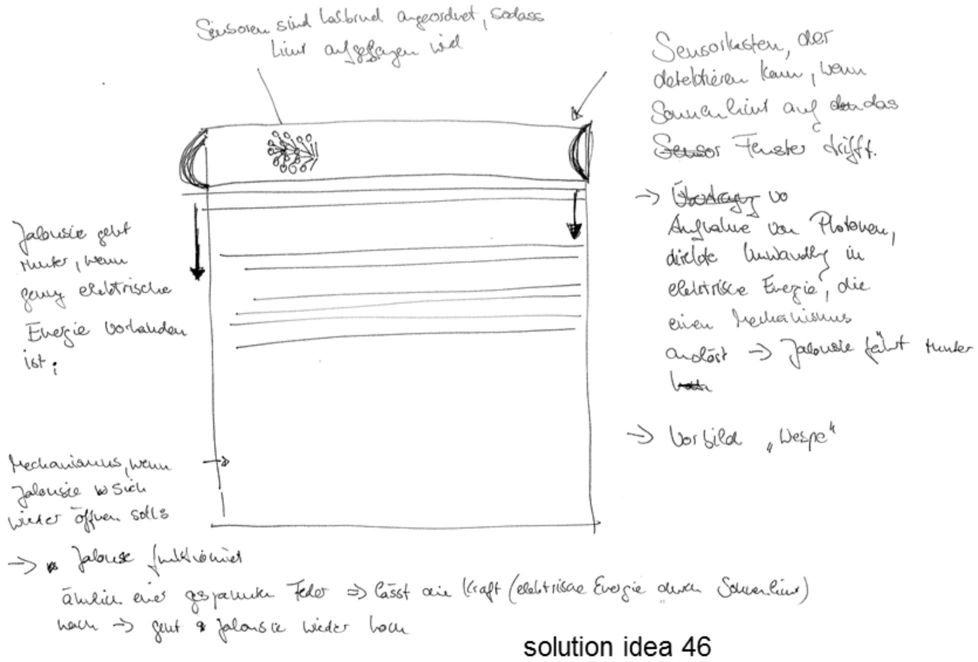


Figure 11-45: Biologist pair 6 – solution idea 46

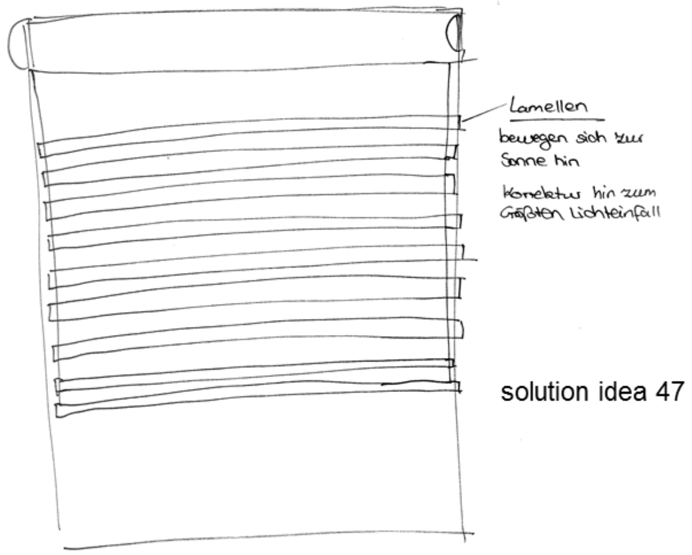


Figure 11-46: Biologist pair 6 – solution idea 47

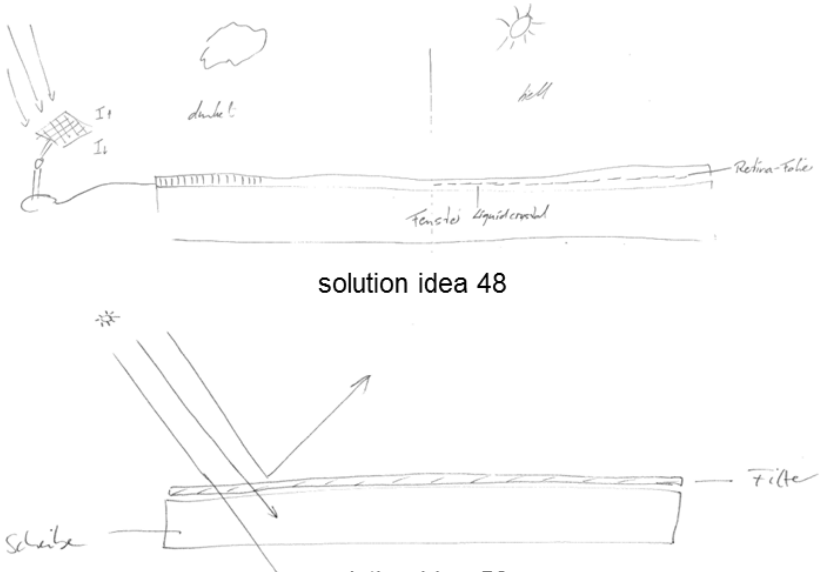


Figure 11-47: Engineer pair 6 – solution ideas 48; 53

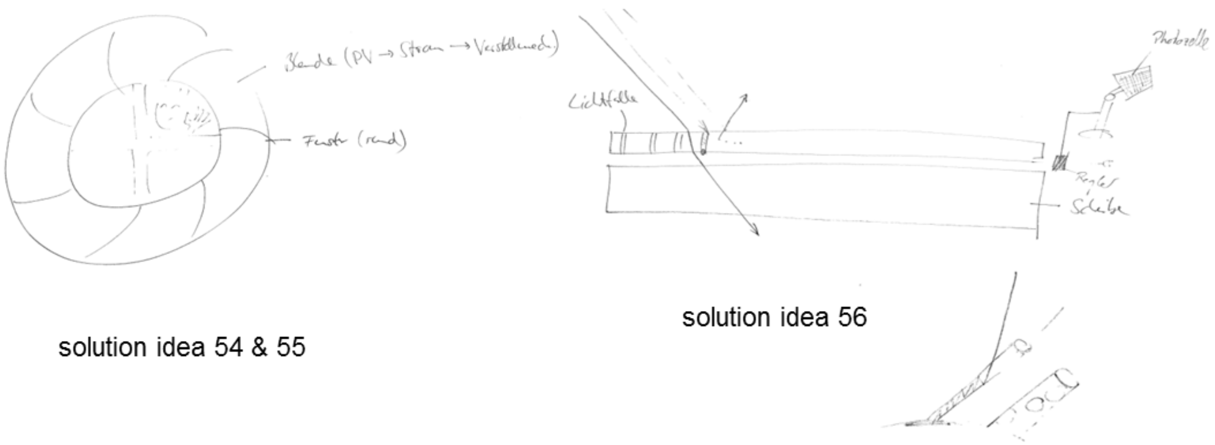


Figure 11-48: Engineer pair 6 – solution ideas 54: 55; 56

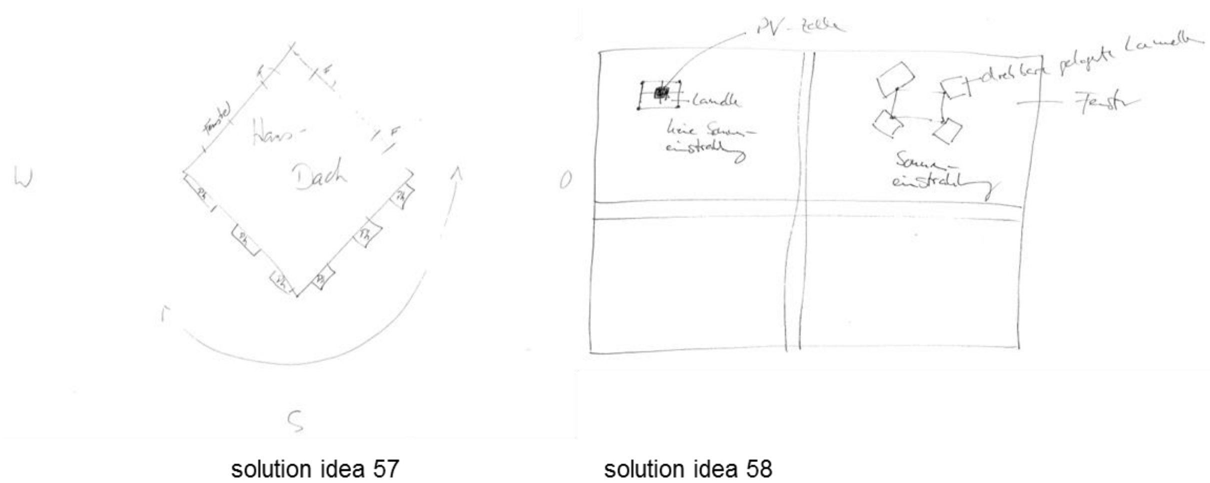
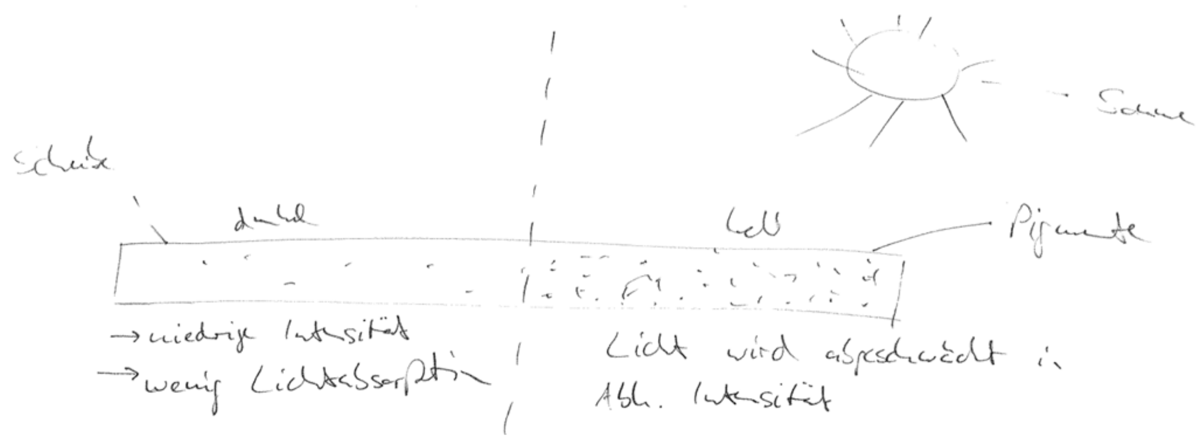
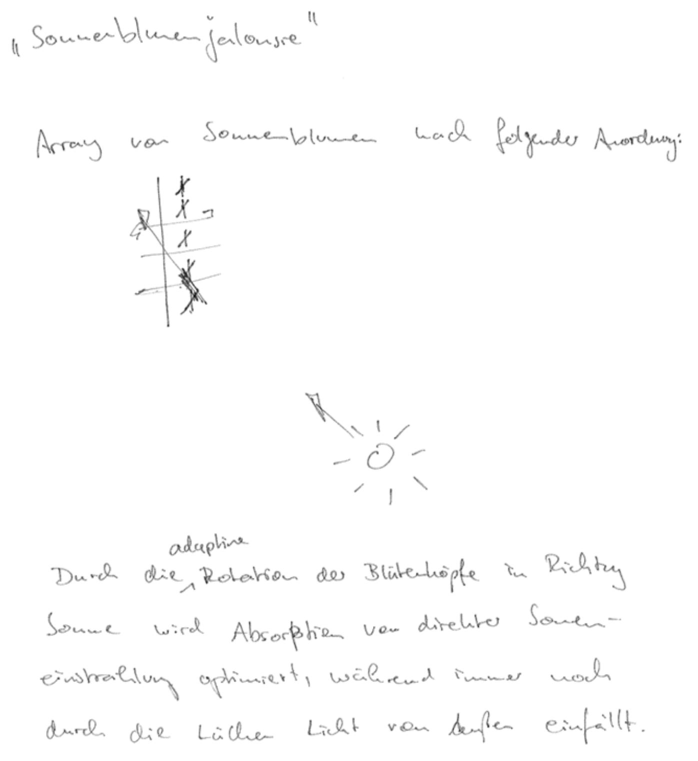


Figure 11-49: Engineer pair 6 – solution ideas 57; 58



solution idea 60

Figure 11-50: Engineer pair 6 – solution idea 60



solution idea 67

Figure 11-51: Bi-disciplinary pair 7 – solution idea 67

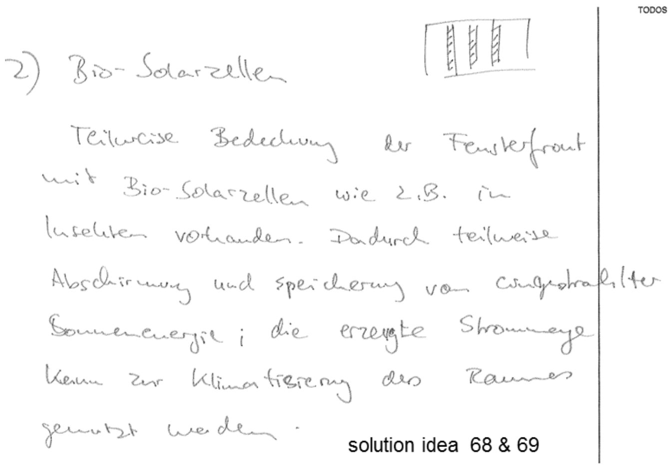


Figure 11-52: Bi-disciplinary pair 7 – solution ideas 68; 69

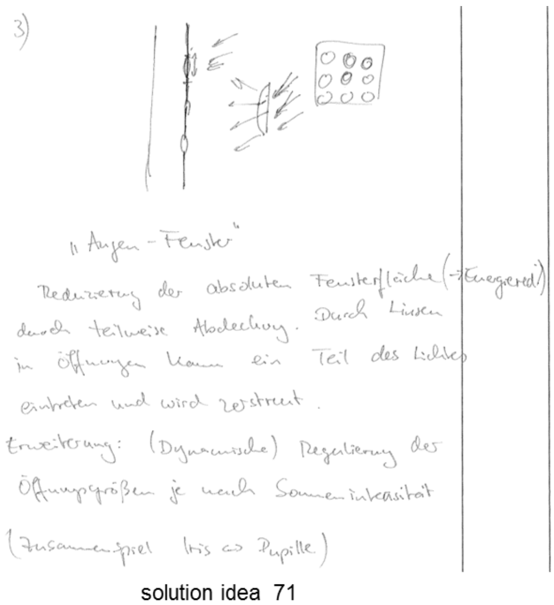


Figure 11-53: Bi-disciplinary pair 7 – solution idea 71

11.4.3 Task III: aquaplaning

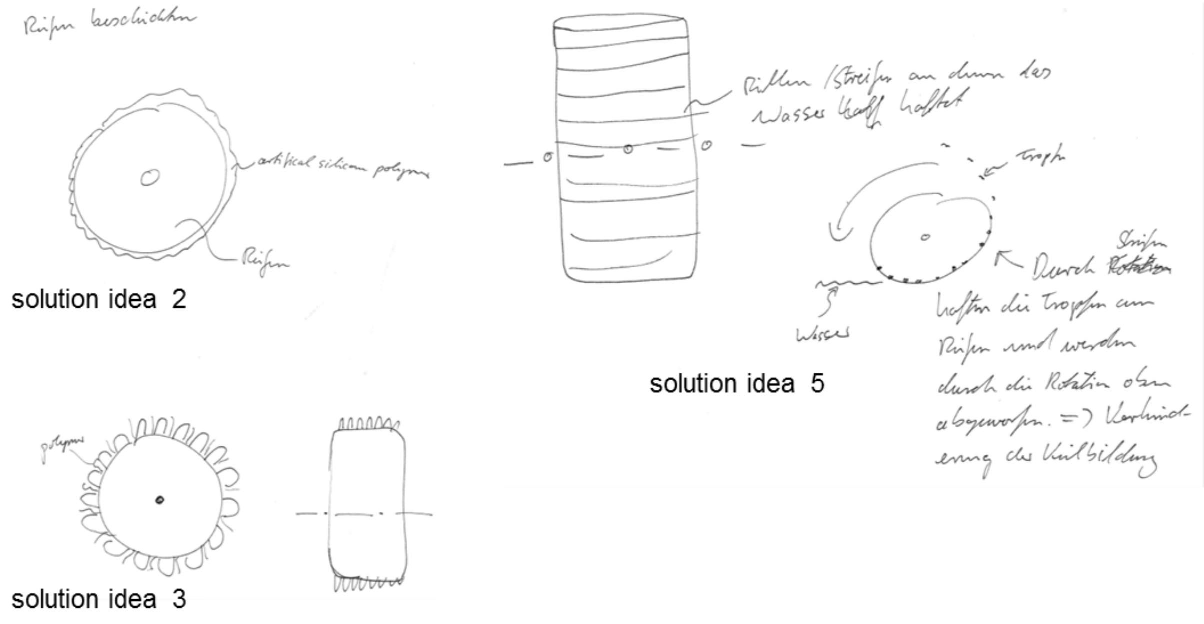


Figure 11-54: Bi-disciplinary pair 2 – solution ideas 2; 3; 5

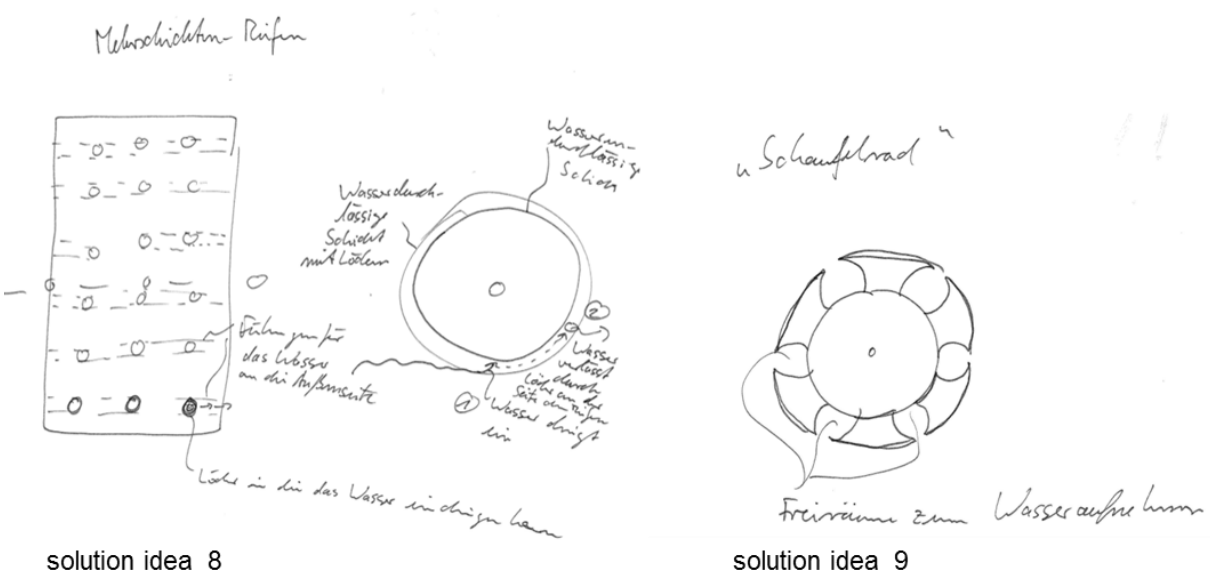


Figure 11-55: Bi-disciplinary pair 2 – solution ideas 8; 9

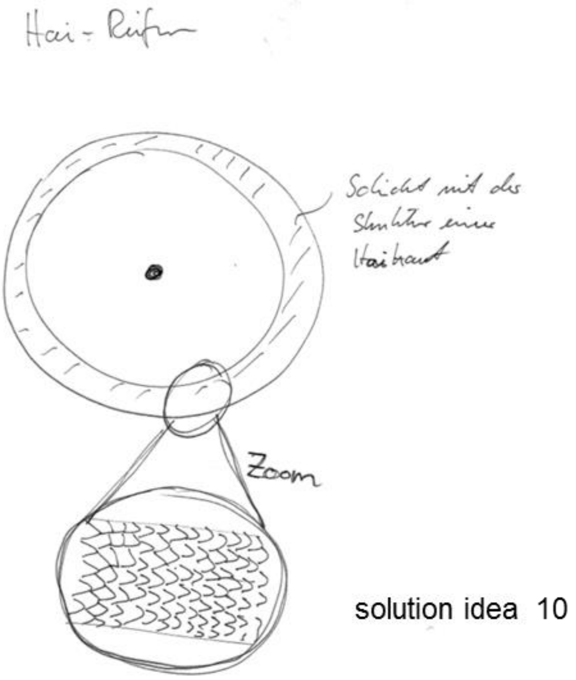


Figure 11-56: Bi-disciplinary pair 2 – solution idea 10

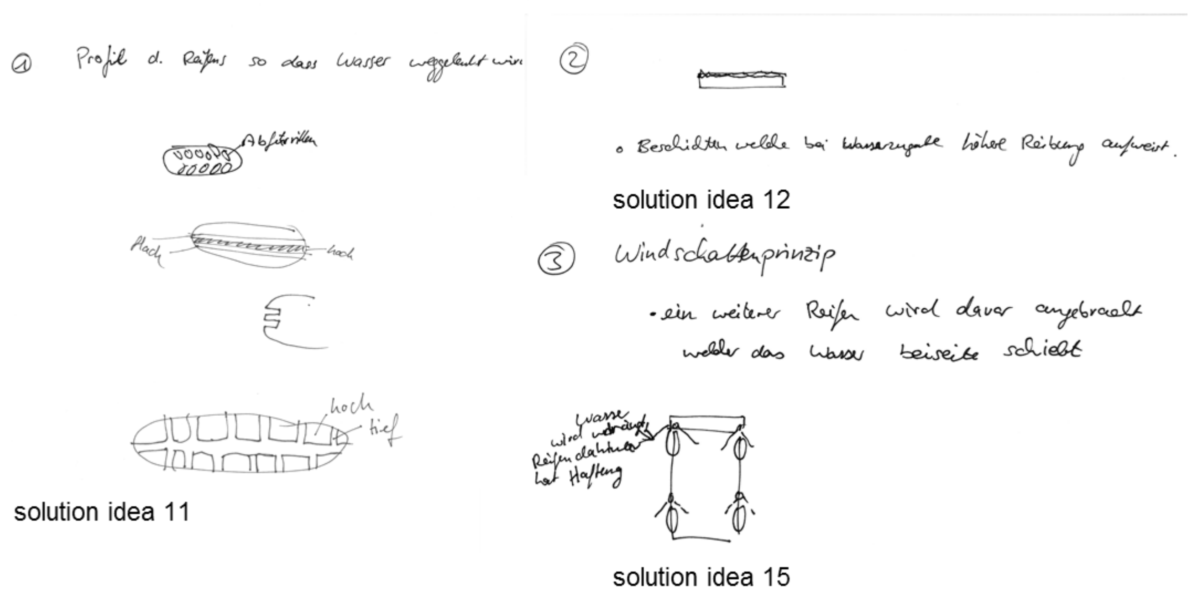


Figure 11-57: Bi-disciplinary pair 5 – solution ideas 11;12; 15

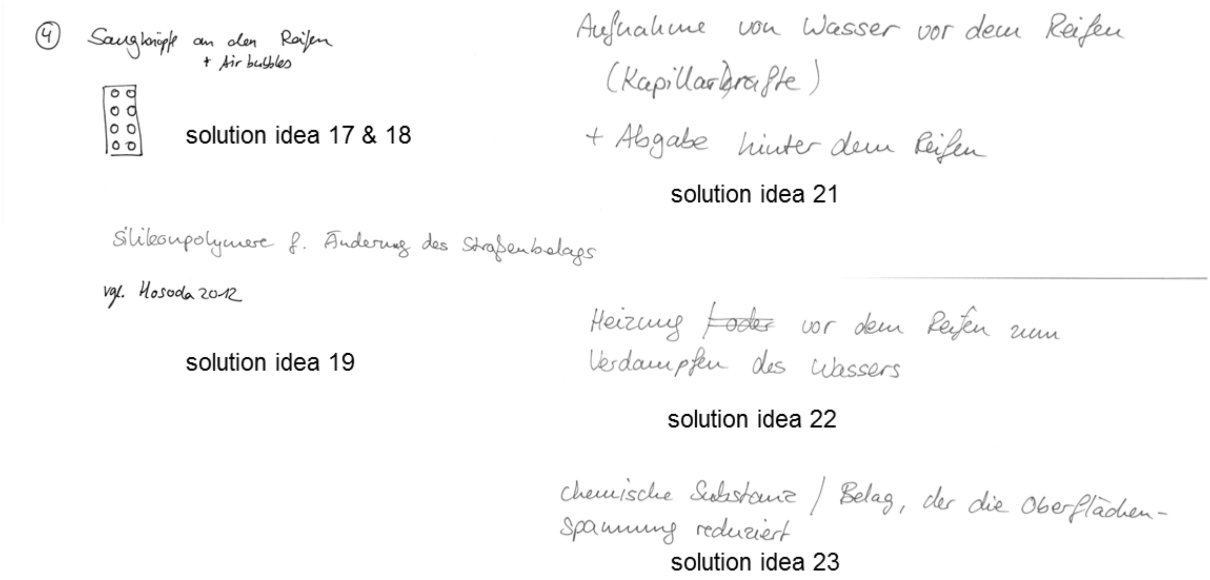


Figure 11-58: Bi-disciplinary pair 5 – solution ideas 17; 18; 19; 21, 22; 23

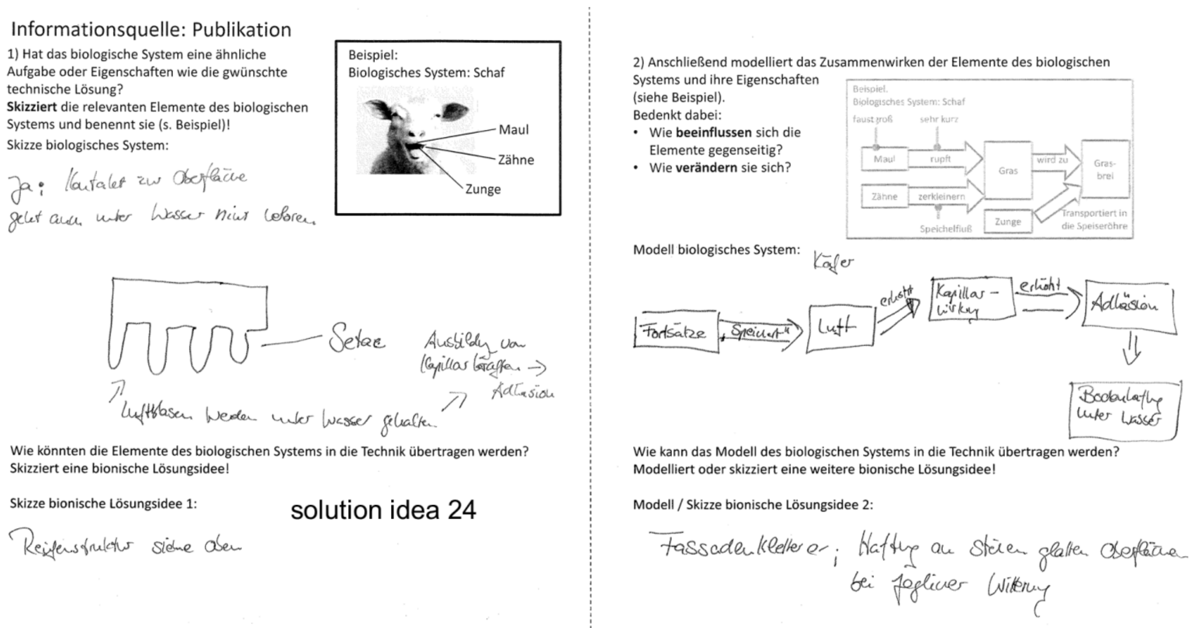


Figure 11-59: Support pair 5 - solution idea 24 (BioId template, biological information publication)

