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DOES THE BIOLOGICALLY INSPIRED DESIGN PROCESS RESULT IN MORE MULTIFUNCTIONAL DESIGNS?

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Abstract: Biological systems in general are multifunctional and environmentally sustainable. Thus, biologically inspired design is posited as leading to multifunctional and environmentally sustainable designs. Design in general is characterized as a problem-driven process. However, biologically inspired design also entails the twin process of solution-based design. Previous work has postulated that the solution-based design process is prone to design fixation but leads to more multifunctional designs. Design Study Library (DSL) is a digital library of eighty-three cases of biologically inspired design. We present a preliminary analysis of the DSL case studies to examine two hypotheses. (1) The process of solution-based design results in more multifunctional designs than the problem-driven design process. (2) The process of solution-based design is more prone to fixation than the problem-driven design process. We find strong evidence in favor of the first hypothesis.

Keywords: Biologically inspired design, design fixation, multifunctional design, solution-based design

1. Introduction

Biological systems in general are robust, multifunctional, and environmentally sustainable, especially when compared with technological systems (Benyus 1997; French 1994; Turner 2007; Vincent & Mann 2002; Vogel 2000). Thus, biologically inspired design is posited to lead to robust, multifunctional, and environmentally sustainable designs, especially when compared with general design methods (Bar-Cohen 2011; Benyus 1997; French 1994; Gleich et al. 2010; Turner 2007; Vincent & Mann 2002; Vogel 2000).

Design in general is characterized as a problem-driven process (Cross 2006; Dym & Brown 2012; French 1985; Hubka & Eder 1988; Pahl et al. 2007; Simon 1996; Suh 2001). However, in earlier work studying biologically inspired design, we observed a twin process of problem-driven design that we called solution-based design (Helms, Vattam & Goel 2009; Goel et al. 2014). In solution-based design, the design process begins with a solution, then abstracts a design pattern from the solution, next identifies the problem to which the pattern may be applicable, and finally uses the pattern to devise a solution to the problem. In general, a case in biologically inspired design may entail both problem-driven and solution-based design processes.

However, at present the characteristics of solution-based design are not well understood. Vattam, Helms & Goel (2007) hypothesized that compared to the traditional problem-driven design process, (1) the process of solution-based design results in more multifunctional designs, but also that (2) the solution-based design process is prone to more fixation on the structure of biological design. By "multifunctional design" we mean a design with two or more independent intended functions. Multifunctionality has long been a goal of much research on design (e.g., Suh 2001). If the first hypothesis is correct, then it would position the solution-based design process as a powerful design method for generating multifunctional designs. Further, design fixation has long been recognized as a major problem in problem-driven design (Jansson & Smith 1991). If the second hypothesis is correct, then the solution-based design process may also have a significant cost.

Design Study Library (DSL for short) is a digital library of eighty-three case studies of biologically inspired design (Goel et al. 2015). The case studies were collected over 2006-2013 from extended, open-ended collaborative projects in a senior-level interdisciplinary class on biologically inspired design at Georgia Institute of Technology. In this paper, we present a preliminary analysis of problem-driven and solution-based design processes in the eighty-three case studies. We find strong evidence in support of the first hypothesis about the solution-based design process resulting in more multifunctional designs.

2. Biologically Inspired Design

The growing movement of biologically inspired design is manifested through an exponentially expanding literature including both patents (Bonser & Vincent 2007), publications (Lepora et al. 2013), and computational techniques and tools (Goel, McAdams & Stone 2014). Since 2006, we have observed biologically inspired design practices in Georgia Institute of Technology's ME/ISyE/MSE/BME/BIOL 4740 course, a yearly interdisciplinary, project-based course ~~on~~ taught jointly by biology and engineering faculty. The class is composed of mostly senior-level undergraduate students from biology, biomedical engineering, industrial design, industrial engineering, mechanical engineering, and a variety of other science and engineering disciplines. The extended design projects in the classes were the focal points of our data collection. The projects involved identification of a design problem of interest to the team and conceptualization of a biologically inspired solution to the identified problem. Each design project grouped together an interdisciplinary team of typically 4-5 students. Each team had at least one student with a biology background and a few from different engineering disciplines. Each team identified a problem that could be addressed by a biologically inspired solution, explored a number of solution alternatives, and developed a final solution design based on one or more biologically inspired designs. Yen et al. (2014) provide a detailed account of the teaching and learning in the course.

