INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED13
19-22 AUGUST 2013, SUNGKYUNKWAN UNIVERSITY, SEOUL, KOREA

WHAT DO THE CONCEPT GENERATION TECHNIQUES OF TRIZ, MORPHOLOGICAL ANALYSIS AND BRAINSTORMING HAVE IN COMMON?

Udo KANNENGIESSER (1), Christopher WILLIAMS (2), John GERO (3)
1: Metasonic AG, Germany; 2: Virginia Tech, United States of America; 3: Krasnow Institute for Advanced Study and University of North Carolina at Charlotte, United States of America

ABSTRACT
One of the goals of design research is to identify regularities across different design processes. This paper presents experimental evidence that there exist commonalities between three separate concept generation techniques: TRIZ, Morphological Analysis, and Brainstorming. This evidence is based on protocol studies involving mechanical engineering students that use the three techniques for performing different design tasks. The protocols have been coded using the function-behaviour-structure (FBS) scheme and then analysed in terms of the cumulative occurrence of FBS design issues. The commonalities found are related to the first occurrence of certain design issues, and to their continuity and linearity.

Keywords: design cognition, design methods, design practice

Contact:
Dr. Udo Kannengiesser
Metasonic AG
Research and Development
Pfaffenhofen
85276
Germany
udo.kannengiesser@gmail.com

1 INTRODUCTION

Designing is the way humans intentionally change the physical and virtual worlds they inhabit. Society recognizes designing as important, and privileges defined groups as designers (e.g., engineers, architects, and software designers). It is therefore surprising that formal research into designing commenced relatively recently. Design research has largely adopted the scientific paradigm in which it is focused on discovering and representing the assumed regularities that underlie design phenomena.

The early seminal works in design research in the 1960s and 1970s focused on methods and processes and produced an array of terminologies to describe designing (Jones 1963; Moore 1970). It was unclear whether the terms used by one group of researchers mapped onto terms used by other researchers or whether they were describing different phenomena. Designing also appeared to present problems for scientific research in that the design results were always unique and therefore there would be no regularity. Consequently, the impact of different methods and tools on designing and design cognition has been difficult to study when looking for regularities in outcomes.

The function-behaviour-structure (FBS) ontology (Gero 1990; Gero and Kannengiesser 2004) provides a uniform representation that is starting to be used for analysing empirical data about designing and comparing different instances of designing. For example, Gero, Jiang and Williams (2012) used the FBS representation for comparing students' design cognition when using different concept generation techniques. It was observed that the use of structured concept generation techniques (specifically morphological analysis and TRIZ) decreases the amount of cognitive effort students expend on the structure of a design solution, and instead increases the amount of cognitive effort they expend on expected behaviour. This suggests that structured methods provide an appropriate framework for designers to think of solutions in an abstract sense before focusing on specific embodiments. However, in another study based on FBS-coded design protocols (Gero, Kannengiesser and Pourmohamadi 2012) it was found that there are commonalities in designing even when different methods are used. These commonalities are related to the cumulative occurrences of design issues during the course of designing.

The current evidence for these commonalities is only preliminary, since in the latter study only a small set of thirteen individual case studies was analysed. This paper presents the results of a similar analysis of a larger dataset, representing design sessions involving mechanical engineering students that use the three concept generation techniques: TRIZ, morphological analysis and brainstorming. This study is based on a grounded theory approach: Rather than commencing with a hypothesis about possible commonalities, we look for regularities in the data as a basis for developing hypotheses about designing.

The paper is structured as follows. Section 2 describes the experiments including the coding scheme used to represent the data derived from them. Section 3 describes the analysis method and the measures used for testing the hypothesis of commonalities across the three concept generation techniques. Section 4 presents the experimental results. Section 5 summarises and discusses the findings.

2 EXPERIMENTS

In order to investigate the effect of different concept generation techniques on the design cognition of engineering students, three experiments were carried out.

2.1 Participants and Design Course

The participants were recruited from a capstone design course where they were taught three concept generation techniques (described below). The students' prior design education was a cornerstone experience in a first-year engineering program and in a sophomore-level course that focused in exposing students to engineering design and design methods at an early stage of their professional development. Students with significant design experience (either professionally or through prior academic experience), as identified through a preliminary interview, were not selected as participants for this study.