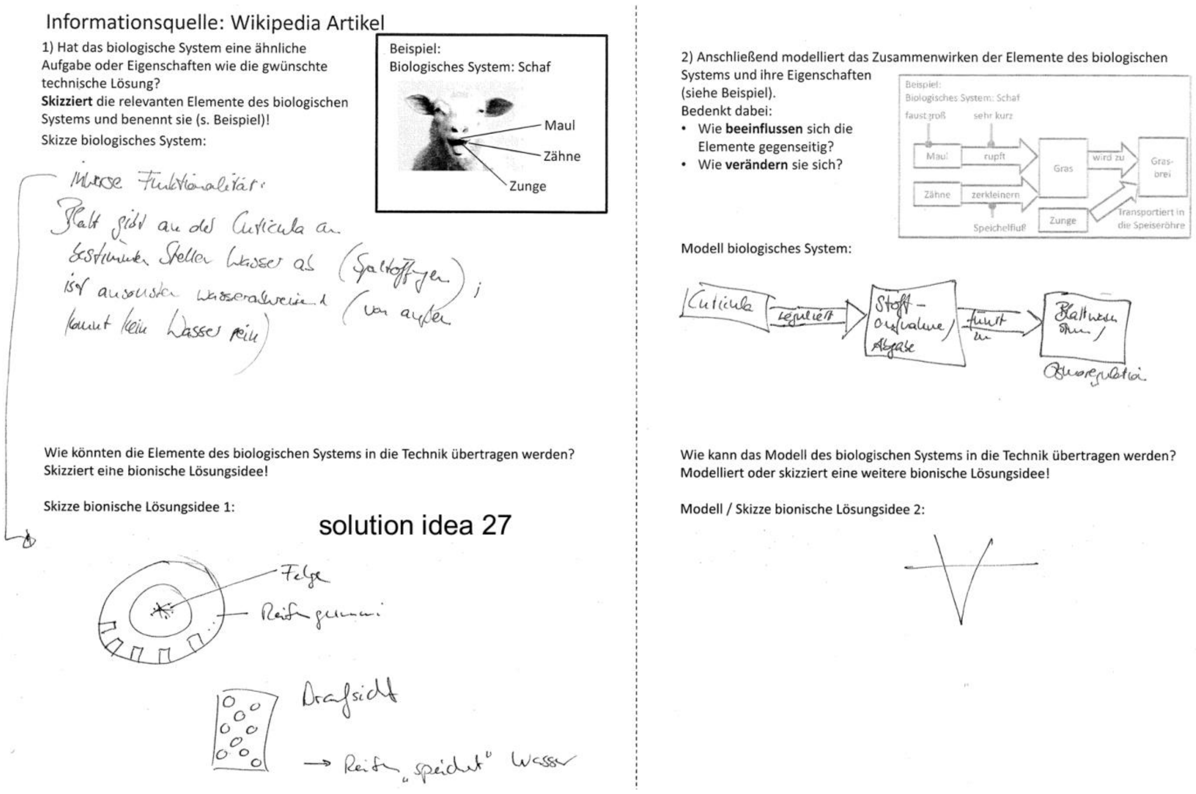


Figure 11-60: Support pair 5- solution idea 27 (BioId template, biological information Wikipedia)

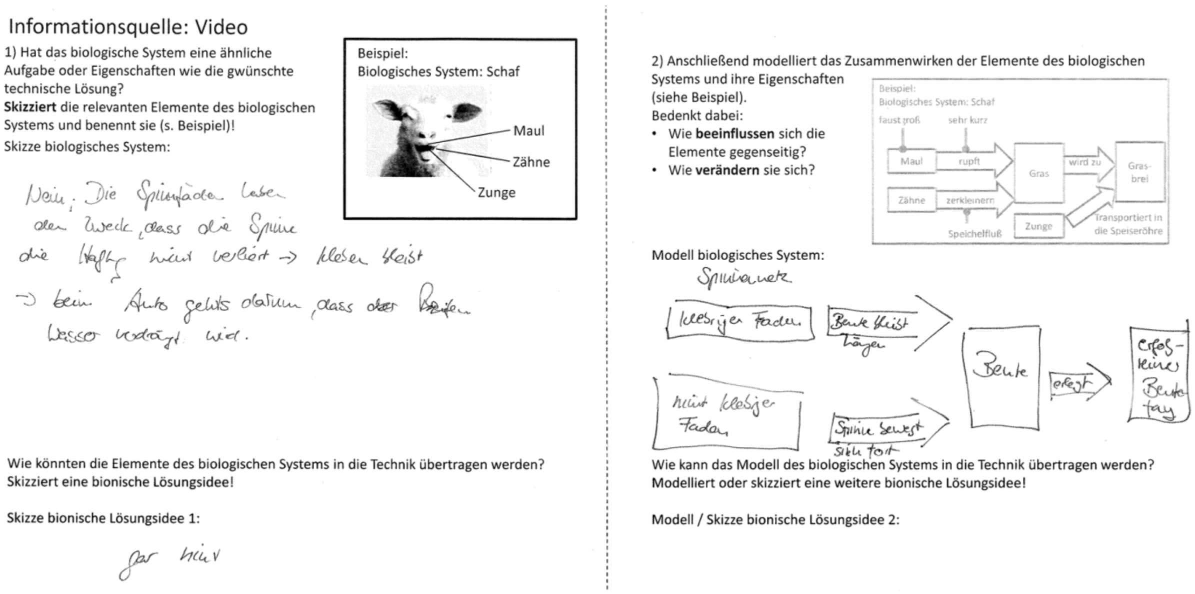


Figure 11-61: Support pair 5-no solution idea (BioId template, biological information video)

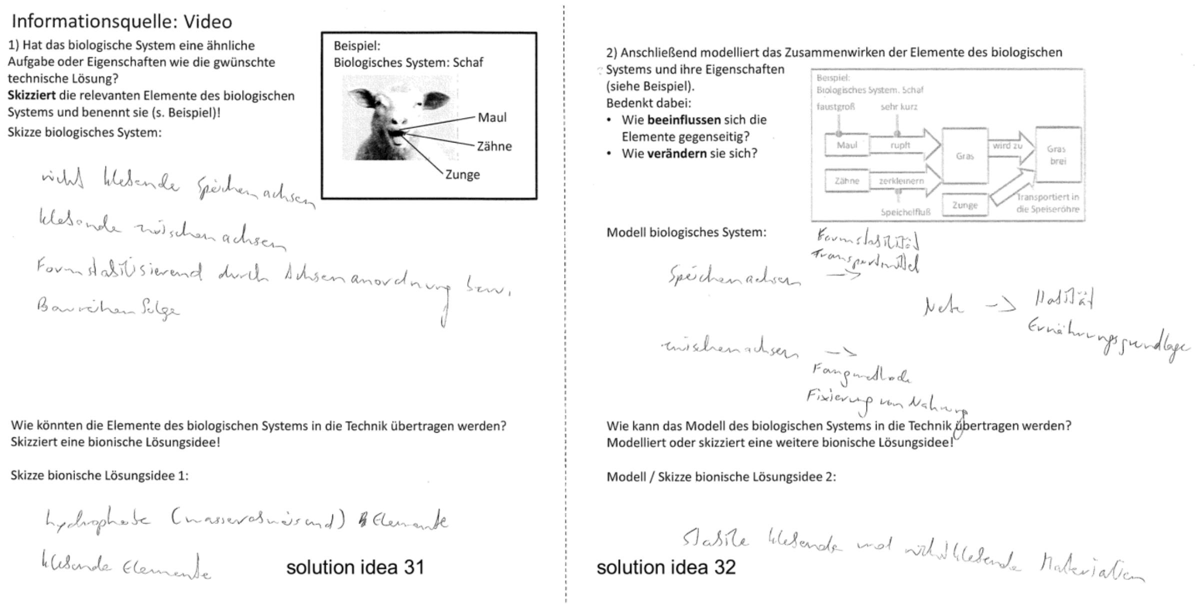


Figure 11-62: Support pair 2- solution ideas 31; 32 (BioId template, biological information video)

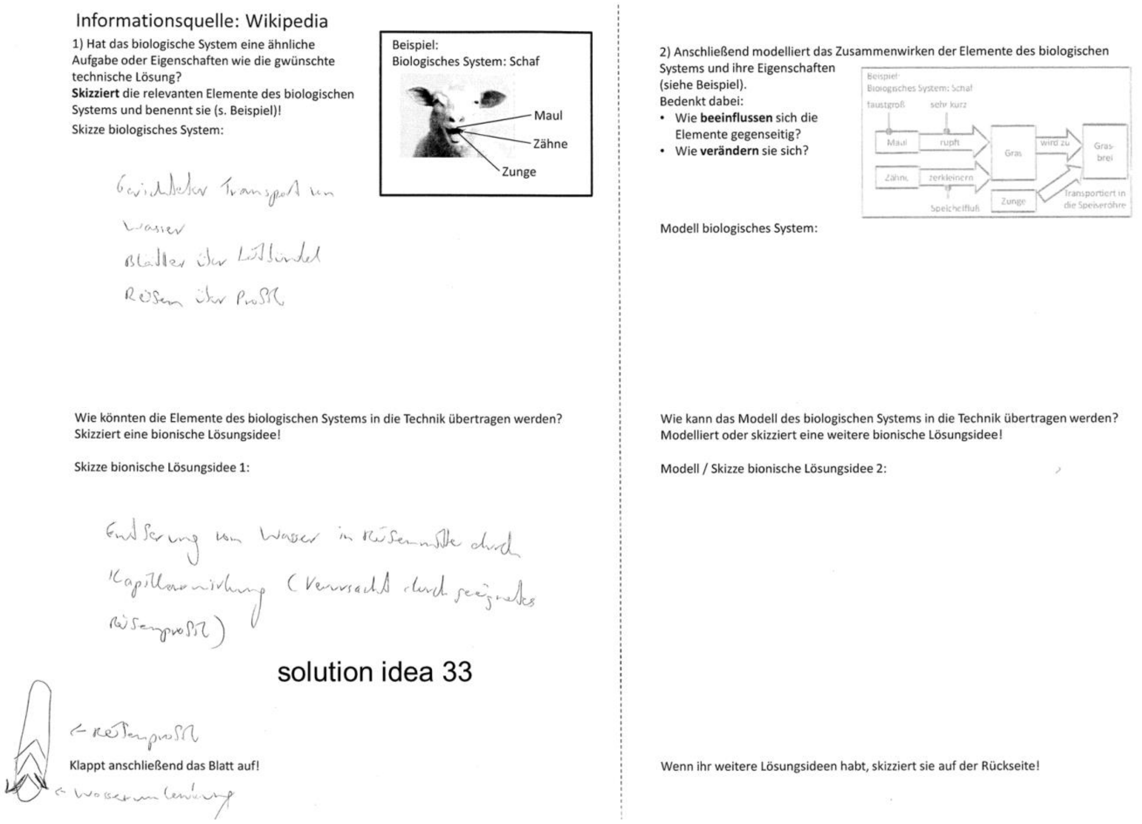


Figure 11-63: Support pair 2- solution idea 33 (BioId template, biological information Wikipedia)

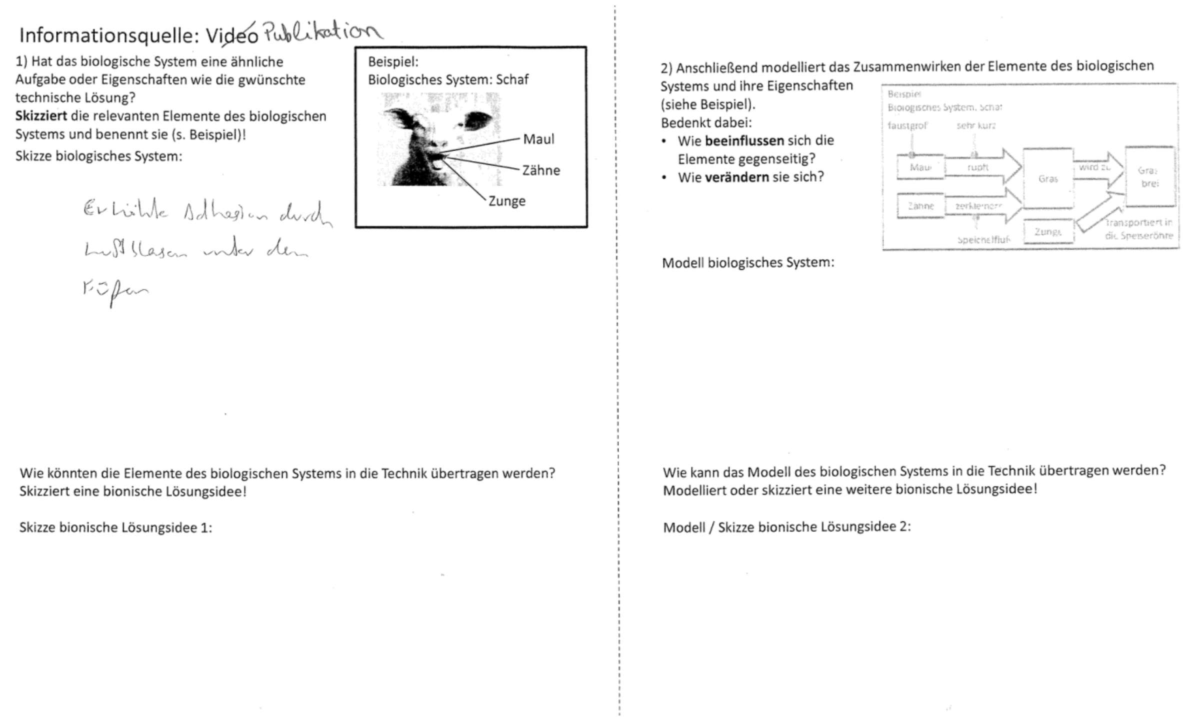


Figure 11-64: Support pair 2-no solution idea (BioId template, biological information publication)

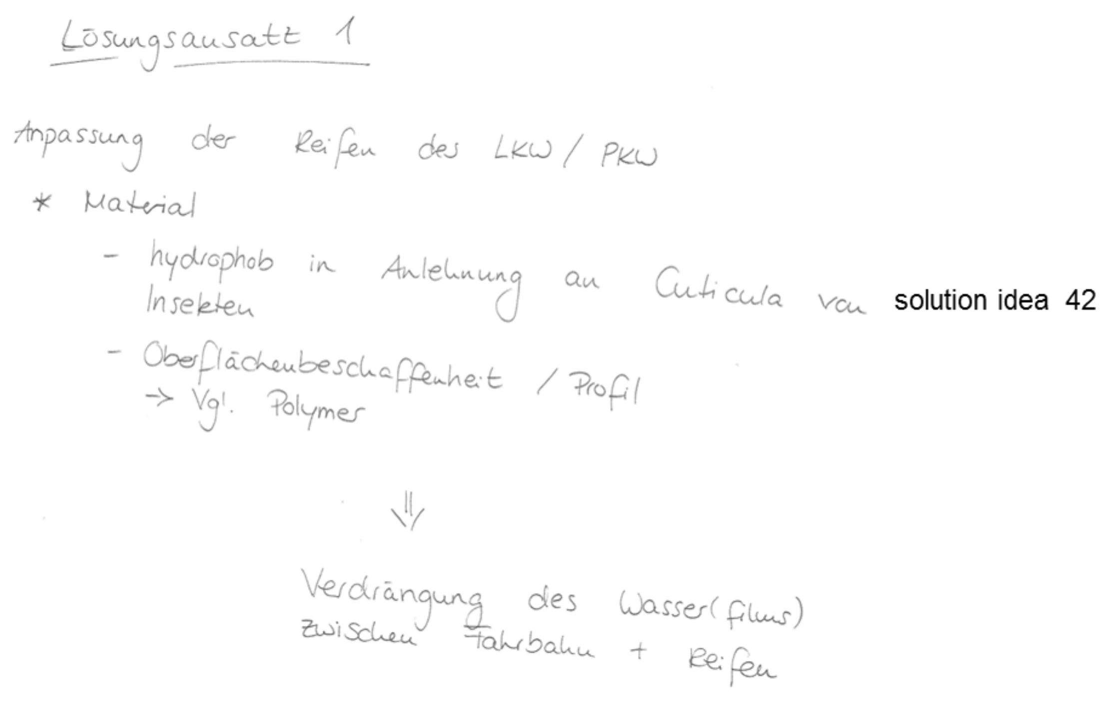


Figure 11-65: Biologist pair 4– solution idea 42

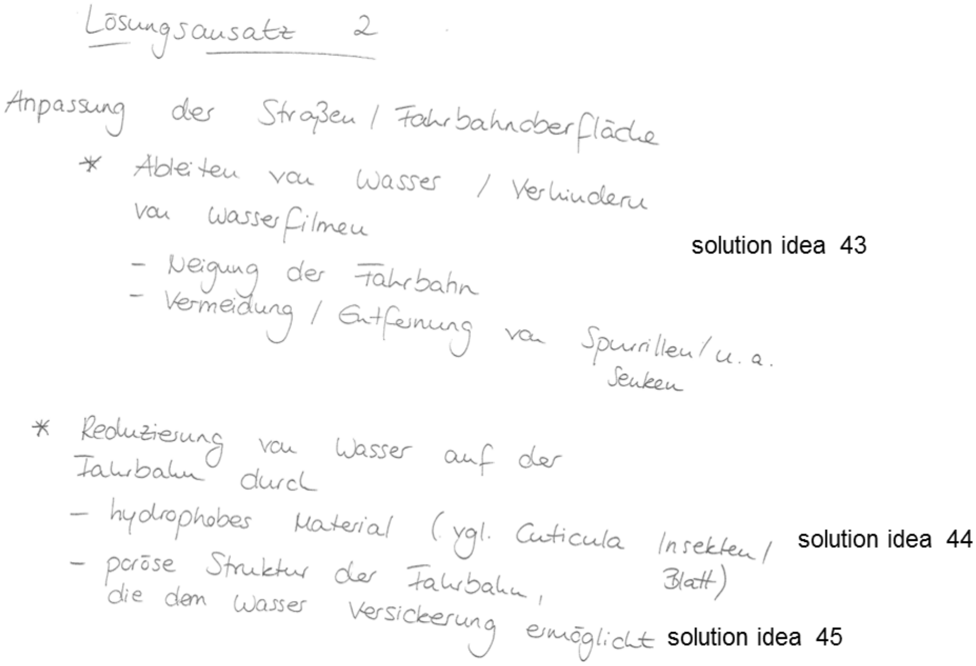


Figure 11-66: Biologist pair 4– solution ideas 43, 44, 45

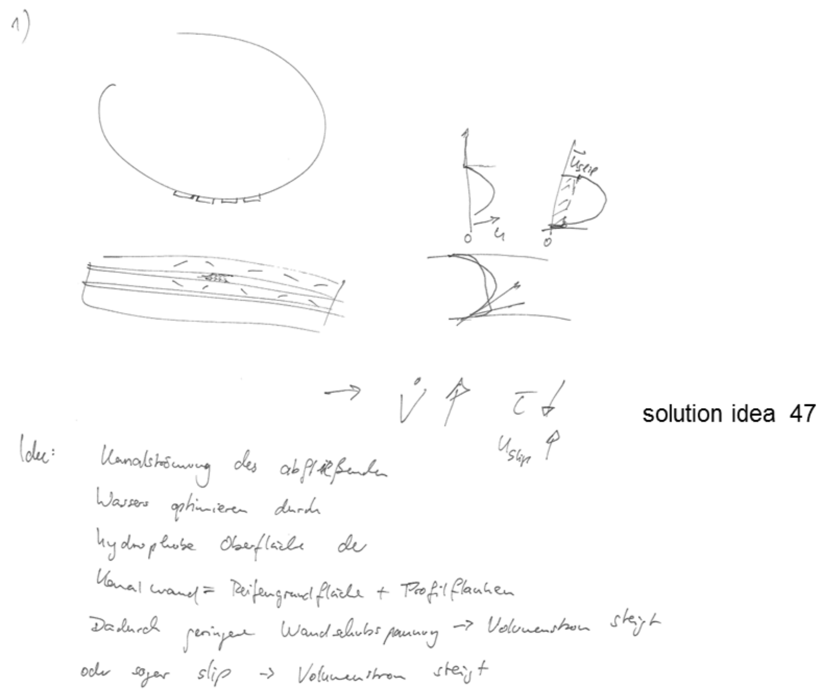


Figure 11-67: Engineer pair 4– solution idea 47

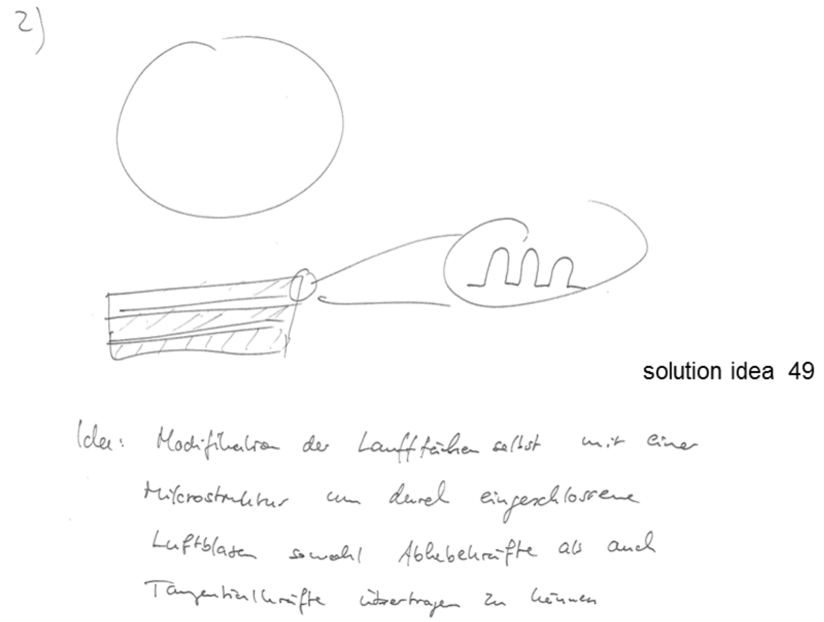


Figure 11-68: Engineer pair 4– solution idea 49

11.5 Lists of solution ideas

In this appendix all generated solution ideas are listed:

Table 11-5 (task I: water pump), Table 11-6 (task II: sun protection) and Table 11-7 (task III: aquaplaning) show the solution ideas on embodiment level as they were generated by the pairs. Moreover, the tables depict the overall task-specific quality *Q* and feasibility *F* calculated by Equation 3-1 and Equation 3-2. The tables list all working principles included by each solution idea on embodiment level by number.

The numbers of working principles indicate their position in Table 11-8 (task I: water pump), Table 11-9 (task II: sun protection) and Table 11-10 (task III: aquaplaning). These tables show the description and analysis of each solution idea on working principle, physical effect and function level. The number of working principle after the comma indicates the source (1: publication, 2: Wikipedia, 3: video, 4: other biological knowledge, 5: no bio-inspiration). In comparison to the source, the analogy types are analysed and shown in the tables. Moreover, the evaluation of feasibility f and task-specific criteria q of each working principle is depicted.