3. The Processes of Problem-Driven and Solution-Based Analogical Design

We observed the existence of two high-level analogical processes for biologically inspired design based on two different starting points – *problem-driven analogy* and *solution-based analogy* (Helms, Vattam & Goel 2009; Goel et al. 2014). As Figure 1(a) illustrates, in a problem-driven analogical process, designers identify a problem that forms the starting point for subsequent problem solving. They usually formulate their problem in functional terms. In order to find biological sources for inspiration, designers "biologize" the given problem, i.e., they abstract and reframe the function in more broadly applicable biological terms. Designers use a number of strategies for finding biological sources relevant to the design problem at hand based on the "biologized" question, and then they research the biological sources in greater detail.

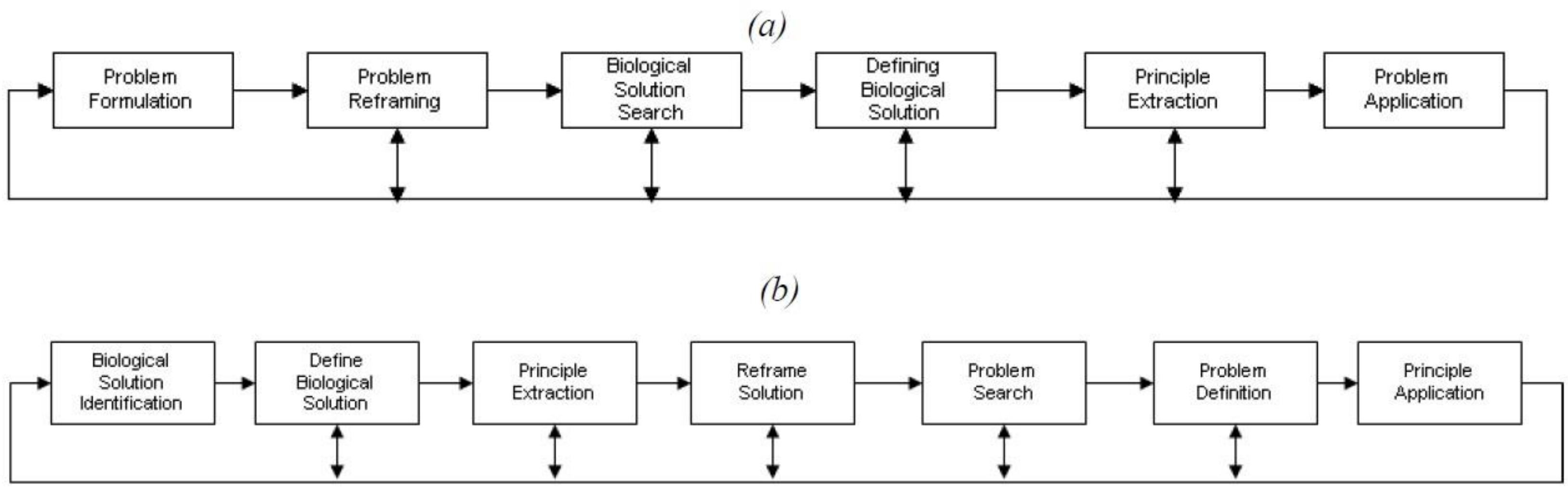

Figure 1. The Processes of Problem-Driven and Solution-Based Design. (Adapted from Helms, Vattam & Goel 2009)

Important principles and mechanisms that are applicable to the target problem are then extracted to a solution-neutral abstraction and applied to arrive at a trial design solution. On the other hand, in the solution-based analogical process, as illustrated in Figure 1(b), designers begin with a biological source of interest. The designers understand (or research) their biological source to a sufficient depth to support the extraction of deep principles from it. T~~hen t~~hey then find human problems to which the principle can be applied. Finally, they apply the principle to develop a design solution to the identified problem. In general a case in biologically inspired design may entail both problem-driven and solution-based design processes. For example, the case may begin with the solution-based design process, but once a design problem has been identified, it may switch to the problem-based design process. Further, the process of solution-based design appears to be applicable not only to biologically inspired design but to analogical design more generally.

4. Design Study Library

The Design Study Library (DSL) is a web-based, interactive, digital library of eighty three case studies of biologically inspired design. Prior analysis of the case studies in DSL examined the postulate that biologically inspired design results in environmentally sustainable designs. Goel et al. (2015) found that environmental sustainability was an explicit goal of about one fourth of the case studies. They also found that although sustainability was not a primary design goal in many case studies, in some case studies the designers' analyses indicated that the designs would be more sustainable than conventional designs anyway. They found this phenomenon of *serendipitous sustainability* in about 8% of the case studies. Taking into account both intentionally and serendipitous sustainability, sustainability was a major factor in about a third of the case studies.

5. Categorization of the Case Studies

We analyzed each of the 83 case studies in DSL to verify the two hypotheses about the process of solution-based design we introduced earlier, namely, compared to problem-driven design, solution-based design leads to (1) more multifunctional designs, and (2) more design fixation on the original solution. Preliminary analysis showed that the documentation for 9 of the case studies in DSL was too sparse or vague to be conclusive, thus leaving 74 case studies for detailed analysis.

