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EFFECTS OF UNFOLDING TECHNIQUES AS DESIGN STIMULI IN BUILDING DESIGN

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Abstract: Through paper folding techniques, i.e. origami, people can make fascinating 3D forms from 2D sheets. Many architects utilise folding techniques in their design process as design stimuli. However, the reverse process, unfolding 3D forms, presents computational geometry problems, and there is limited research that clarifies how designers can use theses unfolding techniques. In this study, we begin by introducing a computational geometry method for generating common developments by unfolding 3D plural cuboids. Next, this paper presents the results of an experiment where extended protocol analysis methods were used to examine the effects of using the unfolding techniques as design stimuli during concept generation. The results show that the unfolding techniques promote creativity in building design and enhance participants' extension of idea space from the microscopic perspective.

Keywords: *unfolding, design stimuli, creativity*

1. Introduction

Currently, folding techniques can be applied to many fields, including industrial design, fashion, interior design, building design, textile industry, and jewellery design (Stavric & Wiltsche, 2014). In building design, there are many studies focusing on creative design methods using folding techniques. For example, Šekularac, Ivanović-Šekularac, and Čikić-Tovarović (2012) analysed the use of folded structures in modern architecture. In addition, there are many architectural examples that explain the potential of folding techniques (Stavric, Wiltsche & Bogensperger, 2015), such as the Folded-Plate Hut in Osaka, the United States Air Force Academy, and the Chapele St. Loup in Switzerland. However, our review (Shen & Nagai, 2017) suggests that most researchers neglect to consider the use of unfolding techniques as design stimuli in building design.

As the reverse process, in this study, we demonstrate how the unfolding technique can determine whether polyhedron Q can be unfolded from polygon P with given polyhedron Q. This is a computational geometry problem originated in Albrecht Durer's masterwork on geometry, 'On Teaching Measurement with a Compass and Straightedge', which created a new field with lots of open problems (O'Rourke, 2011). In 1996, Lubiw and O'Rourke (1996) carried out detailed investigations on polygons that can fold into polyhedra. In 2007, a book that examines geometric unfolding problems from algorithmic perspectives was published by Demaine and O'Rourke (2007).

Although ample research has acknowledged the extensive use of folding techniques in building design, minimal research has focused on the use of unfolding techniques in building design. Therefore, this paper analyses the use of unfolding techniques as design stimuli in building design in an effort to highlight the ability of unfolding techniques to promote creativity in the building design process.

1.1. Creativity and Innovation of Unfolding Techniques as Design Stimuli

Sketching is considered a way to externalise designer's ideas and is used mainly in the early stages of the design process as it is important for the stimulation of creativity in the concept design (Verstijnen, Leeuwen, Goldschmidt, Hamel & Hennessey, 1998). Designers employ sketching to discover new directions for concept generation through representational talkback (Rodgers, Green & Mcgown, 2000)—providing better access to earlier ideas (Hoeben & Stappers, 2005) and improving the exchange of ideas (Van Der Lugt, 2005). Sketches are two-dimensional drawings or paintings, while paper folding may be considered a three-dimensional 'sketch'. While the impact of folding techniques on the design process has been investigated, unfolding techniques are quite different from folding techniques from the designer's perspective. Figure 1 is a model demonstrating the use of unfolding techniques in the building design process. In this model, designers input information of building into computer and use the optimization algorithm to unfold the building into common developments which would stimulate designers to redesign the building.

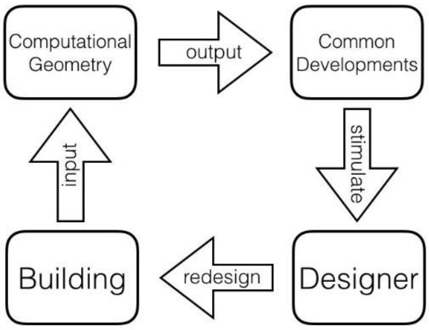

Figure 1. Model of the unfolding technique use in building design.

