Design Knowledge and Theory

The Third International Conference on Design Creativity (3rd ICDC)
ISBN 978-1-904670-60-5
Bangalore, India, 12th-14th January 2015

DO TYPES OF KNOWLEDGE SUPPORTED INFLUENCE CREATIVITY IN DESIGN SOLUTIONS?

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Abstract: In this paper, the influence of types of knowledge of support on creativity of solutions developed using the support is investigated. Data from a completed design project involving development of novel and demonstrable concepts of mobility systems of lunar vehicles by using the GEMS of SAPPhIRE framework (process knowledge) and IDEA-INSPIRE (product knowledge), is used for this study. By using a combination of process and product knowledge and considering a blend of bio- and non-bio-inspired ideas, helps develop concepts that are potentially novel, realisable and satisfy the identified requirements. These together can potentially improve design creativity.

Keywords: *bio-inspired design, ideation, process knowledge, product knowledge*

1. Introduction

Design creativity is the ability of an agent to develop outcomes that are both novel and valuable (Sarkar & Chakrabarti, 2011). The outcomes are creative if they are both novel and valuable; the degree of creativity depends on the combined value of degree of novelty and value.

Biologically-inspired design (BID) is a set of practices, which uses inspirations from systems in the biological domain to design systems in the artificial domain (Benyus, 1997). Due to similarities between biological and artificial systems, biological systems are a source of inspiration for developing innovative and sustainable artificial systems (Papanek, 1984; Vincent, 2001). Various kinds of support are proposed to assist BID, by providing: (a) process knowledge (e.g., (Sartori et al., 2010)); (b) product knowledge (e.g., (Chakrabarti et al., 2005)), or (c) their combination (e.g., (Schild et al., 2004)). Few studies investigate the role of types of knowledge on the quality of ideation of BIDs developed using the supports. Therefore, in this paper, the influence of the process knowledge (provided by GEMS of SAPPhIRE framework for designing) and product knowledge (provided by IDEA-INSPIRE), on the quality of ideation of BID solutions developed using these forms of knowledge, is studied. It is perceived that the identification of the (non) influential knowledge types will help in development of better support to aid improved ideation.

2. Literature on BID and Research Question

Various kinds of BID support providing knowledge of process and product are reviewed in this section. Sartori et al. (2010) presented a generic model of BID based on various biomimetic models from literature, and accordingly, proposed a set of empirically validated guidelines. Generic levels of abstraction at which transfer occurs are identified based on biomimetic design cases. Chakrabarti et al. (2005) developed IDEA-INSPIRE, an interactive tool to search for analogies from a database of biological and engineered systems (reviewed in Section 3.3). Vattam et al. (2010) developed DANE, an interactive knowledge-based design environment to retrieve and transfer analogies in BID. In DANE, the biological and engineered systems are described using the Structure-Behavior-Function (SBF) model using text and images, at several levels of detail: cell, organ and function. Schild et al. (2004) proposed a systematic approach for determining biologically analogous solutions, comprising: formulate problem, evaluate problem, search analogy, and verify result. Four levels of transfer – of an existing technology to a new context, of structure, partial transfer of functional principles, and use of analogy as idea stimulus – are also proposed. Lindemann and Gramann (2004) proposed a BID procedure comprising: (a) formulate search objectives in terms of functions and constraints, (b) relate function categories and biological examples using an association list, (c) identify relevant biological systems from literature on biology, (d) analyse biological systems to check if sufficient knowledge is available for transfer to technical systems, and (e) evaluate systems leading to technical implementation. Shu et al. (2011) developed an approach for cataloguing and searching biological information available in natural-language format, to identify relevant phenomena for solving problems. The natural language model is used to identify "bridge verbs" to connect biology and engineering lexicons, and bridge cross-domain terminology for searching biological knowledge. Hill (2005) developed a BID model consisting of goal setting and solution identification. Contradicting demands are identified in goal setting. Solution identification comprises: identification of basic functions underlying the demands, identification of relevant biological structures with similar functional characteristics, analysis of biological structures to extract underlying principles, development of preliminary solution associations for each biological structure, transfer of preliminary solutions into technical solutions according to requirements and conditions of the goal, varying characteristics of the solutions, combining to form solution variants, and selecting an appropriate solution. To complement the process-knowledge, Hill (1997) developed a catalogue of knowledge about biological structures and their functions, which are distributed over several levels of scale and complexity, and described hierarchically. Vincent et al. (2006) developed a database of biological effects using TRIZ methods of contradiction analysis. The BioTRIZ matrix consists of 2500 conflicts and their resolutions in biological domain. Nagel et al. (2010) proposed a method for functional representation of biological systems to support conceptualisation of BIDs. Functional representation and abstraction are used to translate biological systems into engineering contexts to make biological information more accessible to engineers with limited knowledge of natural systems. AskNature, a free, open source project developed by "The Biomimicry 3.8 Institute", contains description of biological systems. The information is organised using the 'Biomimicry Taxonomy' comprising four layers: group, sub-group, strategy and function.

