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CLASSIFICATION OF DESIGN METHODS FROM THE VIEWPOINT OF DESIGN SCIENCE

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1. Introduction

The specialization and subdivision of each design domain has created a society with many specialized mechanical products. However, it has also realized a complicated process of sharing design purposes and concepts of user values because there is not a common basic environment or foundation across different domains such as product design and urban/architectural design. In addition, the possibility of casualties and human errors has risen due to the remarkable growth of scale and complexity of artifacts. Moreover, as the information society advances, the values of users have diversified, increasing the number of design elements and requirements that a designer must consider. This phenomenon has caused a number of social issues (e.g., global warming, serious and critical accidents of nuclear energy plants, and a lack of mental satisfaction). To combat this, each domain has proposed various deign methods to correspond to the increase in user values and social issues. Because these situations are becoming more unmanageable for subdivided design domains, sharing and accumulating design information across domains is crucial [Matsuoka 2010]. Consequently, many designers are not grasping the features of design methods that others use, decreasing the diversity of the design process.

This research has two objectives. First, we aim to enable sharing of existing design methods across different design domains by constructing a principle of when to apply each design method. Second, we strive to use these results to identify the features of design methods that can facilitate the design process as well as sharing and accumulating design information across different domains. To classify existing design methods, three frameworks proposed in design science are used as the classification basis: "Matusoka's design thinking", "design methodology", and "form of data". Here, design science is an academic domain that theoretically explains the act of designing as a creative human activity and extends beyond each design domain. Along with an extraction and evaluation of design methods, all methods are classified according to their similarities in order to derive the features that promote design information sharing and accumulation.

2. Classification basis of design methods

2.1 Framework of design science

As briefly stated in the introduction, design science is a domain referring to the science that theoretically describes a creative human activity, namely "design", and extends it beyond individual design domains. This domain is comprised of "design knowledge" and "designing". Here, "designing" is defined as an act to be conducted based on "design knowledge", and consists of four layers: "design theory", "design methodology", "design method", and "design practice" [Matsuoka 2008].

"Design theory" expresses the generality of phenomena found in every design. Because "design theory" is the most abstract and general layer, frameworks proposed for this layer can be applied to various design domains. "General Design Theory", advocated by Yoshikawa, is one example [Yoshikawa 1981]. "Design methodology" is the layer that identifies the principles of how to apply a design method. Typically, "design methodology" outlines a specific purpose of design, but it does not offer any design ideas or solutions. As an example, "User Experience Design", also known as "UX", is a methodology focusing on the interaction between a user and a design object, such as a website or a smartphone application [Gothelf 2013].
On the contrary, a "design method" signifies specific procedures to integrate, analyze, or evaluate the phenomenon of a design object. Applying a design method produces new design ideas based on the designer’s previous knowledge.
"Design practice" is comprised of actual practices conducted in various design domains — product design, architectural design, graphic design, etc. Compared to the other layers, "design practice" can be defined as the most specific and detailed layer.
In the layer of "design theory", the relationship between "design elements" is often considered. Here, "design elements" is language or data defining a phenomenon or a requirement of a design object. In general, "design elements" can be classified into two types: "psychological design elements" and "physical design elements". The former expresses the concept of a value that each user carriers or a functionality and an image of a design object. The latter consists of a measureable physical quantity and a physical property. For example, in the case of designing a chair, "comfort" and "sense of fitting" are defined as "psychological design elements", whereas "deflection" and "material" are classified as "physical design elements".

2.2 Frameworks of the classification basis

To classify the existing design methods from the same perspective, three main basic frameworks from design science were applied as the classification basis of our research: "Matsuoka’s design thinking", "design methodology", and "form of data". "Matsuoka’s design thinking" is one of the frameworks proposed in design science [Matsuoka 2008], but it actually originates from the design thinking model of J. Christopher Jones, L. Bruce Archer, and Lionel March [Jones 1970], [Paul 2007], [Cross 2008]. It constitutes three common acts, which are repeatedly performed during the design process (Figure 1). These three acts are "design problem analysis" derived from induction, "idea generation" derived from abduction, and "idea evaluation" derived from deduction. Specifically, a designer initially analyzes the current conditions and the phenomenon of a design problem.