Design is considered to be a goal-oriented, problem-solving activity (Salah & Abdalla, 2008). As Dorst (2011) explained that the basic reasoning pattern humans use in problem solving is equally suitable for using folding techniques in building design, as architects usually use folding techniques to find solutions to architectural problems.

WHAT (paper) **+ How** (folding techniques) leads to **Result** (building design)

However, the model of using unfolding techniques in building design produces a different equation to illustrate the reasoning pattern, "result" is the starting point, while the unfolding techniques lead to redesigning the result so that the designer would generate more creativity and achieve better results. Accordingly, this equation reveals the innovativeness of using unfolding techniques in building design.

Result (building) **+ How** (unfolding techniques) leads to **???**

1.2. Using Unfolding Techniques as Building Design Stimuli during Concept Generation

Several studies have analysed the core of the design process, and numerous significant experiments have identified its creative features within a problem-solving framework (Cross, 2001). Chiu and Shu (2007) proposed a methodology that employed languages as stimuli to enhance concept generation during the design process. In their experiments, verbal protocols were used to examine how designers used semantic stimuli, presented as words related to the problem during concept generation. The authors found that people often used stimuli in noun form, though more new ideas were formulated when people used stimuli as verbs and noun modifiers (Chiu & Shu, 2007).

Concept generation is an important and early stage of the design process; many of design outcomes depend heavily on the designer's intuition and prior design experience (Li & Jin, 2006). Therefore, it is necessary to use design support tools to help designers improve their design efficiency and quality. In this study, we use the extended protocol analysis method to examine the effects of using unfolding techniques as design stimuli during concept generation.

2. Related Studies

Methods for unfolding 3D forms have been proposed by many researchers. Sorkine, Cohen-Or, Goldenthal, and Lischinski (2002) proposed an approach to unfolding mesh models. Mitani & Suzuki (2004) proposed another approach to unfolding rounded toy animal figures from triangulated meshes in order to avoid facial distortions. In this study, we adopt computational geometry methods to solve unfolding problems; we also call these methods ‘computational origami’. Demaine and O’Rourke (2007) presented the concept of computational origami using more than 60 unsolved folding/unfolding problems. A previous study (Xu, Horiyama, Shirakawa & Uehara, 2017) solved one of these problems, and we use the same definition of common development from that study.

A common development is a polyomino that results from unfolding pre-specified polyhedra. Figure 2 is an example of a common development that can fold into two boxes of sizes 1×1×5 and 1×2×3.

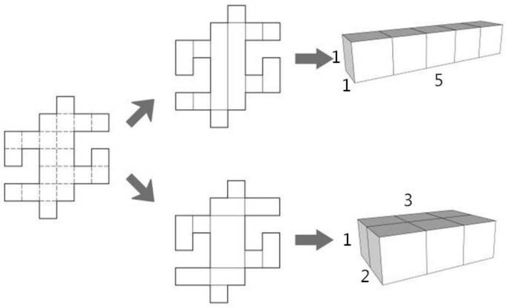

Figure 2. A common development folding into two boxes of sizes 1×1×5 & 1×2×3.

3. The Optimization Algorithm

To generate all possible common developments of the boxes that we desire, we improved the exhaustive algorithm from a previous study (Xu, Horiyama, Shirakawa & Uehara, 2015).

The outline of the algorithm works as follows. Let S(i) be the set of all common partial developments of area i. Then S(1) indicates a set of monomial S(i-1), which is a subset of polyominoes with area i-1. From S(i-1), we can compute S(i) by adding a unit square to the proper location for each i = 2,3 . . . and so on.

The algorithm operates by repeating the following steps for each i = 2, 3...

