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CONSTRUCTING A MULTI-DIMENSIONAL MODEL TO UNDERSTAND TEAM DESIGN THROUGH LANGUAGE

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Abstract

As the support for creative design of complex products, multi-disciplinary team design has always been the focus of researches on design. By taking language as the data resource in design, a multi-dimensional model called linkage which represents the design process in dimensions of the time, the math and the space is proposed. On the basis of traditional research, the process of team design has been transformed into the forms of linkograph, colored-linkograph, matrix and network. Defining the colored-linkograph, the code vector and the link matrix, and introducing the clustering of network, the multi-dimensional representation of the whole design process can be realized. This model disruptively reconstructed the representation of design cognition space and realized the data-driven reasoning and visualization.

Keywords: Design cognition, Computational design synthesis, Collaborative design, Industrial design

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1 INTRODUCTION

The rapid development of science and technology gives rise to the characteristics of complexity and multi-field on product innovation design which has evolved into the innovation behaviour of team collaboration. Design is increasingly regarded as a kind of interactive and social process interpreting creativity, thus team design will become the new design technology of gathering interdisciplinary knowledge and innovation.

This paper will propose a more systematic model named Linkage to study team design in a more comprehensive way by using the unstructured data of language to express cognitive reasoning process in the forms of linkograph, colored-linkograph, matrix and network, and combining quantitative methods to capture hidden information. In the following section, an overview of the related research on team design will be presented. Section 2 details the construction of the Linkage model. Section 3 illustrates the model using a case study. Section 4 formulates discussions showing the applications, and finally the conclusions are drawn.

1.1 Design cognition

Design cognition is the comprehensive results of image thinking and abstract thinking and is also the important category of design behaviour researches which attract many scholars. It is based on the theory of solving problems and the situational behaviour theory to study interdisciplinary research fields. Goldschmidt (1991) investigated the process of sketching in design. Simon (1979) proposed the Symbolic Information Processing Theory (SIP) from the perspective of solving problem which regards design as the process of processing information including information stimulation phase, psychological reaction phase and concept expression phase. In addition, Schön (1983) developed the Situation Theory (SIT) which focuses on the behaviour and deemed design as an interactive communication process in which two characteristic states exist including behaviour cognition and behaviour reflection. In order to further study the behaviour and the process of design, modelling has gradually been introduced in design study. Adams, Turns and Atman (2003) utilized Schön's reflective practitioner theory to discuss the empirical results in the context of educating reflective practitioners to enhance engineering education. Lawson (2006) combined evidence and research on expertise from other cognitive fields and concluded that design expertise cannot be understood by studying actions alone but that their research needs to concentrate on perception and recognition. Cross (2006) considered that design is the synergetic evolutional exploring process of the problem space and the solution space, and constructed the design concept of space evolution model. Kim (2009) described design as a process of information representation and generation, transient expression of evaluating decisions, and circulated process of iterated evolution, including stimulation, coding, storage and extraction behaviour.

1.2 Processing tools

Goldschmidt (1990) first reported the technique of linkography to study designers' cognition and performance. In addition, Goldschmidt (1994) introduced link index and critical moves aiming to quantify the linkograph, and further researches had been approached to compare the behaviour and performance of solo design to group design. Kan and Gero (2009) founded the function-behaviour-structure (FBS) ontology which segmented the framework of design process and coded the design moves in terms of the purposeful nature of design. The FBS framework encodes the design and design creativity through parsing the protocol within three categories: function, structure and behaviour. After segmenting and coding, each category is linked semantically which builds a linkography that embedded the FBS framework. Through transforming recording texts into matrices, Dong (2005) put forward the latent semantic matrix and the recording text accumulation based on the singular value decomposition and the cosine similarity. Concurrent and retrospective protocol methods were used by Chandrasekera and D'Souza (2013) to identify sudden moments of inspiration through recording, coding and analyzing. Tamer and Alan (2012) proposed the merge of qualitative and quantitative models to describe design creativity. They also used linkography to describe the events that happen during the design process and investigated the measures from space syntax to understand when creativity emerges (Tamer and Alan, 2014). Taura, Yamamoto, Fasiha Nagai and Nakashima (2012) used the semantic network to show how people forms deep impressions. Parameters in network have been applied to denote the characteristics of different impression network (Taura et.al, 2012). Taura and Nagai (2013) traced the relationships between concepts in the semantic network to simulate the virtual concept synthesis process. Each of them tries to explain the design process and design space quantitively and qualitively, this paper will provide a more comprehensive way understanding design cognition.