In the capstone sequence, ten student teams each of which consists of two students work with a faculty mentor on a year-long design project. In the second semester, the students work solely on their projects and are primarily focused in the latter stages of design including engineering analysis, prototype development, and detailed design. However, in the first semester of the sequence, the students meet weekly in a classroom setting to discuss the early stages of the design process (problem definition, conceptual design), engineering ethics, and elements of engineering economics. The students' primary goal for this first semester is to scope their given design problem, generate several potential solutions, and select an alternative to embody during the second semester. It is in this semester that the students received instruction on the three concept generation technique investigated in this study.

2.2 Three Concept Generation Techniques

Students participated in instruction related to three different concept generation techniques in the first semester of the capstone design course sequence.

Brainstorming. Brainstorming is a well-developed process and is widely used in industry. It involves having members of the design team produce ideas without any concern for their viability and without any criticism of them during the production phase (Anonymous 1995; Fisher 1996; Lumsdaine and Lumsdaine 1995; Nijstad et al. 2003). The notion is to produce as many ideas as possible. The ideas are then attempted to be linked, with judgment still deferred.

Morphological analysis. Morphological analysis is a well-developed process used in industry. It uses the concept of systematically structuring (shaping) a multi-dimensional problem through its relationships. It is based on bringing together two opposing notions: decomposition and forced associations (Ritchey 2006; Ullman 1992; Zwicky 1969). Once the problem is decomposed, potential solutions for each sub-problem are ideated. These solutions are then organized in a morphological matrix. Potential solutions to the design task are generated by systematically combining concepts from each sub-problem.

TRIZ: TRIZ is the acronym in Russian for a system of inventive problem solving developed by G Altshuller. It a well-developed process and is very widely used in industry. It is a method founded on being directed to a set of fundamental physical principles through a process of resolving contradictions (Altshuller 1973; Altshuller 1984; Altshuller et al. 2002; Leon-Rovira 2007; Rantanen and Domb 2002; Terninko et al. 1998).

Before each experiment, there was a lecture elucidating and detailing one of the techniques. Each lecture was approximately 75 minutes in duration and was structured similarly: the instructor introduced the technique, and would then provide the students with a sample design scenario to address using that technique. As the class met once a week, the three techniques were presented sequentially over the course of three weeks: brainstorming, morphological analysis, and finally, TRIZ. Each lecture was given on a Monday; the corresponding experiment was administered over the course of that week prior to the subsequent class meeting.

2.3 Experimental Design

Twenty-two mechanical engineering students participated in this study voluntarily. They were formed into teams of two. Each team was given the same set of three design tasks, one for each concept generation technique. All design tasks were focused on designing an assistive technology device and were created to be similar in concept, context, and complexity. In the first session, students were asked to use brainstorming to design a device to help disabled users open a stuck double-hung window without relying on electric power. In the second session, students were asked to use morphological analysis to design a device to help stroke patients, who are unable to perform bilateral tasks, with opening doors (adapted from Atman, Kilgore and McKenna (2008)). In the third session, students were asked to use TRIZ to design a device to add to an existing hand/arm-powered wheelchair that will allow paraplegic wheelchair users to traverse a standard roadside curb unassisted.

During the experimental sessions, the students were asked to collaborate with their team members. Then they were instructed to intentionally and actively use one of the concept generation techniques, and to come up with a design solution that meets the given design requirements within 45 minutes.

All the design sessions were audio and video recorded for later analysis. Specifically, two digital camcorders were used, one recording the whiteboard and the other recording the participants' gestures. Each participant had their own individual wireless lapel microphone to ensure a high recording quality of their conversation.