1. We pick up one polyomino P from S(i-1).
2. We add one unit square to P at each possible edge at the boundary of P to obtain a new polyomino P' with area i.
3. For the sizes of both the first and second box, we check if P' is a partial development of the box by trying all possible positions of the box.
4. We introduce P' into S(i) if P' is a common partial development of the two boxes. If the new common partial development has the same shape as the other common partial developments already generated, it will be discarded. Translating, rotating, reflecting, or glide-reflecting an existing common partial development does not differentiate it from the original one.

4. Experiment & Results

4.1. Experimental Methods

In this study, we developed the extended protocol method formulated by Taura and Nagai in 2013. In their study (Taura & Nagai, 2013), the distance between a newly uttered noun and basic concepts was measured by counting the number of nodes along the shortest path between the concepts. In our study, we computed the distances between each pair of words based on WordNet (Miller, 1995), an online lexical reference system that attempts to model the lexical knowledge into a taxonomic hierarchy (Varelas, Voutsakis, Raftopoulou, Petrakis & Milios, 2005). WordNet outputs the semantic distance value between 0 and 1.

4.2. Participants

In this experiment, participants consisted of 20 students pursuing masters degrees who were not experienced designers. Therefore, we evaluated their creativity on the basis of the design concept.

4.3. Analysis

To elucidate the stimuling effect of using unfolding techniques in the concept generation process, we analysed not only the design ideas generated by the participants but also their performance in the design process. This was done to obtain important clues according to Lawson (1997) from the design thinking process.

4.3.1. Analysis of design process

In this experiment, the participants were asked to "think aloud" during the design process in order to collect their utterances to be used as the protocol data for designing (Ericsson & Simon, 1980). After the design process, the participants were asked to explain the reasons behind their design activities while observing videos of their design performance. This procedure was conducted because participants do not always express all the reasons behind their thinking when they are asked to talk aloud during the design process.

4.3.2. Analysis of design results

To analyse the design results of participants, we used the method developed by Finke et al. (1992). We evaluated the design results based on practicality and originality on a five-point scale.

4.4. Design Task

The 20 participants were asked to design a new architecture idea starting from the 10 common developments obtained by the unfolding technique. We believe that the participants were very familiar with building; therefore, they would be able to easily propose their ideas for designing a new building. Figure 3 shows the 10 common developments. To exclude other affecting factors, the 10 common developments were all from the 45 centrosymmetric common developments with a surface area of 22 that can be folded into two square buildings with sizes of 1 × 1 × 5 and 1 × 2 × 3. Participants were, thusly, able to choose optional common developments as their design stimuli.

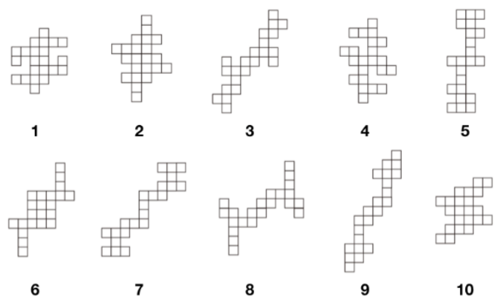

Figure 3. The 10 common developments used in this experiment.

4.5. Design Results

The 20 participants finally generated 20 new architectural ideas. During the design process, every participant chose several common developments and tried to fold those common developments. Although all 10 common developments can be folded into two square buildings with sizes of 1 × 1 × 5 and 1 × 2 × 3, different common developments have different folding methods which are determined by their patterns. This characteristic stimulates the generation of different building ideas.

According to the judging standard, design results were evaluated by eight people, including four professors with degrees in architectural design. They evaluated these design results based on practicality and originality on a five-point scale. If the practicality rating was less than three, the design idea was not qualified. We were able to obtain 17 ideas that satisfied this judging standard.

In addition, to identify the extension of idea space, we extracted new nouns from the utterances recorded in the design process and interviews. Next, we measured the conceptual distance of the new nouns from ‘building’ and ‘development’ based on WordNet (Miller, 1995). For example, Table 1 shows the nine new nouns of participant 1 from the utterances recorded in the design process and interview as well as the distances between each new noun with ‘building’ and ‘development’.

