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Perception-Based Design Space Structures for Evolutionary Design Systems
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Abstract
With computational design strategies, particularly evolutionary generative systems, the understanding of the design activity has been changing. Accordingly, the designerly behaviour and the designer's interaction with and the involvement in the design process have been evolving. Evolutionary design systems generate a large number of design solutions that expand design spaces immensely. Especially in multi-modal fitness landscapes, the existence of many optimal design alternatives complicates the designer's cognitive involvement in design. Moreover, particularly in automated design generation, due to the immense expansion in design search space, the designer's visual interaction with the design artifacts is diminished. Accordingly, the proposed research problematizes two major issues of evolutionary design systems; (1) the broad, dense and non-structured design search spaces and (2) the decrease in the designer's involvement in decision-making and evaluation due to the automated design generation. As a solution, perception-based design space structures are proposed as an evaluative structuring strategy. These network structures are intuitive, case-based, observer-dependent and subjective maps of the designer's cognitive world. By encouraging the integration of designer's cognitive abilities in the design synthesis, these structures aim to bridge the gap between the design artefact and the designer by acting as a mediator during the generation process. Alongside, these structures aim to manage the complexity in design search space by providing an environment for designerly evaluation and decision-making. With those aspects, perception-based design space structures are a designer-centric (human-centric) approach for automated design processes and are based on the designer's perception and identification of common visual features. The identification of the common features of instances, visual resemblance is chosen as a criterion for forming perception-based design structures within the scope of this research, on the basis of Rudolph Arnheim's *Visual Thinking* that highlights forming categories as one of the major ability of a human cognition. Within this scope, a case study is conducted within a group of designers with an existing design space of chairs that are generated by IDEA, an evolutionary system, experimented by Celestino Soddu. In this framework, this paper discusses and presents the experimental study about evolutionary generative design search spaces and perception-based design space structures.

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Main References:
[1] Rudolph, Arnheim, *"Visual Thinking"* California: University of California Press, Berkeley and Los Angeles, 1969.
[2] Celestino, Soddu, *"Generative Art in Visionary Variations"*. Art+Math=X Proceedings, University of Colorado Boulder, 2005.
[3] John Holland, *"Emergence: From Chaos to Order",* Oxford

University Press, 1998.

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Abstract
With computational design strategies, particularly evolutionary generative systems, the understanding of the design activity has been changing. Accordingly, the designerly behaviour and the designer's interaction with and the involvement in the design process have been evolving. Evolutionary design systems generate a large number of design solutions that immensely expand design spaces. Especially in multi-modal fitness landscapes, the generation of many optimal design alternatives complicates the designer's cognitive involvement in design. Moreover, particularly in automated design generation, due to the immense expansion in the design search space, the designer's visual interaction with the design artefacts is diminished. The proposed research problematizes two major issues of evolutionary design systems; (1) the broad, dense and non-structured design search spaces and (2) the decreased level of designer involvement in decision-making and evaluation due to the automated design generation. As a solution, perception-based design space structures are proposed as an evaluative structuring strategy. Within this scope, a case study is conducted within a group of designers with an existing design space of chairs that are generated by IDEA, an evolutionary system, experimented by Celestino Soddu. In this framework, this paper discusses and presents the experimental study about evolutionary generative design search spaces and perception-based design space structures.

1. Introduction
This paper presents a strategy that aims to address the complexity of evolutionary generative systems used in design through proposing a visual structuring strategy. In evolutionary design synthesis, the understanding of a design process differs from conventional design thinking. While the act of design is transformed into a continuous process of re-formulation of an ill-structured design problem in order to be a clearly-defined problem, design artefact is transformed into a continuous process of search and exploration, generation, transformation and evaluation that are guided by algorithms. With this continuous process of searching and generating, the design search space has enlarged, densified and broadened excessively unlike conventional design search spaces. In conventional design exploration processes, the design search space is formed manually by the designer. This limits the number of design alternatives that are generated and evaluated, and therefore narrows the search space. However, the exploration of multiple design alternatives can support better-informed design decision-making and prevent premature design decisions. At this point evolutionary generative design strategies enable designers to

explore multiple design alternatives that are generated in an automated manner. However, the high number of generated design alternatives may challenge the management and organization in design search spaces as well as the designer's involvement through the search space. Due to these changes and challenges, the designer's interaction with the 'artefact(s)' has also changed. The designer's integration and visual contact, therefore his contribution and evaluation in design process are weakened due to the mentioned challenges as a consequence of the automated generation.

Accordingly, this paper problematizes (1) the management of broad, dense and non-structured design search spaces and (2) the decrease in the designer's involvement in decision-making and evaluation due to the automated design generation. Here, we support that the design activity in generative processes must be amplified to facilitate subjective design exploration and visual evaluation. As a result, the potential of the designer-centric management of the design search space can be better fulfilled. For this, there is a need for a method that facilitates the cognitive integration of the designer through the solution space and the design process. In this paper, perception-based design space structures are proposed as a mediator between the designer and the design solutions. These network structures represent the resemblance relations between the design alternatives, and can guide the designer's selection of the eventual design alternatives. These structures have the potential to support the designer's cognitive and visual integration through the generation processes.

Within this scope, a case study is conducted to implement the construction of the proposed structures with a group of designers. The solution space IDEA, an evolutionary system that supports the design of chairs developed by Celestino Soddu will be used for this purpose. There are several concepts that need to be highlighted in this regard that directly associate with the theoretical background of the perception-based design space structures. Primarily, in order to map the relations between the various concepts from different fields of science and design, the concept of emergence within the frame of evolutionary generative systems must be and therefore is discussed prior to the articulation of other concepts. Following, population thinking, and systematics are articulated within the scope of visual resemblance and visual structuring.

1.1 Evolutionary Generative Systems

Evolutionary generative design systems implement synthesis methods that facilitate design exploration and fosters the stochastic search that seek the fittest solution determined by the fitness function designating the fitness degree of the solution [1,2]. Particularly, they simulate the processes of evolution in nature and foster the efficient design exploration processes that extend the capabilities of designers and end up with multiple and unrepeatable design alternatives, that leads to divergence in design search space [3,4,5,6,7]. Through design generation, the designer is only involved at the beginning of the problem by initializing the synthesis process; by defining a design problem, design constraints, design procedures and the boundary conditions [8].