11.5.1 Solution ideas on embodiment level

Table 11-5: solution ideas on embodiment level (task I: water pump)

pair (B: biologist pair, E:engineer pair, BD: bi-disciplinary pair, no support, SBD: support pair)

source (p: publication, w:wikipedia,v:video,b:other biological knowledge;0:no bio-inspiration)

doc: documentation (yes/ no)

Q: task-specific quality *F: feasibility*

n°	pair	description	source	doc.	working principles			Q	F
1	B1	use of a clamp with the same shape as the parasite's, a rope fulfils the muscle's task	p	yes	14,1	30,1		0,56	3
2	B1	use the same configuration as the parasite's clamp has (2 gaps for attaching cable, hose), the rope is used instead of the muscle to open and close the clamp	p	yes	14,1	30,1	48,1	0,56	3
3	B1	use clamps of varying sizes for hose/ different cables, parasite's closing and opening mechanism	p	yes	14,1	30,1	47,1	0,78	3
4	B1	clamp with "fingers" adapting to the different size of cables and hose	p	yes	13,1	52,1		0,56	3

n°	pair	description	source	doc.	working principles			Q	F
5	B1	clamp with spikes distributed with different distances. Each cable can be placed into an adequately sized gap between the spikes. The hose is placed into a larger cavity next to the clamps hinges	v	yes	13,3	45,3		0,44	3
6	B1	use a cable strap with shiftable spikes	v	yes	15,3	20,3	54,3	0,56	3
7	B1	use a cable strap and put wooden sticks to adjust the cable strap and ensure it holds cables and hose tightly	v	no	15,3	20,3	54,3	0,56	3
8	B1	flexible ring with glue which does not dissolve in water but e.g. in salt water (different protein structure)	w	yes	3,2	25,2	55,2	0,94	1
9	B1	use of adhesive tape	w	no	3,2	18,2	55,2	0,83	3
10	B1	use of glue	w	no	4,2	18,2	50,2	0,83	3
11	B1	wrapping an adhesive ribbon around cables, hose and rope (several times)	w	yes	3,2	18,2	56,2	0,83	3
12	B1	use of a disk with several elastic ribbons which have a suction cup at the end. The suction cup is attached to each cable and the hose	b	yes	5,4	42,4	47,4	0,89	3
13	E1	anything which automatically shrinks	p	yes	21,1			0,17	1
14	E1	a ribbon with filling material that adapts to the size of the different cables and hose and is closed with a Velcro© fastener	0	yes	15,5	36,5	58,5	0,89	1
15	E1	a device consisting of elastic and stiff elements adapting to the different cable and hose sizes	0	yes	6,5	53,5		0,67	3
16	E1	a sleeve which automatically	p	yes	15,1	21,1	57,1	0,72	1

n°	pair	description	source	doc.	working principles			Q	F
		shrinks to adapt to the cable, hose etc.							
17	E1	the pump is set on a plate which is lowered by several ropes -> the cables do not have to be fixed	0	yes	63,5			0,33	2
18	E1	heat shrink tube with small barbed hooks	v	yes	15,3	22,3	59,3	0,44	3
19	E1	braiding the cables around the rope (?)	0	yes	12,5	38,5	62,5	0,89	3
20	E1	fixing the cables on one rope, the hose on another rope	0	yes	49,5			0,00	2
21	E1	cables (hose and rope) are kept in a hull, moisture expanding material presses them against the hull. The moisture is sucked from the water hole	0	yes	15,5	28,5	58,5	0,83	1
22	BD6	wind the cable around the hose in analogy to a snake's movement	b	yes	12,4	38,4	62,4	0,89	3
23	BD6	using a clip with hooked "teeth" for fixing a hose to a bucket ("existing" solution)	v	yes	13,3	59,3		0,33	3
24	BD6	use coating to prevent slipping	0	no	16,5			0,11	3
25	BD6	use byssus material as coating to prevent slipping	w	yes	2,2	17,2	51,2	0,83	0
26	BD6	hull cables in a coated device	0	no	16,5	15,5		0,22	3
27	BD6	braid cables in analogy to hair	0	yes	12,5	38,5	62,5	0,89	3
28	BD6	use a plastic casing with holes for cables which is clamped to the hose and fixed with a screw	0	yes	15,5	40,5	44,5	0,67	3
29	SBD1	clamp with barbed hooks	v	no	13,3	59,3		0,33	3
30	SBD1	praying mantis' clamp clasps around hose and cables	v	yes	13,3	59,3		0,33	3
31	SBD1	the clamp is actuated via a spring and a lock is provided	v	yes	13,3	59,3	34,3	0,67	3

n°	pair	description	source	doc.	working principles			Q	F
32	SBD1	byssus threads are wound around cable and hose	w	yes	1,2	17,2	51,2	0,83	3
33	SBD1	add a separating/ cutting element	w	yes	1,2	17,2	43,2	0,83	0
34	SBD1	clamp: has to be opened by force, stays tight "passively"	p	yes	13,1	29,1		0,56	3
35	SBD1	use of a spring to keep clamp closed	p	yes	13,1	34,1		0,56	3
36	B5	cables and hose have spikes that fit together like a zip fastener	v	yes	8,3	35,3	60,3	1,00	2
37	B5	cables and hose are joined by Velcro	v	no	9,3	36,3	61,3	1,00	3
38	B5	replace cable straps by Velcro fasteners	v	yes	15,3	36,3		0,56	3
39	B5	a snapping mechanism which is closed in the "low-energy" state - energy has to be used to re-open it	p	no	29,1	0		0,33	3
40	B5	a copy of the parasite's clamp (material: rubber)	p	no	14,1	31,1		0,56	3
41	B5	two rubber bands - one can be hooked to the other	p	yes	7,1	37,1		0,61	3
42	B5	disperse a material on cable, hose and rope that hardens	w	no	10,2	23,2	58,2	0,83	1
43	B5	pour the hardening material over cables, hose and rope	w	no	10,2	23,2	58,2	0,83	1
44	B5	disperse a material on cable, hose and rope that becomes a polymer, to demount it, the polymer can be cut off the cables/hose and rope	w	no	10,2	24,2	43,2	0,83	1
45	B5	use of open plastic rings to fix cables with different diameters separately	0	no	15,5	32,5	47,5	0,56	3
46	B5	use of a device in analogy to a "snapping" wristlet: bi-stable metal strip	0	yes	15,5	33,5		0,44	3

n°	pair	description	source	doc.	working principles			Q	F
47	B5	use of several ropes closed with knots	w	yes	15,2	39,2	56,2	0,89	3
48	B5	use of wax as a glue(it melts outside of the well due to high temperature)	w	yes	10,2	41,2	58,2	0,94	1
49	B5	hose segments encapsulate cables/ hose and rope	0	no	15,5			0,22	3
50	B5	adhesive wrapping material	w	yes	15,2	18,2	3,2	0,83	3
51	E5	use of clamp in analogy to praying mantis' leg, with rubber elements instead of spikes	v	no	13,3	46,3		0,44	3
52	E5	cable channel	0	no	15,5			0,22	3
53	E5	clamp in analogy to praying mantis' leg with rubber elements instead of spikes to hold the cables (hook to close it) - Velcro fixes the clamp on the "water tube"	v	yes	13,3	36,3	46,3	0,94	3
54	E5	gluing the cables	w	no	4,2	18,2	50,2	0,83	3
55	E5	separate fixture devices for every cable which are fixed to the "water tube" (e.g. by screws), fixture devices can be adapted to the cables diameter	0	yes	15,5	40,5	47,5	0,67	3
56	E5	the cables are threaded into a tube; the tube is fixed to the "water tube" with a clip	0	yes	15,5	32,5		0,33	3
57	E5	replace clip by device consisting of two elements linked by springs	p	yes	13,1	34,1		0,56	3
58	E5	tighten solution n°57 by screws	0	yes	40,5	13,1		0,44	3
59	E5	use of a cable tube which can be opened	0	no	15,5			0,22	3
60	E5	no cable tube, instead one clip per cable (adequate diameter)	0	no	47,5	32,5	15,5	0,56	3
61	E5	no cable tube, instead clip with one opening per cable (adequate	0	no	44,5	32,5	15,5	0,56	3

n°	pair	description	source	doc.	working principles			Q	F
		diameter)							
62	SBD4	fix the pump with nails	v	no	11,3	19,3		0,11	3
63	SBD4	use hooks to fix cables	v	no	37,3			0,28	3
64	SBD4	cables/hose/ rope with a rough surface to better adhere	v	no	16,3			0,11	3
65	SBD4	cable strap with hooks /rough surface	v	no	15,3	20,3	59,3	0,33	3
66	SBD4	wrap hose around tube (notices that there is no tube)	0	no	12,5	38,5	62,5	0,89	3
67	SBD4	hook cables/ hose … to each other	0	no	37,5	47,5		0,50	3
68	SBD4	fix cables/ hose… with Velcro	0	no	9,5	36,5		0,67	3
69	SBD4	use a gel cushion that soaks water and closes a clamp when full	p	yes	13,1	28,1		0,50	1
70	SBD4	glue	w	no	4,2	18,2	50,2	0,83	3
71	SBD4	adhesive fibres hold cable and hose, decompose in air	w	no	3,2	27,2	50,2	0,83	1
72	SBD4	coating on the hose> adhesive when wet	w	yes	4,2	26,2	50,2	0,94	1
73	SBD4	clamp with hooks	v	yes	13,3	59,3		0,33	3

Table 11-6: solution ideas on embodiment level (task II: sun protection)

pair (B: biologist pair, E:engineer pair, BD: bi-disciplinary pair, no support, SBD: support pair)

source (p: publication, w:wikipedia,v:video,b:other biological knowledge;0:no bio-inspiration)

doc: documentation (yes/ no)

Q: task-specific quality *F: feasibility*

n°	pair	description	source	doc.	working principles			Q	F
1	BD1	different layers of glass absorb light with specific wave length, their energy is transformed to electric energy and transported "away" via electric conductors	p	yes	34,1	38,1		0,92	3
2	BD1	shading device which moves	v	no	27,3	20,3		0,58	3

n°	pair	description	source	doc.	working principles			Q	F
		with the sun							
3	BD1	small plates turned by the wind/ the vibrations of the building	v	yes	27,3			0,42	3
4	BD1	use of a parabolic mirror (publication: "along the stripes […] are arranged smooth distensions resembling a miniature parabolic mirror") and a dispersing lens. A portion of the light's energy is discharged in a "bad mirror" placed before the parabolic mirror.	p	yes	22,1	23,1	31,1	0,92	3
5	BD1	use of a lens filled with liquid. When the temperature is high, the liquid expands and fills the lens. The lens than bundles the light in a cooler which absorbs the energy	w	yes	8,2	11,2	23,2	0,83	2
6	BD1	shape memory alloy elements compress and stretch a lens which bundles the light. The shape memory alloy's deformation depend on the temperature	w	yes	23,2	6,2		0,83	3
7	BD1	semi-transparent elements in front of the windows open and close depending on the temperature. The amount of direct sunlight entering the window is reduced.	w	yes	27,2	17,2		0,42	3
8	BD1	the plates are in a liquid and move when temperature rises	v	no	27,3	5,5		0,58	2
9	BD1	algae in the windows grow when there is much direct sunlight and provide shading	b	yes	28,4	3,4		0,75	3
10	BD1	use of many small peripheral photoreceptors which absorb the light and store heat	p	yes	42,1			0,17	1

n°	pair	description	source	doc.	working principles			Q	F
11	E3	solution that folds like a flower	b	no	21,4			0,17	3
12	E3	intransparent device in front of the window with holes that allow the light to enter. When the temperature rises, the size of the holes changes	0	yes	27,5	17,5		0,42	3
13	E3	connect a folding sun shading device with a sunflower	v	no	27,3	4,3	21,3	0,92	3
14	E3	using temperature-sensitive bi-metal for a folding sun shading device	v	yes	27,3	6,3	21,3	0,92	3
15	E3	plants which move their foils dependent on sunlight serve as a shading device	v	yes	29,3	4,3		0,83	3
16	E3	using metal-plastic reels which change their size depending on temperature - they become loose	w	yes	27,2	9,2		0,58	3
17	E3	building with thick walls analogue to old monasteries - the buildings do not heat up	0	yes	24,5			0,33	2
18	E3	using glass which reflects frequencies of heat radiation	0	yes	31,5			0,50	3
19	E3	solar panels store energy and actuate sun protection	p	no	41,1			0,33	3
20	E3	rough surface which changes its shape depending on temperature causes interference in the light -> less/more light gets through	p	yes	26,1			0,17	3
21	B3	use of a foil that filters out UV-light	0	no	34,5			0,42	3
22	B3	using a light receptor (like a wasp) as an actuator	p	no	42,1			0,17	1
23	B3	using a light receptor to actuate a foil	p	no	42,1	34,5		0,58	1

n°	pair	description	source	doc.	working principles			Q	F
24	B3	use a bacterial layer on the windows which absorbs sunlight	p	no	25,1			0,17	1
25	B3	turn the building (?) with the same technology as solar panels (which are turned to absorb maximum sunlight)	0	no	30,5	19,5		0,42	2
26	B3	foil for windows which is built up similar to the wasps cuticular with a reflecting layer and a heat absorbing layer (bacteria)	p	yes	31,1	25,1		0,50	1
27	B3	enabling photosynthesis by using an "electron transport tube"	b	no	39,4			0,17	1
28	B3	artificial inverted iris - device that expands in the sunlight and shrinks when there is no sun, the energy for this movement is absorbed due to the black colour of the device and stored in bacteria	p,w	no	27,2	13,2	37,1	0,75	1
29	B3	bacteria in the window glasses absorb heat	p	no	25,1			0,17	1
30	B3	photoreceptors are located between the window glasses - they produce an electric tension. A liquid flows through honey-comb channels between the window glasses, heats up and is cooled in the heat exchanger driven by the produced electricity.	p	yes	12,5	42,1		0,42	1
31	SBD3	double-glass with water in-between the glasses	0	yes	32,5			0,33	2
32	SBD3	several water layers separated by reflecting lamella	0	yes	31,5	32,5		0,50	2
33	SBD3	using special mirrors as windows: transparent from the	0	no	33,5			0,50	3

n°	pair	description	source	doc.	working principles			Q	F
		inside, reflecting to the outside							
34	SBD3	use of a solar cell (do not know how a solar cell works)	p	no	41,1			0,33	3
35	SBD3	a pigmented glass pane that filters diffused light	w	no	34,2			0,42	3
36	SBD3	dark glass pane	w	no	34,2			0,42	3
37	SBD3	glass pane that changes its colour (exists for cars and spectacles)	w	no	34,2	2,2		0,92	2
38	SBD3	pane that changes the structure of its crystals when heated and becomes less transparent	w	no	34,2	1,2		0,92	1
39	SBD3	set the house on a plate that turns with the sun	v	no	30,3	19,3		0,42	2
40	SBD3	canvas above the house that turns with the sun	v	yes	27,3	20,3		0,58	3
41	SBD3	actuation of the canvas with a control unit, electric supply generated with solar panel	v	yes	27,3	20,3	41,3	0,92	3
42	SBD3	window blinds with adaptable positions (electrically actuated by solar cell)	v	no	27,3	14,3	41,3	0,92	3
43	SBD3	gas-filled cylinders to actuate canvas: the expansion of the gas due to heating by the sun	v	yes	27,3	7,3		0,92	3
44	SBD3	triangular canvas, each edge is actuated by two rods: all 3D movements are possible	v	yes	27,3	7,3		0,92	3
45	B6	use of the wasp's cuticle as a semi-conductor (conductivity increases with temperature) to actuate sun-protection	p	no	10,1			0,17	1
46	B6	solar "collector" in analogy to wasp generates and stores electricity (concave to collect sun light from different angels): sun blind goes down when a certain energy level is	p	yes	27,1	14,1	40,1	0,92	3

n°	pair	description	source	doc.	working principles			Q	F
		reached, the sun blind is pushed upwards by a spring							
47	B6	actuation as in idea n° 46, instead of pushing the sun blind down and up, the position of the lamella is adapted to shield sun (horizontal) or let light through (vertical)	p	yes	27,1	16,1	40,1	0,92	3
48	E6	window glass with "silver halogenids" which darken when the insolation is high (analogy to photochromic glasses)	0	yes	34,5	2,5		0,92	2
49	E6	houses rotate according to sun position (a light sensor detects if the rotation is necessary)	v	no	30,3	19,3		0,42	2
50	E6	sun shading device rotates according to sun position (a light sensor detects if the rotation is necessary)	v	no	27,3	20,3		0,58	3
51	E6	transparent photovoltaics device which turns with the sun to actuate the sun shading device	v	no	27,3	41,3	20,3	0,92	3
52	E6	shading foil (filters infrared light) that absorbs light and generates energy	p	no	34,1	38,1		0,92	3
53	E6	foil that reflects light, in particular infrared light, visible light only to a certain degree	p	yes	31,1			0,50	3
54	E6	round windows with a shutter (in analogy to the "stargate" TV series and cameras)	w	yes	27,2	18,2		0,58	3
55	E6	photovoltaic layer on the shutter elements to actuate it	w	yes	27,2	18,2	41,2	0,92	3
56	E6	small tubes "collect" light (part of the spectrum is "collected", the other part is reflected) and direct it to a photovoltaic layer	w	yes	35,4	41,2		0,50	3

n°	pair	description	source	doc.	working principles			Q	F
		which controls the "collection" (how?)							
57	E6	house rotates according to the sun position, the rotation is driven by solar cells	v	yes	30,3	19,3	41,3	0,75	2
58	E6	photovoltaic cell provides energy to turn elements that shade a window (turning axis normal to window)	v	yes	27,3	20,3	41,3	0,92	3
59	E6	photovoltaic cell provides energy to turn lamella that shade a window (turning axis parallel to window)	v	no	27,3	14,3	41,3	0,92	3
60	E6	windows include "liquid crystals" which have a shading and a non-shading position (actuation by photovoltaic cell)	v	yes	27,5	15,5	41,3	0,75	3
61	E6	no windows	0	no	30,5			0,25	2
62	E6	use of mirrors	0	no	36,5			0,42	3
63	E6	evaporate water for cooling	0	no	11,5			0,50	2
64	BD7	reflecting film (transparent from the inside of the building)	0	no	33,5			0,50	3
65	BD7	crystals changing their position (used as protection from outside viewers)	0	no	1,5	34,5		0,92	1
66	BD7	metal layer reflects sun	0	no	36,5			0,42	3
67	BD7	planting sunflowers in front of the window (their "heads" shade the direct sunlight)	v	yes	29,3	4,3		0,83	3
68	BD7	absorb, convert and store energy (in analogy to wasp?) and cool the building with this energy	p	yes	11,1			0,50	2
69	BD7	integrate solar cells into the window glass (e.g. "stripes" of solar cells provide additional shadow)	p	yes	27,1	41,1		0,75	3

n°	pair	description	source	doc.	working principles			Q	F
70	BD7	using the principle of semi-permeable membranes: sun energy is absorbed/ reflected, light is led through and from the inside the window is transparent	b	no	31,4	33,4	34,4	0,50	3
71	BD7	non-transparent elements in windows that open/ close according to insolation intensity - part of the light is led through a lens which disperses the light (--> diffuse light)	w	yes	23,2	17,2	27,2	0,42	3
72	BD7	use of a water surface (transparent from the inside, reflecting the outside light)	0	no	32,5			0,33	2
73	BD7	use of solar energy to actuate the opening/ closing mechanism of solution n°71	0	no	0	17,2	27,2	0,42	3

Table 11-7: solution ideas on embodiment level (task III: aquaplaning)

pair (B: biologist pair, E: engineer pair, BD: bi-disciplinary pair, no support, SBD: support pair)

source (p: publication, w:wikipedia,v:video,b:other biological knowledge;0:no bio-inspiration)

doc: documentation (yes/ no)

w. princ.: working principles   Q: task-specific quality   F: feasibility

n°	pair	description	source	doc.	w. princ.		Q	F
1	BD2	"silk cover for the tires"	v	no	23,3		1,00	2
2	BD2	"coating of the tires with artificial silicon polymer structure with underwater adhesive properties"	p	yes	26,1		1,00	3
3	BD2	"changing the shape of the tire - pillar-like surface"	p	yes	27,1		0,33	3
4	BD2	"wet tires attach to the ground with a glue - no water wedge can form to cause aquaplaning"	v	no	24,3		0,33	3
5	BD2	"adhesive stripes on which water	v	yes	25,3		0,33	3

n°	pair	description	source	doc.	w. princ.		Q	F
		drops adhere on the tires. Due to rotation they detach from the tires."						
6	BD2	"use of lotus flower effect"	0	no	15,4		0,00	3
7	BD2	"several tires" (analogue to formula 1)	0	no	31,5		0,00	2
8	BD2	tire surface has several layers: holes in the outer layer allow water to enter, the water exits due to rotational forces	w	yes	3,2		1,00	3
9	BD2	paddle wheel has spaces for water and transports it	0	yes	4,5		0,33	2
10	BD2	the tire has a layer with the structure of shark skin	0	yes	5,4		0,33	3
11	BD5	the tire has a profile - the water is diverted through channels	0	yes	1,5		0,33	3
12	BD5	coating (similar to the spider net material) on the tire enables adhesion/friction	v	yes	22,3		0,33	3
13	BD5	if one tire is not controllable, the other tire is controlled (ESP)	0	no	34,5		0,00	3
14	BD5	using a wax layer	0	no	16,5		0,00	3
15	BD5	put a tire in front of the usual tire which pushes the water away	0	yes	7,5		0,67	2
16	BD5	have adhesive and non-adhesive elements in analogy to the spider	v	no	25,3		0,33	3
17	BD5	suction cups on the tires	p	yes	30,1		0,67	3
18	BD5	use of air bubbles between suction cups	p	yes	30,1	18,1	0,67	3
19	BD5	use silicon polymers for the road cover	p	yes	29,1		0,00	3
20	BD5	pump the water off the road	p	no	12,1		1,00	3
21	BD5	intake of water in the front of the wheel through holes, disposal behind the wheel	w	yes	3,2		1,00	3
22	BD5	heating in front of the tire evaporates water	0	yes	19,5		0,00	2

n°	pair	description	source	doc.	w. princ.		Q	F
23	BD5	chemical substance/ coating that reduces the water's surface tension	0	yes	20,5		0,33	1
24	SBD5	tires with "beetle feet" structure retain air bubbles so that they adhere to a surface underwater	p	yes	26,1		1,00	3
25	SBD5	brake with the beetle's structure: blowing air bubbles into the structure will reduce speed	p	no	28,1		1,00	3
26	SBD5	tires absorb and release water via openings	w	no	3,2		1,00	3
27	SBD5	water is sucked into tubes in the tire via capillary forces	w	yes	6,2		0,33	3
28	SBD2	tire with spider net pattern profile	v	no	2,3		0,00	3
29	SBD2	wider tire with a wider contact area (spider net pattern profile makes the tire more stable)	v	no	32,3	2,3	0,00	3
30	SBD2	hydrophobic tire pushes water away more efficiently	v	no	15,3		0,00	3
31	SBD2	hydrophobic elements, adhesive elements	v	yes	15,3	25,3	0,33	3
32	SBD2	stable adhesive and non-adhesive elements	v	yes	25,3		0,33	3
33	SBD2	"adequate" tires profile redirects water by capillary forces	w	yes	6,2		0,33	3
34	SBD2	middle section of the tire adheres more to the ground than outer section (water cannot accumulate)	p	no	21,1		0,33	1
35	B4	curved (?) road so that water runs off	0	no	8,5		0,00	3
36	B4	drainage ditch	0	no	10,5		0,33	3
37	B4	hydrophobic road surface	0	no	13,5		0,33	3
38	B4	increase contact area of the tire	0	no	32,5		0,00	3
39	B4	decrease air pressure in tire to increase contact area of the tire	0	no	33,5		0,00	3
40	B4	hydrophobic tires --> no water under the tires	p	no	15,1		0,00	3

n°	pair	description	source	doc.	w. princ.		Q	F
41	B4	use structure and material with hydrophobic properties of the beetle	p	no	15,1		0,00	3
42	B4	hydrophobic tires (similar to insects' cuticula) with a structure similar to the polymers in the publication -> water pushed away	p	yes	15,4	26,1	1,00	3
43	B4	inclined road surface, prevent or remove lane grooves	0	yes	8,5	9,5	0,00	3
44	B4	hydrophobic road surface similar to the cuticula of insects / leaves	w	yes	13,2		0,33	3
45	B4	pores in road surface so that water can drain away	0	yes	11,5		1,00	3
46	B4	road surface with spider net pattern: hydrophobic elements rupture water layer	v	no	14,3		0,67	3
47	E4	optimization of the profiles surfaces: reduction of friction -> quicker deflection of water	0	yes	1,5	17,5	1,00	3
48	E4	produce an "air affinity" of the tire (so that there is always air between the tire and the liquid)	p	no	18,1		1,00	2
49	E4	give the areas of the tire which are in contact with the road the pillar-shape microstructure of the beetle so that air gets trapped and forces can be taken	p	yes	26,1		1,00	3
50	E4	change the shape of the profile	0	no	1,5		0,33	3

11.5.2 Solution ideas on working principle, physical effect and function level

Table 11-8: Solution ideas on working principle, physical effect and function level (task I:water pump)

n°:number after comma indicates the source: …,1:publication; …,2:Wikipedia;…,3:video;…,4:other biological knowledge;…,5:no-bio-inspiration

wp: working principle p: physical effect f: function

acc. (accuracy):1-unrelated 2-incorrect 3-incomplete 4-correct

sim. (similarity): 1-literal implementation 2-biological transfer 3-analogy 4-anomaly

el. tran.(elements of transfer): 1-parts 2-organs 3-attributes 4-state change

F: feasibility

Q: task-specific quality a: fixation of cables b: fixation in wet state c: easy assembly d: reusable

description				acc.				sim.				el. tran.				F	Q			
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		a	b	c	d
1,2	byssus threads	adhesion	hold				1	1				1				1		3		
2,2	coating with byssus material	adhesion	hold				1	1				1				1		3		
3,2	adhesive fibres/ tape/ ribbon	adhesion	hold				1			1			1			3		3		
4,2	glue	adhesion	hold				1			1			1			3		3		
5,4	disk with several elastic ribbons attached to each cable/ hose	elastic deformation	hold	1							1					3		3		
6,5	enlacement by a chain of elastic and stiff elements	elastic deformation	hold													3		3		
7,1	enlacement by a	elastic deformatio	hold	1							1					3		3		

description				acc.				sim.				el. tran.				F	Q			
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		a	b	c	d
	rubber band	n																		
8,3	cables/hose are fixed with a type of zip fastener	form closure	hold			1				1					1	2		3		
9,3	hook-and-loop fastener (Velcro®)	form closure	hold			1				1					1	3		3		
9,5	hook-and-loop fastener (Velcro®)	form closure	hold													3		3		
10,2	material encloses cables/hose/rope	form closure	hold	1							1					1		3		
11,3	nails	form closure	hold				1			1			1			3		1		
12,4	braiding the cables/hose around the rope	belt friction (F_t<= F_h*$e^{\mu*\alpha}$)	hold	1							1					3		3		
12,5	braiding the cables/hose around the rope	belt friction (F_t<= F_h*$e^{\mu*\alpha}$)	hold													3		3		
13,1	clamp	static friction (F_R= μ*F_N)	hold				1			1			1			3		2		
13,3	clamp	static friction (F_R=	hold				1			1			1			3		2		

description				acc.				sim.				el. tran.				F	Q			
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		a	b	c	d
		$\mu*F_N$)																		
14,1	copy of the parasite's clamp	static friction (F_R= $\mu*F_N$)	hold				1			1			1			3		2		
15,1	enlacement by one part (cable strap/ring/tape...)	static friction (F_R= $\mu*F_N$)	hold	1							1					3		2		
15,2	enlacement by one part (cable strap/ring/tape...)	static friction (F_R= $\mu*F_N$)	hold		1						1			1		3		2		
15,3	enlacement by one part (cable strap/ring/tape...)	static friction (F_R= $\mu*F_N$)	hold	1							1					3		2		
15,5	enlacement by one part (cable strap/ring/tape...)	static friction (F_R= $\mu*F_N$)	hold													3		2		
16,3	anti-slip coating	static friction (F_R= $\mu*F_N$)	hold	1							1					3		1		
16,5	anti-slip coating	static friction (F_R= $\mu*F_N$)	hold													3		1		
17,2	byssus threads/material	adhesion	tighten				1	1				1				1			3	0
18,2	glue/ adhesive	adhesion	tighten				1			1			1			3			3	0

description				acc.				sim.				el. tran.				F	Q			
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		a	b	c	d
	fibres/tape /ribbon																			
19,3	nails	deformation	tighten				1			1			1			3			0	0
20,3	cable strap	form closure	tighten	1							1					3			0	0
21,1	shrinking material		tighten	1							1					1			3	0
22,3	heat-shrink tube	thermo-chemical reaction (molecular forces)	tighten	1							1					3			2	0
23,2	hardening material encloses cables/hose/rope	thermo-chemical reaction	tighten			1				1				1		1			3	0
24,2	hardening polymer encloses cables/hose/rope	thermo-chemical reaction	tighten			1				1				1		1			3	0
25,2	glue (soluble in salt-water)	adhesion	tighten & loosen			1				1				1		1			3	2
26,2	coating/ glue (that is only adhesive in contact with water)	adhesion	tighten & loosen			1				1				1		1			3	2
27,2	adhesive tape/ fibres (decompose in air)	adhesion	tighten & loosen			1				1				1		1			3	0

description				acc.				sim.				el. tran.				F	Q			
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		a	b	c	d
28,1	moisture-expanding material	deformation due to material absorption	tighten & loosen	1							1					1			3	2
28,5	moisture-expanding material	deformation due to material absorption	tighten & loosen													1			3	2
29,1	a snapping mechanism	elastic deformation	tighten & loosen			1				1				1		3			3	3
30,1	elastic strap to actuate a clamp	elastic deformation	tighten & loosen			1				1				1		3			3	3
31,1	copy of the parasite's clamp (rubber)	elastic deformation	tighten & loosen			1				1				1		3			3	3
32,5	plastic ring with opening	elastic deformation	tighten & loosen													3			1	1
33,5	bi-stable metal strip	elastic deformation	tighten & loosen													3			2	2
34,1	spring	elastic deformation	tighten & loosen			1				1				1		3			3	3
34,3	spring	elastic deformation	tighten & loosen			1				1					1	3			3	3
35,3	zip fastener	form closure	tighten & loosen			1				1				1		2			3	3
36,3	hook-and-loop fastener	form closure	tighten & loosen			1				1				1		3			3	3