Table 1. The distance of each new noun of participant 1 between ‘building’ and ‘development’.

New noun	Distance from ‘building’(x_i)	Distance from ‘development’(y_i)
Tree	0.529	0.9
Sky	0.714	0.882
Star	0.429	0.882
Bamboo	0.733	0.789
Bridge	0.143	0.882
Graphic	0.375	0.895
Plate	0.444	0.905
Leaf	0.467	0.889
Skyscraper	0.067	0.889

If $n_i(x_i, y_i)$ is a new noun, then we define the extension of idea space as $\sum_{i=1}^{N} \frac{\sqrt{x_i^2+y_i^2}}{N}$ (where N = number of new nouns). Table 2 presents the creativity evaluation and extension of idea space of 17 ideas as well as the totality of common developments associated with each concept.

Table 2. Creativity evaluation and extension of idea space of 17 ideas and the totality of common developments associated with each idea.

No.	Building Concept	Totality of common developments	Creativity	Extension of idea space
1	A skyscraper like a tree	6	3.625	0.998
2	A anamorphic museum	2	2.875	0.256
3	Twin tower with comprehensive functions	3	2.875	0.133
4	A flexible army base	4	3	0.312
7	A library like UFO	7	2.875	0.584
8	A floating aquarium	3	2.625	0.286
9	A exhibition building like a portfolio	2	2.625	0.255
10	A detachable temporary house	1	3.375	0.557
11	A restaurant like a yacht	5	3.125	0.887
13	Container office room	2	3.75	0.246
14	Overhead house	8	3.875	1.102
15	A divaricate airport	1	2.375	0.863
16	A stop station on the beach	9	4	0.849
17	A hospital can relax people	2	1.875	0.254
18	A nursing home like mountain	6	3.875	0.824
19	A planetarium like a petal	6	3.75	0.519
20	A gym like crystals	2	2.75	0.483

4.6. Analysis Results

4.6.1. Analysis of creativity

Table 3 provides the mean and standard deviation of creativity and totality of common developments associated with each concept. Figure 4 shows the scatter charts depicting the relationship between the creativity and totality of common developments.

Table 3. Mean and standard deviation of creativity and totality of common developments.

	Creativity	**Totality of common developments**
$\bar{X}$	3.18	4.06
SD	0.598	2.536

The pearson correlation coefficient is 0.601, p = 0.011 < 0.05. Because the coefficients is significant, it indicates that there is a strong correlation between the creativity of the participants' ideas and totality of common developments associated with each idea.

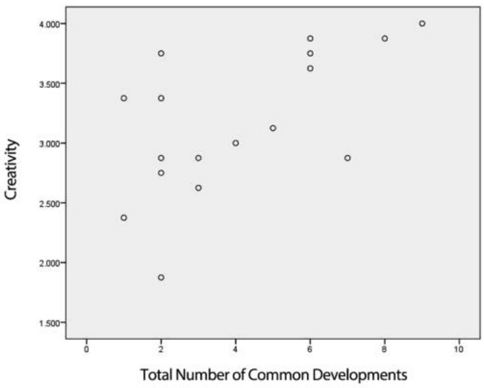

Figure 4. Correlation between creativity and totality of common developments.

Table 4 presents the results of the regression analysis of the totality of common developments and creativity. Because the results are significant, it can be inferred that common developments as the design stimuli have the ability to promote creativity.

Table 4. Regression analysis result of totality of common developments and creativity.

Model	**B**	**t**	**Sig**
Constant	2.602	11.263	0.001
Totality of common developments	0.142	2.909	0.011
Adjusted R Square	0.361		
F	8.462*		

4.6.2. Analysis of extension of idea space

Table 5 provides the mean and standard deviation of the extension of idea space and totality of common developments associated with each concept. Figure 5 shows the scatter charts depicting the relationship between the extension of idea space and totality of common developments.