5.1 Multifunctional Design

Our characterization of multifunctional design builds on the literature. Suh (2001) characterizes multifunctional design as a design with multiple intended independent functions. Both intention and independence are important here: multiple functions need be intrinsic to the design (not ascribed by a user) as well as orthogonal to one another (not ~~subfunctions~~sub functions of each other). However, in the context of biologically inspired design, we need to add another dimension to this characterization. Suh's axiomatic theory pertains to original design in which all the intended independent functions are designed from first principles. Biologically inspired design often is evolutionary and additive. Let us consider, for example, the well-known example of the design of the Japanese Shinkansen 500 train in the 1990s. While the design of Shinkansen 500 train was in part biologically inspired, it evolved from the design of the Shinkansen 300 train, adding the function of reducing noise (McKeag 2012). As an example from DSL itself, consider the case study of designing a surfboard to deter shark attacks. By Suh's definition, the surfboard design is multifunctional: it is streamlined for moving quickly through water and it also deters sharks. However, the basic design of the surfboard already exists; biological inspiration in the case study (the snapping claw of a pistol shrimp) is used for only one function (scaring sharks away). Therefore, we do not view this is an example of biological inspiration resulting in a multifunctional design. From the perspective of studying the processes of biologically inspired design, we characterize a design process as resulting in a multifunctional design only if it transfers more than one function from a biological analogue to a technological system.

Let us consider two more examples from DSL for clarity and precision. The Garden Veins case study in DSL is inspired by the thorny devil lizard. In this case study, the thorny devil's water collection abilities as well as its color changing abilities were transferred to the design solution. We consider this biological inspiration as resulting in a multifunctional design because two independent functions (water collection and changing colors) come from the same biological source (thorny devil). In another case study from DSL (Balloon Fog Collectors), only the water collecting capabilities of the thorny devil (specifically hydrophilic skin) were transferred to the design solution, and we do not consider this biological inspiration as multifunctional. Thus, our characterization of multifunctionality in biologically inspired design is quite conservative.

5.2. Design Fixation

Our definition of design fixation too builds on the literature. Jansson & Smith (1991) characterize design fixation as blind adherence to a limited set of ideas in conceptual design. Again, we use a conservative view of design fixation in analyzing DSL case studies: we view a design process as leading to fixation only if the design process results in the transfer of the structure of the biological analogue for a majority of transferred functions. In the DSL case study of Balloon Fog Collectors, the design process transferred the structure of the thorny devil's skin to the design solution, and thus we deemed this process to be structurally fixated. In the DSL Garden Veins case study, however, two functions were transferred: water collection and color changing. While the function of water collection engaged transfer of a corresponding structure, the function of color changing did not. Given that only 1/2 of the transferred functions also involved transfer of corresponding structures, we deemed this study not to be fixated, as our definition requires a majority.

5.3. Properties of Solution-Based Design

We analyzed the case studies in DSL with two standards for assessing a case study as using the solution-based design process. In (Goel et al. 2016), we tagged our data with a very conservative standard that required the design documentation to explicitly state that it was solution-based (Assessment 1). We later realized some other cases studies in DSL clearly also used solution-based design even though this fact was not explicitly mentioned in the design report. This additional set includes case studies that focus on only one biological source of inspiration, with no mention of any other biological sources (Assessment 2). Table 1 and Table 2 show the results using both assessments.

Table 1. Assessment 1

	Total	**Multifunctional**	**% Multifunctional**	**Fixation**	**% Fixation**
Problem-driven design	64	27	42.2%	42	65.6%
Solution-based design	10	9	90%	8	80%

Table 2. Assessment 2

	Total	**Multifunctional**	**% Multifunctional**	**Fixation**	**% Fixation**
Problem-based design	47	14	29.8%	31	66%
Solution-based design	27	22	81.5%	19	70.4%

Interestingly, the results are much the same irrespective of the method assessment: There is strong evidence in favor of the first hypothesis about the solution-based design resulting in more multifunctional designs than problem-driven design; and there is little evidence supporting the second hypothesis about solution-based design leading to more design fixation than problem-driven design.

6. Statistical Analysis

As Table 2 above indicates, we tagged thirty-six of the seventy-four case studies in DSL as multifunctional (48.6%). Twenty-seven of the seventy-four case studies were classified as solution-based design (36.5%) and nineteen of them showed evidence of fixation. We measured association between the multifunctional and fixation tags and solution-based design using Fisher's exact test and the Pearson correlation coefficient. Fisher's exact test is a statistical significance test for analyzing association tables such as Tables 2(b) and 2(c). Fisher's test is appropriate for this study because the categorical nature of data in the two tables. Pearson correlation coefficient is a standard measure of the linear correlation between two variables X and Y, giving a value between +1 and −1, where 1 is total positive correlation and -1 is a total negative correlation. As Table 3 indicates, we found a strong correlation between multifunctionality and solution-based design ($p < 0.05$) using both the newly reclassified solution based design and the previous solution based design. No correlation was found between structural fixation and solution-based design.