The many forms of support proposed for BID provide process knowledge, product knowledge, or both. However, the influence of the nature of knowledge (process, product or both) in support on the quality of ideation using the support, is rarely explored. Based on this issue, the following research question is posed: What type(s) of knowledge influence(s) quality of ideation of BID solutions?

3. Previous Work

In this section, relevant work related to BID carried out earlier by the authors is described.

3.1 SAPPhIRE Model

The SAPPhIRE (acronym for **S**tate-change, **A**ction, **P**art, **Ph**enomenon, **I**nput, o**R**gan and **E**ffect) model was developed to explain the causality of biological and engineered systems (Chakrabarti et al., 2005). The components and interfaces of a system and its environment (parts) constitute their various properties and conditions (together referred to as organs). The physical quantities (inputs) in the form of material, energy or signal and the relevant organs, activate various principles (effects), which create various interactions between the system and the environment (phenomena), with consequent changes in their properties (state-changes). These changes can be interpreted at a higher level of abstraction (actions), change the parts and interfaces themselves, or act as inputs to other (sub-) systems.

3.2 GEMS of SAPPhIRE (GoS) framework for designing

Srinivasan and Chakrabarti (2010a) developed GEMS of SAPPhIRE as req-sol (GoS), a descriptive model of designing, which combines the GEMS (Generate, Evaluate, Modify, Select) activities, the SAPPhIRE outcomes with co-evolving requirements (req) and solutions (sol). Based on this model, the prescriptive GoS framework is developed to support process knowledge in design for novelty in early phases of engineering design (Srinivasan & Chakrabarti, 2009). The GoS framework comprises two stages: requirements exploration stage (RES) and solutions exploration stage (SES). In RES, requirements at different levels of detail are developed. In SES, alternative solutions at each of the levels of action-, state change-, phenomenon-, effect-, input, organ- and part, are developed, in that order. The use of the GoS framework assists in improving the variety and novelty of solution spaces (Srinivasan & Chakrabarti, 2011).

3.3 IDEA-INSPIRE

IDEA-INSPIRE is a computer-based interactive tool for providing product knowledge to support ideation during early stages of designing. The tool enables search for analogically relevant stimuli from its database of biological and engineered systems (Chakrabarti et al., 2005). Each entry in the database contains verbal-, pictorial- and video- or simulation-based descriptions of a biological or engineered system, explaining the working of the system. The verbal descriptions are explained using the SAPPhIRE model and, function, behaviour and structure. A design problem can be specified using the entities of the SAPPhIRE model and analogical reasoning procedures are used for an automated search from entries in the database to identify stimuli for solving design problems.