2.4 Coding

The FBS ontology (Gero 1990; Gero and Kannengiesser 2004) represents designing as a process that takes externally given requirements (R) as input and produces design descriptions (D) as output, using a set of transformations operating on function (F), expected behaviour (Be), behaviour derived from structure (Bs), and structure (S). These six ontological design issues (R, F, Be, Bs, S, and D) are defined as follows:

- *Requirements (R)*: includes all requirements and constraints that are explicitly provided to the designer by the client or through formal societal codification in terms of codes of practice.
- *Function (F)*: includes teleological representations that can cover any expression related to potential purposes of the design.
- *Expected Behaviour (Be)*: includes attributes of the design used as assessment criteria or target values for potential design solutions. They may include technical, economic, ergonomic and other characteristics.
- *Behaviour derived from structure (Bs)* (or, shorthand, "structure behaviour"): includes attributes of the design that are measured, calculated or derived from observation of a specific design solution.
- *Structure (S)*: includes the components of a design and their relationships. They can appear either as a set of general concept solutions or as detailed solutions.
- *Description (D)*: includes any form of external representation produced by a designer, at any stage of the design process.

The FBS design issues form a principled coding scheme for segmenting and coding transcripts of the experiment videos (i.e., design conversations and gestures, etc.) into a sequence of design issues denoted by semantic symbols, i.e., the FBS codes. The Delphi method (Gero and McNeill 1998; Purcell 1996) was applied to increase the reliability of protocol segmentation and coding. It consists of two separate coding processes undertaken by two independent coders, and an arbitration session to resolve the coding disagreements identified in the previous coding results. Utilizing the Delphi method, the average inter-coder reliability across all protocols reached a relatively high score of 88%. The arbitrated result, namely, a sequence of design issues, becomes the foundational data for subsequent analyses that characterise the design cognition of the participants.

3 ANALYSIS

For analysing the dataset we calculate the cumulative occurrence of each of the six design issues across all segments in a design protocol. Specifically, the cumulative occurrence, *c*, of design issue, *x*, at segment *n* will be $c = \sum_{i=1}^{n} x_i$ where x_i equals 1 if segment *i* is coded as *x* and 0 if segment *i* is not coded as *x*. Plotting the results of this equation on a graph with the segments, *n*, on the horizontal axis and the cumulative occurrence, *c*, on the vertical axis will visualise the occurrence of the design issues in a protocol, as shown in Figure 1.

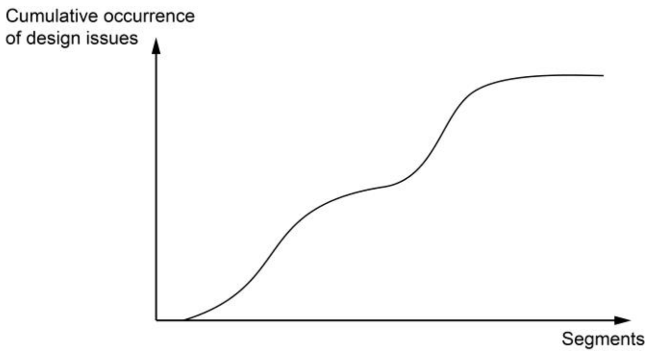

Figure 1. Graphical representation of the cumulative occurrence of a design issue in a design protocol

There are multiple measures that could be used in an exploratory study to characterize commonality. The measures selected here to be used for characterising the cumulative occurrence of design issues are drawn from those developed in Gero, Kannengiesser and Pourmohamadi (2012) and are presented in Table 1. "First occurrence at start" and "Continuity" are Boolean measures that are determined through qualitative assessments of the data. "Linearity", another Boolean measure, is determined quantitatively based on R^2, the statistical measure of the variance from linearity. Finally, "Slope" is a quantitative measure that represents the rate at which design issues are generated.

Table 1. Measures related to the cumulative occurrence of design issues

Measure	Possible values
First occurrence at start	Yes (if first occurrence of design issue is near the beginning of design session) No (if first occurrence of design issue is not near beginning of design session)
Continuity	Yes (if design issue occurs throughout design session) No (if design issue occurs only up to a certain point)
Linearity	Yes (if $R^2 \geq 0.950$) No (if $R^2 < 0.950$)
R^2	(numeric value)
Slope	(numeric value)

4 RESULTS

The measures in Table 1 are used for every individual design session, and then aggregated across design sessions. This Section presents these aggregated results for the three techniques, using mean values for R^2 and slope, and using percentages for first occurrence at start and continuity (in terms of the relative number of sessions in which their value is "Yes"). Linearity is presented as a Boolean value ("Yes" or "No") based on whether or not the mean R^2 value is above 0.950. Slope is calculated based on only those design sessions where linearity is found.