2 DEFINITION AND CONSTRUCTION OF THE LINKAGE MODEL

Linkage is a model composed of three parts: process-link, math-link and concept-link. Each of them translated the design space in a different perspective; however, tight connection existed among them which makes them a whole system. Figure 1 shows the constitution of a Linkage that can reflect the design process in various ways. Both protocol analysis and computational methods can be conducted by using the Linkage model. By representing and analysing the design cognition process in a comprehensive way, an in-depth study can be conducted. In the following part, detailed illustration will be given about this new model.

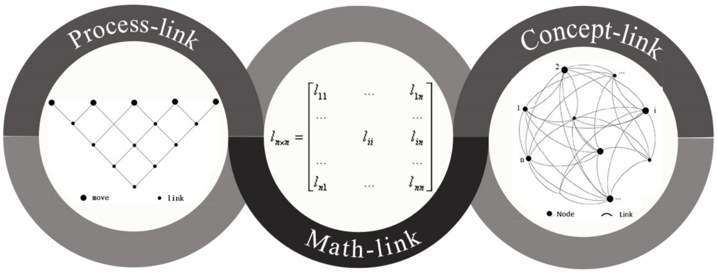

Figure 1. The structure of the Linkage model consisting of the process-link, math-link and concept-link.

2.1 Process-link

The process-link (Pl) expressed design process in time dimension which can be divided into two types: the normal linkograph that was first proposed by Goldschmidt in 1995 as a promising method for analysing idea generation processes, and the colored-linkograph which colored the links according to the different roles in order to explore the team members' character. The left part of Figure 2 shows the constitution of a linkograph by two elements: design move and link. In the process of developing a design solution the designer makes design moves. A design move is a step, an act, an operation, which transforms the design situation related to the state in which it was prior to that move. A link is created when two moves are judged to be relevant and associative according to the meaning of design contents. Here the linkograph is defined as $L(n, l)$ where n is the total number of design moves and l is the link matrix which stores the linking information among the moves.

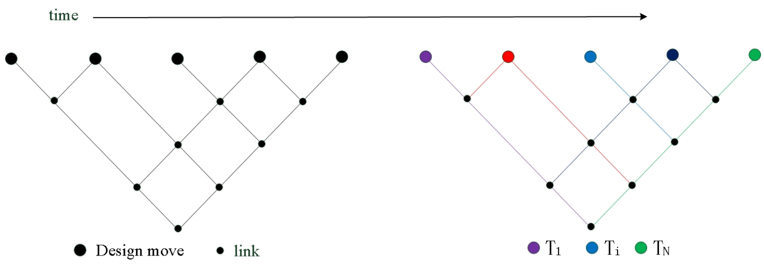

Figure 2. the redefinition of the linkograph and colored-linkograph

During the team communication, different moves result from the different members in fact. The team member set is defined as: $Te = [T_1, T_2, ..., T_N]^T$, where T_i is the symbol of the team member. The total elements of set *Te* is decided upon to the size of the design team, and the two-way matrix $R_{n \times N}$ is built clearly illustrating the belongings of design moves.

$$R_{n\times N} = \begin{array}{c} \\ move_1 \\ \cdots \\ \cdots \\ move_n \end{array} \begin{array}{c} T_1 \qquad\qquad T_n \\ \begin{bmatrix} r_{11} & \cdots & r_{1N} \\ \cdots & & \cdots \\ & & \\ r_{n1} & \cdots & r_{nN} \end{bmatrix} \end{array} \quad (1)$$

For the role T_i,

$$\begin{cases} r_{ji} = 1, & move_j \in T_i \\ r_{ji} = 0, & move_j \notin T_i \end{cases} \quad j \in [1,n],\ i \in [1,N] \quad (1)$$

With the construction of the role matrix, the original linkograph can be operated by giving different colors to nodes and links that pertains to the different members. The right part of Figure 2 illustrates the generation of the colored-linkograph. The colored-linkograph represents more information than linkograph particularly on the distribution and contribution of moves and links given by different person. The process-link realizes and optimizes the process representation of design cognition and enriches the feature extraction about the team roles.