description				acc.				sim.				el. tran.				F	Q			
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		a	b	c	d
	(Velcro®)																			
36,5	hook-and-loop fastener (Velcro®)	form closure	tighten & loosen													3			3	3
37,1	hooks	form closure	tighten & loosen	1							1					3			2	3
37,3	hooks	form closure	tighten & loosen			1				1				1		3			2	3
37,5	hooks	form closure	tighten & loosen													3			2	3
38,4	braiding the cables/hose around the rope	belt friction $(F_t<= F_h*e^{\mu*\alpha})$	tighten & loosen	1							1					3			2	2
38,5	braiding the cables/hose around the rope	belt friction $(F_t<= F_h*e^{\mu*\alpha})$	tighten & loosen													3			2	2
39,2	knot	belt friction $(F_t<= F_h*e^{\mu*\alpha})$	tighten & loosen	1							1					3			3	3
40,5	screw	static friction $(F_R= \mu*F_N)$	tighten & loosen													3			2	2
41,2	wax (hardens due to low temperature in well, melts outside the well)	thermo-chemical reaction	tighten & loosen			1				1				1		3			3	2

description				acc.				sim.				el. tran.				F	Q			
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		a	b	c	d
42,4	suction cups	vacuum	tighten & loosen		1						1			1		3			3	3
43,2	separating/ cutting element	deformatio n	loosen	1							1					3				0
44,5	casing with holes for each cable	form closure	adapt to diameter of cables/ hose (discrete steps)													3	2			
45,3	spikes between cables/ hose/rope	form closure	adapt to diameter of cables/ hose (discrete steps)				1			1			1			3	2			
46,3	rubber elements between cables/hos e/rope	form closure	adapt to diameter of cables/ hose (discrete steps)				1			1			1			3	2			
47,1	several fixture devices for several diameters	form closure	adapt to diameter of cables/ hose (discrete steps)	1							1					3	2			
47,4	several fixture devices for several diameters	form closure	adapt to diameter of cables/ hose (discrete steps)	1							1					3	2			
47,5	several fixture devices for	form closure	adapt to diameter of cables/													3	2			

description				acc.				sim.				el. tran.				F	Q			
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		a	b	c	d
	several diameters		hose (discrete steps)																	
48,1	shape of the parasite's clamp: one gap for cables, one for hose	form closure	adapt to diameter of cables/ hose (discrete steps)		1						1			1		3	0			
49,5	fixing the cables on one rope, the hose on another rope		adapt to diameter of cables/ hose (continuously)													2	0			
50,2	glue	adhesion	adapt to diameter of cables/ hose (continuously)				1			1			1			3	3			
51,2	byssus threads/ material	adhesion	adapt to diameter of cables/ hose (continuously)				1	1				1				0	3			
52,1	flexible "fingers"	elastic deformation	adapt to diameter of cables/ hose (continuously)	1							1					3	3			
53,5	a chain of elastic and stiff elements	elastic deformation	adapt to diameter of cables/ hose (continuou													3	3			

description				acc.				sim.				el. tran.				F	Q			
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		a	b	c	d
			sly)																	
54,3	shiftable spikes between cables/ hose/rope	form closure	adapt to diameter of cables/ hose (continuously)			1				1				1		3	3			
55,2	flexible enlacement	form closure	adapt to diameter of cables/ hose (continuously)				1			1			1			3	3			
56,2	multiple enlacement	form closure	adapt to diameter of cables/ hose (continuously)		1						1			1		3	3			
57,1	sleeve adapted to the cables/ hose diameters (by shrinking)	form closure	adapt to diameter of cables/ hose (continuously)	1							1					1	3			
58,2	material encloses cables/hose/rope	form closure	adapt to diameter of cables/ hose (continuously)		1						1			1		1	3			
58,5	material encloses cables/hose/rope	form closure	adapt to diameter of cables/ hose (continuously)													1	3			

description				acc.				sim.				el. tran.				F	Q			
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		a	b	c	d
59,3	(barbed) hooks	form closure	adapt to diameter of cables/ hose (continuously)			1				1				1		3	1			
60,3	cables/hose are fixed with a type of zip fastener	form closure	adapt to diameter of cables/ hose (continuously)			1				1				1		2	3			
61,3	hook-and-loop fastener (Velcro®)	form closure	adapt to diameter of cables/ hose (continuously)			1				1				1		3	3			
62,4	braiding the cables/hose around the rope	belt friction ($F_t <= F_h * e^{\mu * \alpha}$)	adapt to diameter of cables/ hose (continuously)	1							1					3	3			
62,5	braiding the cables/hose around the rope	belt friction ($F_t <= F_h * e^{\mu * \alpha}$)	adapt to diameter of cables/ hose (continuously)													3	3			
63,5	set pump on a plate (replace single rope)	gravitation	lower pump into well													2			3	3

Table 11-9: Solution ideas on working principle, physical effect and function level (task II: sun protection)
n°: number after comma indicates the source: …,1:publication; …,2:Wikipedia;…,3:video;…,4:other biological knowledge;…,5:no-bio-inspiration
wp: working principle p: physical effect f: function
acc. (accuracy):1-unrelated 2-incorrect 3-incomplete 4-correct
sim. (similarity): 1-literal implementation 2-biological transfer 3-analogy 4-anomaly
el. tran.(elements of transfer): 1-parts 2-organs 3-attributes 4-state change
F: feasibility
Q: task-specific quality a: prevent heating b: autonomous adaptation c: allow view from inside

description				acc.				sim.				el. tran.				F	Q		
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		a	b	c
1,2	glass that changes its crystal structure according to insolation	?	adapt to insolation	1							1					1		3	
1,5	glass that changes its crystal structure according to insolation	?	adapt to insolation													1		3	
2,2	glass that changes its colour according to insolation (photochromic glass)	chemical photochromism	adapt to insolation	1							1					2		3	
2,5	glass that changes its colour according to insolation (photochromic glass)	chemical photochromism	adapt to insolation													2		3	
3,4	algae	photosynthesis	adapt to insolation				1	1				1				3		2	
4,3	sun flowers (or other	phototropism	adapt to sun position				1	1				1				3		3	

description				acc.				sim.				el. tran.				F	Q		
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		a	b	c
	plants)																		
5,5	liquid (movement of particles when temperature rises)	Brownian motion	adapt to temperature													2		1	
6,2	bi-metal/ shape-memory alloy (reversible movement)	thermal expansion	adapt to temperature			1				1					1	3		3	
6,3	bi-metal/ shape-memory alloy (reversible movement)	thermal expansion	adapt to temperature			1				1					1	3		3	
7,3	gas-filled cylinders (reversible movement)	thermal expansion	adapt to temperature			1				1					1	3		3	
8,2	liquid (reversible movement)	thermal expansion	adapt to temperature			1				1				1		3		3	
9,2	metal plastic reels changing their size (reversible movement)	thermal expansion	adapt to temperature			1				1					1	3		1	
10,1	wasp cuticula as a semi-conductor (temperature-sensitive)	chemo-electrical properties	adapt to temperature				1	1				1				1		1	
11,1	"cooler"	evaporation (enthalpy)	cool the building			1				1					1	2	3		3
11,2	"cooler"	evaporation	cool the	1							1					2	3		3

description				acc.				sim.				el. tran.				F	Q		
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		a	b	c
		(enthalpy)	building																
11,5	"cooler"	evaporation (enthalpy)	cool the building													2	3		3
12,5	heat exchanger: cooled water flows through honey-comb structures in the window panes	heat transfer	cool the building													2	1		2
13,2	black element expanding & shrinking according to insolation	?	enable adaptation			1				1				1		1		0	
14,1	window blinds (angular positions)	rotation	enable adaptation	1							1					3		1	
14,3	window blinds (angular positions)	rotation	enable adaptation	1							1					3		1	
15,5	glass that changes its crystal structure (electric actuation)	rotation	enable adaptation													3		1	
16,1	window blinds (up-down position)	translation	enable adaptation	1							1					3		1	
16,5	window blinds (up-down position)	translation	enable adaptation													3		1	

description				acc.				sim.				el. tran.				F	Q		
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		a	b	c
17,2	elements opening & closing according to insolation	rotation	enable adaptation			1				1					1	3		0	
17,5	elements opening & closing according to insolation	rotation	enable adaptation													3		0	
18,2	camera shutter ("stargate") windows	rotation	enable adaptation			1				1					1	3		1	
19,3	rotation of the whole building	rotation	enable adaptation			1				1					1	2		1	
19,5	rotation of the whole building	rotation	enable adaptation													2		1	
20,3	rotation of a sun-shielding device	rotation	enable adaptation			1				1					1	3		1	
21,3	folding sun shading device	folding	enable adaptation			1				1					1	3		1	
21,4	folding sun shading device	folding	enable adaptation			1				1					1	3		1	
22,1	parabolic mirror	reflection	redirect sunlight				1			1			1			3	3		2
23,1	lens	refraction	redirect sunlight	1							1					3	2		2
23,2	lens	refraction	redirect sunlight				1			1			1			3	2		2
24,5	building with	heat capacity	shield heat													2	1		3

description				acc.				sim.				el. tran.				F	Q		
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		a	b	c
	thick stone walls																		
25,1	heat-absorbing bacteria	?	shield heat		1				1			1				1	1		1
26,1	rough surface	interference	shield sun		1						1			1		3	0		2
26,5	rough surface	interference	shield sun													3	0		2
27,1	sun shading device	object shadow	shield sun	1							1					3	3		2
27,2	sun shading device	object shadow	shield sun				1			1			1			3	3		2
27,3	sun shading device	object shadow	shield sun	1							1					3	3		2
27,5	sun shading device	object shadow	shield sun													3	3		2
28,4	algae	object shadow	shield sun		1				1			1				3	3		2
29,3	sun flowers (or other plants)	object shadow	shield sun		1				1			1				3	2		2
29,4	sun flowers (or other plants)	object shadow	shield sun		1				1			1				3	2		2
30,3	building without windows (in direction of the sun)	object shadow	shield sun	1							1					2	3		0
30,5	building without windows (in direction of the sun)	object shadow	shield sun													2	3		0
31,1	reflecting foil/ glass (letting	reflection	shield sun		1						1			1		3	3		3

description				acc.				sim.				el. tran.				F	Q		
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		a	b	c
	through only specific wave-length of light)																		
31,4	reflecting foil/ glass (letting through only specific wave-length of light)	reflection	shield sun		1						1			1		3	3		3
31,5	reflecting foil/ glass (letting through only specific wave-length of light)	reflection	shield sun													3	3		3
32,5	water layer	reflection	shield sun													2	2		2
33,4	semi-transparent mirror	reflection	shield sun		1						1			1		3	3		3
33,5	semi-transparent mirror	reflection	shield sun													3	3		3
34,1	(coloured) light-absorbing foil /glass (letting through only specific wave-length of light)	absorption	shield sun			1				1				1		3	3		2
34,2	(coloured) light-absorbing foil /glass (letting through only	absorption	shield sun				1			1			1			3	3		2

description				acc.				sim.				el. tran.				F	Q		
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		a	b	c
	specific wave-length of light)																		
34,4	(coloured) light-absorbing foil /glass (letting through only specific wave-length of light)	absorption	shield sun		1						1			1		3	3		2
34,5	(coloured) light-absorbing foil /glass (letting through only specific wave-length of light)	absorption	shield sun													3	3		2
35,4	small (glass) tubes reflecting specific wave-length of light	reflection	shield sun		1						1			1		3	1		1
36,5	mirror	reflection	shield sun													3	3		2
37,1	bacteria	chemo-electrical properties	store electric energy				1	1				1				1		2	
38,1	light-absorbing foil/ glass (solar cells)	chemo-electrical properties	transform solar energy to electric energy				1			1			1			3		3	
39,4	"electron transport tube"	photosynthesis	transform solar energy to electric energy				1			1			1			1		1	
40,1	concave solar	photovoltaics	transform				1			1			1			3		2	

description				acc.				sim.				el. tran.				F	Q		
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		a	b	c
	collector		solar energy to electric energy																
41,1	solar cells	photovoltaics	transform solar energy to electric energy	1							1					3		2	
41,2	solar cells	photovoltaics	transform solar energy to electric energy	1							1					3		2	
41,3	solar cells	photovoltaics	transform solar energy to electric energy	1							1					3		2	
42,1	light receptor (biological cell)	chemo-electrical properties	transform solar energy to electric energy				1	1				1				1		1	
42,4	light receptor (biological cell)	chemo-electrical properties	transform solar energy to electric energy				1	1				1				1		1	

Table 11-10: Solution ideas on working principle, physical effect and function level (task III: aquaplaning)
n°:(number after comma indicates the source: ...,1:publication; ...,2:Wikipedia;...,3:video;...,4:other biological knowledge;...,5:no-bio-inspiration)
wp: working principle p: physical effect f: function
acc. (accuracy):1-unrelated 2-incorrect 3-incomplete 4-correct
sim. (similarity): 1-literal implementation 2-biological transfer 3-analogy 4-anomaly
el. tran.(elements of transfer): 1-parts 2-organs 3-attributes 4-state change
F: feasibility
Q: task-specific quality: improve contact tire/road

description				acc.				sim.				el. tran.				F	Q
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		
1,5	(optimized) tire	continuity of	redirect water													3	1

description				acc.				sim.				el. tran.				F	Q
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		
	profile	fluid flow: $v_2=A_1/A_2 \cdot v_1$															
2,3	spider net tire profile	continuity of fluid flow: $v_2=A_1/A_2 \cdot v_2$	redirect water		1						1			1		3	0
3,2	holes in tire's outer layer: intake of water - outlet of water to the back of the wheel	continuity of fluid flow: $v_2=A_1/A_2 \cdot v_1$	redirect water			1				1					1	3	3
4,5	(additional?) paddle wheel	continuity of fluid flow: $v_2=A_1/A_2 \cdot v_1$	redirect water													2	1
5,4	shark skin structure	continuity of fluid flow: $v_2=A_1/A_2 \cdot v_1$	redirect water		1						1			1		3	1
6,2	tubes in tire suck in water	capillary effect	redirect water				1			1			1			3	1
7,5	additional tire in front of the car	deflection of water	redirect water													2	2
8,5	inclined road surface	gravitation	redirect water													3	0
9,5	even road surface (no lane grooves)	gravitation	redirect water													3	0
10,5	drainage in the road	gravitation	redirect water													3	1
11,5	pores in road surface	gravitation	redirect water													3	3
12,1	pump water off the road	active displacement of fluid	redirect water	1							1					3	3

description				acc.				sim.				el. tran.				F	Q
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		
13,2	hydrophobic road surface	hydrophobic effect (molecular repulsive force)	redirect water				1			1			1			3	1
13,5	hydrophobic road surface	hydrophobic effect (molecular repulsive force)	redirect water													3	1
14,3	road surface with spider net pattern: hydrophobic elements rupture water layer	hydrophobic effect (molecular repulsive force)	redirect water				1			1			1			3	2
15,1	hydrophobic tire surface	hydrophobic effect (molecular repulsive force)	redirect water				1			1			1			3	0
15,3	hydrophobic tire surface	hydrophobic effect (molecular repulsive force)	redirect water				1			1			1			3	0
15,4	hydrophobic tire surface	hydrophobic effect (molecular repulsive force)	redirect water				1			1			1			3	0
16,5	wax layer on tires	hydrophobic effect (molecular repulsive force)	redirect water													3	0
17,5	profile surface material with low friction coefficient	reduce friction ($F_R = \mu * F_N$)	redirect water													3	3
18,1	blow/ ensure air between tire		redirect water			1				1					1	2	3

description				acc.				sim.				el. tran.				F	Q
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		
	and road																
19,5	heating in front of the tires	evaporation	evaporate water													2	0
20,5	coating of the tire with a chemical substance	chemical reaction	reduce water surface tension													1	1
21,1	middle section of the tires adhere more to the ground than outer section		adhere underwater			1				1					1	1	1
22,3	coating of the tires	adhesion	adhere underwater				1			1			1			3	1
23,3	(spider) silk coating of the tires	adhesion	adhere underwater				1			1			1			2	3
24,3	glue	adhesion	adhere underwater				1			1			1			3	1
25,3	adhesive stripes/ elements on tires	adhesion	adhere underwater				1			1			1			3	1
26,1	tire surface: pillar-shape nano structure (silicon polymers)	capillary forces	adhere underwater				1			1			1			3	3
27,1	tire surface: pillar-shape macro structure	capillary forces	adhere underwater				1			1			1			3	1
28,1	blow air into pillar-shape nano structure of the tires	capillary forces	adhere underwater				1			1			1			3	3

description				acc.				sim.				el. tran.				F	Q
n°	wp	p	f	1	2	3	4	1	2	3	4	1	2	3	4		
29,1	road surface: pillar-shape nano structure (silicon polymers)	capillary forces	adhere underwater				1			1			1			3	0
30,1	suction cups on the tires	vacuum	adhere underwater			1				1					1	3	2
31,5	use of several tires	gravitation	modify contact pressure													2	0
32,3	tire with increased width	gravitation	modify contact pressure	1							1					3	0
32,5	tire with increased width	gravitation	modify contact pressure													3	0
33,5	decreased tire air pressure	gravitation	modify contact pressure													3	0
34,5	ESP	digital signals	automatically control the car													3	0

11.6 Procedures of the pairs

In this sub-section, the procedures of the pairs are shown.

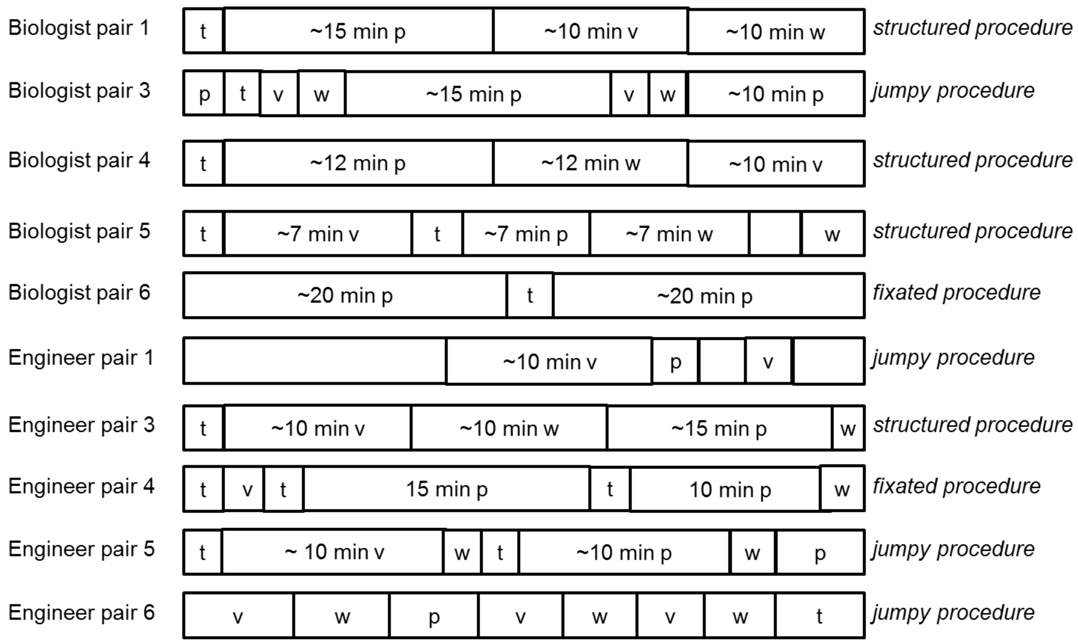


Figure 11-69: Procedures of uni-disciplinary pairs(p: publication, v: video, w: Wikipedia, t: task) – durations of less than 7 min are not explicitly stated, longer durations are indicated by approximations (minutes)

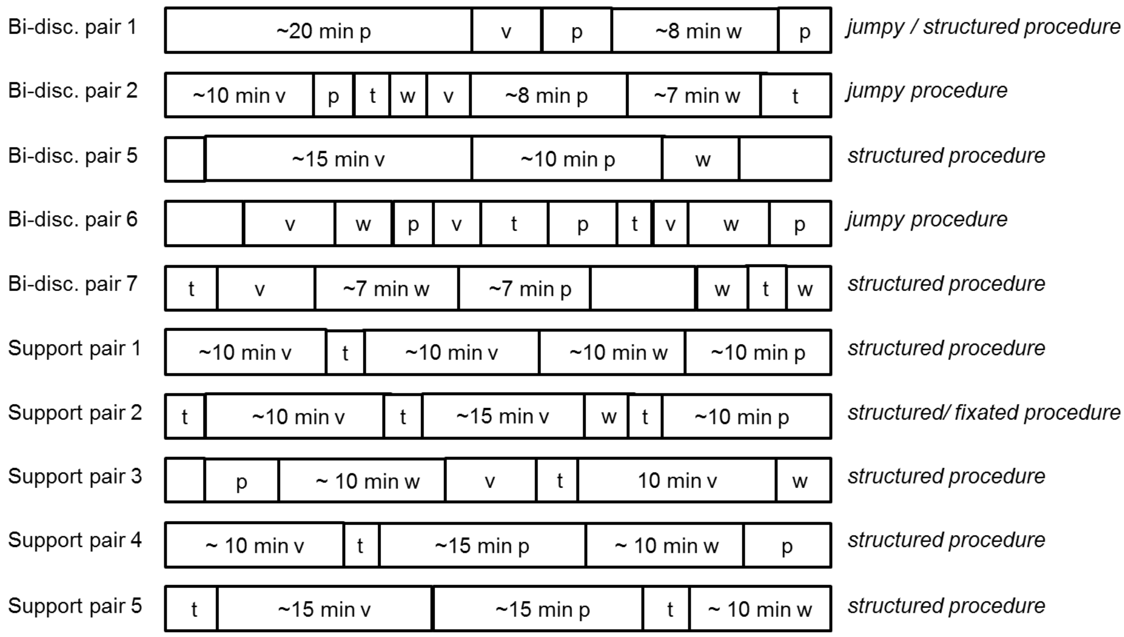


Figure 11-70: Procedures of bi-disciplinary and support pairs (p: publication, v: video, w: Wikipedia, t: task) – durations of less than 7 min are not explicitly stated, longer durations are indicated by approximations (minutes)

11.7 Questionnaire templates

In this sub-section, the complete questions of the questionnaires are shown and an English translation is given. As explained in section 3.2.1, the participants filled out a questionnaire twice: after the ideation in uni-disciplinary pairs and after the ideation in bi-disciplinary/ support pairs. At the beginning of the first questionnaire, the participants were asked to give some information on themselves. At the end of the second questionnaire, they were asked for additional comments on the "workshops" (i.e. the design experiments). In the main part of the questionnaire, the participants were asked questions on five topics (topic 1 to 5). The support pairs had to answer questions to three additional topics (topics 6 to 8).

Note: The questions are listed in the order they were printed on the questionnaires.

<u>Complete questionnaire:</u>

Only first questionnaire (after ideation in uni-disciplinary pairs):

Name *(name)*:

Lehrstuhl *(chair/institute)*:

Fakultät *(faculty)*:

Promotionsthema *(topic of the PhD thesis)*:

Only second questionnaire for support pair (variables 6-8)

Variable 6a and 6b:

Hat die Verwendung der Arbeitsblätter das Verständnis der Informationen erleichtert?

(Did the use of the templates facilitate understanding the information?)

6a: Technische Aufgabenstellung: gar nicht O O O O O sehr stark

(Technical task: not at all…very much)

6b: Informationen aus der Biologie: gar nicht O O O O O sehr stark

(Biological information: not at all…very much)

Woran lag das?

(What was the reason for this?)

Space for answer

Variable 7:

Hat die Verwendung der Arbeitsblätter die bionische Ideenfindung erleichtert?

(Did the use of the templates facilitate the bio-inspired ideation?)

gar nicht O O O O O sehr stark

(not at all…very much)

Woran lag das?

(What was the reason for this?)

Space for answer

Variable 8:

Wie funktionierte die Übertragung der biologischen „Lösung“ in die Technik am besten?

(How did the transfer of the biological „solution“ to the technical domain work best?)

a) Inspiration durch Skizze O

b) Inspiration durch Modell O

c) Weitere Idee O

(a) inspiration by sketch, b) inspiration by model c) further idea)

Both questionnaires (after ideation in uni-disciplinary pairs and in bi-disciplinary pairs): variables 1 to 5:

Variable 1:

Würdest du sagen, ihr habt für die Dauer des Workshops wenige oder viele unterschiedliche Lösungsideen gehabt?

(Would you say you had few or many different solution ideas for the duration of the workshop?)

Wenige unterschiedliche Lösungsideen O O O O O O viele unterschiedliche Lösungsideen

(Few different solution ideas … many different solution ideas)

Woran lag das?

(What was the reason for this?)

Space for answer

Variable 2:

Wie ist es euch gelungen, diese Lösungsideen weiterzuentwickeln?

(How did you succeed in further developing these solution ideas?)

schlecht O O O O O gut

(badly… well)

Woran lag das?

(What was the reason for this?)

Space for answer

Variable 3:

Inwieweit hat euch die Biologie zu eurer technischen Lösung inspiriert?

(In how far did biology inspire your technical solution?)

gar nicht O O O O O sehr stark

(not at all… very much)

Woran lag das?

(What was the reason for this?)

Space for answer

Variable 4:

Habt ihr alle Lösungsideen dokumentiert?

(Did you document all solution ideas?)

Keine Lösungsideen dokumentiert O O O O O alle Lösungsideen dokumentiert

(we did not document any solution ideas… we documented all solution ideas)

Woran lag das?

(What was the reason for this?)

Space for answer

Variable 5:

Wie würdest du die Qualität euer Lösungen bewerten?

(how would you rate the quality of your solution ideas?)

schlecht O O O O O gut

(bad…good)

Welches war die beste Lösung?

(Which was the best solution idea?)

Space for answer

Only in the second questionnaire:

Hast du weitere Anmerkungen zu den Workshops?

(Do you have further comments on the workshops?)

Space for answer

11.8 Questionnaire responses

This section shows the translated responses to the questionnaires. All participants had to evaluate five variables after each ideation in pairs (for details see appendix 11.6). The ratings, translated into values from 0 to 1 are listed in Table 11-11. The reasons given by the participants to explain their ratings are shown in Table 11-12. The participants of the support pairs were additionally asked for the evaluation of three further variables (variables 6 to 8, for details see appendix 11.6). The evaluation and the reasons given by the participants for the evaluation are depicted in Table 11-13.