Table 5. Mean and standard deviation of extension of idea space and totality of common developments.

	Extension of idea space	**Totality of common developments**
$\bar{X}$	0.55	4.06
SD	0.311	2.536

The Pearson correlation coefficient is 0.621, p = 0.008 < 0.05. Because the coefficient is significant, it indicates that there is a strong correlation between the extension of idea space of the participants and totality of common developments associated with each idea.

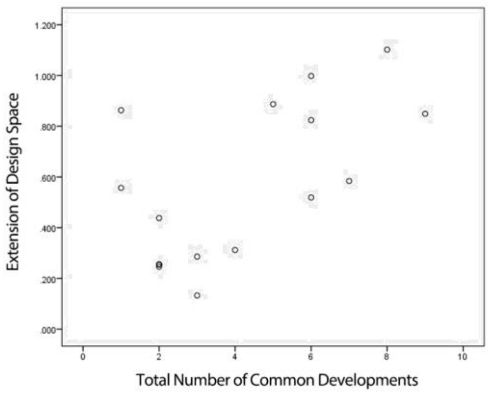

Figure 5. Correlation between extension of idea space and totality of common developments.

Table 6 presents the results of the regression analysis of totality of common developments and extension of idea space. Because the results are significant it can be inferred that common developments as the design stimuli also have the ability of promoting participants' extension of idea space.

Table 6. Regression analysis result of totality of common developments and extension of idea space.

Model	B	t	Sig
Constant	0.241	2.048	0.048
Totality of common developments	0.076	3.070	0.008
Adjusted R Square	0.386		
F	9.425*		

5. Discussion

The participants developed a total of 20 new building concepts from the stimulating common developments. Participant 2 and participant 9 both chose common developments No. 4 and No. 7 as their stimulating common developments. Though participant 2's 'An anamorphic museum' and participant 9's 'An exhibition building like a portfolio' concepts share the core concept 'transformation', 'An anamorphic museum' highlights 'shape deformation' and 'An exhibition building like a portfolio' tends to exhibit 'variation of function'. During their design processes, we observed the two participants developed common developments No. 4 and No. 7 into 3D forms in different ways, which is ideal for conceptual design and drives increased creativity.

Benami and Jin (2002) classified creative stimulation into function, form, behaviour, and knowledge entity stimulations to capture the relationship between properties stimulating cognitive processes. This study presents the uniquely dynamic stimulation, the 'developing process' stimulation, through which designers develop varied developments obtained by unfolding techniques at the concept generation stage leading to increased creativity in the development process. This finding may provide a novel view of design stimuli and help us increase our understanding of creative stimulation.

6. Summary & Future Work

In this article, we argue that using unfolding techniques as design stimuli in building design is effective. We first introduce a computational geometry method for generating common developments by unfolding 3D forms that are plural cuboids. Through the extended protocol analysis method, we found that the unfolding technique has the ability to promote creativity in building design and enhance participants' extension of idea space from the microscopic perspective.

In this study, we discuss only the use of unfolding techniques for plural cuboids in building design. However, building forms include forms other than cuboids, such as freeform architecture. We will continue to investigate this topic using additional unfolding techniques in building design in the future.

References

Benami, O., & Jin, Y. (2002). Creative stimulation in conceptual design. In *ASME 2002 international design engineering technical conferences and computers and information in engi-neering conference* (pp. 251-263). American Society of Mechanical Engineers.

Chiu, I., & Shu, L. H. (2007). Understanding the use of language stimuli in concept generation. In *Proceedings of the ASME International Design Engineering Technical Conferences, Las Vegas, NV, Sept* (pp. 4-7).

Cross, N. (2001). Strategic knowledge exercised by outstanding designers.*Strategic knowledge and concept formation III*, 17-30.

Demaine, E. D., & O'Rourke, J. (2007). *Geometric folding algorithms* (pp. 288-289). Cambridge: Cambridge university press.