1.2 Emergence

Evolutionary generative systems demonstrate emergent behavior as a consequence of complexity [9,10]. In such systems, procedures determine the local interactions between the parts, resulting in emergent behavior of the whole system [11]. Emergent behavior is a result of the reconfiguration of parts, therefore the change, as a result of the underlying internal dynamics of a system that demonstrates itself with recognizable and iterative patterns [9,12,13,14]. Each part of a system act and reorganize themselves according to these procedures to adjust and maintain their internal dynamics. These procedures act as a mediator between the parts of the system and are termed as the *schema* by Gell-Mann and as *internal model* by Holland [13]. In this paper, these procedures are termed as schema. The schema is inherent to all design instances that are generated for a single design problem. As a schema determines the internal structure of a system, the internal structure demonstrates itself with recognizable patterns as an emergent behavior in each design instance in common.

In evolutionary design systems, in reference to the concept of emergence there are two terms that are adopted from its original science fields as phenotype and genotype. Genotype is the genetic composition of an organism as designation of the generation logic associates with the schema, while phenotype is the environmentally and genetically determined traits of an organism as an outcome of the process associates with the emergent behavior [16,17,18]. As evolutionary systems generate an evolutionary lineage of design instances, each design instance is only one emergent state of a generation process. When the genotype is subjected to a change, a different phenotype through the process emerges.

2. Visual Resemblance, Emergence and the Perception-Based Design Structures

2.1 Visual Resemblance and Emergence

Resemblance is a state of being or looking similar to something. Accordingly, in this paper, visual resemblance refers to the common features, the generic characteristics, of design instances that are generated by the same *schema*. When the generic characteristics and resemblance are considered together, both Arnheim's 'structural pattern' in visual reasoning and Holland's emergence with 'recognizable iterative patterns' in generative design systems, illustrate the same principle, which is the perception of the commonness. According to Arnheim (1969) "[t]he perception of the shape is the grasping of structural features found in, or imposed upon, the stimulus material." Accordingly, the perception of a shape is based on the common characteristics that are perceived by the observer. The process of shape perception is mainly based on the engagement of an abstraction and generalization mechanism in visual reasoning processes [19]. Through abstraction, the observer perceives the generic characteristics of a shape. Moreover, ignoring the details of a shape leads to generalization, which Holland defines as a process of model-building [9,19].

In this regard, a major statement can be articulated as; perception is based on the main features that are identified by the observer. Therefore, resemblance has the potential to be a major organizational criterion in design spaces [9]. In evolutionary algorithms, the population is generated as an evolutionary lineage and as generic characteristics are determined by the genotype, new design variations emerge as the design variables change [20]. Here, each instance is a variation of the schema; they are of the same type but are not identical. At this stage, this paper argues that design instances generated from the same schema may form a design family due to their resemblance. Hence, as the designer perceives and evaluates these phenotypic characteristics, the design families can be manually formed in a designer-centric manner.

2.2 Perception-Based Design Space Structures

In this paper, structuring is accounted as to give structure to the parts (design instances) of a complex design search space. The act of structuring aims to represent the resemblance relations between the design instances. Additionally, in such processes, the designer is in contact with the design artefact by means of symbolic representations, rather than visual. For these challenges, the perception-based structuring has the potential for assisting the design space management, navigation and design exploration as well as for supporting the involvement and the amplification of the designer's cognition by means of establishing a visual guidance. Due to the designer's important role in the identification of common features

between the design instances, perception-based structures are build-up in a manual and intuitive manner. They are case-based.
Perception-based structuring may take place after the design generation and requires the identification of the generic characteristics in a set of design instances. In reference to Arnheim, as forming categories is one of the major abilities of human cognition [21], the generic characteristics give way to the formation of resemblance clusters, consequently, the classification of the design instances based on visual commonness.
The construction of a structure starts with the identification of the resemblance relations between the instances by the designer. The identification of the resemblance ends up with the emergence of visual similarity groups, namely the resemblance clusters. Each resemblance feature as a clustering criterion can lead to a separate cluster. The identification of the visually distinctive first parameter structures the whole classification, and this influences the whole taxonomy. In the case of the identification of many parameters, the designer has to undergo multiple phases of classification. This leads to the formation of sub-clusters.

2.1.1 The Representation of the Visual Resemblance: Population Thinking and Systematics

For the representation in perception-based structuring, population thinking is selected as a model for classification. It is a concept in evolutionary biology based on Darwin's early theories on evolution and natural selection. It is directly opposed to typological thinking by stating uniqueness of each individual in a population based on complex multidirectional behaviour between the parts of the system.
The concepts of type and variation are needed to be analysed to map the opposition between the concepts. In typological thinking, the type is the real and the variations which are dependent on type are illusions [22]. On the contrary, population thinking defines type as an average abstraction of the common features of a population and considers variation as real. Population thinking propounds the evolution, evolution which is mainly based on the gradual alterations on species, therefore the uniqueness of the individual. For populationists, the type is an abstraction, which bears the average characteristics of a species, that consolidates the uniqueness of each organism that are composed of unique features can be collectively described by generic outlines based on shared features. In this research, type is the identification of the internal schema, the generic characteristics that directly associates with reiterative recognizable patterns of emergence.
Population thinking consolidates complexity management in design space by fostering the mental construction of archetypes for the formation of clusters of perception-based structures, asserting type as an abstraction of design variations by bearing average characteristics of design variations.
For design variations, the generation logic of evolutionary algorithms can be used as an explanatory model. In genetics, the regulatory genes control the growth of the individual and make minimal changes in body plan, which increases the diversity in a population and the generated individuals are variations of constructed schema. The procedures remain the same but varying parameter values as a response to external conditions generate the design variations. Each individual bears the same schema with altered responses to changing conditions. Design variations are similar to each other but they are not identical.
On the basis of population thinking, perception-based structuring is mainly inspired by taxonomical classification in evolutionary biology. The taxonomical methods may serve as a tool for mapping the interrelations between the design instances, however without the evaluation of designer, design space will only be classified in means of its genotypic data

and will be lacking of designerly understanding. For instance, in evolutionary biology there are phylogenetic trees which are the family trees that show ancestry - posterity relations between the species. In comparison to phylogenetic trees, perception-based structures are the mental mappings which are the designerly re-organized versions of phylogenetic trees. In this sense, cladistic systematics of evolutionary biology can be a model, a strategy for perception-based structuring. Cladistics is a classification strategy/method for species of animals and plants that focuses on the shared characteristics that identifies the connection of common ancestry [24]. It is chosen as model for the structures due to the evaluations of the phenotypic attributes in correlation to visual resemblance relations.