3.4 Collaborative design project

To analyse the influences of the types of knowledge on the ideation of conceptual solutions, data from a completed collaborative design project is used. The design project aimed at developing novel, demonstrable concepts of the mobility system for lunar vehicles by using the GEMS of SAPPhIRE (GoS) framework (see Section 3.2) and IDEA-INSPIRE (see Section 3.3), which provide the process- and product-knowledge, respectively. Apart from funding, the collaborating partner provided the requirements for the mobility system, and acted as final selectors of designs at each stage of the design process within the project. The design team consisted of three members including one of the developers of the GoS framework; this member trained the other two members to use the framework and IDEA-INSPIRE, and also acted as the guide for the team through the various stages of the designing. The following requirements are identified for the mobility system: (a) mobility-capabilities (accelerate, decelerate), (b) steering-capabilities (veer left or right), (c) gradient-handling capabilities (±X°), and (d) stability, subject to the following constraints: (a) vehicle-mass (m_v kg), (b) payload-mass (m_p kg), (c) vehicle-size (A x B x C mm) and, (d) vehicle-speed (v_1-v_2 mm/s). The numbers are not revealed here to preserve confidentiality. An idea is defined here as a solution which is a constituent of a concept and is intended to satisfy only one or a few requirements. A concept is defined as a solution that is intended to satisfy all the requirements. For each aforementioned requirement, several ideas are developed by using the GoS framework and IDEA-INSPIRE. Several design concepts are developed by combining ideas from each requirement. In the advanced stages of the project, a group of experts from the collaborating body selected the final concept for further modelling and testing. None of these experts had been part of the design team which developed the ideas and concepts. After the completion of the project, another design concept, chosen by the members of the design team, is modelled and tested. The description of the ideas and the concepts selected within the project are shown in (Srinivasan et al., 2011).

4. Approach

To answer the research question, data from the collaborative, design project for developing proofs of concept for mobility systems of lunar vehicles is used. In this project, the designers are instructed to develop ideas and solutions by using the GoS framework and IDEA-INSPIRE. However, ideas are developed by using designers' knowledge only or in combination with either or both of the GoS framework and IDEA-INSPIRE, and in varying quantities. This is the basis for answering the question; the underlying assumption being that the number of ideas developed using a type of knowledge is indicative of the influence of that type of knowledge.

5. Results

In this section, the ideas developed for the requirements of mobility, steering, handling gradient and stability, are analysed; all the ideas are explained in (Srinivasan et al., 2011). As stated before, some ideas are developed using either the GoS framework or IDEA-INSPIRE, while the rest are developed using a combination of these, and a few using only the knowledge of the designers i.e., neither the GoS framework nor IDEA-INSPIRE. Since inspirations from designers' knowledge and IDEA-INSPIRE can be both biological and non-biological, both biologically (B) and non-biologically (NB) inspired ideas are included in this analysis. This is gauged based on the nature of inspiration used in developing the ideas. Table 1 shows the distribution of biologically- (B) and non-biologically (NB) inspired ideas, developed using various degrees of support for each requirement. Twenty-one ideas are developed for vehicle-mobility by using: (i) the designers' knowledge and the GoS framework (abbreviated, D+F), and (ii) the designer's knowledge, the GoS framework, and IDEA-INSPIRE (abbreviated, D+F+I). Thirteen ideas are developed for steering the vehicle by using: (i) D+F and (ii) D+F+I. Ten ideas are developed for handling gradients by using: (i) D, (ii) D+I, and (iii) D+F+I. Six ideas are developed for stabilising the vehicle by using: (i) D, (ii) D+F, and (iii) D+F+I.