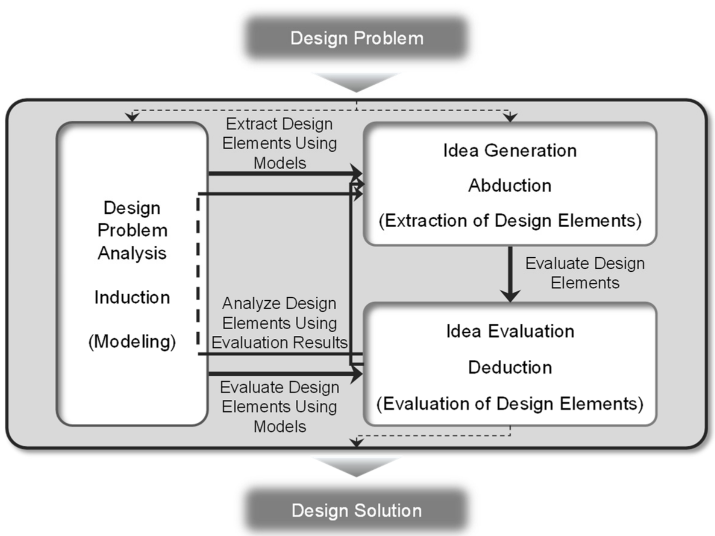

Figure 1. Matsuoka's Design Thinking Model [Matsuoka 2008]

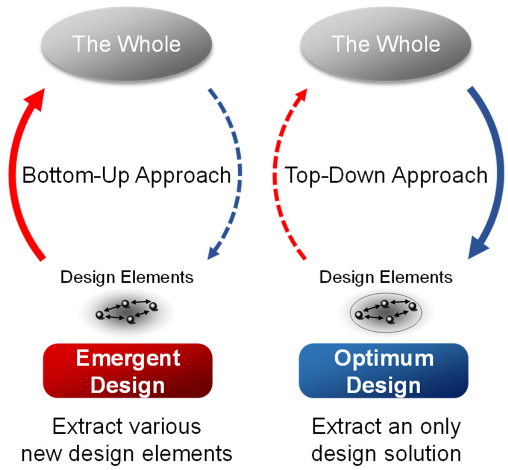

Figure 2. Description of design methodology [Nomura 2007]