4.1 Requirement Issues

The results of our analysis related to requirement issues are shown in Table 2. As the number of occurrences of requirement issues was too low (less than 10 for all design sessions) to allow for meaningful statistical analyses, we did not derive any values for the quantitative measures of slope and R^2, and for the linearity measure as it is based on the mean R^2. However, even with the few occurrences available, it was possible to make qualitative assessments for the measures of first occurrence at start and continuity.

Table 2. Requirement issues: Measures

Dataset	Mean Slope (Stdev)	Mean R^2 (Stdev)	First occur-rence at start [%]	Continuity [%]	Linearity
TRIZ	---	---	90	0	---
Morphological Analysis	---	---	73	9	---
Brain-storming	---	---	90	10	---
Total	---	---	84	6	---

First occurrence of requirement issues at start was observed in 84% of all design sessions, irrespectively of the use of a specific concept generation technique. Continuity was observed in 6% of all design sessions.

4.2 Function Issues

The results for function issues, now including the mean values with standard deviations for slope and R^2 for the three datasets, as the average number of occurrences was more than 10 for every design session, are shown in Table 3.

Table 3. Function issues: Measures

Dataset	Mean Slope (Stdev)	Mean R^2 (Stdev)	First occur-rence at	Continuity [%]	Linearity

			start [%]		
TRIZ	---	0.849 (0.087)	90	10	No
Morphological Analysis	0.066 (0.028)	0.855 (0.132)	91	55	No
Brain-storming	0.037 (0.001)	0.867 (0.073)	70	50	No
Total	0.070 (0.045)	0.857 (0.098)	84	39	No

The total results of all design sessions have a mean slope of 0.070. They also include a mean R^2 of 0.857, which is below the threshold of 0.950 and therefore does not support linearity. First occurrence of function issues at start is observed in 84%, and continuity in 39% of all design sessions.

4.3 Expected Behaviour Issues

The results for expected behaviour issues are shown in Table 4.

Table 4. Expected Behaviour issues: Measures

Dataset	Mean Slope (Stdev)	Mean R^2 (Stdev)	First occur-rence at start [%]	Continuity [%]	Linearity
TRIZ	0.175 (0.045)	0.963 (0.027)	100	70	Yes
Morphological Analysis	0.154 (0.038)	0.926 (0.027)	100	36	No
Brain-storming	0.075 (0.024)	0.950 (0.034)	80	40	Yes
Total	0.131 (0.060)	0.946 (0.033)	94	48	No

The total results for expected behaviour issues of all design sessions include a mean slope of 0.131. They also include a mean R^2 of 0.946, which is just below the threshold of 0.950 and therefore does not support linearity. It should be noted, however, that the TRIZ and brainstorming datasets, individually, pass that threshold (i.e. exhibit linearity). First occurrence of expected behaviour issues at start is observed in 94%, continuity in 48%, of all design sessions. When employing the structured techniques (morphological analysis and TRIZ), expected behaviour issues were mentioned at the start of 100% of the design sessions (as compared to 80% for brainstorming). A similar trend is found in the function issues (Table 3). This corroborates previous observations that designers using structured methods think of solutions in an abstract sense before focusing on specific embodiments.

4.4 Structure Behaviour Issues

The results for structure behaviour issues are shown in Table 5.

The total results for structure behaviour issues of all design sessions include a mean slope of 0.275. They also include a mean R^2 of 0.987, which is above the threshold of 0.950 and therefore supports linearity. The standard deviation for R^2 is very low (0.012). First occurrence of structure behaviour issues at start is observed in 81%, continuity in 97% of all design sessions. Note that the individual percentage for first occurrence at start in the morphological analysis dataset is only 55%, while it is 100% and 90% in the TRIZ and brainstorming datasets.