Moreover in the second questionnaire, all participants were asked for further comments. The following responses were given:

- “publications a little too long” (e2)
- “publications too long” (e1)
- “had fun” (b2)
- “introduction of participants at the beginning of the design experiments” (e7)
- “a *personality* questionnaire should be used” (e10)
- “interesting to see how someone from another domain approaches the problem” (b11)
- “it was fun, next time I would rather spent more time on the tasks” (b12)
- “adorable” (e11)

Table 11-11: Evaluation of the variables 1 to 5 by each participant question.: questionnaire – 1:first questionnaire after ideation in uni-disciplinary pairs, 2:second questionnaire after ideation in bi-disciplinary/ support pairs

participant	question.	variable 1	variable 2	variable 3	variable 4	variable 5
e2	1	0,4	0,4	0,8	1	0,8
e2	2	0,8	0,4	1	1	0,6
b1	1	0,8	0,4	0,6	1	0,2
b1	2	1	1	0,8	0,8	1
e1	1	0,8	0,8	0,8	1	0,8
e1	2	0,6	0,4	0,6	1	0,4
b2	1	0,8	1	1	1	0
b2	2	0,4	0,6	0,4	1	0
e5	1	0,8	0,75	1	1	0,75
e5	2	0,25	0,25	0,5	1	0,25
e6	1	0,6	0,6	0,75	1	0,75
e6	2	0,5	0,75	0,75	1	0,75
b5	1	0,4	0,5	1	1	0,5
b5	2	1	0,75	0,5	1	0,75

participant	question.	variable 1	variable 2	variable 3	variable 4	variable 5
b6	1	0,5	0,5	1	1	0,5
b6	2	0,6	0,75	0,5	1	0,75
b7	1	0,6	0,5	0,75	0,75	0,5
b7	2	0,75	0,75	1	0,75	0,75
b8	1	0,8	0,75	0,75	1	0,75
b8	2	0,25	0,5	0,5	1	0,5
e7	1	0,2	0,5	0,75	1	0,5
e7	2	0,75	0,75	1	0,75	0,75
e8	1	0,6	0,75	0,75	0,5	0,25
e8	2	0	0	0,5	0,25	0
b9	1	0,8	0,75	0,75	0,75	0,5
b9	2	0	0	0,25	0,5	0
b10	1	1	1	0,5	1	1
b10	2	0,25	1	0,5	0,8	1
e9	1	0,4	0,5	0,75	1	0,75
e9	2	0	0,25	0,5	1	0
e10	1	0,4	1	0,25	1	1
e10	2	0,25	0,8	0,75	1	1
b11	1	0	1	1	1	0,5
b11	2	0,75	0,75	1	1	0,25
b12	1	0,2	0,75	0,75	1	0,5
b12	2	0,25	0,25	0,25	0,8	0,25
e11	1	0,8	0,75	1	1	0,75
e11	2	0,25	0,5	1	1	0
e12	1	0,8	0,8	0,75	1	0,75
e12	2	0,25	0,25	0,5	0,8	0,25

Table 11-12: Reasons given for the evaluation of the variables 1 to 5 by each participant p: participant q: questionnaire – 1:first questionnaire after ideation in uni-disciplinary pairs, 2:second questionnaire after ideation in bi-disciplinary pairs

p	q	variable 1	variable 2	variable 3	variable 4	variable 5
e2	1		lack of time			combination of Velcro and filling material
e2	2	variety of biological effect	lack of time	task: no (electric) energy supply		shading due to thermal expansion
b1	1	variety and quality of information material	similar mind-set of participants, development of as many ideas as possible	task could be solved with well-known devices and material (e.g. tape)	very simple solution ideas	finger-shaped device
b1	2	different, complementary approaches of the participants, complex paper	relations to other biological/ technical systems were found, chemical/ physical processes were considered	very "technical" task, no known devices could be used	some ideas were rejected (no fulfilment of requirements or further development)	expandable shading elements
e1	1	good exchange of ideas, high number of ideas due to information material	possible to concretize ideas			rope-actuated clamp
e1	2	fixation on formula-1 tires, solution are probably not feasible	not enough exchange of ideas			two-layer tires
b2	1	inspiration by biological information	"un"-detailed development of ideas	use of biological information	task	none (goal was a high n° of ideas)

p	q	variable 1	variable 2	variable 3	variable 4	variable 5
b2	2	biological information not helpful (Wikipedia article and video)	only rough sketches, no complete solution	only 3 bio-inspired solutions	task	idea sketch n° 1
e5	1	technical topic, many possibilities	much knowledge (on the topic?)	good biological information		insolation through holes of a device - alloy: change of size due to thermal expansion
e5	2	few starting points for ideas	"stopped"	(illegible)		unsure which idea is feasible
e6	1	systematic thinking				-
e6	2	many boundary conditions		(illegible)		sketch n° 3
b5	1	only ideas for existing products	no possibilities for technical application	"biologist"		pane with liquid and photo receptors
b5	2	increased range of knowledge		"more difficult to develop biologically"		tires with leaf vein structure
b6	1	lack of technical knowledge	lack of technical knowledge	approach highly oriented at biology		foil which filters out UV-light or deflects it to the sides
b6	2	mutual support, building on the ideas of each other	positive interplay technology-biology	praying mantis' legs: evenly distributed pressure on prey		tube with guide rails for different cables

p	q	variable 1	variable 2	variable 3	variable 4	variable 5
b7	1	missing technical knowledge; preliminary solution ideas were found, detailing was difficult then; new unknown topic requires training	similar to question 1, missing background knowledge on material properties	more knowledge than in technical domain; influence of the given information sources	one idea was rejected, because we did not know if and how the biological model can be applied in the technical domain	tire structure (?)
b7	2	information sources provided good inspiration	easy transfer of the biological solutions to the technical domain, because in both domains sun light/ energy is an aspect	information sources/ literature	no application of the idea "foil on window"	biological solar cells
b8	1	negative: little knowledge on material properties and the structure of tires; positive: much knowledge on insect/ plant surfaces	transfer of special material properties (in particular insects) to technical ideas	see last question, insects' cuticula is exceptional, extremely hydrophobic in comparison to other materials	all ideas that seemed to be useful were documented by bullet points	hydrophobic materials
b8	2		-	in particular in case of the praying mantis, a secure fixation of the prey is crucial - this is similarly important for	discussed only few ideas	difficult to say

p	q	variable 1	variable 2	variable 3	variable 4	variable 5
				pumps		
e7	1	unfamiliar task, provided material influenced the approach and limited the perspective	lack of time (solution 2), known alternative "influencing possibilities" for solution 1	material, preceding tests [individual tasks?]	-	difficulties in understanding the publication, maybe it will not work that way
e7	2	different approaches of mechanical engineer and biologist	detected further analogies to biological systems	-	contributed to the further development of the solution ideas	"iris-window" with lenses to diffuse light
e8	1	new topic, information sources were analysed and applied in a solution	inspirations could be applied quite well	the information sources provided good ideas for a technical solution	From the ideas, solutions could be developed, a first solution sketch was developed	increase the hydrophobic properties of the tire profile channel
e8	2	task was not "idea-friendly", technical solution approaches are evident, application is still difficult, therefore it cannot be planned	see last question	beetle provided a new solution[previous ideation!], byssus introduced a new aspect	documentation of 2 ideas	clamp as a reversible solution better applicable
b9	1	bad quality of technical drawings, examples triggered many different ideas	thought-provoking impulses from the examples, good understanding with other participant	helped to understand examples	had enough time	we are no engineers, technical feasibility questionable

p	q	variable 1	variable 2	variable 3	variable 4	variable 5
			(similar domain knowledge)			
b9	2	biological information sources distracted us from the task	no solution ideas (to develop further)	-	lack of time	vascular bundle
b10	1	we were just good :-)	see above	-	-	there are several good solution, the best is probably a combination of several solutions
b10	2	too many questions on the worksheets	collaboration with engineer	-	-	
e9	1	-	-	-	-	clamp without spring
e9	2	-	-	-	-	vascular bundle
e10	1	we quickly found one plausible solution	thought of improvements due to experience/ creativity/ intuition - I am unsure	did not completely understand the paper, byssus information was not helpful	task	clamp without spring
e10	2	use of electric energy was forbidden, solution space was therefore highly constraint/ limited	interdisciplinarity	sun flower is a best practice example (benchmarking)	task	there is only one solution
b11	1	deeper understanding	team work: other person	when reading [the	first collected everything,	solution with sensor

p	q	variable 1	variable 2	variable 3	variable 4	variable 5
			has a new idea	publication] it first came into mind; the technical details needed more time	then combined the best [ideas]	
b11	2	we approached the topic differently than the engineers (rather an undetailed solution than technically correct)	sketch->talk->new idea->change the sketch	I can work better with biology than with technical information, because basic knowledge on this is missing	documented all so that several solution could be linked, new idea can emerge when ideas are documented	cable binder with jelly cushion
b12	1	I could have worked longer on the topic, with more research maybe I would have had more ideas	worked as a team -> more ideas	it is easier to understand the biological information [than the technical] due to my professional background	we documented everything we discussed	solution with sensor
b12	2	difficult task	complex task	we had difficulties in connecting the ideas from biology to the technical task	lack of time	-
e11	1	similar base of discussion, similar previous knowledge/ education	brilliant ideas	functional models which are already successful in the world of animals	-	liquid crystals
e11	2	topic (fixation of cables/ hose) not very interesting	-	task	task	expanding coating as glue

p	q	variable 1	variable 2	variable 3	variable 4	variable 5
e12	1	fruitful discussion, common basis for discussion, similar knowledge/ education	development by discussion	ideas for functional principles	formation in technical drawings	pigments as filter
e12	2	"distance" between nature and the technical problem	did not find a possibility for transfer	missing analogy	"guided" analogy development	tires with holes to store water

Table 11-13: Evaluation and reasons of the topics 6 to 8 by each participant of the support pairs p: participant

p	6a	6b	reason	7	reason	8
b8	0,5	0,75	transfer was partly difficult	0,75	biological models could be compared to the task in a goal-oriented manner	sketch
e8	0,5	0,75	task descriptions were partly redundant (good for aquaplaning task, unnecessary for water pump task)	0,25	not always, only with a better task	sketch
b9	0	0	mainly misleading	0,25	support limited scope of ideation	sketch
b10	0	0	too much structure	0	-	other idea
e9	0	0	-	0	-	sketch
e10	0	0,25	-	0,25	-	sketch
b11	0,25	0,25	without support worksheet, one has done this "in his head" and can concentrate on the technical aspects	0,5	was a support, but not crucial	sketch, other idea: talk to the partner
b12	0,5	0,25	difficult transfer	0,5	it facilitated a structured approach	diagram
e11	0,25	0,25	empty slides are better for	0,25	empty slides are	other idea

			ideation		better for ideation	
e12	0,25	0,25	difficulties to identify analogies	0,25	had the impression that creativity was limited	sketch

11.9 Individual tasks

Table 11-14 lists the aspects of biological and technical systems named by the participants in the individual tasks. Moreover, the table shows if the aspect was counted as a new aspect.

Table 11-14:Results of the individual tasks

p: participant, t: test – 0:pre-test, 1:post-test 1, 2: post-test 2

s: biological/ technical system (a: airplane, b: bat, d: dolphin, e: elephant, r: robot, s: ship

technical appl./biol. model: technical application (of a the aspect of a biological system) or biological model (chosen to improve the aspect of a technical system)

n: novelty of the aspect(1: new, 0:not new)

r: explanation if an aspect is not new – b: no biological model, t: no technical application, numbers indicate the number of the previously named similar aspect

n°	p	t	s	aspect	technical appl./ biol. model	n	r
1	b1	0	e	sensitive trunk	grabbing/ moving of small components	1	
2	b1	0	e	cooling of the blood through large ear surface	cooling of industrial waste heat, wastewater etc.	1	
3	b1	0	e	sole of foot sensitive to vibrations	sensitive measuring equipment, e.g. for earthquake warning systems	1	
4	b1	0	e	strong teeth , suitable for crunching branches	grinding stones, production of wood fibres, wood pellets	1	
5	b1	0	e	tusks	production of materials	1	
6	b2	0	e	anatomy	development of walking on 4 feet	1	
7	b2	0	e	vision	camera/ photography	1	
8	b2	0	e	hearing	audio recording	1	
9	b2	0	e	transpiration (skin)	temperature regulation	1	
10	e1	0	e	trunk	grabber, e.g. for a robot or suction tube	1	
11	e1	0	e	sensitive and soft soles of foot	sensor technique; emittance of few noise despite high weight	1	
12	e1	0	e	behaviour in groups	how can robots behave in groups	1	
13	e1	0	e	perseverance as elephants can walk long distances without drinking water	energy efficiency: energy-efficient use of raw material	1	
14	e1	0	e	bone structure	elephants are very heavy: how	1	

n°	p	t	s	aspect	technical appl./ biol. model	n	r
					is the skeleton built up?		
15	e1	0	e	skin	very hard-wearing --> materials: elastic and hard wearing at the same time	1	
16	e2	0	e	trunk	grabber	1	
17	e2	0	e	ears	heat drain	1	
18	e2	0	e	feet/ legs	moving of high weights	1	
19	e2	0	e	tongue	grabber/ moving	1	
20	e2	0	e	tusks	blending, moving	1	
21	b1	0	s	water resistance	streamlined shape of fish	1	
22	b1	0	s	more resistant surface under water	shark skin	1	
23	b1	0	s	navigation	echolocation of wales	1	
24	b1	0	s	manoeuvrability	fin movement of fish	1	
25	b1	0	s	more flexible lift properties	swim bladder of fish	1	
26	b1	0	s	lightweight design with constant stability	hollow bones of birds	1	
27	b1	0	s	more stable ropes	spider silk	1	
28	b2	0	s	displacement of water	shark scales	1	
29	b2	0	s	absorption of air in surface	ducks absorb air between their feathers to swim	1	
30	b2	0	s	hydrophobic properties	lotus flower effect	1	
31	b2	0	s	prevention of small animal infestation (e.g. shells adhere to the surface)	-	0	b
32	e1	0	s	fin	fish fin	1	
33	e1	0	s	sails	birds, leaves	1	
34	e1	0	s	ship surface	shark skin, birds feathers, snake skin	1	
35	e1	0	s	shape	fish, birds (e.g. penguins)	1	
36	e1	0	s	mast	tree, e.g. oak, bamboo	1	
37	e1	0	s	building material for ships - requirements: water tight, hard wearing		0	b

n°	p	t	s	aspect	technical appl./ biol. model	n	r
38	e1	0	s	ballast	some animals eat stones to gain weight	1	
39	e2	0	s	drive	fish / fin movement	1	
40	e2	0	s	stability against tipping	duck, dove	1	
41	e2	0	s	friction in water	fish skin (shark)	1	
42	b1	1	d	streamlined shape	reduction of water resistance of ships	1	
43	b1	1	d	echolocation	navigation at low visibility	0	23
44	b1	1	d	very smooth skin	water-repellent surfaces	1	1
45	b1	1	d	strong tail fin	robot mechanics	1	26
46	b1	1	d	ability to dive long without breathing	storage of gases	1	21
47	b1	1	d	hunting in groups	communication of robots, autonomous vehicles in traffic	1	41
48	b2	1	d	sonar	sonar	1	165
49	b2	1	d	fins	turbines, motor	1	186
50	b2	1	d	teeth	saw	1	192
51	e1	1	d	fins	boats, surfboard, air planes	1	177
52	e1	1	d	skin	aerodynamic surfaces	1	197
53	e1	1	d	"language"/ noises, communication	sonar	1	141
54	e1	1	d	skeleton	lightweight structures	1	142
55	e1	1	d	swarm behaviour	simulation of human groups, communication of vehicles/ robots in big groups	1	256
56	e2	1	d	skin	ships' hulls or low friction surfaces in general	1	303
57	e2	1	d	fin, fin movement	ship drives	1	253
58	e2	1	d	fin	steering of ships, air planes	1	351
59	e2	1	d	shape of tail	ship bow, car front, air plane front	1	335
60	e2	1	d	communication between dolphins	information technology	1	449

n°	p	t	s	aspect	technical appl./ biol. model	n	r
61	e2	1	d	weight distribution, body shape	ships: stability against tipping	1	438
62	b1	1	r	spacial vision in different directions	chameleon	1	
63	b1	1	r	holding to / hanging from objects without the use of force	gecko (suction cups)	1	
64	b1	1	r	fast movement	movement patterns of fast mammals (e.g. cheetah)	1	
65	b1	1	r	movement in sand	movement patterns of snakes	1	
66	b1	1	r	orientation in darkness	echolocation of bats	1	
67	b1	1	r	holding/ gripping small and sensitive components	elephant trunk	0	1
68	b1	1	r	camouflaging by changing the surface structure	chameleon or octopus	1	
69	b1	1	r	use of sun energy	photosynthesis	1	
70	b2	1	r	walking on 8 - 4 - 2 legs	all animals that walk on 8 - 4 - 2 legs	1	
71	b2	1	r	aerodynamic flight	birds, turtles, fish	1	
72	b2	1	r	vision	animals that can see a higher spectrum than humans	1	
73	b2	1	r	grabbing	human hand	1	
74	b2	1	r	sensing by touch	human skin, skin in general	1	
75	e1	1	r	behaviour in groups	swarms: birds, fish	1	
76	e1	1	r	movement (balance)	walking: mammals, insects, reptiles, spiders	1	
77	e1	1	r	grabbing mechanisms	trunk, pliers, hands	1	
78	e1	1	r	orientation in space (does not have to be exclusively optical)	bats, wales, snakes	1	
79	e1	1	r	regeneration of components (damaged)	shark: teeth, snake: skin, plants	1	
80	e1	1	r	design appearance (e.g. cute, dangerous)	kittens, feline predators, wolf	1	

n°	p	t	s	aspect	technical appl./ biol. model	n	r
81	e2	1	r	control	human body awareness	1	
82	e2	1	r	drives	tendons, muscles	1	
83	e2	1	r	grabbers	hands, paws	1	
84	e2	1	r	force sensors	skin touch sensors	1	
85	e2	1	r	structural components	lightweight strategies of bamboo	1	
86	e2	1	r	optical sensors	insect eyes	1	
87	e2	1	r	planning of routes	ant trail	1	
88	e2	1	r	robot swarm cooperation	bird/ fish swarms	1	
89	b1	2	b	light bones	aircraft design	1	
90	b1	2	b	echolocation	navigation	1	
91	b1	2	b	folding of wings	storing of objects with large surface	1	
92	b1	2	b	big ears	location/ recording of sound emitters	1	
93	b1	2	b	holding to objects without the use of force	robot joints, fixations	1	
94	b1	2	b	microstructure of teeth as protection against caries	surfaces that stay clean	1	
95	b2	2	b	sonar	sonar	1	
96	b2	2	b	flight	flight	1	
97	b2	2	b	hearing	audio recording	1	
98	b2	2	b	hair	they act as acoustic insulation	1	
99	e1	2	b	communication	sonar/ radar	1	
100	e1	2	b	group behaviour	control of robot groups	1	
101	e1	2	b	legs (claws)	fixation of objects	1	
102	e1	2	b	sense of smell	improvement of sensors	1	
103	e1	2	b	wings that are wrapped around the body for sleeping	packaging	1	
104	e1	2	b	bone structure	lightweight structures	1	
105	e1	2	b	structure of wings	aircrafts, flying machines	1	
106	e1	2	b	flying membrane	flying suits	1	

n°	p	t	s	aspect	technical appl./ biol. model	n	r
107	e2	2	b	wings	drive/ wings airplane	1	
108	e2	2	b	sense of orientation	ultrasound (…[illegible])	1	
109	e2	2	b	behaviour in flight	control of UAVs	1	
110	e2	2	b	wings (when sleeping)	protective hull	1	
111	e2	2	b	feet/ claw	gripper, pincers, joining	1	
112	b1	2	a	lightweight design	hollow bones of birds	0	26
113	b1	2	a	air resistance	streamlined shape of fish	0	21
114	b1	2	a	clean surface	lotus flower leave	1	
115	b1	2	a	distraction of electricity (lightning strikes)	electric eel	1	
116	b1	2	a	wing shape	bird wing shape	1	
117	b1	2	a	navigation	orientation of migratory birds: magnetic field	1	
118	b2	2	a	camouflaging of military planes	specific birds (prey)	1	
119	e1	2	a	wings	wings of insects, birds	1	
120	e1	2	a	structure	bone structure of animals, cellular structure of plants	1	
121	e1	2	a	shape	body shape of birds, insects, fish; shape of water drops	1	
122	e1	2	a	drive	flap of insects, birds	1	
123	e1	2	a	gliding flight	albatross, very good at gliding flight	1	
124	e1	2	a	material	plants	1	
125	e1	2	a	connection of wings to the fuselage	tree roots	1	
126	e1	2	a	pressure resistance	fish and other organisms in deep-sea resist to high pressure	1	
127	e1	2	a	energy efficiency	birds fly very energy efficient	1	
128	e2	2	a	aerodynamics	birds, fish	1	
129	e2	2	a	surface/ wings: low friction	fish	0	41
130	e2	2	a	wings	birds	1	

n°	p	t	s	aspect	technical appl./ biol. model	n	r
131	e2	2	a	avionics	bats, wales, snakes	1	
132	e2	2	a	landing gear & shock absorbers	[illegible]-legs, grasshopper	1	
133	e2	2	a	drives	birds, fish	1	
134	e2	2	a	flight dynamics	birds, fish	1	
135	e2	2	a	lightweight design	plant (bamboo), shells (fibres)	1	
136	b5	0	d	body-shape: stream-lined shape	submarine	1	
137	b5	0	d	orientation	shipping industry, automotive industry	1	
138	b5	0	d	long-distance communication	shipping industry, navy	1	
139	b5	0	d	energy consumption	aircraft industry, shipping industry, isolation	1	
140	b5	0	d	skin surface	shipping industry, for objects which make movements with low energy consumption (low friction)	1	
141	b6	0	d	orientation - echo sounder	orientation/ location in shipping industry, location of fish swarms (fishing industry)	1	
142	b6	0	d	body shape	shipping industry - shape ship/ submarine	1	
143	b6	0	d	texture of skin/ body surface	development of diver's suits (e.g. research divers)	1	
144	b6	0	d	fin shape	shipping industry: shape rotor blades	1	
145	e5	0	d	sonography	ultrasound	1	
146	e5	0	d	skin, surface texture	aerodynamics: low resistance, automotive industry, shipping industry	1	
147	e5	0	d	strategy of movement, jumping up and down	devices that move	1	
148	e5	0	d	healing of sick people, therapy	if one knows why it works, a device can imitate the effect, e.g. warmth, contact…	1	

n°	p	t	s	aspect	technical appl./ biol. model	n	r
149	e6	0	d	speed	submarines/ airplanes, cars	1	
150	e6	0	d	fast reactions	robots	1	
151	e6	0	d	ergonomics	robots	1	
152	e6	0	d	contact with other dolphins/ tracking	radars, sending frequencies in special situations	1	
153	e6	0	d	live in cold waters (skin)	type of isolation material	1	
154	e6	0	d	clever	teaching other animals	1	
155	b5	0	r	orientation	dolphin/ whale for location; bat	1	
156	b5	0	r	improvement of movement sequence (joints)	joints (hip)	1	
157	b5	0	r	energy consumption	aerodynamic surface, shark	1	
158	b5	0	r	movement on uneven terrain, sand	snakes	1	
159	b5	0	r	energy production	reloading in the sun for quicker movements in the heat (reptiles)	1	
160	b6	0	r	gripper movement	structure and movement of hand (human)	1	
161	b6	0	r	walking movement	structure and movement of leg/ foot (human/ animals)	1	
162	b6	0	r	network, information transfer	structure of neuronal networks (human/ animal)	1	
163	b6	0	r	receiving information from environment	biological sensors/ receptors, e.g. pressure/ temperature	1	
164	e5	0	r	range of movement, range of vision	owl can rotate a wide range	1	
165	e5	0	r	detection of obstacles in the darkness, e.g. by ultrasound	bat	1	
166	e5	0	r	balance by means of a second arm	tail of monkeys is used for balancing	1	
167	e5	0	r	quicker movement by dynamic jumping	e.g. as cats, kangaroos	1	
168	e5	0	r	only saving of relevant information, e.g. routes, but not saving information about the whole environment	brain	1	

n°	p	t	s	aspect	technical appl./ biol. model	n	r
169	e5	0	r	carrying heavy weights in comparison to own weight, e.g. by means of having several legs	ant, spider	1	
170	e5	0	r	if something is damaged/ not useful any more, throw it away	lizard	1	
171	e6	0	r	joints	human/ animal joints	1	
172	e6	0	r	dynamic reactions	human body	1	
173	e6	0	r	sight/ seeing/ sensing	dolphins' obstacle detection at night (radar)	1	
174	e6	0	r	catching different types of things	snakes (how they move and catch)	1	
175	e6	0	r	walking/ moving	snakes, alligators	1	
176	e6	0	r	self-repairing	lizards	1	
177	b5	1	b	echolocation	airplanes, space flight, automotive industry - autonomous driving	1	
178	b5	1	b	circulatory system	pressure system when hanging headfirst for tubular systems	1	
179	b5	1	b	flying, quick, fast movements	aircraft industry, air force, space flight, toy airplanes	1	
180	b5	1	b	digestion	faeces as fertiliser -> storing of N2	1	
181	b5	1	b	structure of wings	lightweight design for sailplanes, kites	1	
182	b6	1	b	echolocation in air	location in flight space	1	
183	b6	1	b	design wings: skin texture	design of specific flight suits	1	
184	b6	1	b	sleeping in caves-> inner rhythm of day and night	sensors for devices that are actuated depending on the time of day	1	
185	b6	1	b	orientation by earth magnetic field (?)	application in space flight, shipping industry and onshore	1	
186	e5	1	b	ultrasound	detection of obstacles in the darkness	0	165

n°	p	t	s	aspect	technical appl./ biol. model	n	r
187	e5	1	b	soundless flight	military	1	
188	e5	1	b	thin wings/ skin between the fingers	for flying, carrying of multiple weights, military/ aircraft industry	1	
189	e5	1	b	hang to legs when sleeping, stable position as the weight is facing downwards	stapling components with different weights	1	
190	e6	1	b	size/ very small	in finding damaged people under emergency situations (earthquake)	1	
191	e6	1	b	skin for cold weather	isolation	1	
192	e6	1	b	sight at night	radars for robots	1	
193	e6	1	b	hard nails/ teeth	drills	1	
194	b5	1	a	shape of wings	albatross, swift	1	
195	b5	1	a	movement of wings during flight (only tips)	albatross	1	
196	b5	1	a	use of upwind/ gliding (air turbulence)	albatross, eagle	1	
197	b5	1	a	surface of airplanes	placoid scales of sharks	1	
198	b5	1	a	ultrasound, echolocation	bats	1	
199	b5	1	a	orientation at the earth' magnet field	storks	1	
200	b6	1	a	aerodynamics and thereby low consumption of fuel	design of bird's body	1	
201	b6	1	a	increase of speed	design/ flying of long distance flyers (e.g. albatross)	1	
202	b6	1	a	decrease of weight	design of birds	1	
203	b6	1	a	improved control by adapting wings of the airplanes	hand wings of birds	1	
204	e5	1	a	uplift by warmth	gliding of birds	1	
205	e5	1	a	centre of gravity (in the middle)	big birds	1	
206	e5	1	a	energy only necessary when starting and landing, in-between gliding	birds	1	