Table 1. Distribution of biologically and non-biologically inspired ideas developed using various degrees of support

	Mobility			Steering			Handling gradient			Stability			Overall		
	B	NB	Total	B	NB	Total	B	NB	Total	B	NB	Total	B	NB	Total
D	0	0	0	0	0	0	1	4	5	0	2	2	1	6	7
D+F	0	7	7	0	5	5	0	0	0	0	3	3	0	15	15
D+I	0	0	0	0	0	0	2	0	2	0	0	0	2	0	2
D+F+I	11	3	14	3	5	8	2	1	3	1	0	1	17	9	26
Total	11	10	21	3	10	13	5	5	10	1	5	6	20	30	50

The following inferences are drawn from Table 1:

a. For mobility, 11 out of 21 ideas (52.38%), steering 3 out of 13 ideas (23.08%), handling gradient 5 out of 10 ideas (50%) and stability 1 out of 6 ideas (16.67%) are bio-inspired.
b. Only 1 out of 20 bio-inspired ideas (5%) and 6 out of 30 non-bio-inspired ideas (20%) are developed using only the designers' knowledge. The remaining are developed using the GoS framework and IDEA-INSPIRE, individually or in combination. It is inferred that it is more difficult to develop bio-inspired ideas than non-bio-inspired ideas without support.
c. In total, out of 20 bio-inspired ideas, 1 (5%) required the designers' knowledge only, 2 (10%) required a combination of the designer's knowledge and the GoS framework, and 17 (85%) required the designers' knowledge, the GoS framework and IDEA-INSPIRE. Out of 30 non-

bio-inspired ideas, 6 (20%) required the designers' knowledge only, 15 (50%) required the designers' knowledge and the GoS framework, and 9 (30%) used the designers' knowledge, the GoS framework and IDEA-INSPIRE. The following are inferred from these findings: (i) for developing bio-inspired ideas, product knowledge provided by IDEA-INSPIRE plays a more significant role, (ii) for developing non-bio-inspired ideas, process knowledge provided by the GoS framework plays a more prominent role, and (iii) a combination of product and process knowledge, while influential in both cases, is more potent for developing bio-inspired ideas.

d. In total, irrespective of the type of inspiration, out of the total of 50 ideas developed, 7 (14%) used the designers' knowledge only, 15 (30%) used the designers' knowledge and the GoS framework, 2 (4%) used the designers' knowledge and IDEA-INSPIRE, and 26 (52%) used the designers' knowledge, the GoS framework and IDEA-INSPIRE. 41 ideas (82%) are developed using the GoS framework, in combination with either the designers' knowledge or IDEA-INSPIRE. This indicates that the effect of the GoS framework in developing ideas, whether bio- or non-bio-inspired, has been substantial. A substantial number of bio-inspired ideas (17 out of 20; 85%) and non-bio-inspired ideas (9 out of 30; 30%) are developed when both the GoS framework and IDEA-INSPIRE are used. This could also mean that process knowledge through the framework has a major impact on the application of appropriate product knowledge.
e. Both the GoS framework (82%; 41 out of 50 cases) and IDEA-INSPIRE (56%; 28 out of 50 cases) have substantial influence on the creation of ideas.

From the space of ideas, potentially many concepts could be developed (combinatorially $21 \times 13 \times 10 \times 6 = 16{,}380$ concepts); however, due to constraints of feasibility and time, 20 concepts are developed for further consideration (see Table 2). The important findings are as follows:

a. The concepts constitute a majority of non-bio-inspired ideas: 56.25% (9/16) for mobility, 75% (6/8) for steering, 66.67% (6/9) for handling gradient, and 75% (3/4) for stability. This can be due to the fact that designers with primarily engineering product knowledge felt more comfortable in selecting ideas that are non-bio-inspired, as these are within their comfort zones, which they might have known to be realisable.
b. A substantial number of these ideas – 100% (20/20) for mobility, 100% (20/20) for steering, 46.67% (7/15) for handling gradients, 12.50% (2/16) for stability and 69.01% (49/71) overall – in these concepts are developed using some form of support. It is inferred that the ideas developed using some degree of support played a major role among concepts created from ideas developed using: (i) no support, and (ii) some degree of support. It is also possible that designers selected these ideas in concepts considering their realisability – a major objective of the project.
c. In these concepts, out of a total of 34 ideas, 18 (52.94%) are developed using the designers' knowledge, the GoS framework and IDEA-INSPIRE, 9 (26.47%) using the designers' knowledge and the GoS framework, and 7 (20.59%) using the designers' knowledge only. This shows the dominant effect of the combined use of the GoS framework and IDEA-INSPIRE, not only in the creation of initial ideas, but also in the use in concepts from the pool of ideas developed using various degrees of support. Therefore, it can be argued that a combination of the GoS framework and IDEA-INSPIRE also helps in developing ideas that can be realised as concepts.

