THE RELATIONSHIP BETWEEN FUNCTIONS AND OUTCOMES OF BIOLOGICALLY-INSPIRED DESIGN

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ABSTRACT

Research in biologically-inspired design (BID) practice often focus on team composition or ideation based on an already discovered fascinating biological solution principle. However, how are the outcome of the early design phases affecting BID projects' quality?
In this study, historical data from 91 reports from student teams documenting their BID efforts from a 3-week course constitute the data source. Thus, the relationship between design problem types, function types, functions descriptions and BID projects' quality is addressed.
The study show that especially design problem types and function descriptions affect the BID projects' quality. For instance, BID projects dealing with open-ended problems yield better results than redesign problems with existing solutions operating in a very domain-limited solution space. Next, BID projects obtain the best results when using functions as drivers for analogy searching rather than properties. Finally, BID projects with certain function types seem to have more complicated conceptualization phases.

Keywords: Bio-inspired design / biomimetics, Design practice, Design process, Function descriptions, Design problem types

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1 INTRODUCTION

The basic motivation for this research is to unveil insights from practice of biologically inspired design (BID), where the relationships between BID-projects' quality and design problem types, function categories and function descriptions are in focus. This paper present the study of BID-practice and the results applied in conceptual design work from students' BID-projects. As defined by (Pahl and Beitz, 2007), conceptual design is a phase within the process of designing covering the following tasks: Identification of essential problems(1), establishing function structures(2), searching for working principles and working structures(3), generating concept variants(4) and evaluating concept variants against technical and economic criteria(5). In the context of this study, conceptual design tasks 1-2 will be in focus. Thus, the relationship between different outcomes of conceptual design task 1-2 and the BID-project outcome will be investigated.

Biologically-inspired design (BID) designate the design process where biological knowledge is captured as a biological solution principle, abstracted to fit a technical problem and a solution to this technical problem is developed. This process can be executed in two ways, following a problem-driven approach or a solution-driven approach (Helms, Vattam and Goel, 2009). Solution-driven BID designate the approach, where the advantages of a fascinating biological phenomenon is understood and a technical problem benefitting from these advantages is searched for. Problem-driven BID designate the approach, where a technical problem is faced and biological solution principles fitting the problem is searched for. This practice is also referred to as biomimetics, biomimicry, bionics and bioreplication, however due to the broadness of the BID term, this will be used as the all-encompassing umbrella term in this paper.

As the research area of BID is still developing (Lenau, 2018), studies on BID practice have also emerged both using BID-practitioners and BID-students as data source. In a study combining interviews with 69 inventors of BID-products and market analyses, a range of challenges, effects and success factors are outlined. Building onto these findings, assessing the suitability of BID in relation to different types of problems and projects before initiating a BID-effort is recommended. Additionally, creating business models allowing acceleration of BID products' commercialisation process is also suggested (Chirazi et al., 2019). In another study with practitioners, a survey was completed by 270 biomimicry-practitioners. This study revealed a range of opportunities for growing the practice, like fostering industry-academia collaboration to merge the biggest employment sector of biomimicry practitioners (academia) with the highest likelihood of biomimicry projects reaching implementation (industry projects) or promoting best-practices for interdisciplinary working effectively involving life-science personnel (Rovalo *et al.*, 2019). The latter opportunity is also put to attention in an experimental setup with postdoctoral students, where the superiority of engineer/biologist pairs in analogical transfer and ideation when compared to single-disciplinary design pairs are displayed (Hashemi Farzaneh, 2020). Similarly, students has also been used as data source in a study using historical data to compare 51 bio-inspired design concepts from 51 students instructed with Concept-Knowledge design theory with 54 bio-inspired design concepts from students instructed in using the biomimicry institute design lens, where nature resembling or copying was evaluated (Nagel *et al.*, 2019).

From the abovementioned studies, it is displayed that retrospective analysis using historical data from student projects has been done and research regarding the composition of the design team practicing BID exist. However, not much detailed data exist on the relationship between the quality of BID-projects and how designers work with functions faced with different design problem types - neither from studies of practitioners or students. Also, different authors recommend to adopt multi-functional biological solution principles in design (Vattam et al., 2007; Liu and Jiang, 2011; Sane, 2016), due to the inherited integration easing synthesis. Although, no support or understanding of how to discover multi-functional biological solution principles are provided. Thus, the need of a better understanding of handling of functions in BID practice are emphasized further to allow the discovery of biological phenomena contributing to multiple functions. Therefore, this study will focus on the relationships between BID-projects' quality and design problem types, function categories and function descriptions in this study in order to generate knowledge useful for BID practice.