Table 5. Structure Behaviour issues: Measures

Dataset	Mean Slope (Stdev)	Mean R^2 (Stdev)	First occur-rence at start [%]	Continuity [%]	Linearity

TRIZ	0.286 (0.042)	0.994 (0.002)	100	90	Yes
Morphological Analysis	0.251 (0.043)	0.978 (0.015)	55	100	Yes
Brain-storming	0.288 (0.040)	0.990 (0.007)	90	100	Yes
Total	0.275 (0.044)	0.987 (0.012)	81	97	Yes

4.5 Structure Issues

The results for structure issues are shown in Table 6.

Table 6. Structure issues: Measures

Dataset	Mean Slope (Stdev)	Mean R^2 (Stdev)	First occur-rence at start [%]	Continuity [%]	Linearity
TRIZ	0.291 (0.055)	0.971 (0.022)	80	90	Yes
Morphological Analysis	0.391 (0.041)	0.994 (0.004)	82	100	Yes
Brain-storming	0.401 (0.057)	0.997 (0.001)	90	100	Yes
Total	0.364 (0.070)	0.988 (0.017)	87	97	Yes

The total results for structure issues of all design sessions include a mean slope of 0.364. They also include a mean R^2 of 0.988, which is above the threshold of 0.950 and therefore supports linearity. The standard deviation for R^2 is very low (0.017). First occurrence of structure issues at start is observed in 87%, continuity in 97% of all design sessions.

4.6 Description Issues

The results for description issues are shown in Table 7.

Table 7. Description issues: Measures

Dataset	Mean Slope (Stdev)	Mean R^2 (Stdev)	First occur-rence at start [%]	Continuity [%]	Linearity
TRIZ	0.163 (0.045)	0.951 (0.071)	80	90	Yes
Morphological Analysis	0.195 (0.055)	0.975 (0.023)	100	91	Yes
Brain-storming	0.203 (0.032)	0.980 (0.020)	80	80	Yes
Total	0.188 (0.047)	0.969 (0.044)	87	87	Yes

The total results for description issues of all design sessions include a mean slope of 0.188. They also include a mean R^2 of 0.969, which is above the threshold of 0.950 and therefore supports linearity. First occurrence of structure issues at start as well as continuity is observed in 87% of all design sessions.

5 DISCUSSION

Do the results presented in Section 4 support a hypothesis of commonalities across design sessions irrespective of the specific concept generation technique used? To answer this question, we need to define commonalities based on conditions related to our five measures. These conditions, as shown in Table 8, are based on the total results presented in Tables 2 to 7.

Table 8. Definition of commonalities

Commonality	Condition
Slope (quantitative value)	Average Stdev ≤ 5% of mean slope
First occurrence at start ("Yes" value)	Average ≥ 90%
Continuity ("Yes" value)	Average ≥ 90%
Linearity ("Yes" value)	Average mean $R^2 \geq 0.950$

Based on the conditions for commonality outlined in Table 8, a number of commonalities can be identified across the entire dataset derived from the cognitive study of students utilizing three separate concept generation techniques as shown in Table 9.

Table 9. Commonalities in the empirical results

Design issue	Common Slope	First occurrence at start	Continuity	Linearity
R	---	No	No	---
F	No	No	No	No
Be	No	**Yes**	No	No
Bs	No	No	**Yes**	**Yes**
S	No	No	**Yes**	**Yes**
D	No	No	No	**Yes**

We explored whether commonalities would exist in the cognitive behaviour of designers when using different concept generation techniques. This work expanded an earlier exploratory study (Gero, Kannengiesser and Pourmohamadi 2012) by analysing statistically significant samples, rather than case studies, of student designers while designing using concept generation techniques. We measured potential commonalities across four dimensions:

1. Slope – this measures the slope of the cumulative design issue, slope is a commonality if the standard deviation of the slopes are less than 5 per cent of the mean slope of all the design sessions.
2. First occurrence – this measures whether the first occurrence of a design issue occurs near the beginning of the design session, first occurrence is a commonality if it occurs in at least 90 per cent of all the design sessions.
3. Continuity – this measures whether the cumulative occurrence of a design issue is continuous across the design session, continuity is a commonality if it exists in at least 90 per cent of the all the design sessions.
4. Linearity – this measures whether the line of best fit of the cumulative design issue is linear as indicated by its R^2 being at least 0.95.