6. Discusssion

Even though both forms of knowledge – process and product – were supported, designers chose to use neither, either or a combination of these. This allows an investigation into the comparison of the roles of the types of knowledge on the quality of ideation, which is assessed in terms of the number of ideas developed by each type of knowledge. By using a combination of the GoS framework and IDEA-INSPIRE, the designers developed the most number of bio-inspired ideas for each of the requirements (see Table 1), thereby possibly increasing the combinatorial space of bio-inspired concepts that can be created by combining the bio-inspired ideas. On the other hand, by using the GoS framework, the designers were able to develop most number of non-bio-inspired ideas for most of the requirements (see Table 1). In total, most of the ideas, irrespective of the kind of inspiration, were developed by using a combination of the GoS framework and IDEA-INSPIRE. Exploring more ideas increases the chances of developing a concept space of higher variety and novelty (Srinivasan and Chakrabarti, 2010b). Therefore, it can be argued that by using a combination of process and product knowledge can enhance the chances of developing design concepts of higher variety and novelty.

Table 2. Concepts developed from pool of ideas

Concept	Mobility		Steering		Handling gradients		Stability	
	Degree of support	Inspiration	Degree of support	Inspiration	Degree of support	Inspiration	Degree of support	Inspiration
1	D+F+I	NB	D+F+I	B	D+F+I	B	D	NB
2	D+F	NB	D+F	NB	D	NB	D	NB
3	D+F	NB	D+F+I	NB	D	B	D	NB
4	D+F	NB	D+F+I	NB	D	B	D	NB
5	D+F	NB	D+F	NB	D+I	B	D+F	NB
6	D+F+I	B	D+F	NB	-	-	-	-
7	D+F+I	B	D+F	NB	-	-	-	-
8	D+F+I	NB	D+F	NB	D+F+I	NB	D	NB
9	D+F+I	NB	D+F+I	B	D+F+I	B	D	NB
10	D+F+I	B	D+F	NB	-	-	D	NB
11	D+F+I	NB	D+F	NB	D+I	B	D	NB
12	D+F+I	B	D+F+I	B	D+F+I	NB	-	-
13	D+F+I	B	D+F	NB	D+F+I	NB	D	NB
14	D+F+I	B	D+F	NB	-	-	D	NB
15	D+F+I	B	D+F	NB	-	-	-	-
16	D+F	NB	D+F+I	NB	D	NB	D	NB
17	D+F	NB	D+F+I	NB	D	NB	D	NB
18	D+F+I	NB	D+F+I	NB	D	NB	D	/NB
19	D+F	NB	D+F+I	NB	D	NB	D	NB
20	D+F	NB	D+F+I	NB	D+F	NB	D+F+I	B

Most of the ideas that were used in the twenty bio-inspired concepts were developed by using a combination of the GoS framework and IDEA-INSPIRE. Most of the ideas in the concepts were also non-bio-inspired. Two concepts (Concepts 1 and 20 in Table 2) were realised by modelling and testing them physically using LEGO Mindstorms robotics kit, virtually using MSC ADAMS and analytically using force- and moment-balance equations; the physical, virtual, and analytical models were found to satisfy all the requirements (Ranjan et al., 2009; Srinivasan et al., 2011). A preliminary assessment of novelty of the two concepts was carried out by comparing these concepts against other lunar vehicles that perform similar functions, and both the concepts were found to have elements of novelty in their designs and performance (Ranjan et al., 2009). Most of the ideas in these two concepts were also non-biologically inspired and developed by using a combination of the GoS framework and IDEA-INSPIRE. These observations show that that by using a combination of the GoS framework and IDEA-INSPIRE also helped in development of ideas that satisfy requirements and can be realised. Concepts constituted mostly by non-bio-inspired ideas also satisfy requirements and can be realised. Both realisation of solutions and satisfaction of requirements contribute to value of concepts, because without these products cannot be realised and therefore, cannot be novel or creative. Therefore, by using a combination of process knowledge (provided by the GoS framework) and product knowledge (provided by IDEA-INSPIRE) can potentially enhance both novelty and value of concepts, the two measures of design creativity as proposed by Sarkar and Chakrabarti (2011). In addition, by considering a blend of biologically and non-biologically inspired ideas will enhance both novelty and value of concepts.