In continuation of the focus of the study, it is worthwhile to notice that the notion of *function* contain many different meanings - it is flexible and context-dependent (Vermaas, 2013) and the domain in which it is used also affects its meaning (Far and Elamy, 2005). Within the field of engineering design have researchers previously proposed many different definitions and ways of dealing with functions including

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The theory of Technical Systems (Hubka and Eder, 1984) and The Function-Behavior-Structure framework (Gero, 1990). This study will focus on other aspects than providing new insights on the notion of function, however as function has a central role in BID, the theoretical foundation for using the notion must be established. As students describe functions in a very broad way, the verb-object characterization of function from the Functional Basis (Stone and Wood, 2000) is adopted due to its simplicity. Furthermore, the notion *properties* (Andreasen, Hansen and Cash, 2015) is adopted. Thus, the three hypothetical function descriptions of a glue gun - *To dispense glue*, *to heat glue quickly* and *recyclability* - can be distinguished as a function (*To dispense glue*), a function property (*to heat glue quickly*) and a product property (*recyclability*). These theoretical distinctions will be used in the study.

2 RESEARCH APPROACH

This study is descriptive, whereby the hypotheses regarding BID practice is formulated to increase the understanding of the relationships between functions employed in BID-projects and BID-projects' quality that will be benchmarked by grades for submission reports and concepts. To do so, following research questions (RQ) and hypotheses (H) will guide the study:

RQ1. How are functions handled in BID-projects?
H1: Open-ended design problems are better suited for BID-projects than others
H2: Some function categories are better suited for BID-projects than others
H3: Search driven by more functions yield better BID-projects than search driven by one function
H4: Search driven by functions yield better BID-projects than search driven by properties

3 DATA COLLECTION APPROACH

Historical data from BID student reports documenting their work constitute the data source of the study.

3.1 Biologically-inspired design project report data

Historical data from 91 reports documenting the work of student projects during a 3-weeks course on BID training in the period 2015-2020 is used. Engineering students of different study lines compose the project groups, although the majority of the students are studying engineering design (around 60%). The course is on Master's level, although students on Bachelor's level participate as well. Usually, the distribution is 70-75% of Master students (3-5 years experience) and 25-30% of Bachelor students (1-3 years experience). Throughout the course's 3-week duration, groups have access to supervision on a daily basis, but are not obliged to use this opportunity. Project reporting follows the documentation structure of scientific papers (introduction, methods, results, discussion and conclusion) and vary in size, but are typically around 12-20 pages long without appendices. Three supervisors grade the projects in a two-step approach. First, each supervisor individually grade 1/3 of the projects and afterwards the supervisors settle on the grades of all projects using the individual grades as a starting point. The course is project-based dealing with problem-driven BID. Following the biomimetic design procedural model of (Lenau et al., 2010), results of different types are produced in each phase, as displayed in *figure 1*.

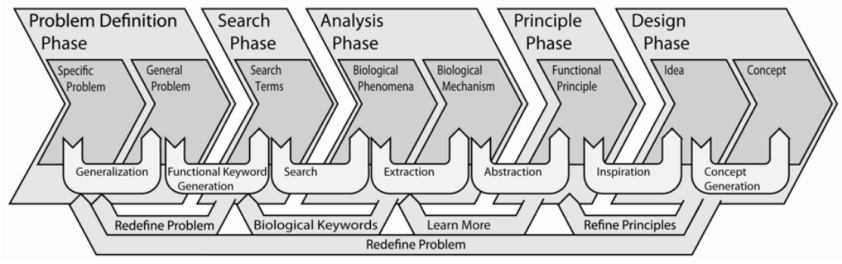

Figure 1. Procedural model followed in the BID-project course.

3.1.1 Problem definition phase data

The objective of this phase is functional keyword generation as indicated in *figure 1*. To diversify the functional keywords allowing an extensive exploration of the biological solution space, the students are instructed to produce four elements. 1) An analysis of the functional problem with the 4-box method

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(Helms and Goel, 2014), 2) A functional problem drawing, 3) A functions tree decomposition of the functional problem and 4) A table with specific and general problems related to their functional problem.