2.2 The Representation of the Perception-Based Design Space Structures

Based on cladistics in evolutionary biology, dendrograms can be used for the representation and build-up of perception-based design space structures. Dendrograms are tree-like diagrams that represents the phenetic relations based on hierarchical similarity relations between the classes (clads or taxa in biology), or individuals in these classes [23]. They are similar to phylogenetic trees; however, in biology there are slight differences in the usage of the terms, dendrograms, cladograms or phylogenetic trees. They all refer to the same classification model, but they differ by means of the different understandings and stances in evolutionary biology. Dendrograms, as called as binary trees, are used widely in general within these terms.

The main principles of dendrograms can be explained by means of graph theory. Dendrograms have the data points and the roots that bind points together [15]. The graph is a set of points and connections that defines a mathematical object, and consists of edges (relationships) and vertices/ nodes (elements). All vertices are related to each other by means of edges. Edges can have directions, in this case it is called ‘directed edges’ and graphs are called as ‘digraphs’ or ‘directed graphs’. An edge that connects two vertices defines direction by having tail and head, direction is defined from tail to head. In this regard, data point of dendrograms are the nodes, as the roots are the edges of the graph. In this sense, perception-based design space structures can be classified as directed graphs. While vertices are design individuals, edges illustrate its resemblance relation to other design individuals. In some cases, vertices can define resemblance- without defining a design individual- that is seen between design individuals which are found in different resemblance sub-clusters.

3. The Case Study

To test and illustrate the perception-based design space structures, a case study with a group of designers is conducted. This case study aims to demonstrate the classification strategy and the clustering behaviours of different designers. To this end, we aim to observe the subjective decision-making schemes rather than testing an implemented system. An existing search space is used for this study that is developed by Celestino Soddu by using an evolutionary generative mechanism *IDEA* [6]. According to Soddu, the evolutionary mechanism in IDEA describes the generation and transformation procedure, but does not have an evaluation. Therefore, the algorithm does not aim to converge towards the fittest but to generate a number of different alternatives. Soddu states that the generative mechanism without optimization is selected on purpose to explore all possible design variations [6]. As a result, unique end results emerge. IDEA prioritizes divergence over convergence, therefore can generate a many design alternatives that none is superior to another. Therefore, IDEA offers an opportunity for our case study participants to explore visually distinguishing parameters of a large number of alternatives (Fig.1).

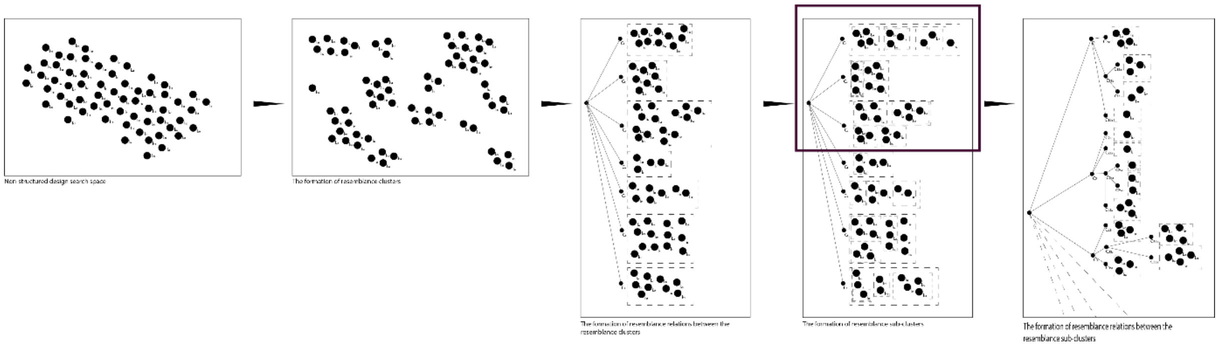

Fig.1 Structuring in a Design Search Space

For the case study, there are three participants trained as architects with couple years of professional experience and academic background. Within the scope of this paper, structures of three participants are explained, evaluated and compared in detail. The participants are coded as *Participant 1 (P1), Participant 2 (P2)* and *Participant 3 (P3)*. Before giving the design set, the participants are informed about the representation model and method of the structuring. The design search space of IDEA is made of 110 unique chair instances. The structuring process starts with the random 2D graphical arrangement of the chairs on a sheet of paper (Fig.2). On this paper, the case study participants are expected to see the complete set of design instances at once. Each design instance is given an ID number.