The number of ideas developed for each of the four requirements is not the same due to the following reasons. The ideas for these requirements were developed sequentially one after another by the three designers. Fatigue may have played a part in the gradual decrease in the number of ideas for these requirements as the project progressed. Besides, the number of relevant entries in IDEA-INSPIRE was significantly more for mobility and steering than for handling gradient and stability. Since a significant number of ideas are developed using IDEA-INSPIRE (see Table 1), the number of relevant entries may also have played a role in the variation of ideas for each requirement.

The combination of GoS framework and IDEA-INSPIRE was primarily used to only generate ideas i.e., supported only 'generate' activity in early designing stages; the other activities were dependent on the skills and experience of the designers and experts (Table 3). The scenario might have been different had the other activities also been supported.

Table 3. Type of knowledge used in project for ideation and conceptualisation

	Generate	Evaluate	Modify	Select
Ideas	Designers' cognition, GoS framework, and IDEA-INSPIRE (individually or in combination)	Designers' cognition and GoS framework	Designers' cognition and GoS framework	Designers' cognition and GoS framework
Concepts	Designers' cognition	Cognition of space mechanism experts and designers	Cognition of space mechanism experts and designers	Cognition of space mechanism experts and designers

A major limitation of this research is that the results are based on a single case-study i.e. data from the funded project. By investigating empirical studies of comparative nature (e.g., no-support vs process knowledge support vs product knowledge support vs process and product knowledge support) will help further substantiate the findings. On one hand, industrial projects have longer durations and are closer to real-world situations, although at the cost of variables with less controllability. On the other hand, comparative empirical studies are constrained to have shorter durations, and are farther from real-world situations while having greater control on variables. Both these kinds of case-studies have their own pros and cons. Therefore, the results in this paper should be taken in the context of industrial projects – providing greater realism while sacrificing controllability.

For non-biological inspiration, most ideas were developed when a combination of the designers' knowledge and the GoS framework was used. In other words, supporting the process knowledge was sufficient to produce most ideas for non-biologically inspired ideation, due to prior knowledge of the designers.

7. Summary and Conclusions

This paper uses data from a completed design project to address the role of process- and product-knowledge, provided by the GoS framework and IDEA-INSPIRE respectively, on ideation using these pieces of support. It is found that a combination of process and product knowledge helps develop the most number of ideas for all the requirements in comparison to other degrees of support, in particular for biologically inspired ideas. Few ideas from each requirement are combined to create twenty concepts; out of these, two concepts are physically, virtually and analytically modelled and tested, and are found to satisfy all the requirements. Most of the ideas in these concepts are non-biologically inspired and are developed by using a combination of the GoS framework and IDEA-INSPIRE.

The following conclusions are drawn:

a. The type of knowledge from a support influences solution development using the support. A combination of process and product knowledge provided by the GoS framework and IDEA-INSPIRE, respectively, has a substantial influence compared to other degrees of support.

b. Creativity of concepts is more influenced by using a support that combines knowledge of both process and product, over other degrees of support. By considering a blend of biologically and non-biologically inspired ideas can also enhance novelty and value of concepts, and thereby, creativity of concepts.

Acknowledgement

The authors acknowledge the contributions from the Spacecraft Mechanisms Group of ISRO Satellite Centre, Bangalore, for its technical inputs and support.

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