3.1.2 Search phase data

The objective of this is searching for biological solution principles. This is often done iteratively, thus the instructions are less rigid, still the students are encouraged to display how searching are done.

3.1.3 Analysis phase data

The objective of this phase is to improve the understanding of the discovered biological solution principles to aid analogy selection. Thus, the students are instructed to elaborate analogy selection metrics and encouraged to provide overview of the discovered analogies.

3.1.4 Principle phase data

The objective of this phase is to document the analogies selected to address the functional problem. Documentation is aided by biocards (Lenau et al., 2010), where the biological mechanism is explained, abstracted into a technical principle accompanied with a drawing capable of facilitating later ideation.

3.1.5 Design phase data

The objective of this is to generate biologically-inspired solution concepts corresponding to the functional problem and evaluate the feasibility. Thus, the students are instructed to document metrics for biocard(s) selection, build function models and conduct experiment(s) to test the concept's feasibility.

3.2 Data collection protocol

For hypotheses 1, BID-projects' descriptions of the functional challenges are collected to constitute the variable for measuring which design problem type that yields the best results. The design problem type is evaluated on a 1-4 scale by the study's three authors. The ratings '1' and '2' designate a redesign problem (well-defined solution space) and ratings '3' and '4' designate an open-ended problem (not domain-limited solution space). The ratings are informed by the questions in *figure 2*.

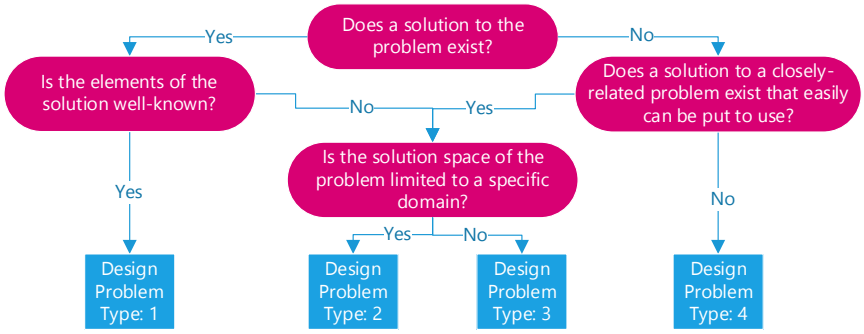

Figure 2. Flow diagram with questions used for determination of design problems' type.

For hypotheses 2, the BID-projects' function descriptions used for searching for biological solution principles are collected to constitute the variable to investigate which function categories yield the best results. In this context, functions are grouped when similar, i.e. *to puncture* and *to move through matter* are grouped under penetration function categories. For hypotheses 3 and 4, the BID-projects' function descriptions are collected to constitute the variable for measuring which functional abstraction level driving the biological analogy search that yields the best results (H3) and the variable for measuring which analogy search-driver yields the best results (H4). As analogy search is driven by a combination of functions and properties in some of the BID-projects, the groups' functional challenge descriptions and biocards will be used to inform this categorization (property-driven or function-driven), if an equal number of properties and functions has been noted in the function descriptions.

In addition to the measures described, two benchmark types will be used: BID-submission grades (1) and BID-concept grades (2), assuming that a BID-project's quality is constituted by a group's learnings (1) and the solution to developed (2). The final grades of the BID-submissions are evaluated on a 7-step scale (-3 0, 2, 4, 7, 10 and 12). The assessment of BID-concepts are constituted by the BID groups' fulfilment of two learning goals in 2015-2019 and an additional learning goal in 2020. Thus, the BID-concept grade is stipulated on a scale from 0-1 in this study, calculated as the total achieved

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score across the learning goals divided by the possible score across the learning goals. However, as the grades are awarded on different scales, a common rating spanning across 4, 3, 2 and 1 is introduced to allow for comparison. Thus, the grades are triangulated as follows:

- 4 corresponds to 12 for BID-submissions and 1-0.875 for the BID-concepts
- 3 corresponds to 10 for BID-submissions and 0.875-0.75 for the BID-concepts
- 2 corresponds to 7 for BID-submissions and 0.75-0.625 for the BID-concepts
- 1 corresponds to 4 for BID-submissions and 0.625-0.5 for the BID-concepts

4 HANDLING FUNCTIONS IN BID-PROJECTS RESULTS

The grading distribution of the 91 BID-projects are summarized in *figures 3-4*.