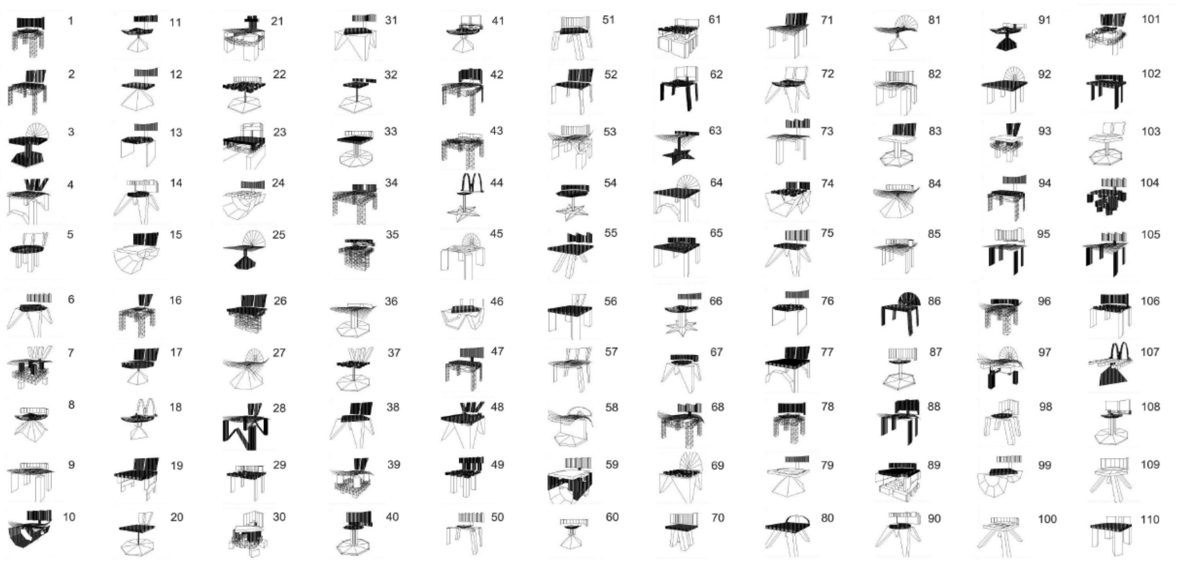

Fig.2 Design Set Generated by IDEA

Before giving the design set, the participants are informed about the representation model and method of the structuring. Before building-up the structures, they are also asked for a chart that shows the resemblance clusters in general (Fig.3). The difference of the chart and the structure is, the chart only shows the resemblance groups in general and does not map the interrelations between the design instances. The resemblance chart can be perceived as preliminary phase of the design space structures. Following, the participants are encouraged to use image-editing software to illustrate their charts and structures. They are also asked for a brief statement of their structuring strategy and their grouping criteria.

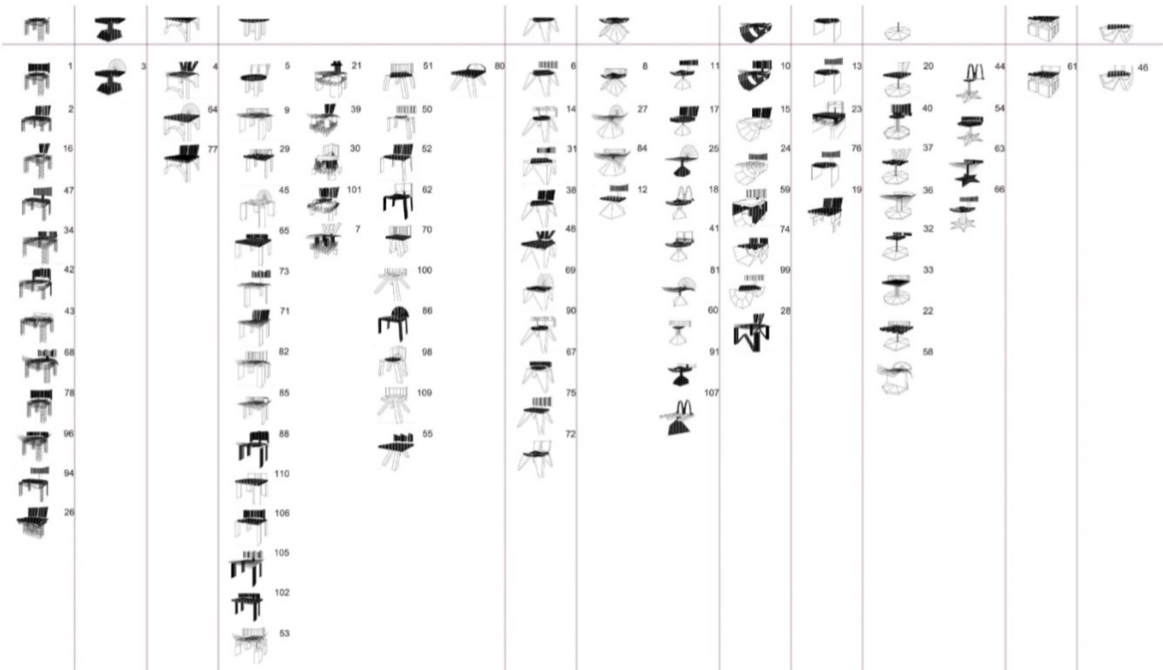

Fig.3 Resemblance Chart of P1

P1 selected chair legs as a primary visually distinguishing criterion which points the clustering criteria that associates with the resemblance in the given design set (Fig.3-4). Accordingly, P1 identifies eleven types of chair legs and the design search space is divided into eleven clusters. With the identification of 11 types of chair legs, P1 created her chart to structure the design space roughly. Then, P1 aimed to analyze the possible interrelations between the design instances that are gathered under the same cluster (Fig.5).