Dorst, K. (2011). The core of 'design thinking'and its application. *Design studies*, *32*(6), 521-532.

Ericsson, K. A., & Simon, H. A. (1980). Verbal reports as data.*Psychological review*, *87*(3), 215.

Finke, R. A., Ward, T. B., & Smith, S. M. (1992). Creative cognition: Theory, research, and applications.

Hoeben, A., & Stappers, P. J. (2005). Direct talkback in computer supported tools for the conceptual stage of design. *Knowledge-Based Systems*, *18*(8), 407-413.

Lawson, B. (1997). How Designers Think, ed.

Li, W., & Jin, Y. (2006). Fuzzy preference evaluation for hierarchical co-evolutionary design concept generation. In *ASME 2006 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*.

Lubiw, A., & O'Rourke, J. (1996, June). When can a polygon fold to a polytope. In *AMS Conference*.

Miller, G. A. (1995). WordNet: a lexical database for English.*Communications of the ACM*, *38*(11), 39-41.

Mitani, J., & Suzuki, H. (2004, August). Making papercraft toys from meshes using strip-based approximate unfolding. In *ACM transactions on graphics (TOG)* (Vol. 23, No. 3, pp. 259-263). ACM.

O'Rourke, J. (2011). *How to fold it: the mathematics of linkages, origami, and polyhedra*. Cambridge University Press.

Rodgers, P. A., Green, G., & Mcgown, A. (2000). Using concept sketches to track design progress. *Design studies*, *21*(5), 451-464.

Salah, F., & Abdalla, H. (2008). Creative design tools (CDT): stimulating creative design thinking. *International Journal of Design Engineering*, *1*(2), 125-148.

Šekularac, N., Ivanović-Šekularac, J., & Čikić-Tovarović, J. (2012). Folded structures in modern architecture. *Facta universitatis-series: Architecture and Civil Engineering*, *10*(1), 1-16.

Shen, T. & Nagai, Y. (2017). An Overview of Folding Techniques in Architecture Design. *World Journal of Engineering and Technology*, **5**, 12-19.

Sorkine, O., Cohen-Or, D., Goldenthal, R., & Lischinski, D. (2002). Bounded-distortion piecewise mesh parameterization. In *Proceedings of the conference on Visualization'02* (pp. 355-362). IEEE Computer Society.

Stavric, M., & Wiltsche, A. (2014). Quadrilateral Patterns for Rigid Folding Structures. *International journal of architectural computing*, *12*(1), 61-79.

Stavric, M., Wiltsche, A., & Bogensperger, T. (2015). Generative Design for Folded Timber Structures. In *Proceedings of the 20th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA 2015)* (pp. 673-682).

Taura, T., & Nagai, Y. (2013). A systematized theory of creative concept generation in design: first-order and high-order concept generation. *Research in Engineering Design*, *24*(2), 185-199.

Van der Lugt, R. (2005). How sketching can affect the idea generation process in design group meetings. *Design studies*, *26*(2), 101-122.

Varelas, G., Voutsakis, E., Raftopoulou, P., Petrakis, E. G., & Milios, E. E. (2005). Semantic similarity methods in wordNet and their application to information retrieval on the web. In *Proceedings of the 7th annual ACM international workshop on Web information and data management* (pp. 10-16). ACM.

Verstijnen, I. M., van Leeuwen, C., Goldschmidt, G., Hamel, R., & Hennessey, J. M. (1998). Sketching and creative discovery. *Design studies*,*19*(4), 519-546.

Xu, D., Horiyama, T., Shirakawa, T., & Uehara, R. (2015). Common Developments of Three Incongruent Boxes of Area 30. In *International Conference on Theory and Applications of Models of Computation* (pp. 236-247). Springer, Cham.

Xu, D., Horiyama, T., Shirakawa, T., & Uehara, R. (2017). Common developments of three incongruent boxes of area 30. *Computational Geometry*, *64*, 1-12.