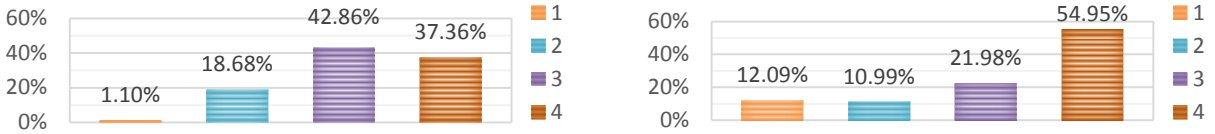

Figure 3-4. The grading distribution of the BID-projects. Left: submissions reports, right: concepts.

Investigating the grading distribution, more concepts than submission reports are awarded with 4's, although the distribution of the highest grades 3's and 4's are highest for the submission reports (80.2% compared to 76.9%). The average grade of the submission reports is 3.16 and the average grade of the concepts is 3.20. The relationships between the measures and respectively submission grades and concept grades (hypotheses 1.1-1.4) are presented beneath in the upcoming sections.

4.1 Design problem types' relationship with BID-projects' outcome

The distribution of projects with respect to design problem types (DPT) is as follows: 11 DPT 1, 37 DPT 2, 31 DPT 3 and 12 DPT 4. The relationship between DPT and submission grades is shown in *figure 5*.

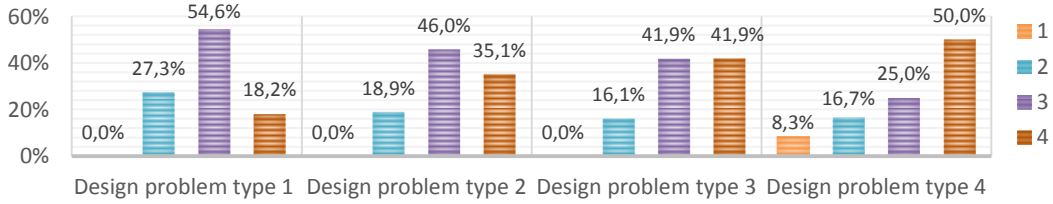

Figure 5. Design problem types vs. BID-submission grades

Analysing the relationship, the relative amount of submissions graded with 4's increase along the x-axis. Thus, a tendency that the more openly framed a design problem is, the more likely it is to get the highest grade, can be observed. In addition, 3's are the most prominent grade of the redesign problem types, whereas 4's are most frequent for DPT 4 while 3's and 4's are equally frequent for DPT 3. The average grades are the following: 2.91 (DPT 1), 3.16 (DPT 2), 3.26 (DPT 3) and 3.17 (DPT 4).
The relationship between DPTs and concept grades is shown in *figure 6*.

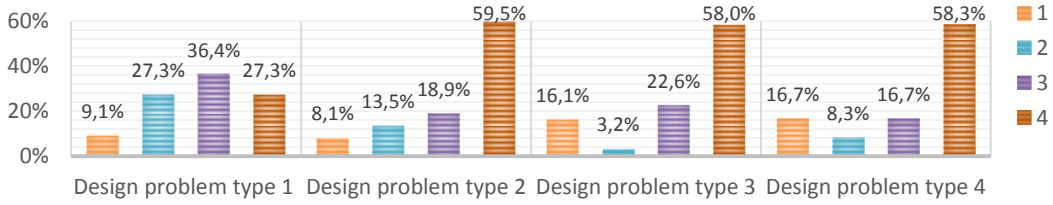

Figure 6. Design problem types vs. BID-concept grades

Investigating the relationship, 4's are most frequent of DPT 2-4, while 3's is most frequent for DPT 1. The average grades are the following: 2.82 (DPT 1), 3.30 (DPT 2), 3.23 (DPT 3) and 3.17 (DPT-4).

4.2 Functions types' relationship with BID-projects' outcome

The relationship between function categories and submission grades is shown in *figure 7*.