n°	p	t	s	aspect	technical appl./ biol. model	n	r
207	e5	1	a	detection of obstacles in the darkness by ultrasound	bat	0	186
208	e5	1	a	changing of the route when in danger (for example thunderstorm)	rats	1	
209	e5	1	a	control by smaller components	tail tip of birds, fish	1	
210	e6	1	a	aerodynamic	all kinds of flying animals/ dolphins	1	
211	e6	1	a	radars	bats	0	192
212	e6	1	a	isolation	walls [illegible]	1	
213	e6	1	a	stability	birds' stability in storm	1	
214	b5	2	e	temperature reduction, heat emission by ears	machines	1	
215	b5	2	e	orientation by points	navigation	1	
216	b5	2	e	handling of high weights and movement	robot	1	
217	b5	2	e	trunk	manoeuvrability and flexibility for robot arms	1	
218	b5	2	e	exploitation of food, cellulose	gain of substrates, processing industry	1	
219	b6	2	e	whole weight is supported by only four feet special structure of feet	transportation of high weights	1	
220	b6	2	e	absorb water despite gravity without effort	transportation of high weights: reduction of effort and energy	1	
221	b6	2	e	ears: heat exchanger (African elephant)	protection against over-heating in electric devices	1	
222	b6	2	e	long-time memory; saving of information crucial for survival	artificial intelligence --> selection of important information	1	
223	e5	2	e	big ears with large surface to emit heat	heating, oven	1	
224	e5	2	e	tusks for scaring and transportation	staple boxes	1	

n°	p	t	s	aspect	technical appl./ biol. model	n	r
225	e5	2	e	thick skin, resistance against branches, can be covered with mud for cooling	cover for cooling or gel layer	1	
226	e5	2	e	trunk, transportation of water	fire fighter's hose	1	
227	e5	2	e	tail for children to hold on to	large vehicles, several vehicles, trains	1	
228	e6	2	e	teeth/ sharp	for drilling	1	
229	e6	2	e	trunk	holding anything (very flexible)	1	
230	e6	2	e	ears	cooling	1	
231	b5	2	s	echolocation, radar	whales, bats	0	177
232	b5	2	s	reduction of surface resistance	placoid scales of sharks	0	197
233	b5	2	s	manoeuvrability	whales	1	
234	b5	2	s	faster boats with lower energy consumption (drive)	whales, sharks, tuna	1	
235	b5	2	s	gliding abilities of catamarans	landing birds	1	
236	b5	2	s	movement without energy consumption	use of streams as jelly fish/ turtles	1	
237	b6	2	s	orientation, fishing, fish location	echolocation whale/ dolphin	0	141
238	b6	2	s	consumption of energy due to ship body design	fish- body structure	0	142
239	b6	2	s	steering of ship	fin design sea bear, seals, sharks (fish)	1	
240	b6	2	s	ship drive	fin design sea bear, seals	1	
241	b6	2	s	reduction of water resistance	texture surface fish (rays, shark)	1	
242	b6	2	s	speed	fish- body structure	1	
243	e5	2	s	weight should depend on size -> wider structures	animals swim overwater if they do not divert too much water (duck)	1	
244	e5	2	s	steering behind has much influence	steering by tail fin (behind, middle)	1	
245	e5	2	s	straight movement	symmetric drive, duck fins	1	
246	e5	2	s	streamlined water lines	front with wedge-shape, e.g. head of duck, fish	1	

n°	p	t	s	aspect	technical appl./ biol. model	n	r
247	e6	2	s	aerodynamics	dolphins, whales, fish	1	
248	e6	2	s	controlling	all kinds of fish	1	
249	e6	2	s	reduction of friction at the surface	fish skin	1	
250	b7	0	b	flight (movement)	adapted body structure, skeleton, imitation by flying machines	1	
251	b7	0	b	hearing (ultrasound)	development of location possibilities	1	
252	b7	0	b	skin	-	0	t
253	b8	0	b	general echolocation	non-visual navigation	1	
254	b8	0	b	acoustic perception of distances by echo-delay	distance measurement to objects (e.g. cars in traffic)	1	
255	b8	0	b	echolocation: perception of object size/ shape because of the composition of a reflected echo	object identification / analysis and robotics	1	
256	e7	0	b	Flapping/ structure of wings/ wing material	adaptive wing design, elastic membranes	1	
257	e7	0	b	ultrasound for hunting	biological radar/ ultrasound sensors	1	
258	e7	0	b	bones/ skeleton	lightweight designs	1	
259	e7	0	b	orientation	navigation systems	1	
260	e8	0	b	location by sound waves	acoustic measurement of distance	1	
261	e8	0	b	feet/ claws for gripping on the ceiling	fixation of any kind	1	
262	e8	0	b	wing material	material development	1	
263	e8	0	b	communication between bats	alternative communication	1	
264	b7	0	a	wings -> shape, weight, stability	wings -> shape, bone structure	1	
265	b7	0	a	air resistance > shape of the airplane	bird -> aerodynamic	1	
266	b8	0	a	general aerodynamics	birds, shape of wings, body etc.	1	

n°	p	t	s	aspect	technical appl./ biol. model	n	r
267	b8	0	a	surface texture regarding friction	rough skin of sharks	1	
268	b8	0	a	surface texture regarding dirt/ ice	body surface of insects -> hydrophobic insect cuticula	1	
269	e7	0	a	uplift	air foil shapes of bird wings	1	
270	e7	0	a	adaptive aerodynamics	bat wings	0	256
271	e7	0	a	drag coefficient	shark skin	1	
272	e7	0	a	energy efficient drive	flapping, swinging?	1	
273	e7	0	a	navigation/ optimization of flight route	artificial migrator birds' intelligence	1	
274	e7	0	a	energy-efficient fuel, flight dynamic/ stability	balance organs of a moth	1	
275	e8	0	a	fibre-reinforced material -> [illegible] fibres	spiders	1	
276	e8	0	a	sandwich design, hollow cylinder shape	hollow plant structures	1	
277	e8	0	a	fibre-reinforced material with directed properties	wood	1	
278	e8	0	a	improve aerodynamics	birds, insects (particularly interesting)	1	
279	e8	0	a	wing material	bat	1	
280	b7	1	e	foot shape -> wide surface, distribution of high weight on 4 feet	stability of objects, balance	1	
281	b7	1	e	trunk -> shape, orientation	absorption of liquids via tubes	1	
282	b7	1	e	skin -> rough, thick, protective	dirt protection, injury of materials, surfaces	1	
283	b7	1	e	large ears -> transpiration	creation of large surfaces for enhanced evaporation	1	
284	b8	1	e	movement possibilities of the trunk	steering/ movement of robot arms	1	
285	b8	1	e	trunk movement, particularly with regards to gripping objects (food etc.)	precise steering of robot grippers	1	
286	b8	1	e	skeleton structure	weight distribution	1	

n°	p	t	s	aspect	technical appl./ biol. model	n	r
287	e7	1	e	skeleton	stability of building structures	1	
288	e7	1	e	skin	resistant, breathable membranes	1	
289	e7	1	e	orientation in savannah	navigation	1	
290	e7	1	e	force and carrying of weights	transportation on difficult terrain	1	
291	e8	1	e	flexible trunk	mechanism of the trunk can be used as an example for developing flexible instruments -> endo[illegible], flexible cameras	1	
292	e8	1	e	skeleton	skeleton can carry high weights	1	
293	e8	1	e	ears for cooling	large area for cooling blood in the ear	1	
294	b7	1	s	material for building ships	tree -> both strong and flexible wood	1	
295	b7	1	s	shape of the ship -> lowest water resistance	fish/ water organisms -> stream lined shape	1	
296	b7	1	s	sail -> orientation, size, material	inspired by birds/ flying animals: e.g. catching upwind in the wings	1	
297	b7	1	s	outer material/ layer water repellent	protective skin/ membrane everywhere in animal world	1	
298	b7	1	s	much space inside, few inner walls	building of nests by birds > stability	1	
299	b8	1	s	reduction of friction	rough skin surface of sharks/ rays	1	
300	b8	1	s	prevention of vegetation on ship's hull	skin surface of fish	1	
301	e7	1	s	flow resistance (microscopic)	shark skin structure	1	
302	e7	1	s	prevention of erosion on ship's propeller by cavitation	fin tips of tuna	1	
303	e7	1	s	flow resistance (macroscopic)	streamlined shape (e.g. dolphin)	1	
304	e7	1	s	energy optimization drive	flapping of fins	1	
305	e7	1	s	optimization uplift -> resistance optimization	lighter materials	1	

n°	p	t	s	aspect	technical appl./ biol. model	n	r
306	e8	1	s	hydrophobic surface of the ship's hull to reduce water resistance	leaves -> lotus effect	1	
307	e8	1	s	protection of the surface against corrosion	organic material does not show this type of corrosion	1	
308	e8	1	s	sandwich design to reduce weight and water displacement	plants and wood	1	
309	b7	2	d	skin-> smooth surface, low resistance in water	movement in water -> ship	1	
310	b7	2	d	muscles tail fin	force for jumping	1	
311	b7	2	d	body shape -> long body, pointed	fast movement in water	1	
312	b8	2	d	shape/ anatomy reduces flow resistance	reduced flow resistance of ships, etc.	1	
313	b8	2	d	skin surface prevents dirt, vegetation	surface optimization of ships	1	
314	e7	2	d	streamlined shape	optimization of ships' and airplanes' hulls	0	303
315	e7	2	d	communication between dolphins	sonar for underwater scans	1	
316	e8	2	d	faster swimmer	faster boats	1	
317	e8	2	d	communication under water	long-distance communication without cables/ radio	1	
318	e8	2	d	can endure long times without breezing	improvement of diving abilities	1	
319	e8	2	d	skin is hydrophobic -> low gliding resistance in water	energy efficient and fast boats	1	
320	b7	2	r	movement	imitation of neurons (human, animal) which transfer impulses to muscles	1	
321	b7	2	r	body shape, balance	structure of human skeleton, distribution of proportions	1	
322	b7	2	r	intelligence -> storing devices	imitation of brain	1	
323	b8	2	r	navigation	echolocation of bats	0	253

n°	p	t	s	aspect	technical appl./ biol. model	n	r
324	b8	2	r	object identification	echolocation bats or visual processing in general by animals	1	
325	b8	2	r	structure and movement of grippers	joint structure and muscle anatomy (fixation to joints, tendons, etc.) of animals	1	
326	b8	2	r	movement	leg movement	1	
327	e7	2	r	quickness/ security by perceiving obstacles/ objects in the arm	octopus arms with "thinking" neurons	1	
328	e7	2	r	ability to carry weights and mobility	artificial camel walking on 4 legs	1	
329	e8	2	r	moving objects	elephant trunk	1	
330	e8	2	r	joints [?, illegible]	bone structure and evolutionary solutions of humans and animals	1	
331	e8	2	r	options for perceiving the environment	orientation at the evolutionary model (eye)	1	
332	e8	2	r	central processing unit	human brain	1	
333	e8	2	r	decentralised control	cockroach and other insects	1	
334	e8	2	r	self-reproduction	all biological models	1	
335	b9	0	d	aerodynamic shape	reduction of resistance	1	
336	b9	0	d	skin	protective layer, resists environmental influences	1	
337	b9	0	d	sonar	efficient echolocation underwater	1	
338	b9	0	d	skin and fat layer	heat isolation methods	1	
339	b9	0	d	communication/ language	efficient information transfer (no words)	1	
340	b9	0	d	hunting behaviour in group	military strategy for attacks	1	
341	b9	0	d	lasting movement	example for efficient forms of movement / low-energy updrift methods	1	
342	b9	0	d	composition of milk with many fats	replacement of food/ shows necessary composition of food	1	

n°	p	t	s	aspect	technical appl./ biol. model	n	r
343	b10	0	d	composition/ structure of the skin surface	race car/ outer parts of ships/ airplane	1	
344	b10	0	d	shape of the dolphin	race car/ outer parts of ships/ airplane: aerodynamics	1	
345	b10	0	d	detection of sounds	detection of sounds, for what? Space?	1	
346	b10	0	d	movement of fins	movement of water vehicles	1	
347	b10	0	d	production of sound	futuristic music instruments	1	
348	b10	0	d	trajectory of dolphin when jumping	building of airplanes	1	
349	e9	0	d	skin - friction	reduce friction resistance, technology in general	1	
350	e9	0	d	spine - movement	adapt movement - robotic	1	
351	e9	0	d	perception of other animals by sound/ acoustic	location of objects in water	1	
352	e10	0	d	skin surface	optimization of resistance, if necessary lotus flower effect	1	
353	e10	0	d	fin types	drive technology	1	
354	e10	0	d	ultra sound communication	interpretation of communication behaviour -> recognition of patterns	1	
355	e10	0	d	material structure of hard nose	modern building / machine structures	1	
356	b9	0	r	speed	moving method of cheetahs	1	
357	b9	0	r	height of jumps	hind legs of grasshoppers	1	
358	b9	0	r	protective layer	shark skin	1	
359	b9	0	r	swimming with little resistance	shape of shark	1	
360	b9	0	r	low weight despite stable shape	bird bones	1	
361	b9	0	r	principles of vision (360°)	insect eyes (facet eyes)	1	
362	b9	0	r	efficient flight	flight movement of eagles	1	
363	b9	0	r	sensing by touch	human fingertips	1	
364	b10	0	r	movement	e.g. human legs	1	

n°	p	t	s	aspect	technical appl./ biol. model	n	r
365	b10	0	r	production of sound	human -> throat	1	
366	b10	0	r	ability to grip	hands	1	
367	e9	0	r	movement	spider	1	
368	e9	0	r	stiffness	bamboo	1	
369	e9	0	r	energy efficiency/ lightweight design	honeycomb patterns bees' hives	1	
370	e9	0	r	detection of possible collisions via sound impulses	dolphin	0	351
371	e10	0	r	swarm intelligence, several robots collaborate	ants, birds	1	
372	e10	0	r	dirt-rejecting surface	lotus flower	1	
373	e10	0	r	optimized movement trajectory	migratory birds	1	
374	e10	0	r	vacuum gripper / arm	salamander feet -> adhesion forces	1	
375	e10	0	r	robot joint	human joint	1	
376	b9	1	b	echolocation	sonar	1	
377	b9	1	b	processing of echo signals in the brain	improvement of sonar technology / understanding of acoustics (stealth helicopter)	1	
378	b9	1	b	flying abilities (large radius of wings)	improvement of helicopter flight	1	
379	b9	1	b	eyes (sight in dusk)	night-vision device	1	
380	b10	1	b	behaviour in flight	building of airplanes/ rockets	1	
381	b10	1	b	wing structure	airplane wings	1	
382	b10	1	b	visual abilities in darkness	night-vision device	1	
383	b10	1	b	gripping on cave ceiling	anyplace where fixation devices/ snapping devices are necessary	1	
384	b10	1	b	body shape	aerodynamics	1	
385	e9	1	b	orientation in darkness	ultra sound location	1	
386	e10	1	b	ultrasound location	navigation… driver assistance	1	
387	e10	1	b	wings	aircraft	1	

n°	p	t	s	aspect	technical appl./ biol. model	n	r
388	b9	1	a	outer layer, aerodynamics	shark skin	1	
389	b9	1	a	reduction of turbulences	eagle: feathers at the border of wings	1	
390	b9	1	a	uplift	eagle flight	1	
391	b9	1	a	weight (hollow structures)	bird bone structure	1	
392	b9	1	a	reduction of sounds	flapping	1	
393	b10	1	a	shape of the hull	bird hull	1	
394	b10	1	a	wing shape	bird wings	1	
395	b10	1	a	landing	landing of birds	1	
396	b10	1	a	outer hull	birds' outer hull	1	
397	b10	1	a	manoeuvring	birds	1	
398	e9	1	a	aerodynamics	birds	1	
399	e10	1	a	flap system, wing profile	bird -> uplift	1	
400	b9	2	e	trunk	gripper arm	1	
401	b9	2	e	thickness of skin	protective layer, resists environmental influences	1	
402	b9	2	e	skeleton (adapted to high weight and size)	stabilizing structures	1	
403	b9	2	e	adaption to heat/ heat transfer in body	water-based cooling systems	1	
404	b9	2	e	feet/ increase in weight	stability of large structures	1	
405	b10	2	e	trunk	water tube/ hose	1	
406	b10	2	e	ears	sun protection	1	
407	b10	2	e	water storage	polymer with water	1	
408	b10	2	e	skin	breathable for cooling polymers/ sport clothing	1	
409	e9	2	e	trunk	gripping of objects	1	
410	e10	2	e	big ears	ventilator	1	
411	e10	2	e	good memory	specific brain structure?	1	
412	e10	2	e	robust skin	surface treatment	1	
413	b9	2	s	aerodynamic shape/ resistance	whale	0	335
414	b9	2	s	water redirection, properties	whale, seal	1	

n°	p	t	s	aspect	technical appl./ biol. model	n	r
415	b9	2	s	reduction of flow turbulences	shark fins	1	
416	b9	2	s	reduction of portion of ship underwater (catamaran)	jelly fish - species with sails	1	
417	b10	2	s	outer skin	fish skin	1	
418	b10	2	s	speed	fish shape	1	
419	b10	2	s	movement ship propeller	fish/ wind wheel	1	
420	e9	2	s	resistance	fish shape, skin	1	
421	e9	2	s	drive	fish flapping of fins	1	
422	e10	2	s	stream line shape (flexible)	fish	1	
423	e10	2	s	uplifting object for emergency situations	swim bladder	1	
424	e10	2	s	surface texture	fish/ scales -> resistance	1	
425	b11	0	e	feet are very sensitive	earthquake warning system	1	
426	b11	0	e	trunk	gripper in manufacturing	1	
427	b11	0	e	tusks: ivory	material for hard objects	1	
428	b11	0	e	large ears	catch more sound/ waves for detection	1	
429	b12	0	e	texture of skin	specific surfaces	1	
430	b12	0	e	trunk	tubes	1	
431	b12	0	e	force/ weight distribution; body structure in general	design/ stability	1	
432	b12	0	e	efficient temperature management, ratio of extremities in comparison to surface	heat transfer, efficient use of energy	1	
433	e11	0	e	trunk	flexible vacuum and blow tube with gripper function for example for big dirt particles	1	
434	e11	0	e	skin	weather/ shock protection, flexible, robust	1	
435	e11	0	e	size and weight	security due to own weight (or securing)	1	
436	e11	0	e	eyes	optic measurement/ identification systems	1	

n°	p	t	s	aspect	technical appl./ biol. model	n	r
437	e11	0	e	horny skin on foot soles	adaptive, robust surface for difficult terrain	1	
438	e12	0	e	trunk: flexibility	gripper: flexibility	1	
439	e12	0	e	ears	heat exchanger	1	
440	e12	0	e	multi-functionality of trunk (smelling, water absorption, gripper)	combination gripper and sensors	1	
441	e12	0	e	skin	isolation	1	
442	b11	0	s	sonar	whales, dolphins, bat	1	
443	b11	0	s	ship paint, water repellent	lotus flower	1	
444	b11	0	s	driving characteristics with little resistance in water (flow characteristics)	shape of shark (example)	1	
445	b11	0	s	navigation	birds: orientation at sun position	1	
446	b12	0	s	shape: more uplift and better gliding through water	fish	1	
447	b12	0	s	surface: better gliding through water, no adherence of shells	fish?	1	
448	e11	0	s	gliding properties of the trunk in water	shark skin, feathers, e.g. of the great crested grebe, hair as a beaver	1	
449	e11	0	s	streamlined shape of hull	body shape of dolphins, shark, penguin	1	
450	e12	0	s	propulsion by propeller (cavitation, turbulence, etc.) (reduction of fuel)	movement of fish	1	
451	e12	0	s	resistance by ship hull	fish, penguin, etc.: body structure	1	
452	e12	0	s	resistance by outer hull	"air-bubble" outer layer of penguin	1	
453	e12	0	s	reduce torsion of ships	"stiff" structures in nature: honeycombs	1	
454	b11	1	d	ultra sound	sonar, ultrasound in medical applications	1	
455	b11	1	d	texture of skin	water repellent materials	1	

n°	p	t	s	aspect	technical appl./ biol. model	n	r
456	b11	1	d	shape	for better underwater devices -> better flow properties	1	
457	b11	1	d	tail fin	movement of devices, humans in water	1	
458	b12	1	d	shape of the dolphin	resistance in water of specific objects (ship building)	1	
459	b12	1	d	communication	water communication	1	
460	b12	1	d	skin of the dolphin	surface properties	1	
461	b12	1	d	movement	ship building, movement of water (turbines?)	1	
462	e11	1	d	body shape	flow optimized hulls of ships and submarines	0	449
463	e11	1	d	sonar	sonar	1	
464	e12	1	d	movement	ship drive	1	
465	e12	1	d	dolphin skin	layer for ships	1	
466	e12	1	d	sonar	detection of movement when vision is limited	1	
467	b11	1	r	movement of arms	joints and tendons, modular structure	1	
468	b11	1	r	movement in direction of chemical gradient	bacteria searching for nutrient	1	
469	b11	1	r	registration of the environment	linking of two eyes through the brain	1	
470	b11	1	r	balance by means of a second arm	ear	1	
471	b12	1	r	signal receiving	receptors of animals (wasp, facet eyes)	1	
472	b12	1	r	joint of robots for movement	spine	1	
473	e11	1	r	actors	self-controlling (artificial) fibres, similar to muscles	1	
474	e11	1	r	gyroscope	cochlea	1	
475	e11	1	r	capacitive layer of the fingertips	sense of touch	1	
476	e11	1	r	light weight design by	for example joints in the bones	1	

n°	p	t	s	aspect	technical appl./ biol. model	n	r
				topology optimization			
477	e12	1	r	sensors (e.g. security when in contact with humans)	elephant trunk	1	
478	e12	1	r	flexibility ("joints")	elephant trunk	0	438
479	e12	1	r	multi-functionality of a gripper	human hand	1	
480	e12	1	r	stiffness of a robot	bones	1	
481	b11	2	b	wings	paraglider	1	
482	b11	2	b	navigation by sound	aircraft industry, navigation	1	
483	b11	2	b	hooks on wings	mounting	1	
484	b12	2	b	hearing/ communication	ultrasound -> communication	1	
485	b12	2	b	wing	flying machines	1	
486	b12	2	b	body structure, proportions	flying machines	1	
487	b12	2	b	living headfirst	medical devices	1	
488	e11	2	b	whistle sounds	ultra sound	1	
489	e11	2	b	flying membrane	cover of wings	1	
490	e11	2	b	ear	radar	1	
491	e11	2	b	fur	isolation	1	
492	e12	2	b	cover of wings	optimization wings of airplanes	1	
493	e12	2	b	sonar	identification of environment when view is restricted	1	
494	e12	2	b	sleeping headfirst -> blood cannot stay in head	use of phenomenon for pumps	1	
495	b11	2	a	aerodynamics	birds	1	
496	b12	2	a	dynamics	eagle	1	
497	b12	2	a	shape	"fast" bird, insect	1	
498	b12	2	a	proportions	bird	1	
499	b12	2	a	manoeuvrability, steering	dragonfly	1	
500	e11	2	a	resistance of outer skin	feathers	1	
501	e11	2	a	orientation	magnet receptors in bird beaks	1	
502	e11	2	a	light weight design	hollow bird bones	1	

n°	p	t	s	aspect	technical appl./ biol. model	n	r
503	e11	2	a	uplift systems	spread wings	1	
504	e12	2	a	wings -> weight reduction by "skin cover"	bird, bat	1	
505	e12	2	a	weight reduction	biological light weight design -> hollow bird bones	1	
506	e12	2	a	air resistance	imitate surface of feathers	1	
507	e12	2	a	agility/ manoeuvrability	dragon fly control	1	

11.10 Wilcoxon rank-sum test

This section includes the tabulated values for the Wilcoxon rank-sum test (Table 11-15) and the Wilcoxon signed-rank test (Table 11-16). Moreover, an example for comparing the histograms (distribution and standard deviation) is shown in Figure 11-71.

Table 11-15: 1.1 Critical values of U for the Wilcoxon rank-sum test (one-sided test) (Sachs, 2004, pp. 381–392)
$n_{1/2}$: number of values for each population; α: level of significance (probability of error)

n_1	n_2	U (α=2.5%)	U (α=5%)	U (α=10%)
5	5	5	4	2
7	8	16	13	10
10	5	13	11	8
10	10	32	27	23
14	6	17	21	25
15	5	22	18	14

Note: The lower U-value has to be lower than the values shown in the table for the specific probability of error α.

For example: $n_1=14$, $n_2=6$, $U_1=17$, $U_2=34$ → $U_1 < U_2$, therefore U_1 is regarded:

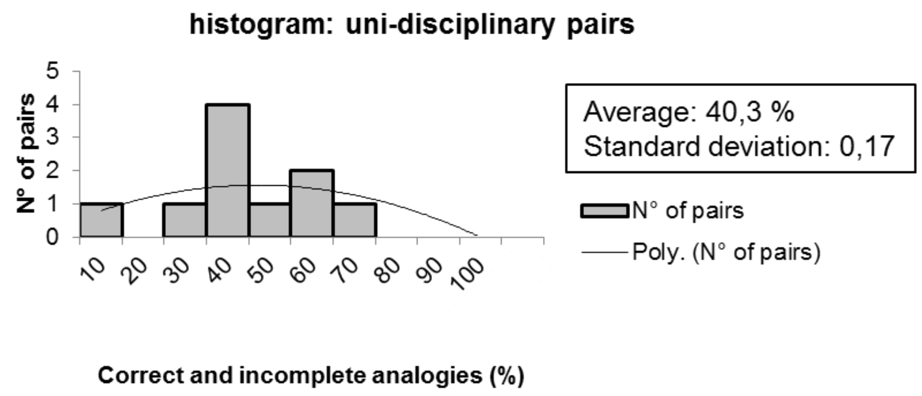
For α=2.5%: U_1 has to be lower than 17, this is not the case

For α=5%: U_1 has to be lower than 21, this is the case, for this test the probability of error is therefore α<5%:

Table 11-16: 1.1 Critical values of U for the Wilcoxon signed-rank sum test (two-sided test) (Sachs, 2004, p. 393)
$n_{1/2}$: number of values for both populations; α: level of significance (probability of error)

n	U (α=10%)	U (α=5%)
15	30	25
16	35	30
17	40	35
18	46	40
19	52	46
20	60	52

Note: The lower rank sum (absolute value) has to be lower than the values shown in the table for the specific probability of error α.



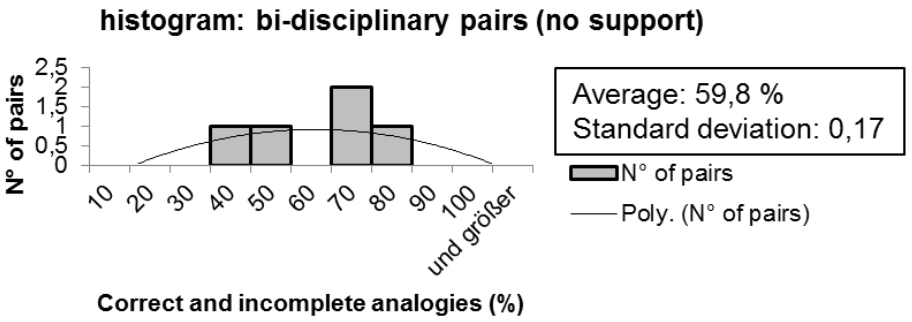


Figure 11-71: Exemplary histograms- distribution and standard deviation are similar

11.11 *BioId* support (first version)

This sub-section shows the templates of the first version of *BioId* for the technical task and the biological information.