It is not expected that there would be commonalities across all four measures for all design issues as this implies that there are no differences between designing with these three techniques. Rather what is expected is that there will be one or more commonalities across these measures and this is what is found in the results from this empirical data. Based on the earlier case study (Gero, Kannengiesser and Pourmohamadi 2012), of particular interest are the three measures of first occurrence, continuity and linearity.

None on the design issues exhibited a commonality across all these three measures. Bs and S exhibited continuity and linearity as commonalities. Be is the only design issue that has the first occurrence as a commonality across all three techniques.

A common continuous and linear behaviour of both Bs and S are both surprising results as they imply a uniformity of cognitive effort across a design session once each is initiated.

These results provide statistically robust support for regularities in empirical data about designing. Based on this study it is possible to formulate a number of commonality hypotheses about designing that can be empirically tested. This forms the basis for studying designing as a distinct human activity that shares the same fundamental characteristics, transcending the use of any particular concept generation technique.

ACKNOWLEDGMENTS

This research is supported by the National Science Foundation under Grant Nos NSF CMMI-0926908, EEC-0934824 and CMMI-1161715. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

Altshuller G (1973) *Innovation Algorithm*, Technical Innovation Center.

Altshuller G (1984) *Creativity as an Exact Science*, Gordon & Breach.

Altshuller G, Shulyak L and Rodman S (2002) *40 Principles: TRIZ Keys to Technical Innovation*. Technical Innovation Center.

Anonymous (1995) *IdeaFisherPRO*, IdeaFisher Systems.

Atman CJ, Kilgore D and McKenna AF (2008) Characterizing design learning through the use of language: A mixed-methods study of engineering designers. *Journal of Engineering Education* **97**(3): 309-326.

Fisher M (1996) *The Idea Fisher*, Pacesetter Books.

Gero JS (1990) Design prototypes: A knowledge representation schema for design. *AI Magazine* **11**(4): 26-36.

Gero JS, Jiang H and Williams CB (2012) Does using different concept generation techniques change the design cognition of design students? *Proceedings of the ASME 2012 International Design Engineering Technical Conferences (IDETC) & Computers and Information in Engineering Conference (CIE)*, Chicago, IL, paper no. DETC2012-71165.

Gero JS and Kannengiesser U (2004) The situated function-behaviour-structure framework, *Design Studie*s **25**(4): 373-391.

Gero JS, Kannengiesser U and Pourmohamadi M (2012) Commonalities across designing: Empirical results, *Design Computing and Cognition'12*, (to appear)

Gero JS and McNeill T (1998) An approach to the analysis of design protocols, *Design Studies* **19**(1): 21-61.

Jones C (ed) (1963) *Conference on Design Methods*, Pergamon.

Leon-Rovira N (ed.) (2007) *Trends in Computer Aided Innovation*, Springer.

Lumsdaine E and Lumsdaine M (1995) *Creative Problem Solving: Thinking Skills for a Changing World*, McGraw-Hill.

Moore GT (ed) (1970) *Emerging Methods in Environmental Design and Planning*, MIT Press.

Nijstad B, Stroebe W and Lodewijkx HF (2003) Production blocking and idea generation: Does blocking interfere with cognitive processes? *Journal of Experimental Social Psychology* **39**(6): 531-548.

Purcell T, Gero JS, Edwards H and McNeill T (1996) The data in design protocols: The issue of data coding, data analysis in the development of models of the design process, *in* Cross N, Christiaans H and Dorst K (eds) *Analysing Design Activity*, John Wiley & Sons Ltd, pp. 225-252.

Rantanen K and Domb E (2002) *Simplified TRIZ: New Problem-Solving Applications for Engineers and Manufacturing Professionals*. CRC Press.

Ritchey T (2006) Problem structuring using computer-aided morphological analysis, *Journal of Operations Research Society* **57**(7): 792-801.

Terninko J, Zusman A and Zlotin B (1998) *Systematic Innovation: An Introduction to TRIZ*. St Lucie Press.

Ullman DG (1992) *The Mechanical Design Process*, McGraw-Hill.

Zwicky F (1969) *Discovery, Invention, Research through the Morphological Analysis*, Macmillan.