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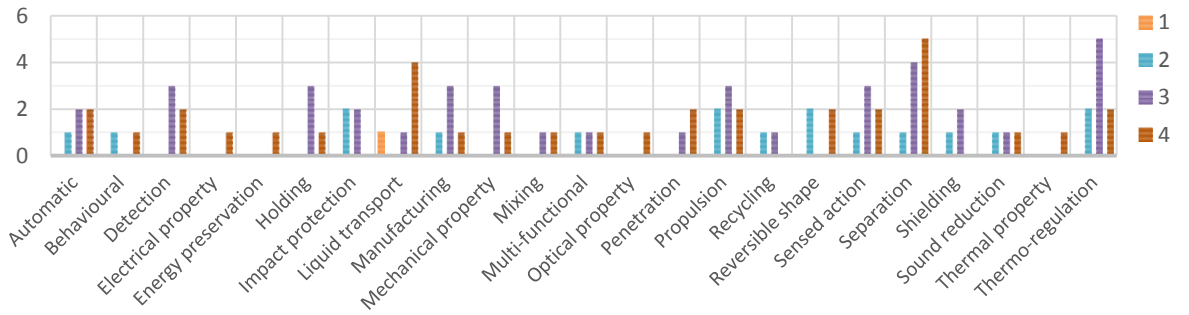

Figure 7. Function categories vs. BID-submission grades

Analysing the relationship, function categories explored once, are the only function categories only graded with 4's. Three of these function categories are handled in BID-projects, where a certain property was in focus (*electrical property*, *optical property* and *thermal property*). Focusing on the function categories explored more than five times in BID-projects, following are the average grades: 3.00 (*propulsion* and *thermoregulation*), 3.17 (*sensed action*), 3.33 (*liquid transport*) and 3.40 (*separation*).
The relationship between function categories and concept grades is shown in *figure 8.*

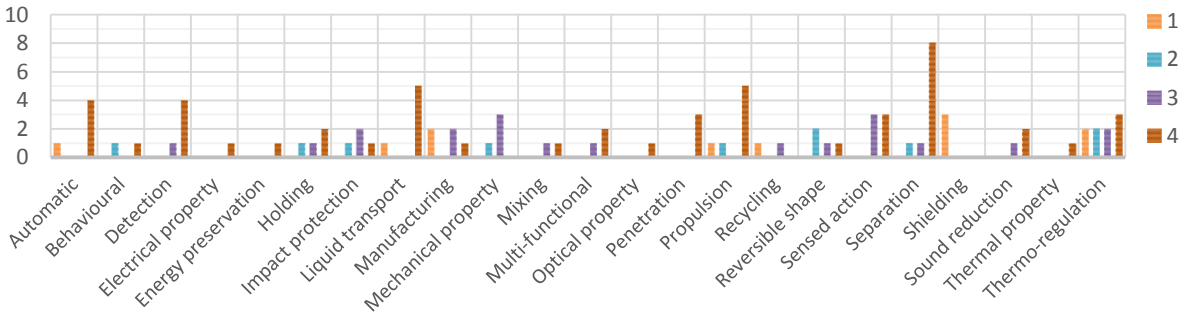

Figure 8. Function categories vs. BID-concept grades

Investigating the relationship, the function category *penetration*, in addition to the function categories only explored once, are only graded with 4's for the concepts. Focusing on the function categories explored more than five times in BID-projects, following are the average grades: 2.67 (*thermoregulation*), 3.29 (*propulsion*), 3.50 (*sensed action* and *liquid transport*) and 3.70 (*separation*).

4.3 The level of search driving function's relationship with BID-projects' outcome

The distribution of projects with respect to the level of the search driving function(s) is as follows: 28 projects apply one main function as search-driver, five projects apply one sub function as search-driver and 58 projects apply more sub function as search-driver. The relationship between the search driving function level and submission grades is shown in *figure 9.*