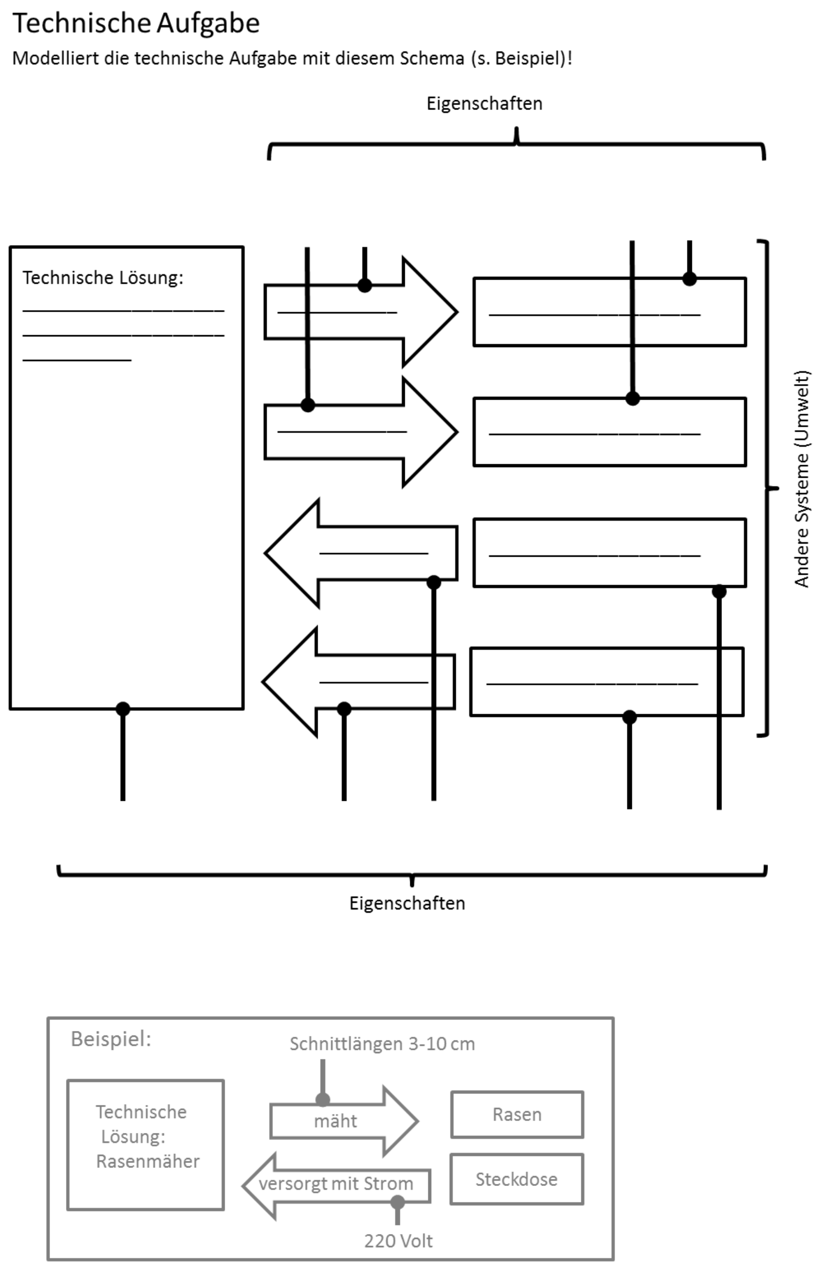


Figure 11-72: First version BioId: template technical task

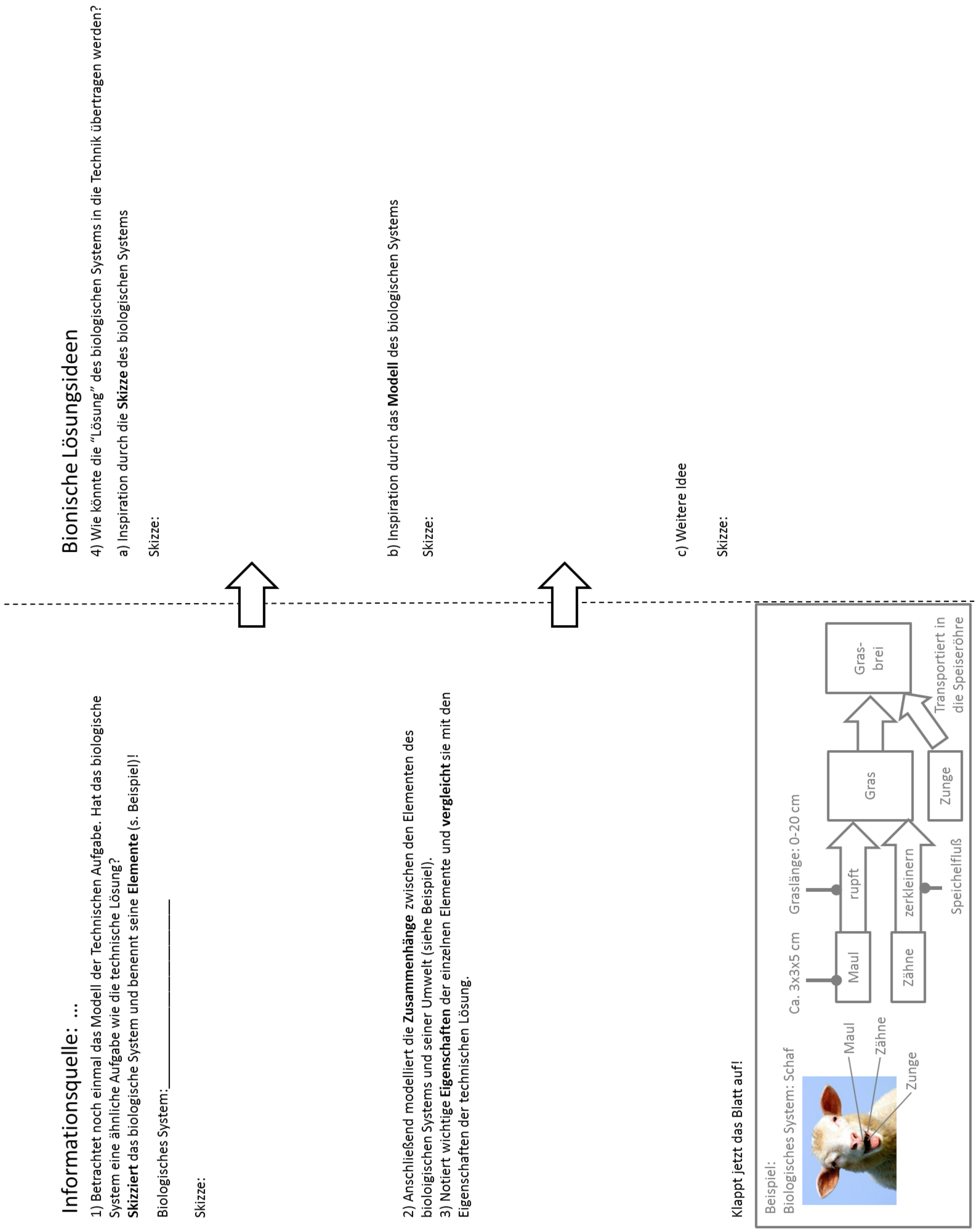


Figure 11-73: First version BioId: template biological information

11.12 Documentation of the support evaluation (prescriptive study)

This section shows the documentation of the support evaluation for the collaborating pair and the pair that worked individually a part of the time.

11.12.1 Collaborating pair

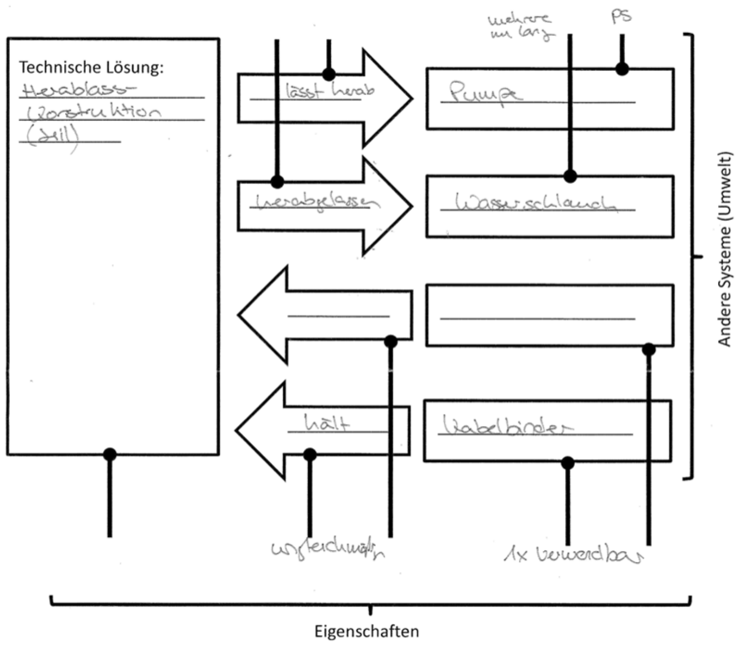


Figure 11-74: Collaborating pair – template technical task

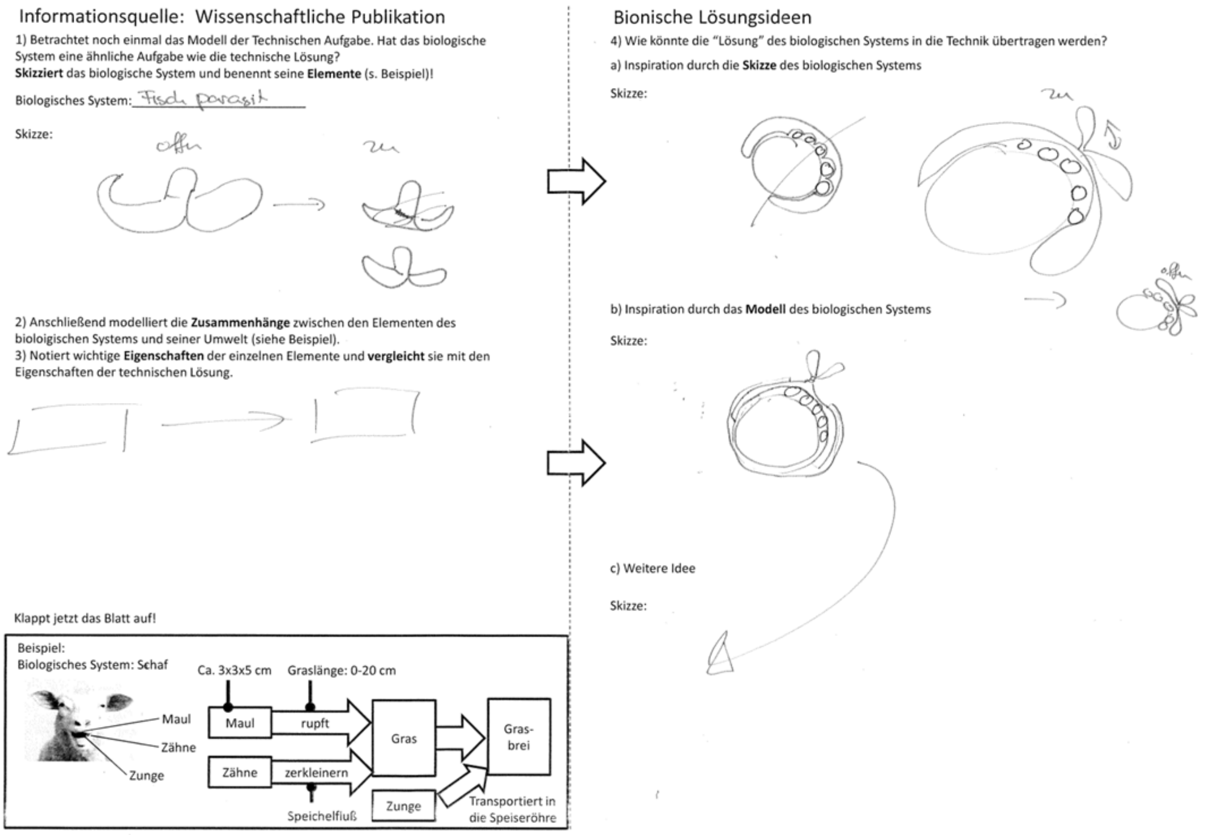


Figure 11-75: Collaborating pair – template biological information (publication)

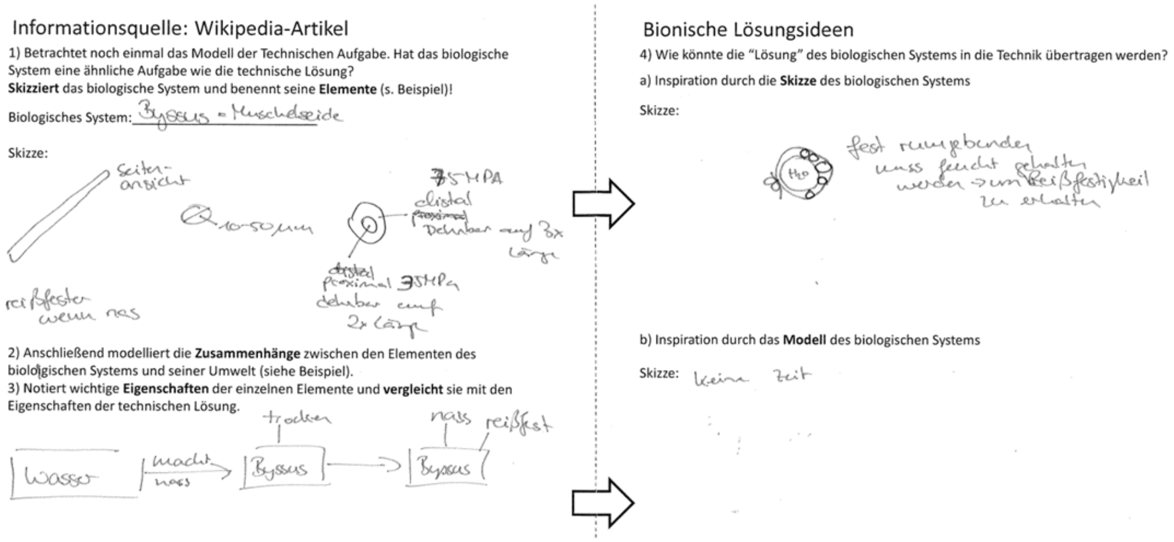
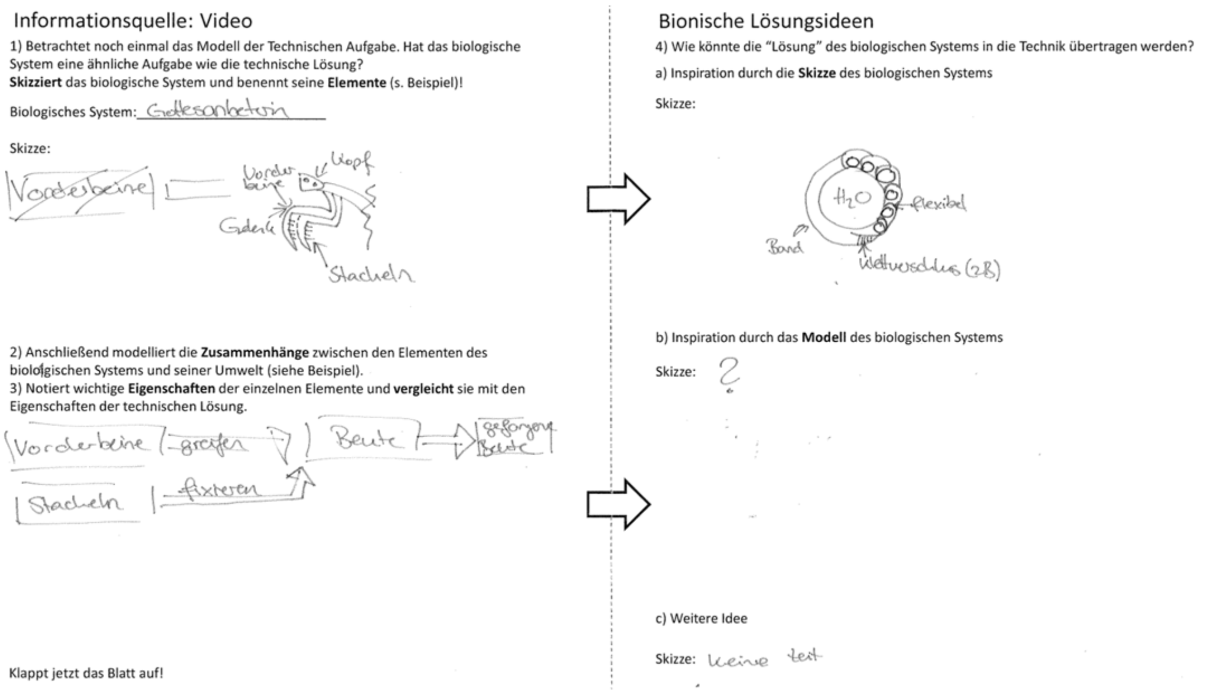


Figure 11-76: Collaborating pair – template biological information (Wikipedia article)



Informationsquelle: Video

1) Betrachtet noch einmal das Modell der Technischen Aufgabe. Hat das biologische System eine ähnliche Aufgabe wie die technische Lösung?
Skizziert das biologische System und benennt seine **Elemente** (s. Beispiel)!

Biologisches System: Gottesanbeterin

Skizze:

2) Anschließend modelliert die **Zusammenhänge** zwischen den Elementen des biologischen Systems und seiner Umwelt (siehe Beispiel).
3) Notiert wichtige **Eigenschaften** der einzelnen Elemente und **vergleicht** sie mit den Eigenschaften der technischen Lösung.

Klappt jetzt das Blatt auf!

Bionische Lösungsideen

4) Wie könnte die "Lösung" des biologischen Systems in die Technik übertragen werden?

a) Inspiration durch die **Skizze** des biologischen Systems

Skizze:

b) Inspiration durch das **Modell** des biologischen Systems

Skizze: ?

c) Weitere Idee

Skizze:

Figure 11-77: Collaborating pair – biological information (video)

11.12.2 Individually working pair

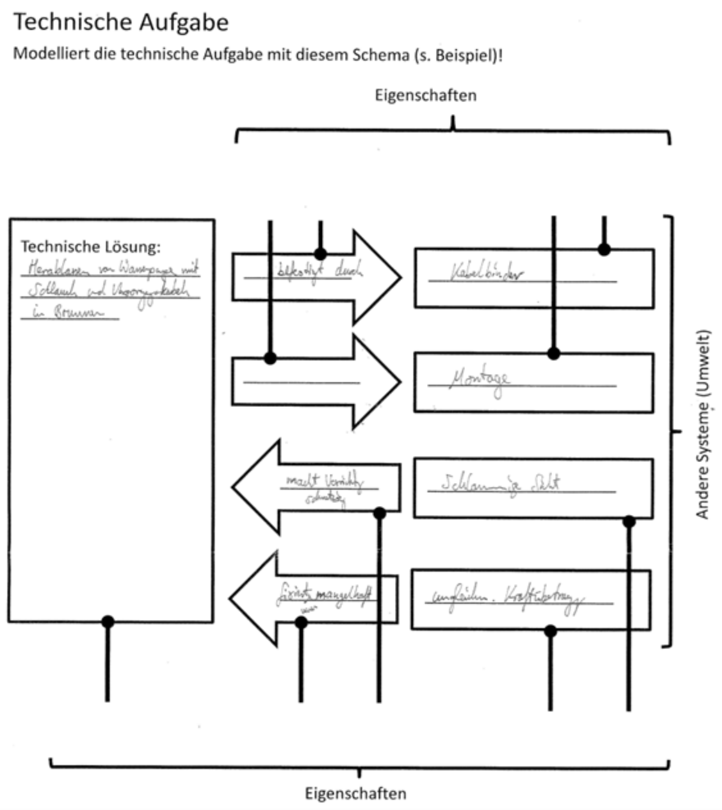


Figure 11-78: Engineer – template technical task

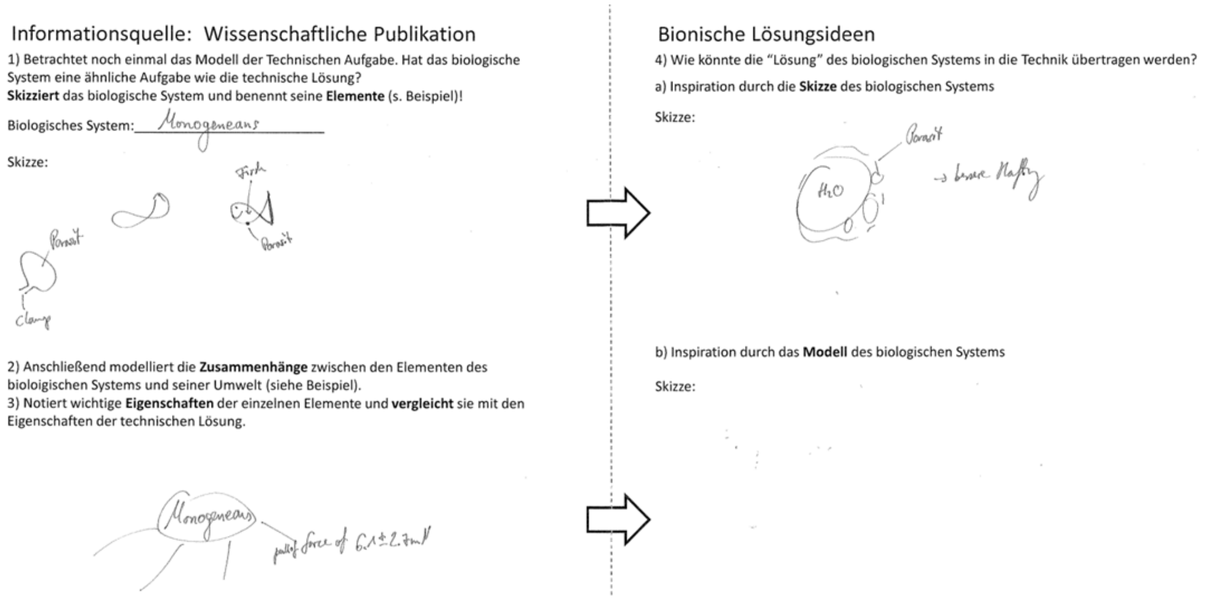


Figure 11-79: Engineer – template biological information (publication)

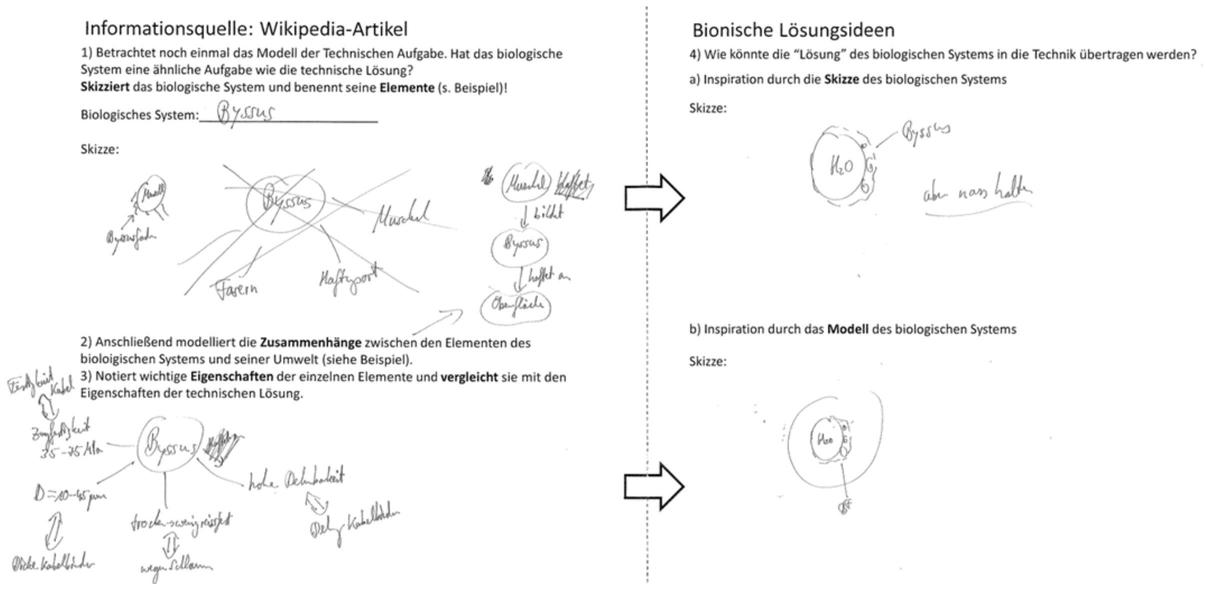


Figure 11-80: Engineer – template biological information (Wikipedia article)

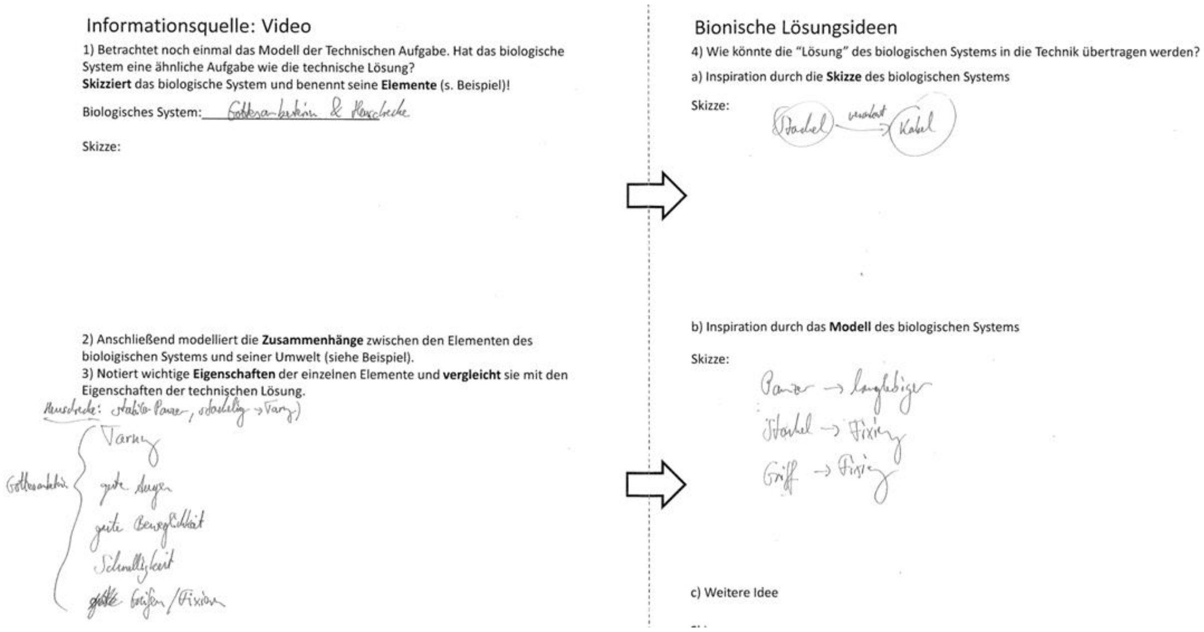


Figure 11-81: Engineer – template biological information (video)