Fig.4 11 Different Chair Legs Identified by P1

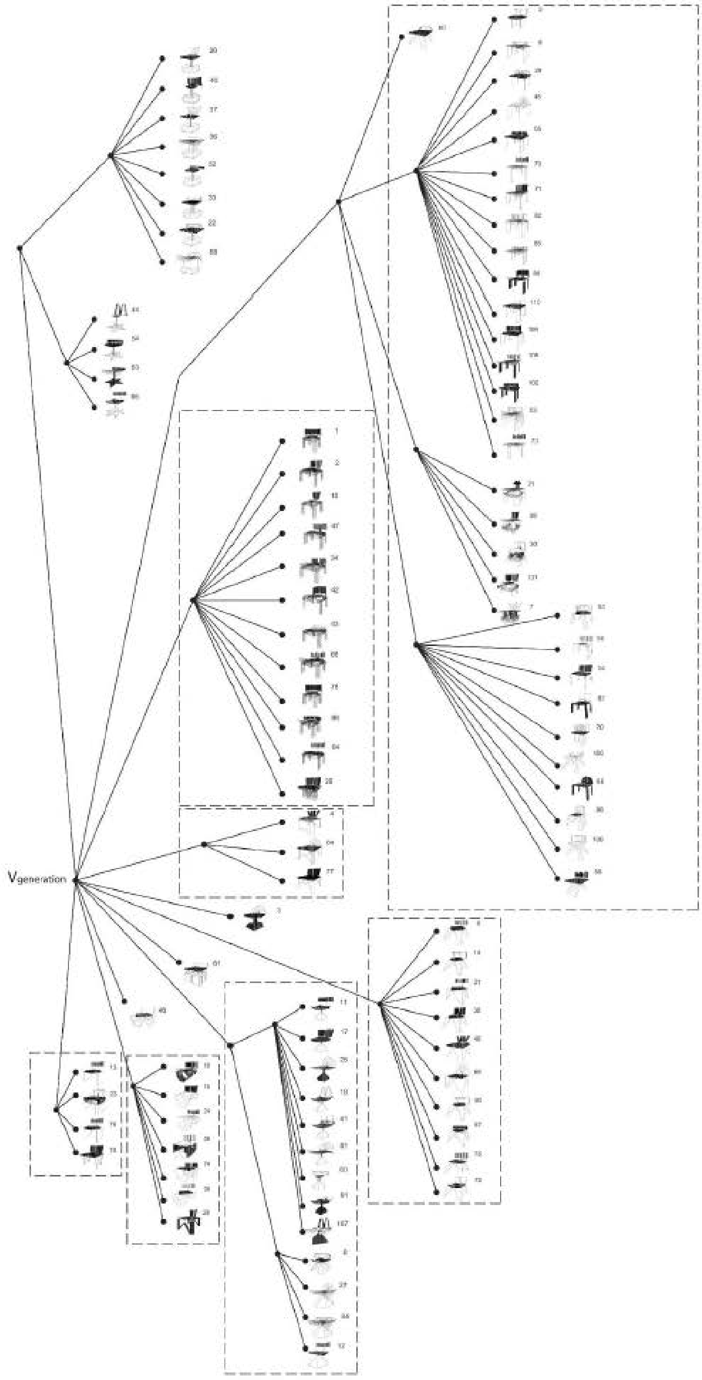

Fig.5 Perception-Based Design Space Structure of P1

P2 divided the design set into five resemblance clusters that are based on the formal appearance of the chair legs as; chair legs with (1) straight angle, (2) circular base, (3) widening angle, (4) box-like formed base, (5) rounded form of the leg components (Fig.6). In the structuring process of P2, the sub-clustering based on form of the backrests is observed. In each cluster, there are five sub-clusters as; (1) singular, (2) dual, (3) triple, (4) elongated and (5) semi-circular backrests. Before moving from the chart to the structure, P2 started to structure internal relations in sub-clusters. At the end of the structuring (Fig.8), when it is compared to P1's structure, rather than sole interrelations between the design instances, the relations that are defined between the sub-clusters are observed in the structure of P2. Also this behaviour is observed in P3. (Fig.7).