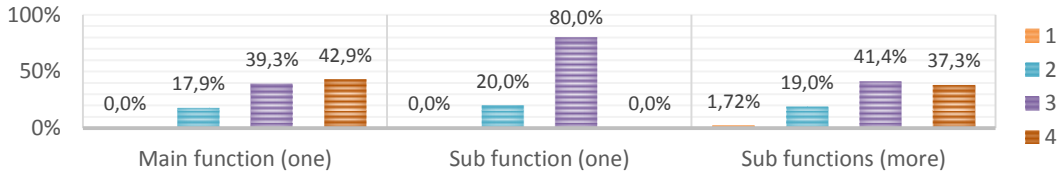

Figure 9. Level of search driving function(s) vs. BID-submission grades

Analysing the relationship display that no projects driving the search with one sub function receive 4. Furthermore, the relative amount of high grades (3's and 4's) is comparable between projects applying respectively one main function (82.2%) or more sub functions as search-driver (78.7%). The average grades of the Bid-submissions are the following: 3.25 (one main function as search-driver), 2.80 (one sub function as search-driver) and 3.16 (more sub functions as search-driver).
The relationship between the search driving function level and concept grades is shown in *figure 10.*

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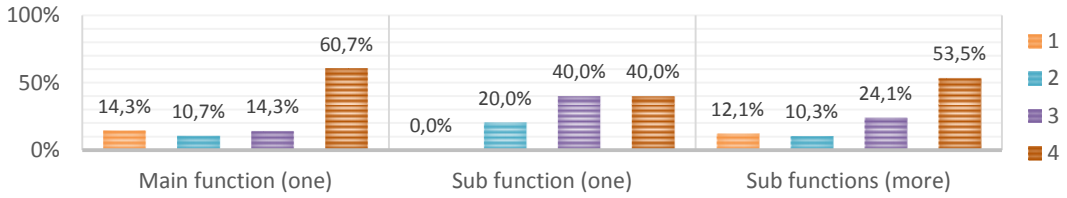

Figure 10. Level of search driving function(s) vs. BID-concept grades

Investigating the relationship, the project applying either one main function or more sub functions as search-driver have highly similar distributions of grades. The projects applying one sub function as search-driver have the highest relative amount of the highest grades (3's and 4's). Although only five project applied one sub function as search-driver making this part of the data foundation very limited in size. The average grades of the BID-concepts are very similar: 3.21 (one main function as search-driver), 3.20 (one sub function as search-driver) and 3.19 (more sub functions as search-driver).

4.4 Analogy search-driver types' relationship with the BID-projects' outcome

The distribution of projects with respect to analogy search-driver types is as follows: 68 projects apply functions and 23 projects apply properties. The relationship between analogy search-driver types and submission grades is shown in *figure 11*.

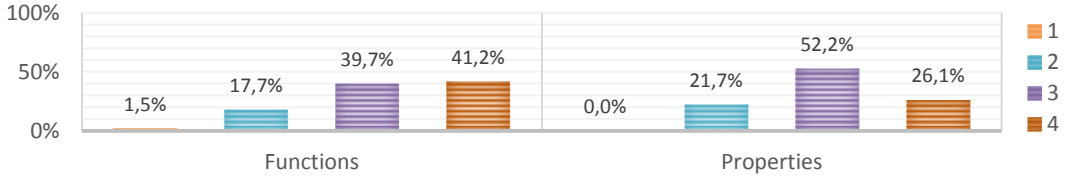

Figure 11. Analogy search-driver types vs. BID-submission grades

Analysing the relationship, employing functions as search-driver yields the highest relative amount of the highest grades (80.9%) compared to employing properties as search-driver (78.3%). Likewise, applying functions as search driver yield a higher average submission grade (3.21) than applying properties as search driver (3.04).
The relationship between analogy search-driver types and concept grades is shown in *figure 12*.

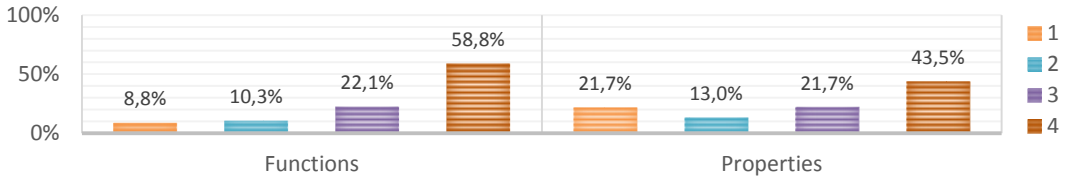

Figure 12. Analogy search-driver types vs. BID-concept grades

Investigating the relationship, employing functions as search-driver yields the highest relative amount of the highest grades (80.9%) compared to employing properties as search-driver (65.2%). Likewise, applying functions as search driver yield a higher average concept grade (3.31) than applying properties as search driver (2.87).