2.2 Math-link

Computational methods can help to analysis the design cognition deeply which shows great advantages. In the Linkage, the mathematical expression and computation is made through the math-link (Ml) creatively. Ml consists of the two parts: the link matrix which is conducted by coding the linkograph shown in Figure 3, and the block matrix (Mb) which is used to operate Ml logically.

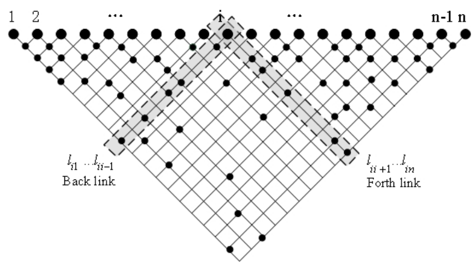

Figure 3 Coding process of the linkograph

For arbitrary move *i* in the design process, a linked vector *li* can be created through coding the links using character 0 and 1.

$$l_i = [l_{i1}, l_{i2}, \ldots, l_{in}] \quad \begin{cases} l_{ij} = 1, & \text{if } i \text{ and } j \text{ are linked} \\ l_{ij} = 0, & \text{if } i \text{ and } j \text{ are not linked} \end{cases} \quad j \in [1,n],\ j \neq i \quad (2)$$

All the moves' vectors can be generated in the same way, thus the link matrix l can be constructed to describe all the links as shown blow:

$$l_{n\times n} = \begin{bmatrix} l_{11} & \cdots & l_{1n} \\ \cdots & & \cdots \\ & l_{ii} & l_{in} \\ \cdots & & \cdots \\ l_{n1} & \cdots & l_{nn} \end{bmatrix} \quad (2)$$

In the link matrix $l_{n\times n}$, element $l_{ij}(i \neq j)$ means the link value of move i and move j, if the link existed, l_{ij} will be 1; if not, it will be 0. When $i = j$, it has no real meaning and will be set as 0.

While Ml stores the essential information of links between design moves, Mb is also defined to show the relationship between the team members. It can be created through operations from the link matrix and the role matrix which means changing the order of rows and columns will contribute to analysing the different member's characters. The formula below helps to generate the block matrix:

$$B_{N*N} = {R_{n\times N}}^{T} \cdot (l_{n\times n} \cdot R_{n\times N}) \tag{3}$$

The block matrix is shown as follow, where T_{ij} means the linking degree between person *i* and *j*. If $i = j$, then T_{ij} means one link generated from the person himself. Thus for every column or row in the block matrix, the link block can be divided as self-links and tinter-links which can be very useful to study the relationships between team members. Ml is not only a valuable computation tool, but also provides the innovative thought for analysing the mechanism of design cognition logically and explicitly.

$$\begin{array}{cc} & \begin{array}{ccccc} T_i & & T_j & & T_n \end{array} \\ B_{N\times N} = \begin{array}{c} T_1 \\ \\ T_i \\ \\ T_N \end{array} & \left[\begin{array}{c:c:c:c:c} T_{11} & \cdots & T_{1i} & \cdots & T_{1n} \\ \hdashline \cdots & & & & \cdots \\ \hdashline T_{i1} & & T_{ii} & & T_{in} \\ \hdashline \cdots & & & & \cdots \\ \hdashline T_{N1} & \cdots & & \cdots & T_{NN} \end{array}\right] \end{array} \tag{4}$$

2.3 Concept-link

As another part of the Linkage, concept-link (Cl) represents the design content visually in the form of network. Compared with the linkograph, concept-link is moreover applied to explore the concept relations and the orientation of team members in content dimension. The concept-link is defined as *N(n,l)* where n means the number of design concepts and l represents the link matrix of the concepts (Figure 4). Since the similarity to linkograph, concept-link can be automatically associated and generated from the link matrix. There also exist operations for a concept-link which can categorize it as the clustered semantic network and the clustered social network.