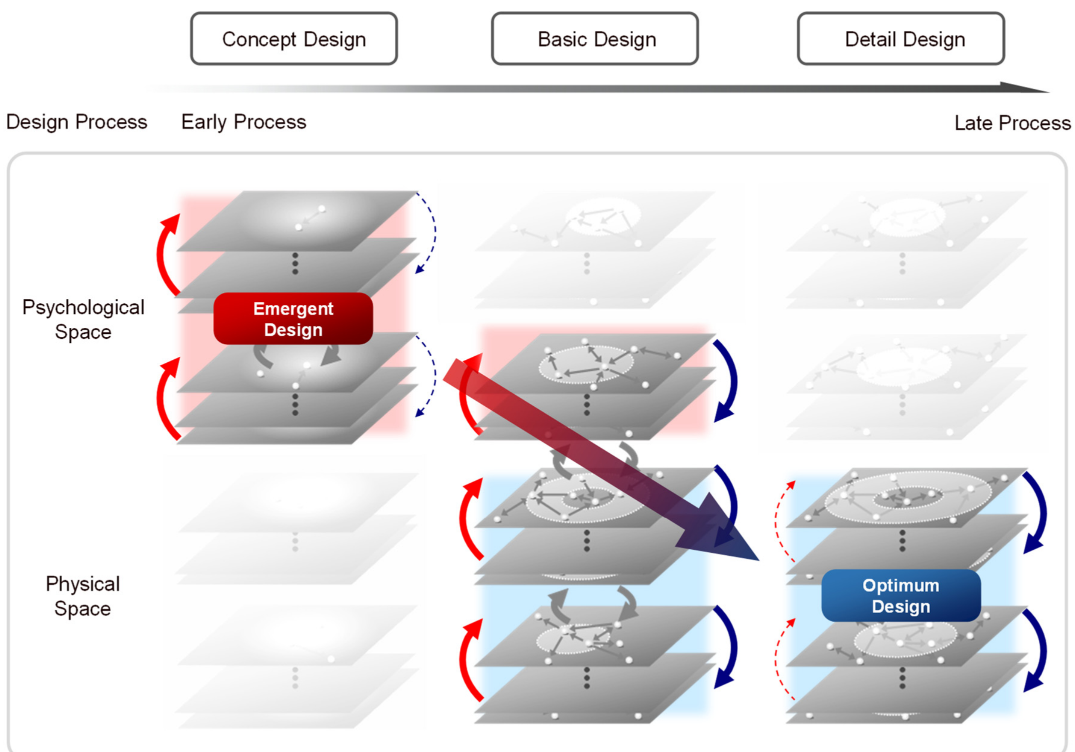

Figure 3. Relations between design and methodology design process [Matsuoka 2013]

Then the results are used to generate a number of design elements that would solve the design problem. In addition, each design element is evaluated using the results derived from the analysis. If the elements are inadequate for the design problem, the designer reanalyzes the problem and generates design elements over again until the proper design solution is derived. By setting this "design thinking" as one of the classification basis, it should be possible to classify design methods according to the acts performed during their usages.

Moreover, both "design problem analysis" and "idea generation" can be subdivided into three categories. "Design problem analysis" is divided into "classification", "structuration", and "formulation" [Asanuma et al. 2007]. "Classification" represents the act of sorting design elements according to their similarities. "Structuration" is the act of structuring design elements based on their correlations. "Formulation" corresponds to the act of expressing the relations of design elements in mathematical forms. "Idea generation" is split into "free association", "forced analogy", and "analogy" [Takahashi 2002]. "Free association" is the act of generating design elements at the mercy of a designer. "Forced analogy" represents the act of generating only the intended ideas by setting up a theme of idea generation. "Analogy" signifies the act of generating ideas using a design object that has a similar purpose of use as a clue.

Second, "design methodology" is a framework to discuss the relations between design methods. This framework can be divided into two types: "emergent design" and "optimum design" (Figure 2) [Nomura 2007]. "Emergent design" is a bottom-up approach considering the whole from its components. Because it brings forth new design elements, "emergent design" is often used in the early process of design, such as in "conceptual design", where a designer determines the concept and objectives, and "basic design", where a designer decides the basic shape and materials. On the contrary, "optimum design" is a top-down type of design where the components are optimized from the whole design object. As shown in Figure 3, because "optimum design" requires the whole from the beginning, it is mainly used in the late process of design, or "detailed design" where a designer determines the shape and material details. Thus, adding "design methodology" to the classification basis allows design methods to be grouped according to their design process while being used.

Lastly, "form of data" is constituted by "qualitative data" and "quantitative data" [Nomura 2007]. The former signifies data that cannot be expressed by numerical numbers, such as a nominal scale or an ordinal scale. Although nominal scales represent language data or numbers assigned to each product, ordinal scales include rank order. The latter indicates data containing numerical numbers, such as intervals and ratio scales. An example of an interval scale is temperature, while mass and length belong to ratio scales. Hence, design methods are classified accordingly to the type of data they mainly handle when used.

Setting these contents as the classification basis of design methods should allow the features common to the methods to be extracted.