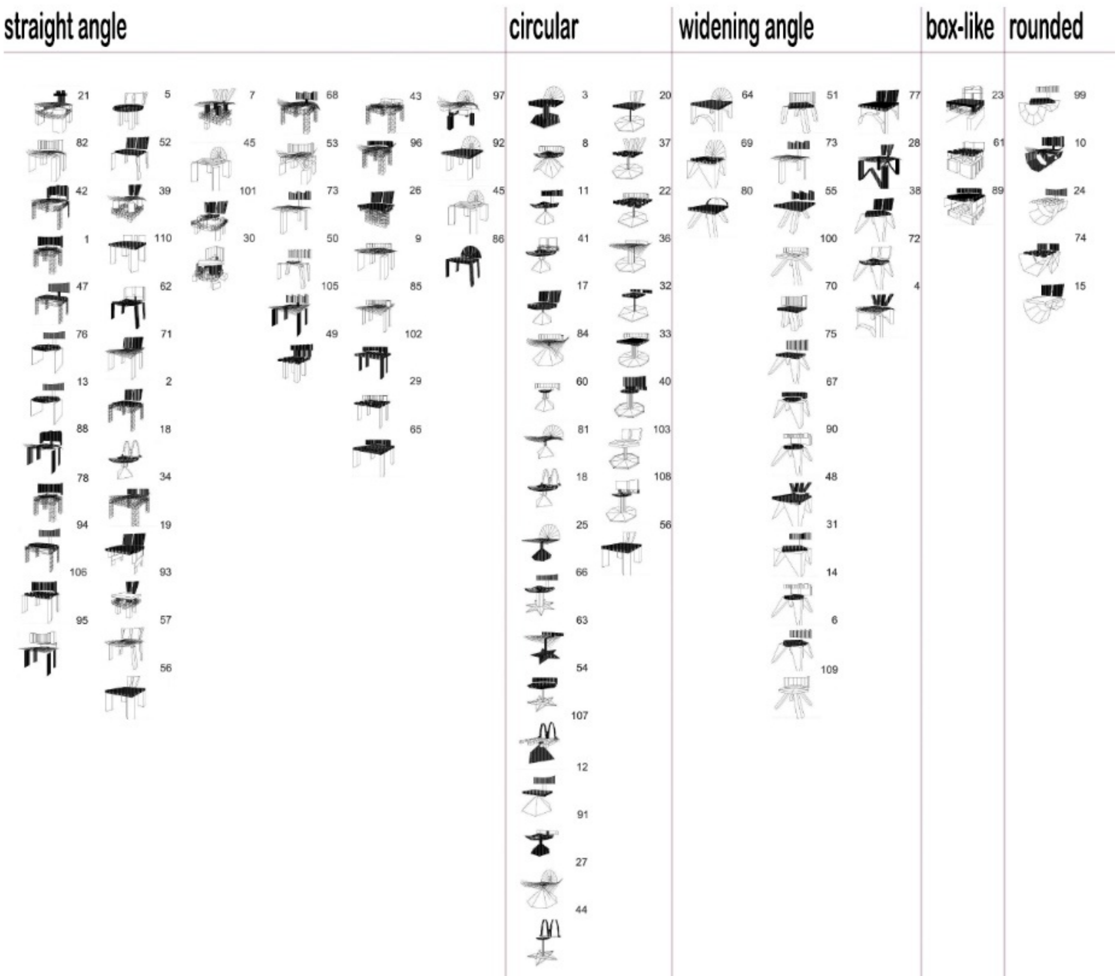

Fig. 6 Resemblance Chart of P2

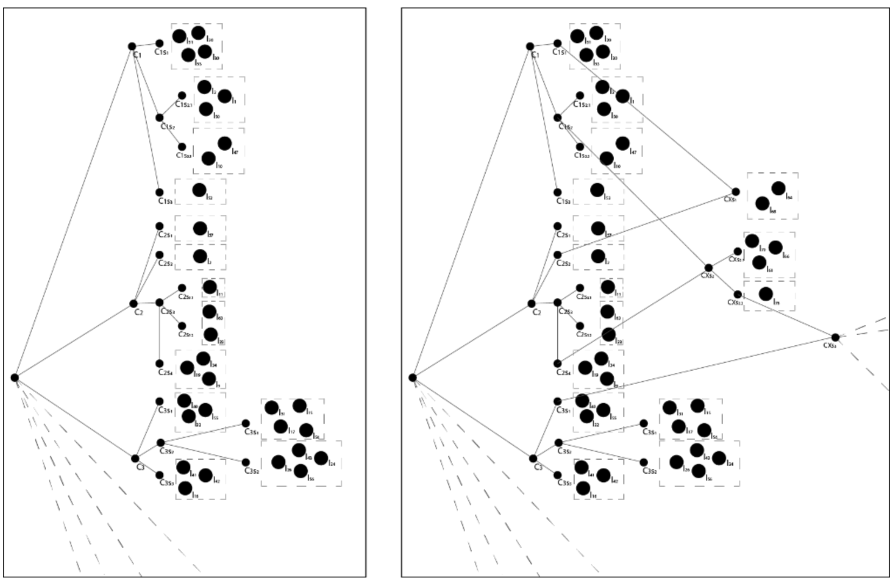

Fig.7 The Different Structuring Behaviours Structures of P1 (left) and P2, P3 (right)

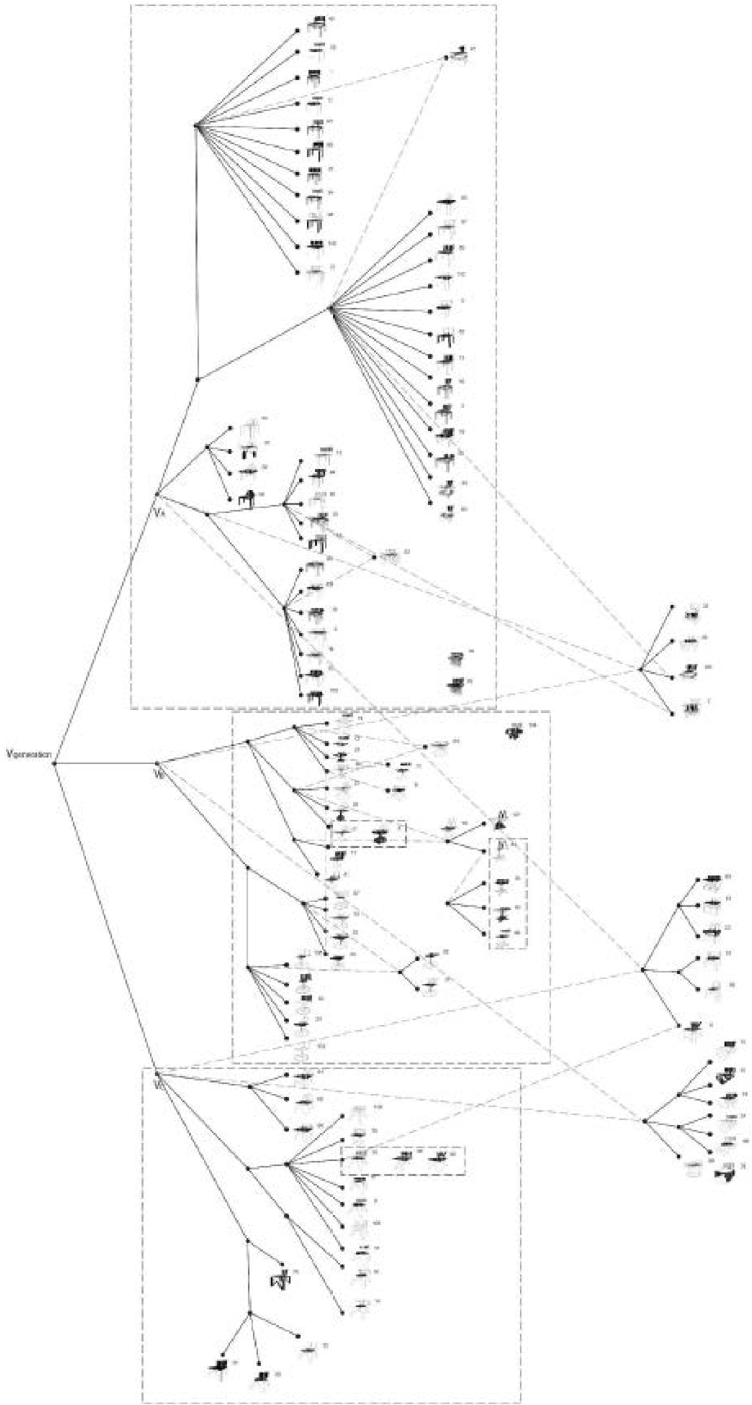

Fig.8 Perception-Based Design Space Structure of P2

P3 followed much more different behaviour of structuring throughout the process compared to P1 and P2 by identifying two visually distinguishing criteria for the initial formation of the resemblance clusters based on (1) backrests, and (2) chair legs (Fig.9). However, after encountering the incoherencies and difficulties while grouping the design set according to the two criteria, P3 decided to divide the design set in fifteen resemblance clusters according to the backrests and following that, P3 decided to form sub-clusters in reference to chair legs (Fig.10).