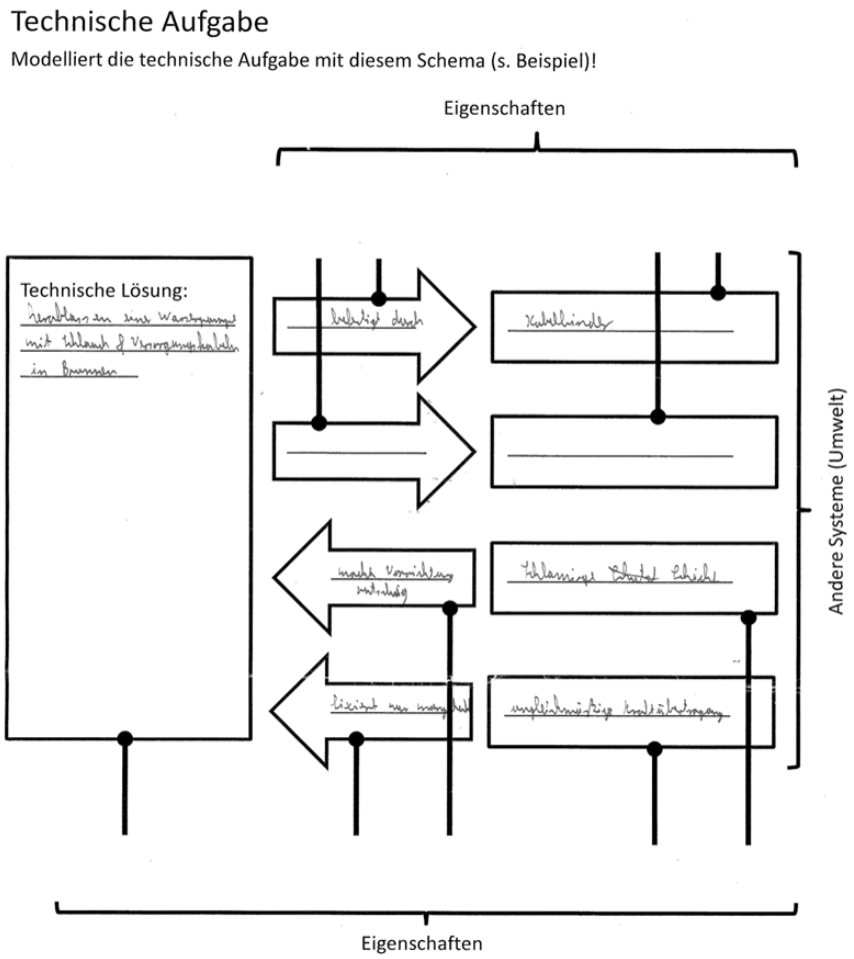
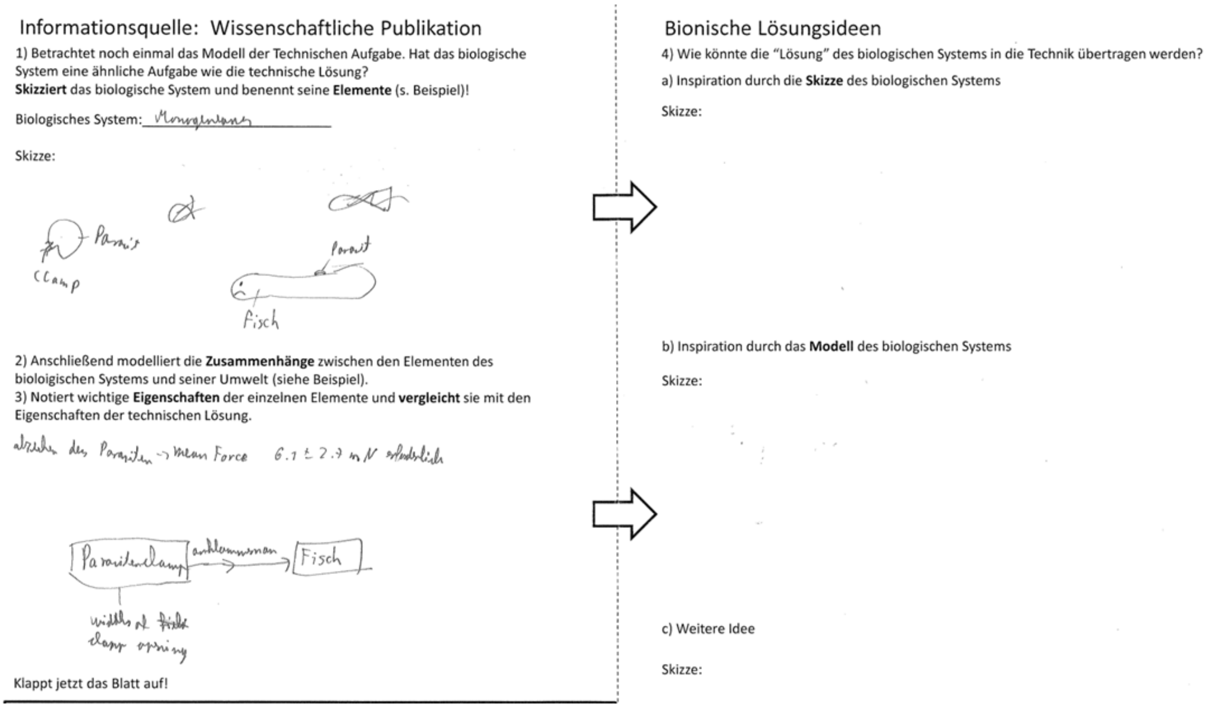


Figure 11-82: Biologist – template technical task



Informationsquelle: Wissenschaftliche Publikation

1) Betrachtet noch einmal das Modell der Technischen Aufgabe. Hat das biologische System eine ähnliche Aufgabe wie die technische Lösung?
Skizziert das biologische System und benennt seine **Elemente** (s. Beispiel)!

Biologisches System:

Skizze:

Fisch

2) Anschließend modelliert die **Zusammenhänge** zwischen den Elementen des bioloigischen Systems und seiner Umwelt (siehe Beispiel).
3) Notiert wichtige **Eigenschaften** der einzelnen Elemente und **vergleicht** sie mit den Eigenschaften der technischen Lösung.

Mean Force 6.1 ± 2.7 mN

Fisch

Klappt jetzt das Blatt auf!

Bionische Lösungsideen

4) Wie könnte die "Lösung" des biologischen Systems in die Technik übertragen werden?

a) Inspiration durch die **Skizze** des biologischen Systems

Skizze:

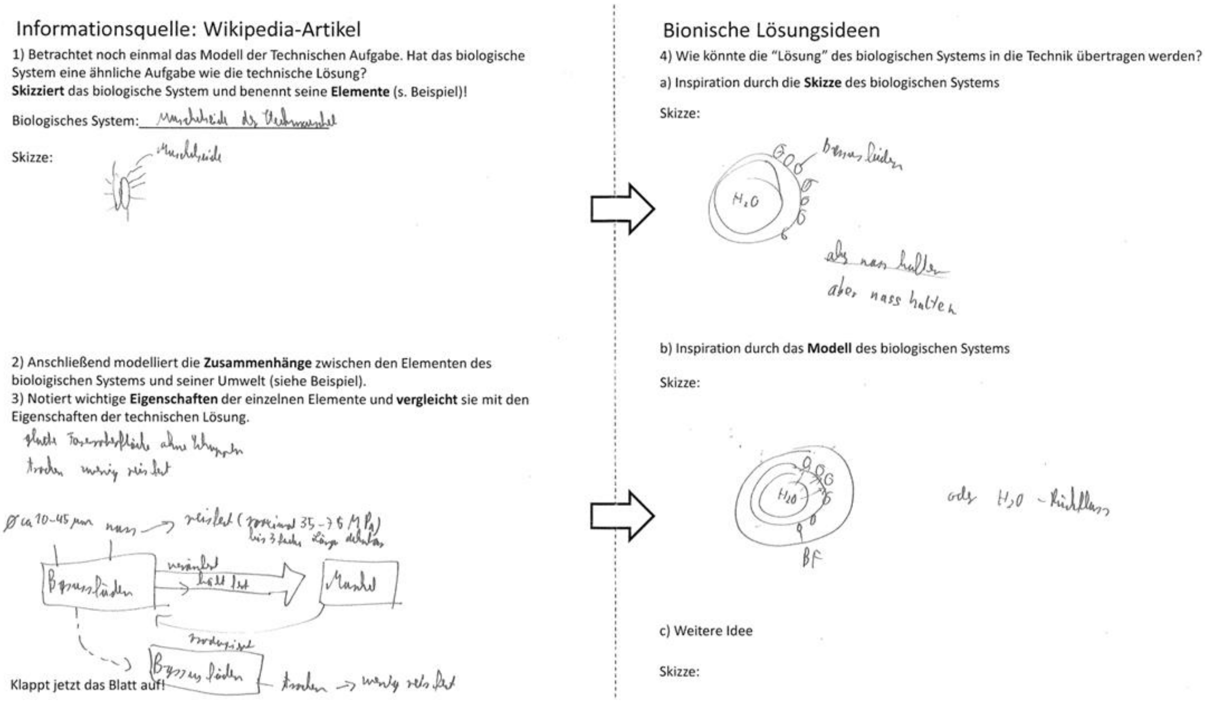
b) Inspiration durch das **Modell** des biologischen Systems

Skizze:

c) Weitere Idee

Skizze:

Figure 11-83: Biologist– template biological information (publication)



Informationsquelle: Wikipedia-Artikel

1) Betrachtet noch einmal das Modell der Technischen Aufgabe. Hat das biologische System eine ähnliche Aufgabe wie die technische Lösung?
Skizziert das biologische System und benennt seine **Elemente** (s. Beispiel)!

Biologisches System:

Skizze:

2) Anschließend modelliert die **Zusammenhänge** zwischen den Elementen des bioloigischen Systems und seiner Umwelt (siehe Beispiel).
3) Notiert wichtige **Eigenschaften** der einzelnen Elemente und **vergleicht** sie mit den Eigenschaften der technischen Lösung.

Klappt jetzt das Blatt auf!

Bionische Lösungsideen

4) Wie könnte die "Lösung" des biologischen Systems in die Technik übertragen werden?

a) Inspiration durch die **Skizze** des biologischen Systems

Skizze:

aber nass halten

b) Inspiration durch das **Modell** des biologischen Systems

Skizze:

c) Weitere Idee

Skizze:

Figure 11-84: Biologist– template biological information (Wikipedia article)

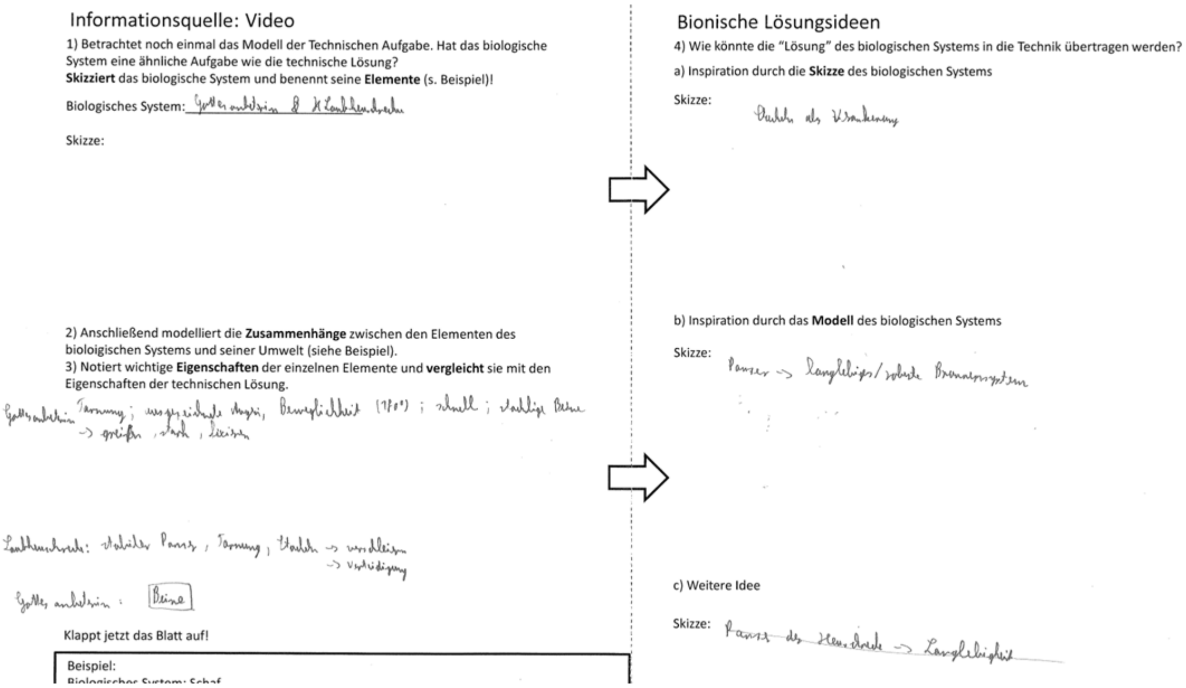


Figure 11-85: Biologist– template biological information (video)

11.13 *BioId* support (revised version)

This sub-section shows the templates of the first version of *BioId* for the technical task and the biological information.

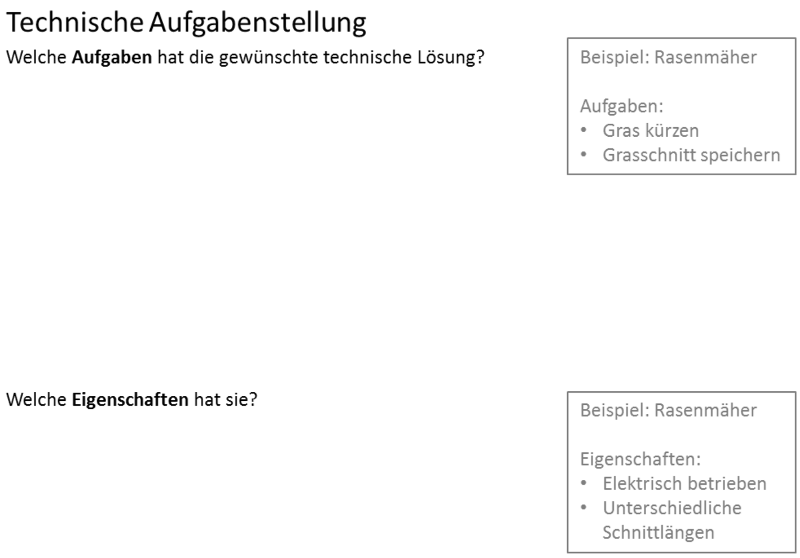


Figure 11-86: Revised version BioId: template technical task

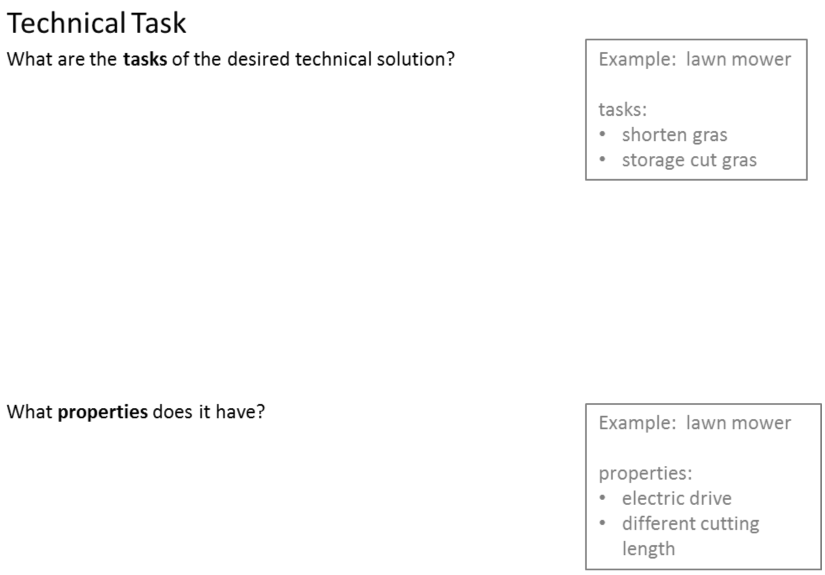
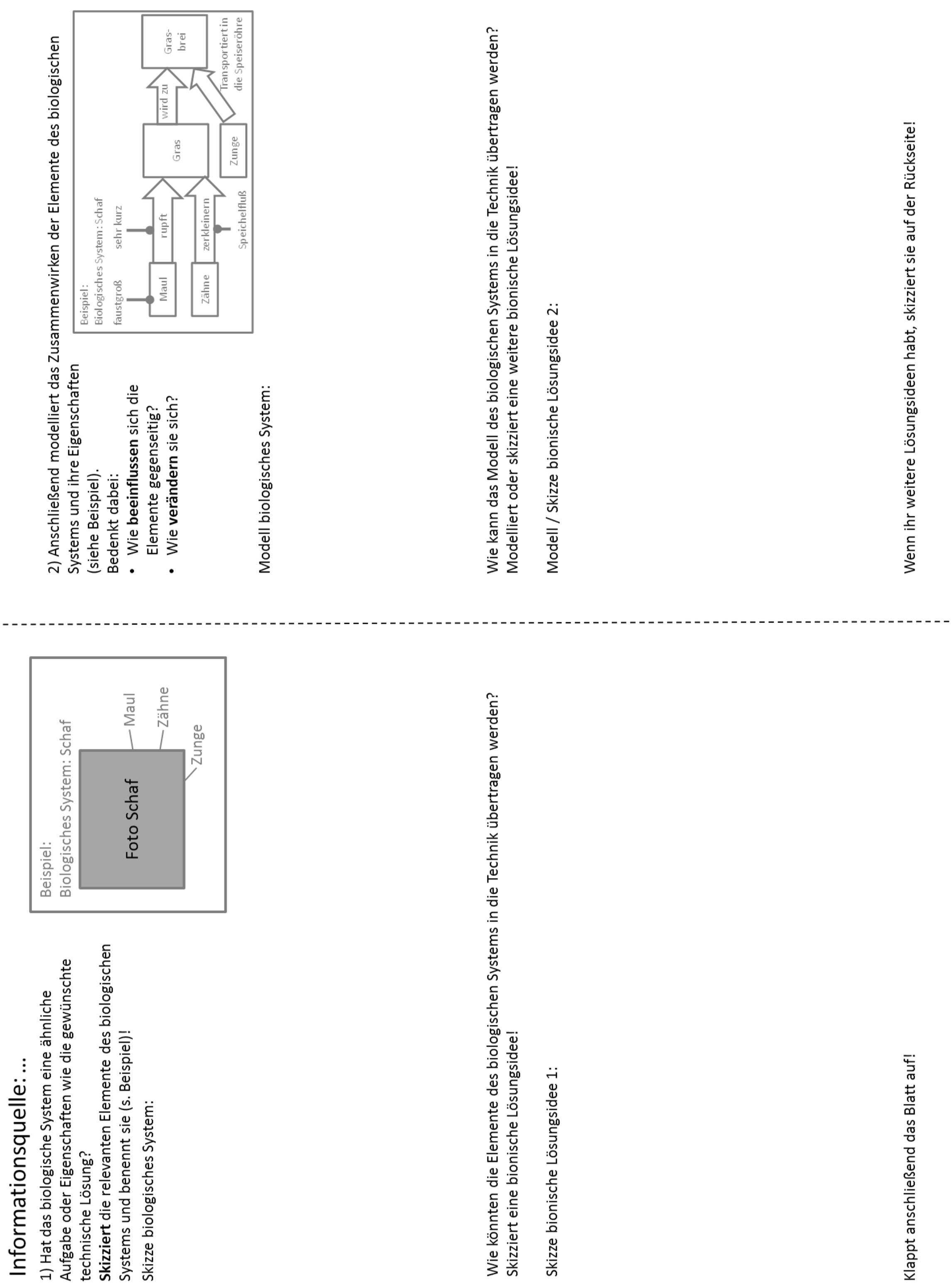


Figure 11-87: Revised version BioId: template technical task (English translation)



Informationsquelle: …

1) Hat das biologische System eine ähnliche Aufgabe oder Eigenschaften wie die gewünschte technische Lösung?
Skizziert die relevanten Elemente des biologischen Systems und benennt sie (s. Beispiel)!
Skizze biologisches System:

Wie könnten die Elemente des biologischen Systems in die Technik übertragen werden?
Skizziert eine bionische Lösungsidee!

Skizze bionische Lösungsidee 1:

Klappt anschließend das Blatt auf!

2) Anschließend modelliert das Zusammenwirken der Elemente des biologischen Systems und ihre Eigenschaften (siehe Beispiel).
Bedenkt dabei:

- Wie **beeinflussen** sich die Elemente gegenseitig?
- Wie **verändern** sie sich?

Modell biologisches System:

Wie kann das Modell des biologischen Systems in die Technik übertragen werden?
Modelliert oder skizziert eine weitere bionische Lösungsidee!

Modell / Skizze bionische Lösungsidee 2:

Wenn ihr weitere Lösungsideen habt, skizziert sie auf der Rückseite!

Figure 11-88: Revised version BioId: template biological information

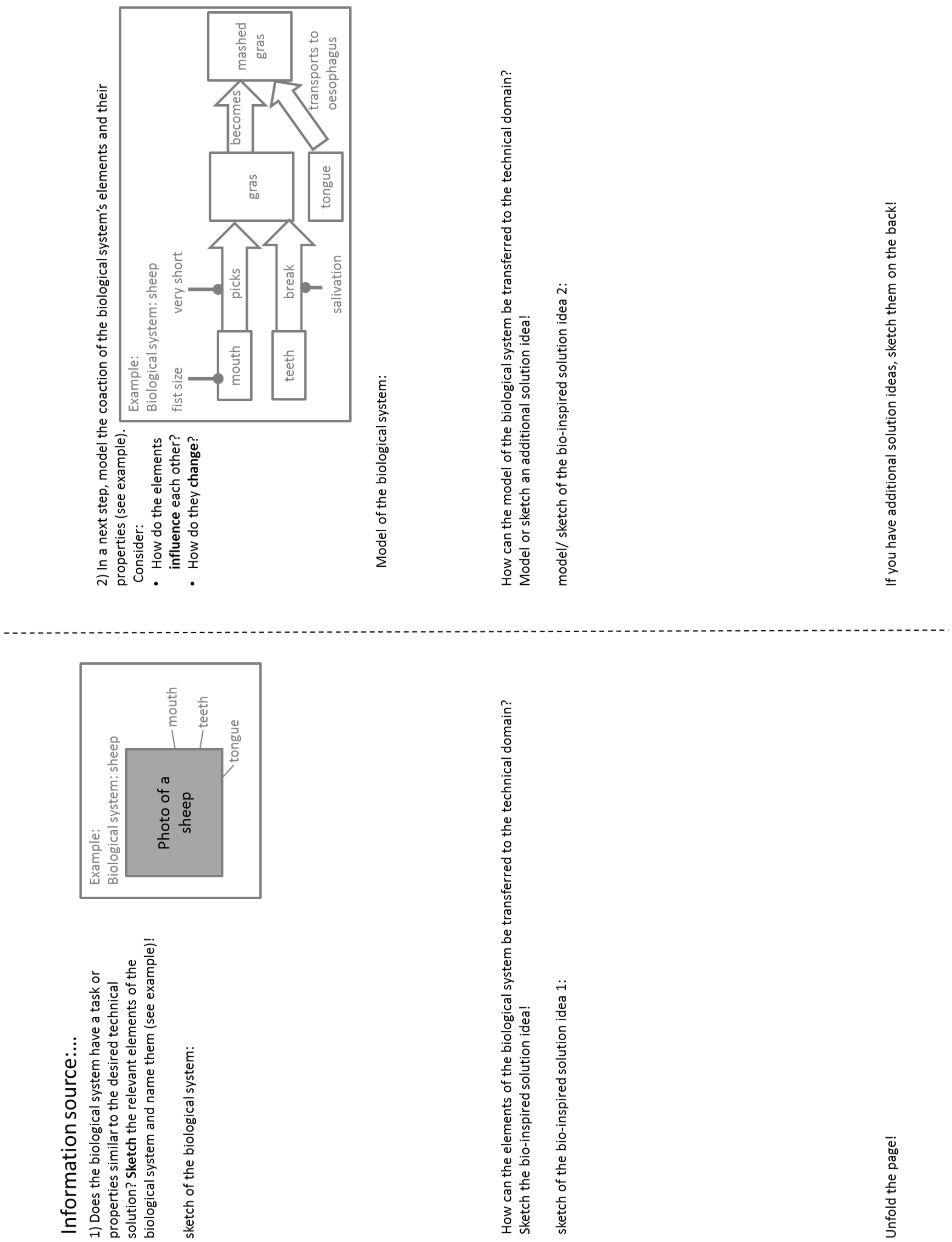


Figure 11-89: Revised version BioId: template biological information (English translation)

12. Glossary

analogy	*"comparison between one thing and another [two "analogues"], typically for the purpose of explanation or clarification."*(Oxford Dictionary, 2013)
bio-inspired design	the application of knowledge of biological systems in research and development to solve technical problems and develop technical inventions and innovations (VDI, 2012)
discipline	research area which possesses a *"specific body of teachable knowledge"* with its *"background of education, training, procedures, methods and content areas"*(Apostel, 1972)
embodiment	detailed design of the components of a technical solution or solution idea
function	the purpose of a technical solution or solution idea and its elements
ideation	the generation of new, unknown solution ideas (especially required in the early phases of the product development process)
information	data set into context (Probst et al., 2012, p. 16); it can be presented in different forms, e.g. via text, pictures, videos
innovation (product)	successful implementation of a creative novel idea or invention with a benefit for company and customer (Reichle, 2006, p. 20)
invention	novel technical solution
knowledge	cross-linked information (Probst et al., 2012, p. 16); it is acquired by humans through education and practical experience
technical solution	fulfilment of a design task (based on the further development of solution ideas)
solution idea	communicated thought that proposes a (partial) fulfilment of the given design task
physical effect	physical law that supports the function
product	commercial application of a (technical) solution
working principle	combination of geometric and material properties that enable the physical effect

13. Dissertations at the Institute of Product Development

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Technical University of Munich, Boltzmannstraße 15, 85748 Garching
Dissertations supervised by

- Prof. Dr.-Ing. W. Rodenacker,
- Prof. Dr.-Ing. K. Ehrlenspiel und
- Prof. Dr.-Ing. U. Lindemann

D1 COLLIN, H.:
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D29 HILLEBRAND, A.:
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D30 DYLLA, N.:
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