3. Extraction and classification of design methods

3.1 Process to extract design methods

To determine various design methods proposed in both domestic and international original articles, four search phrases are selected as search criteria: "design method", "design technique", "design skill", and "design thinking". Using these phrases in Web of Science, JDream III, and Google, about 500 design methods are extracted from approximately 2,000 original articles and 3,000 websites published after 2001. Furthermore, by setting the methods obtained from Google as the search phrases for Web of Science and JDream III, only the design methods written in original articles after 2001 are selected (Table 1). In addition to the 174 extracted design methods, the results indicate that even though only the original articles written after 2001 are evalulated, numerous design methods proposed before this timespan are extracted. Thus, there is a low correlation between the publication year of original articles and the creation of new design methods.

3.2 Process of classifying design methods

Quantification theory class III and the cluster analysis are conducted to classify design methods based on common features. Quantification theory class III is a statistical data analysis method in which design elements are separated according to their similarities [Flury 1997] and a scatterplot is derived based on qualitative data, or binary data. Specifically, how much each element is similar to the others is visualized by plotting like methods near each other.

Cluster analysis is another statistical data analysis method to classify design elements. Its output is a dendrogram, or a tree diagram that represents the similarity of elements as well as the process of combining clusters. Although several types of cluster analysis exist, herein the Ward method is used. The Ward method combines clusters so that the sum of the squared deviation within a cluster is minimized. In addition, clusters are generated and combined until all samples end up in one single cluster; the sum of the squared deviation within the remaining cluster is the minimum [Ueda 2003].

To employ two analyses, a list of qualitative data is compiled beforehand by evaluating each design method. This evaluation focuses on the process of the design methods because differences between design results often depend on how designing is conducted. In addition, we noted differences between "why you use" and "how you use" in numerous discussions with professionals. Thus, these points are unified in the evaluation. As an example of the evaluation, "hierarchical neural network" is a design method that first feeds quantitative data to neurons as the input layer. Thereafter, neurons in the middle layer repeatedly change the combination coefficient between the input and the output neurons until it converges; through the process, a network model is constructed. Considering the features of this method, marks are placed on the columns of "qualitative data", "structuration", "evaluation", and "emergent design". In regard to a scatterplot produced with massive numbers of method names, methods with the same evaluation are grouped into several categories beforehand.