5 DISCUSSION

The results of the study and the approach for data collection will be discussed in the following sections.

5.1 Results

On a general level, it is worth to notice the difference in grade distribution between the BID-submission grades and the BID-concept grades, where 37.4% of the BID-submissions got an A compared to 56% of the BID-concepts receiving an A. This is possibly due to the experience and competencies of the BID students, who are mainly engineering design students very familiar with project-based conceptual design and prototyping, but less experienced with scientific reporting.
The results from analysing the relationships between design problem types (DPT) and respectively the BID-submission grades and the BID-concept grades (hypothesis 1), reveal an interesting pattern. BID-projects working with DPT 1 are generally receiving a low relative amount of 4's (18% for the BID-

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submissions and 27% for the BID-concepts) compared to BID-projects working with DPT 2 (35% and 59%), DPT 3 (42% and 61%) and DPT 4 (50% and 58%). Furthermore, averaging the average grades of the BID-submissions and the BID-concepts, this pattern continues. Thus, with the averages of submissions and concepts (DPT 1: 2.86, DPT 2: 3.23, DPT 3: 3.24 and DPT 4: 3.17), the findings suggest that BID projects working with DPT 1 yields the least convincing results. Digging into the learning goals of the BID-submissions, results of all phases of the biomimetic design procedural model are evaluated, which suggest that students might have troubles with abstracting throughout the design process, when dealing with a DPT, where existing solutions are present and well-known. The BID-concepts are also evaluated on learning goals, these are related to the biological solution space expanded, the quality of the bio-inspired concepts and the validation of these. Likewise, dealing with problems where domain-limited solutions exist might complicate the process of developing novel solutions, while validating these solutions might yield too simple experiments. This could be the case in projects dealing with the functional challenges *'protecting eggs from impact when dropped*' and *'collapsible devices that allows elderly people*'- both BID-projects receiving C's as grades for the BID-submission and the BID-concept. Nonetheless, results suggest that DPT 2-4 yield better results than DPT 1. Although, indications towards open-ended problems wielding better results is put forwards and as better results are developed in BID-projects working with DPT 4 than DPT 1.

The results from evaluating the relationships between function categories and respectively the BID-submission grades and the BID-concept grades (hypotheses 2) are more difficult to distil as so many function categories are revealed, whereby a small amount of BID-projects are represented in most of the function category columns. However, for the function categories represented more than five times, it appears that some function categories yield the best results. Averaging the average grades of BID-submission and BID-concepts of the five most frequent function categories (separation: 3.55, liquid transport: 3.42, sensed action: 3.33, propulsion: 3.14 and thermoregulation: 2.83), a large difference can be observed. Recalling that the averages of the BID-submissions varies from 3.00 (propulsion and thermoregulation) to 3.40 (separation), while the averages of the BID-concepts varies from 2.83 (thermoregulation) to 3.55 (separation), the findings indicate that impact of working with different function categories has a larger impact on the BID-concept grade than the BID-submission grade. Remembering the learning goals corresponding to the evaluation of the BID-concepts, this indicate that some function categories are more difficult to develop impressing bio-inspired solutions for. Although, the foundation for concluding are limited as the number of BID projects working with the different function categories are low, analysing the grades of BID-submissions and BID-concepts with respect to function categories. However, the findings indicate that working with the function categories separation and liquid transport is recommendable, especially compared to working with thermoregulation. Thereby hypothesis 2 is confirmed, while more research are needed to determinate the nature of the function categories best suited for BID.

The results from analysing the relationships between the level of search driving function(s) and respectively the BID-submission grades and the BID-concept grades (hypotheses 3) are not containing findings suitable for recommendation. Firstly, the number of BID-projects driven by one sub function is too low (5) to interpret from. Moreover, BID projects driven by either one main function or more than one sub function have very similar average submission grades (3.25 and 3.16) and average concept grades (3.21 and 3.19). Likewise, very similar grade distributions and combined averages of both BID-submissions and BID concepts (3.23 for project driven by one main function and 3.17 for projects driven by more than one sub function) are observed. Therefore, no recommendation regarding an advisable level of search driving function(s) can be put forward.