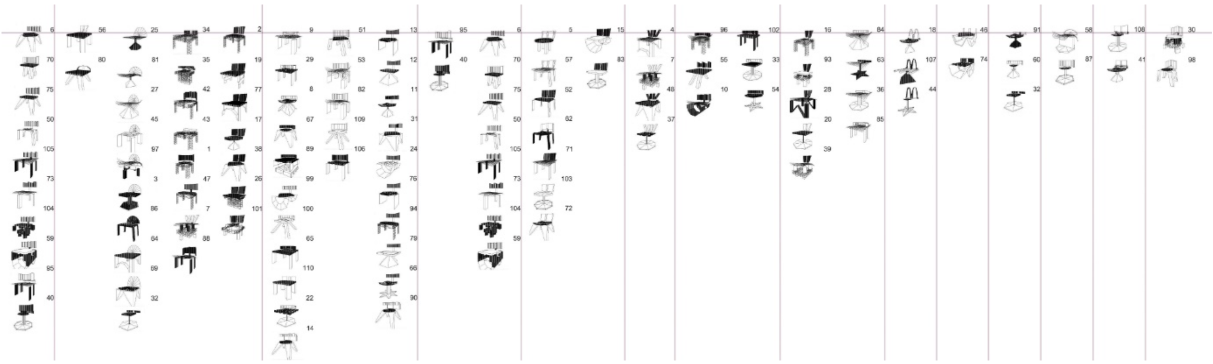

Fig.9 Resemblance Chart of P3

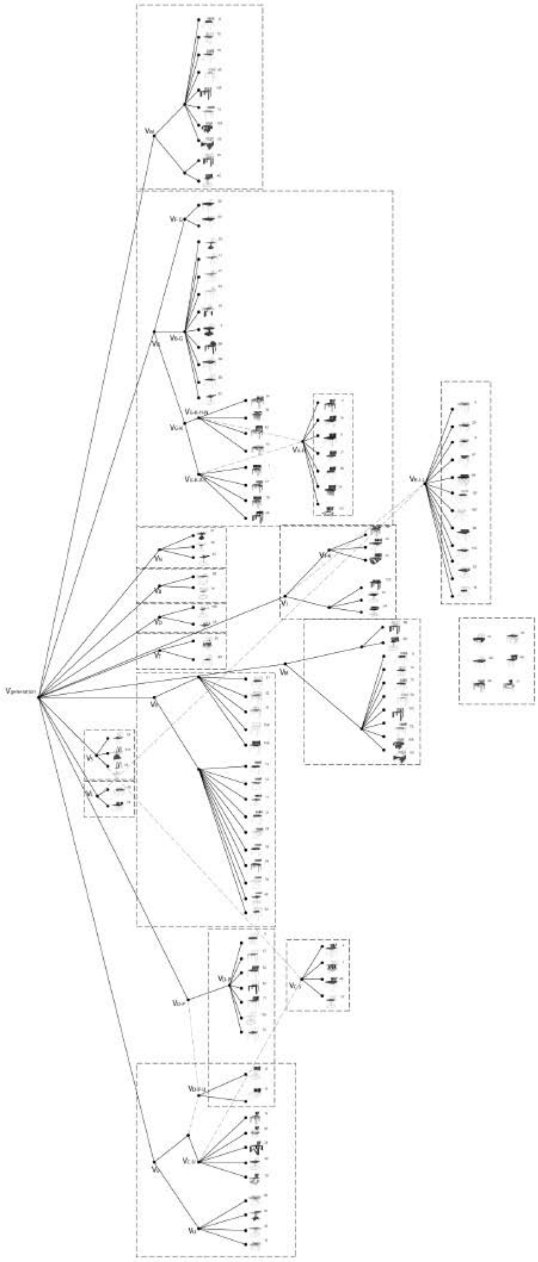

Fig.10 Perception-Based Design Space Structure of P3

4. Findings, Implications and the Further Study

There are several conclusions that have to be highlighted. Primarily, this study emphasizes the subjectivity of the designer, designerly evaluation and how valuable they are in a design process.

One of the major conclusion of the case study is that the structuring process revealed the subjectivity of perception-based structuring. During the case study, it is observed that the resemblance clusters and the interrelations between the design instances are structured on the repeating/common elements. (Fig.11) All participants identify different visually distinguishing criteria for the resemblance clusters, but the strategy for structuring is based on the identification of common features in general. Each designer demonstrated different clustering behaviour, every time clustering behaviour changes according to the perception of a designer. Accordingly, each designer built a unique structure with the same design instances with different clustering criteria due to their unique visual perception, cognition and understanding. Therefore, the study revealed that the formation of resemblance clusters, accordingly the construction of visual structures, actualized in a subjective and designer-dependent manner. Therefore, each structure is observer-dependent, subjective and personal.