Table 1. List of design methods

No.	Name of Design Method	No.	Name of Design Method	No.	Name of Design Method
1	Affinity Diagram Method	59	FMMA (Failure Mode and Maintenance Analysis)	117	Performance Evaluation
2	AHP (Analytical Hierarchy Process)	60	Focus Group Interview	118	Personal Analogy
3	AIDA (Analysis of Interconnected Decision Areas) Method	61	Focused-Object Technique	119	Petrinet
4	Algebra Education	62	Forecasting	120	Positioning Method
5	Alphabet System	63	Freelisting	121	Principal Component Analysis
6	Association Diagram Method	64	FTA (Fault Tree Analysis)	122	Process State Table
7	Attribute Listing	65	F-Test	123	Product Life Cycle Management
8	Autoethnography	66	Functional Analysis	124	Protocol Analysis
9	Axiomatic Analysis	67	Fuzzy Inference	125	Pugh Method
10	Backcasting	68	GA (Genetic Algorithm)	126	Purpose Expansion Method
11	Benchmarking	69	Gordon Method	127	QFD (Quality Function Deployment)
12	Bionics Method	70	Grounded Theory	128	Quantification Theory Class I
13	BIOTRIZ	71	HAZOP (Hazard and Operability)	129	Quantification Theory Class II
14	Brainstorming	72	Hierarchicial Neural Network	130	Quantification Theory Class III
15	Brainwriting	73	Histogram	131	Quantification Theory Class IV
16	Business Design Method	74	How to's	132	Questionnaire
17	Canonical Correlation Analysis	75	Hyponymy Analysis	133	Reliability Based Topology Optimization
18	Card Brainstorming	76	ICR (Inform Creat Reflect) Grid	134	Relevance Tree Method
19	Card Brainwriting	77	Idea Sketch	135	Road Map
20	Card Sorting	78	IDEM (Inductive Design Exploration Method)	136	Role Playing
21	Casting Method	79	Identify Mapping Model	137	Rough Sets
22	Catalog Method	80	Incentive Word Method	138	Routes Chart Method
23	Causal Analysis	81	Interaction Matrix	139	SCAMPER (Substitute Combine Adapt Modify Put other purposes Eliminate Rearrange)
24	Commonality Versus Diversity Index	82	Interconnected Neural Network	140	Scenario Method
25	Cellular Automaton	83	Interviews	141	Section Property Method
26	Check Sheet	84	Inverse-Setting Method	142	Section Shape Method
27	Checklist	85	ISM (Interpretive Structual Modeling)	143	Self-Organizing Map
28	CID (Convex Integrated Design) Method	86	KJ (Kawakita Jiro) Method	144	Semantic Differential Method
29	Cluster Analysis	87	Kozane Method	145	Sensitivity Analysis
30	Cocreation	88	KT (Kepner Tregoe) Method	146	Service Blueprint
31	Cognitive Walkthrough Method	89	Laddering Method	147	Set-Theoretic Analysis
32	Cohort Analysis	90	Life Story Method	148	Shape Grammar
33	Collaborative Optimization	91	Linear Programming	149	Simulated Annealing
34	Compatibility Matrix	92	Linkography Mapping	150	Sizing Optimization
35	Control Chart	93	L-System	151	Skit
36	Correspondence Analysis	94	Material Flow Analysis	152	State Transition Diagram
37	Cost-Benefit Analysis	95	Matrix Method	153	Stop & Go Brainstorming
38	Co-Variance Structure Analysis	96	Multidiciplinary Design Optimization	154	Story Boarding
39	Critical Incident Technique	97	MET (Materials Energy Toxicity) Matrix	155	Structured Concept

40	Crossing Method	98	Metaphors	156	Stupa Method
41	Data Distribution	99	Mindmap	157	SWOT (Strengths Weakness Opportunities Threats) Analysis
42	Delphi Study	100	Modified Input-Output Method	158	Symbolic Analogy
43	DEMATEL (Decision Making Trial and Evaluation Laboratory)	101	Mood Board	159	Synectics
44	Direct Analogy	102	Morphological Analysis	160	T.T-HS (Tree Thinking-Harmonic Selection) Method
45	Discriminant Analysis	103	Multi-Dimensional Scaling	161	Taguchi Method
46	Divergent Tree Method	104	Multiple Regression Analysis	162	Task Analysis
47	DSM (Design Structure Matrix)	105	Non-Adaptive Random Search	163	Teaching Method
48	DTM (Disturbance Transformation Matrix)	106	NID (Need Idea Development) Method	164	Technology Road Map
49	Dual Scaling	107	NM (Nakayama Masakazu) Method	165	T-Plan
50	Ethnography	108	Ordinaly Differential Equation	166	TRIZ
51	Experiental Design	109	Paired Link Method	167	t-Test
52	Factor Analysis	110	Pairwise Testing	168	Two-Step Manipulation Method
53	Fault Enumeration Method	111	Parametric Design	169	Value Analysis
54	FFDM (Function Failure Design Method)	112	Pareto Chart	170	Virtual Matter Setting Method
55	Field Work	113	Partial Differential Equation	171	Wants and Needs Analysis
56	Fishbone Diagram	114	Particle Swarm Optimization	172	Work Design
57	Fly-on-the-Wall Observation	115	Path Analysis	173	WTM (Work Transformation Matrices)
58	FMEA (Failure Mode Effect Analysis)	116	Performance Distribution Analysis	174	ZK (Zenji Kawakita) Method

3.3 Results

Based on the list of design methods being evaluated, a scatterplot is derived using the qualification theory type III. Furthermore, the coordinates of each design method's plot are used in the cluster to classify the design methods on the basis of the distances between plots. Table 2 and Figure 4 show the results. In Figure 3, yellow, red, and blue indicate a group of design methods used for "design problem analysis", "idea generation", and "idea evaluation", respectively. In addition, black circles drawn under the plots express the results of the cluster analysis, while the blue and red frames, which enclose design methods, correspond to "optimum design" and "emergent design", respectively.