The results from evaluating the relationships between analogy search-driver types and respectively the BID-submission grades and the BID-concept grades (hypotheses 4), uncover some interesting aspects. Applying functions as analogy search-driver yields a larger relative amount of the highest grade with respect to both BID-submissions (functions: 41.2%, properties: 26.1%) and BID-concepts (functions: 58.8%, properties 43.5%). Furthermore, averaging the averages grades of BID projects' submissions and concepts, applying functions as search-driver (3.26) yields better results than applying properties as search-driver (2.96). Similarly, as for the case with DPT 1, conducting a thorough and very abstract search while also producing novel concepts might be complicated as a property is quite easy to grasp, whereby fixation could occur. This could be the issue in the BID-projects dealing with the functional challenges *'protecting eggs from impact when dropped*' and *'avoiding contagious contamination'*,

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where solutions are inspired by different surface properties and structures from nature. Thus, it can be recommended to apply functions as search-driver rather than properties.

5.2 Limitations of the pursued approach for data collection and processing

Constituting the data source by students' 91 BID-project reports is considered a fair amount of data to extract knowledge from for addressing the hypotheses of the study. While employing students' grades as performance metrics, the BID-submission grades are obviously influenced by other factors than outlined, the BID-concepts grades are only related to the conceptualization and validation, whereby existence of bias is accounted for and minimized.

The quality of the variables expressed as measures for the different hypotheses is generally good. Despite using BID-projects' functions descriptions to inform variables used as measures for both hypotheses 2-4, the functions descriptions are used differently in all instances, whereby results are not duplicating. Likewise, developing a flow diagram with question for design problem type evaluation allows for reproduction. However, the data processing approach could have been outsourced to a researcher without relation to the study or validated further by calculating and displaying the kappa statistic to put forward the authors' interrater reliability (McHugh, 2012). Furthermore, conducting statistical analysis should be done to assess the results' statistical validity.

Finally, it is worth to notice that the participants in the BID-projects are students and therefore novice designers. Thereby, conducting a similar study with experienced designers might yield different results, one might presume that experienced designers will produce results receiving higher grades independent of the different variables tested in the hypotheses. However, it is important to reflect on the fact that, experienced designers are often employed in industry, where R&D-processes are more heavily influenced by time frames and budgets than in academia, thus the experience-difference might even out.

6 CONCLUSIONS

This study presents the findings from answering one research question regarding the relationship between BID-projects' quality and design problem types, function categories and function descriptions. In this context, project reports documenting the findings from a Master's course in BID is used as data source. The BID-projects' quality is benchmarked as the grade of the BID report submissions and the grade of the BID-concepts.

The investigation of hypothesis 1, the relationship between BID-projects' quality and design problem types, reveals that BID-projects with open-ended design problems (DPT 3-4) generally yield better results than BID-projects with redesign problems (DPT 1-2). While, BID projects working with DPT 4 yields better results than BID projects working with DPT 2 in terms of average submission (DPT 4: 3.17, DPT 2: 3.16), average concept grades of projects working with DPT 4 (3.17) are lower than projects working with DPT 2 (3.30). Thus, hypothesis 1 are only partly confirmed, not conclusively.

The investigation of hypothesis 2, the relationship between BID-projects' quality and function categories, BID-projects working with function categories *separation* and *liquid transport* yield good results measured both by the means of grades for BID-submissions and BID-concepts, especially compared to BID projects working with *thermoregulation*. However, while recommendations on function categories to use BID for can be made, with the limited number of BID projects mapped in each function category, a final assessment of hypothesis 2 deserves further study with a larger data set. The investigation of hypothesis 3, the relationship between BID-projects quality and the abstraction level of search driving function(s), the difference between BID-projects applying either one main function or more than one sub function as search-driver is very limited. Further, the number of BID-projects driven by one sub function is very limited. Thereby, applying a particular abstraction level of the search driving function(s) cannot be recommended. Thus, hypothesis 3 is rejected.

The investigation of hypothesis 4, the relationship between BID-projects' quality and analogy search-driver types reveals that using functions yields better results than using properties. Thus, hypothesis 4 is confirmed.

Thus, the study indicate that the analogy search-driver type is of big importance, while design problem types seem to have a relation to the quality of the BID-projects. Therefore, while the applicability of BID with respect to different design problem types deserve further study, the authors suggest to adopt a functions-focus through the BID process, to maximize the results from the BID effort.

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