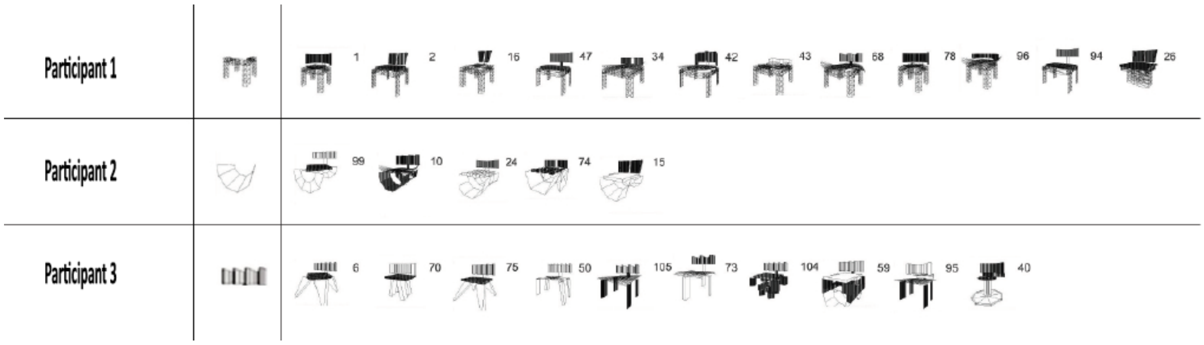

Fig.11 The Repetition of Different Textures Identified by Different Participants

Also, perception-based structuring enhances the designer's direct dialogue with the generated complete design set by involving the designer to integrate the cognitive abilities through a subjective act. Within this scope, these structures provide visual guidance to the designer and facilitate the designerly interaction and evaluation after the design synthesis. Secondly, depending to designer's cognition, the identification of resemblance can be used as an operational method for structuring.

For the further phases of the research, it might be one of the priorities to split this research into two part by means of the (1) improvement as a method of structuring and (2) the cognitive analysis of the designer's involvement through the process.
To start with the improvements in the proposed strategy, there is a need for the feedback from the results that are obtained through the research process. Primarily, as perception-based structuring strategy requires manual construction, it may not be quite efficient for the designer in complex and large design search spaces. Here, these kind of search spaces pose a challenge for the future use of this method. However, for the further improvements, there are several strategies that hold the potential to develop the use of perception-based structuring as (1) the software implementation with a visually supportive interface, or (2) a filtration software (may evaluate design instances according to the filtering criteria and that narrows the search space) before the manual build-up of the structuring.
Perception-based structuring may be utilized with the help of software prototype implementations, which may extend the proposed use of them. A platform with a visually rich and supportive interface that contains a whole set of visual representations of design instances, may enable designers to structure their resemblance clusters literally as a tree-structures.
For the analysis of the designer's involvement, there further research efforts are necessary that implement structured protocol studies. The methods like eye-tracking with think-aloud protocols may hold the potential to clarify the decision-making patterns of the designer's cognition.
The suggested prototypes and cognitive analysis protocols can lead to other research tracks to explore and to analyse the integration of the designer through the design synthesis process.

References

[1] Frazer, J., An Evolutionary Architecture, Architectural Association, 1995.
[2] Kalay, Y. E., Arhitecture's New Media: Principles, Theories, and Methods of Computer-Aided Design, The MIT Press, 2004.
[3] Soddu, C., Generative Design. A swimmer in a natural sea frame. Generative Art International Conference Milan, 2006.
[4] G. Dino, İ., Creative Design Exploration by Parametric Generative Systems in Architecture, Middle
East Technical University JFA, 2012, p. 204-224.
[5] Krish, S., A Practical Generative Design Method, Computer-Aided Design, vol. 43, 2011, p. 88-100.
[6] Soddu, C., Generative Art in Visionary Variations, Art+Math=X Proceedings, 2005, University of Colorado, Boulder.
[7] Shea, K., Aish, R., & Gourtovaia, M., Towards Integrated Performance-Driven Generative Design Tools. Automation in Construction, vol.14, 2005, p. 253-264.
[8] Cagan, J., Campbell, M. I., Finger, S. and Tomiyama, T. A Framework for Computational Design Synthesis: Model and Applications. Journal of Computing and Information Science in Engineering, vol.5, 2005, p. 171-181.
[9] Holland, J., Emergence: From Chaos to Order, Oxford University Press, 1998.
[10] Shiffman, D., http://natureofcode.com/book/chapter-8-fractals/
[11] Gell-Mann, M., Complex Adaptive Systems, In G. A. Cowan, D. Pines, & D. Meltzer, Complexity: Metaphors, Models, and Reality, Addison-Wesley, 1994, p. 17-45.
[12] Kauffman, S., At Home in the Universe: The Search for Laws of Self-Organization and Complexity, Oxford University Press, 1995.
[13] Holland, J., Constrained Generating Procedures, In A. Menges, & S. Ahlquist, Computational Design thinking, John Wiley & Sons, 2011, p. 131-142.
[14] Weinstock, M., The Architecture of Emergence, John Wiley & Sons, 2010.
[15] Mucha, H.-J., H.-G. Bartel and J. Dolata (2005). "Techniques of Rearrangements in Binary Trees
(Dendrograms) and Applications." MATCH: Communications in Mathematical and in Computer
Chemistry 54: 561-582.
[16] Holland, J. Complex Adaptive Systems. Daedalus, vol.121(1), 1992, p. 17-30.
[17] Haupt, R. L., and Haupt, S. E., Practical Genetic Algorithms, John Wiley & Sons, 2004.
[18] Sastry, K., Goldberg, D., and Kendall, G., Genetic Algorithms. In E. K. Burke, and G. Kendall, Search Methodologies: Introductory Tutorials in Optimization and Decision Support Techniques, Springer, 2005, p. 96-127.
[19] Les, Z., & Les, M. (2008). Shape Understanding System. Berlin: Springer-Verlag.
[20] DeLanda, M., Deleuze and the Use of the Genetic Algorithm in Architecture, In N. Leach, Designing for a Digital World, Wiley, 2002.
[21] Couchman, J. J., Coutinho, M. V., and Smith, J. D., Rules and Resemblance: Their Changing Balance in the Category Learning in Humans (Homo Sapiens) and Monkeys (Macaca Mulatta). J Exp Psychol Anim Behav Process., vol.36(2), 2010, p.172–183.
[22] Trummer, P. (2011). Associative Design: From Type to Population. In A. Menges, & S. Ahlquist, Computational Design Thinking (pp. 179-197). Chichester, UK: John Wiley & Sons.
[23] Sokal, Robert R., and F. James Rohlf. "The Comparison of Dendrograms by Objective Methods." Taxon 11, no. 2 (1962): 33-40.

[24] Mayr, E. (1974), “Cladistic Analysis or Cladistic Classification?” Journal of Zoological Systematics and Evolutionary Research, 12: 94–128.