Following the analysis, the 174 design methods are classified into 13 clusters. Details of each cluster are described below:

- Cluster 1 consists of 27 design methods involving "forced analogy", such as "Backcasting", "Benchmarking", "Role Playing", and "TRIZ". All of these design methods are utilized to generate qualitative design elements through a cyclical process of group or private discussions. Thus, cluster 1 methods belong to "emergent design".
- Cluster 2 consists of 13 design methods involving "free association", such as "Brainstorming", "Autoethnography", "Focus Group Interview", and "Critical Incident Technique". Similar to cluster 1, each design method is used to generate qualitative design elements along with an individual and a group discussion. Therefore, cluster 2 methods belong to "emergent design".
- Cluster 3 consists of 7 design methods involving "analogy", such as "Synectics", "Gordon Method", and "Bionics Method". All are used to generate qualitative design elements. These methods are accompanied with an activity involving a group of people, indicating that cluster 3 also belongs to "emergent design".
- Cluster 4 consists of 33 design methods used for "free association" along with "classification" or "structuration", such as "Affinity Diagram", "Linkography Mapping", "Morphological Analysis", and "Quality Function Deployment". Each design method involves a discussion in a group or with itself to generate qualitative design elements. Similarly, cluster 4 is classified as "emergent design".
- Cluster 5 consists of 19 design methods used for "forced analogy" along with "classification" or "structuration", such as "Attribute Listing", "SWOT Analysis", "FTA", and "MET Matrix". All methods are utilized during a discussion about use of qualitative design elements. For the same reasons as above, cluster 5 is classified as "emergent design".

Table 2. Principle of each cluster

Cluster				1	2	3	4	5	6	7	8	9	10	11	12	13
Matsuoka's Design Thinking	Idea Genereation	Free Association	Qualitative		●		●									
			Quantitative													
		Forced Analogy	Qualitative	●				●								
			Quantitative											▲		▲
		Analogy	Qualitative			●										
			Quantitative													
	Design Problem Analysis	Classification	Qualitative				●	●	▲							
			Quantitative							▲		●				
		Structuration	Qualitative				●	●	▲							
			Quantitative								▲	▲	▲			
		Formulation	Qualitative							▲						
			Quantitative									▲				
	Idea Evaluation		Qualitative											▲		
			Quantitative									●▲	▲	▲	▲	▲