Table 3. Significant correlation between solution-based design and multifunctionality,

Tag A	Tag B	Fisher P value	Pearson's Correlation
Multifunctional	Problem-driven design	0.001	-0.374
Multifunctional	Solution-based design	< 0.001	0.662

7. Discussion

Why does the solution-based design process result in more multifunctional designs? At first, the hypothesis that the process of solution-based design results in more multifunctional designs seems counter-intuitive. By definition, the solution based design process starts with only one biological source of inspiration, and therefore only one chance to transfer multiple functions. The process of problem-based design however may engage multiple (n>1) biological sources, and therefore n>1 opportunities to transfer multiple functions. Yet, our analysis of the case studies in DSL found that the process of solution-based design results in more multifunctional designs than the problem-based design process.

We posit two reasons for this finding: (1) The initial fixation of solution-based design affords complex analogical transfer, and (2) the nature of constrained search inherent to problem-based designs limits the complexity of analogical transfer. Let us consider the DSL case study "Ant Traffic Control" that aims to optimize traffic flow inspired by the swarm navigation of some ant colonies. The design process in this case study is problem-driven and results in the transfer of one function to the biological system (ant navigation). Now let us consider another DSL case study called Pascobot that is also ant inspired. The design process in the Pascobot study is solution-based and aims to create a robot that can search disaster sites and perform reconnaissance. The Pascobot study transfers two major functions: swarm navigation as well as replaceability of individual units, resulting in a multifunctional design. We posit that before the design process starts in either case study, the designer has a complex mental model of the entire biological source of ant navigation including its multiple functions. When the design begins through the process of solution-based design, the designer seeks to transfer the entire mental model with its multiple functions (distributed navigation and replaceability of units) resulting in a multifunctional design. Thus, the solution-based design process leads to *serendipitous multifunctionality!*

We can contrast the above solution-based design process with the traditional process of problem-driven design. Problem decomposition is a fundamental element of the problem-driven design process (Cross 2006; Dym & Brown 2012; French 1985; Hubka & Eder 1988; Pahl et al. 2007; Simon 1996; Suh 2001).

Typically problem decomposition typically takes the form of decomposition of a design function into subfunctions. The advantage of this functional decomposition of the problem is that it constrains the search of design solutions into smaller and simpler spaces. However, it also implies that solution is more likely to satisfy only one function. Thus, in the "Ant Traffic Control" case study, the high-level function of controlling traffic does not lead to the reminding of the "replaceability" analogy.

Following Vattam, Helms & Goel (2007), we initially hypothesized that the process of solution-based design would lead to more fixation on the structure of the biological analogue. Based on our analysis of the DSL case studies, we posit an alternative hypothesis: the solution-based design process leads to more fixation on the problem decomposition in the biological analogue. Vattam, Helms & Goel (2010) found that biologically inspired design transfers not only causal mechanisms for achieving specific functions but also problem decompositions. We hypothesize that while the problem-driven design process dynamically decomposes the problem, the process of solution-based design may lead to fixation on the problem decomposition available in the biological analogue. Verifying this hypothesis is part of future work.

8. Conclusions

DSL is a digital library of eighty-three case studies of biologically inspired design. Preliminary analysis of the DSL case studies establishes two postulates from previous research. First, the analysis establishes that the biologically inspired design process does result in multifunctional designs (the title of this paper). In particular, we found that thirty six of the seventy four meaningful case studies in DSL, or 48%, - resulted in multifunctional designs. Second, the analysis establishes that biologically inspired design does entail the process of solution-based design. In particular, we found that twenty seven of the seventy four meaningful case studies in DSL, or 36%, entailed the solution-based design process.

Further, in this paper we analyzed two specific hypotheses: Compared to the traditional problem-driven design process, the process of solution-based design leads to (1) more multifunctional designs, and (2) more fixation on the structure of biological design. Our analysis of the DSL case studies indicates strong support for the first hypothesis: while twenty two of twenty seven, or 81%, of the case studies engaging the solution-based design process resulted in multifunctional designs, only 14 or 47, or 30%, of the case studies entailing the problem-driven did so. However, we found little evidence in favor of the second hypothesis: both problem-driven design (66%) and solution-based design processes (70%) appear equally prone to design fixation. We posit that this makes biologically inspired design, and especially solution-based biologically inspired design, a very attractive method for generating multifunctional designs.

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