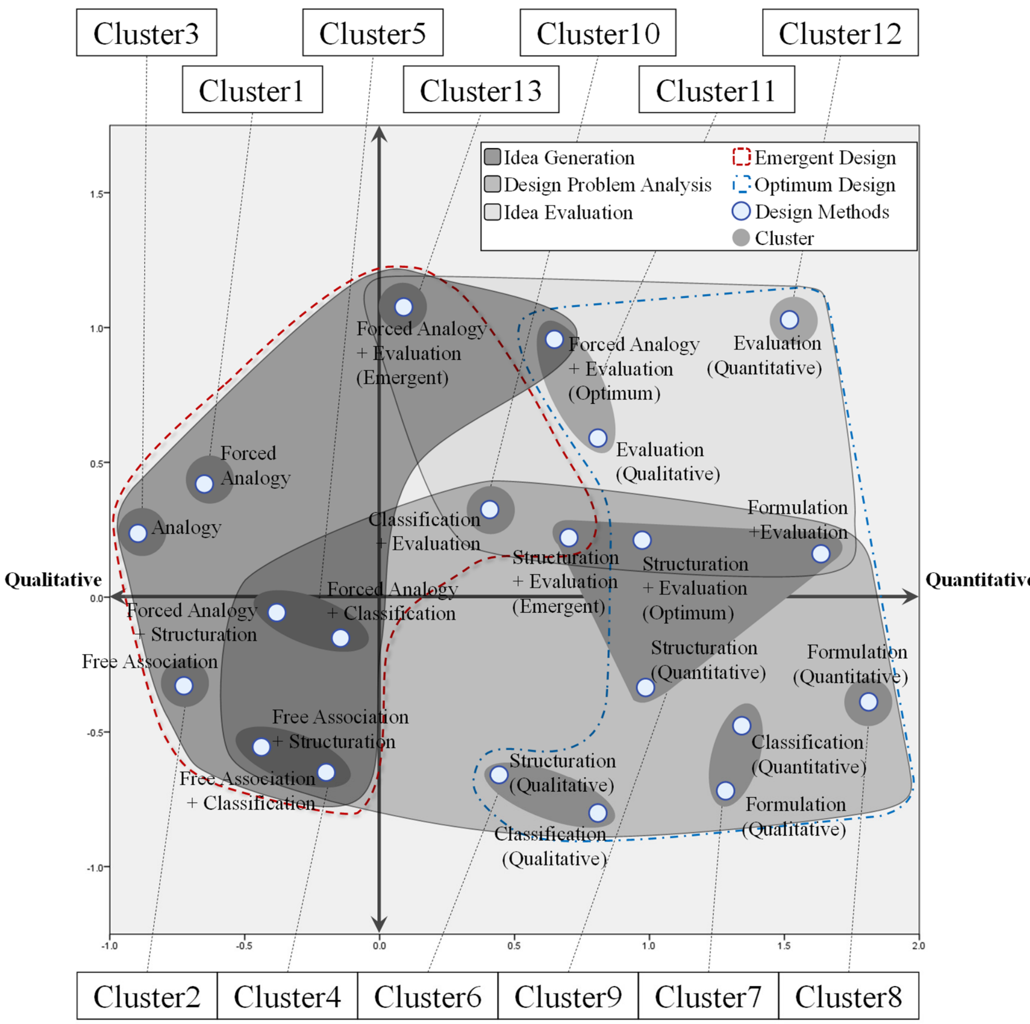

Figure 4. Result of the analysis

- Cluster 6 consists of 7 design methods containing features of "classification" or "structuration", such as "ISM", "DSM", "Qualification Theory Type 3", and "Correspondence Analysis". Unlike the aforementioned clusters, cluster 6 methods use quantitative design elements. In addition, the purpose of using these methods is to clarify relationships between each design element that comprises a design object. Therefore, cluster 6 belongs to "optimum design".
- Cluster 7 consists of 9 design methods involving "formulation" along with the use of qualitative elements, and "classification" using quantitative elements. As an example, "Qualification Theory Type 1" belongs to the former, and "Factor Analysis", "Cluster Analysis", and "Discriminant Analysis" all belong to the latter. It can be interpreted that design methods possessing completely different features are classified in the same cluster. One possible reason for this phenomenon is that a design method with the same features as "Qualification Theory Type 1" does not exist. The only common content of both clusters is that they both belong to "optimum design".
- Cluster 8 consists of 11 design methods utilized for "formulation" using quantitative design elements, such as "DTM", "Multiple Regression Analysis", "Canonical Correlation Analysis", and "Fuzzy Influence". All of these design methods aim to elucidate the relationships between each design element. Thus, cluster 8 belongs to "optimum design".
- Cluster 9 consists of 9 design methods leveraged for "classification", "structuration", and "formulation" in parallel with "evaluation", such as "Path Analysis", "Experimental Design", "Self-Organizing Map", and "Sizing Optimization". What each method has in common is that they all use quantitative elements. Furthermore, most of the design methods aim to define the relationship of a design object and its composition elements. Thus, cluster 9 is classified as "emergent design". Incidentally, there is no design method with the same features as the ones written above, causing diverse methods to be classified in one cluster.
- Cluster 10 consists of 6 design methods involving "structuration" along with "evaluation" using quantitative elements, such as "Cellular Automaton", "Petrinet", "Hierarchical Neural Network", and "Identify Mapping Model". All of these design methods belong to "emergent design" because they intend to state relationships between design elements.
- Cluster 11 consists of 9 design methods utilized for "evaluation" along with the use of qualitative elements, such as. "Fly-on-the-Wall Observation", "Ethnography", "Delphi Study", and "Cognitive Walkthrough Method". Each design method is used to clarify relationships between design elements and investigate against a user. Thus, cluster 11 is classified as "optimum design".
- Cluster 12 consists of 5 design methods containing features of "evaluation" using quantitative elements, such as "t-Test", "Semantic Differential Method", and "Performance Evaluation". Similar to cluster 11, each method specifies connections between design elements. Accordingly, cluster 12 belongs to "optimum design".
- Cluster 13 consists of 19 design methods leveraged for "forced analogy" in parallel with "evaluation", such as "Collaborative Optimization", "Genetic Algorithm", "Simulated Annealing", and "Shape Grammar". They all belong to "emergent design" due to the fact that they signify the relationships between a design object and its composing elements.

Meanwhile, to clarify the meanings of the both axes, the horizontal axis in Figure 3 represents the "form of data" where design methods on the left (right) show qualitative (quantitative) data. On the other hand, the vertical axis is inconvertible to any content because "design thinking" cannot be ordered in a certain direction.

Consequently, through the classification of the 174 design methods based on "design thinking", "design methodology", and "form of data", a number of features that design methods have in common are extracted. In order to clarify the features of design methods that should be proposed for prompt information sharing and accumulation, the perspective of the design process is considered. Both "optimum design" and "emergent design" have correlations with the design process. The appropriate use for each cluster is summarized below:

1. Conceptual design is the process when a designer conceives a design object using psychological design elements based on the emergent design. In response, design methods classified in clusters 1 through 5 generate design elements and groups under emergent design. Consequently, they are appropriate for conceptual design.
2. Basic design is the process when basic specifications such as shapes and materials are determined using both psychological and physical design elements. Additionally, these acts are conducted based on both optimum design and emergent design. Clusters 6 through 10 extract models of design elements describing their relations by classifying, structuralizing, or deriving formulas. In some methods, psychological elements are replaced with physical elements through the derived models. Accordingly, these design methods are appropriate for use in basic design.
3. Detailed design is the process when a designer determines details of shapes and materials using physical design elements mainly under optimum design. In regards to prior results, clusters 11 through 13 investigate or evaluate each design element, and extract an optimal design solution on the basis of the emergent design. Despite the fact that emergent design is often conducted during an early process of design, these clusters can be utilized during detailed design.

Considering that basic design is a process where psychological design elements are converted into physical design elements, this process can be described as an indispensable process for sharing information between designers, where industrial designers mainly use psychological design elements and engineers mostly use physical design elements. Therefore, a proposition of new design methods based on the ones included in clusters 6 through 10 is necessary to facilitate the sharing and accumulation of design information.

4. Conclusion

In this research, the principle of the design methods to apply to each design process is acquired, enabling design methods to be shared across different domains. Specifically, 174 design methods are extracted from various original articles, and subsequently classified into 13 clusters based on "Matsuoka's design thinking", "design methodology", and "form of data". The results are used to identify the proper use of every cluster from the viewpoint of the design process. Furthermore, the features of design methods, which must be expanded or proposed for prompt design information sharing and accumulation, are extracted. This research clarifies that the using methods considered appropriate for basic design is one approach to ensure correspondence against today's design problems. This is due to the fact that basic design is a process where psychological design elements are replaced with physical design elements. However, design methods have yet to be built based on the gained knowledge. In the future, we plan to construct a specific design method using this knowledge and validate its usability by applying it to an actual design.

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