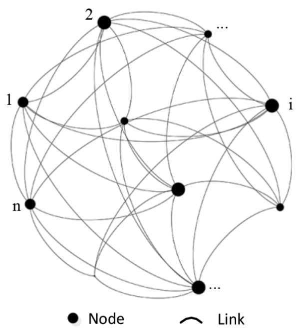

Figure 4. Concept-link definition consists of nodes and links

In Figure 4, the painted circle means the design concept, and the line means the link between two concepts. By using the concept-link, the path between two concepts can be easily acquired. Criterions on the network can be applied to reflect the properties of a concept-link N(n,l). The centrality parameter (C_{RDi}) from the network can be used for calculation to show the importance of some concepts or design moves quantitively, which is defined as follows:

Point centrality:

$$C_{RDi} = D_i /(n-1) \tag{4}$$

Di means the degree of node i.

2.3.1 Clustered semantic network

Clustered semantic network is developed from the normal semantic network which aims at analysing the structure of concepts. The whole design content can be separated into phases according to the semantic relationship. Ideas are usually represented in the means of semantic concepts, such as the words or phrases or some sentences. In the phases the concepts swarmed as the Concept-blocks with the inherent and subordinated relation. In Figure 5, every concept block has its internal links which form a semantic sub-network, through the bridge links these sub net-works can be connected as a whole network. The clustered semantic network can not only map the concept generation process dynamically, but also excavate the concept relation hierarchically, thus clearly reflecting the concept-oriented discipline during the team cognition.

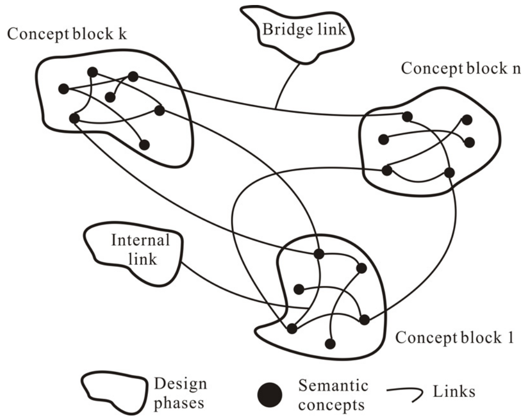

Figure 5. Clustered semantic network

2.3.2 Clustered social network

Clustered social network mainly emphasizes on the membership in the design team. It is used to explore the relationship of roles instead of design concepts. For every link, if the two design moves it connected belongs to one same person, it is called a self-link, meanwhile, if the moves belong to different person, the link will be taken as an inter-link. After categorizing the links, we put the self-links and their owner together which forms small nets shown in Figure 6, then inter-links are used to link all the small nets. That is how the clustered social network is founded. In Figure 6, N_{ij} means links from *i* to *j*. By resorting links according to people and dividing links into self-links and inter-links, the relationship between team members can be illustrated.
For every team member, he has both self-links and inter-links. The amount and ratio of these two different kinds of links reflect different characteristics and mutual impacts of team members, that is why this model can be used to study the design groups.

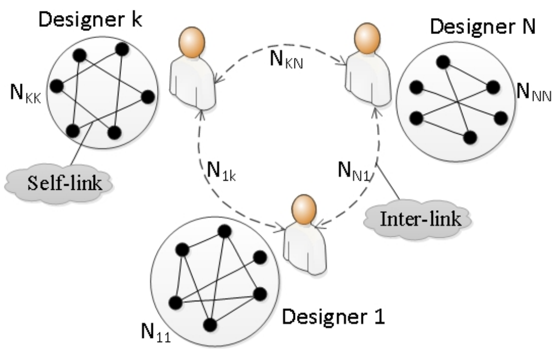

Figure 6. Clustered social network

3 CASE ILLUSTRATION

The following part shows how Linkage can be applied into study of design cognition by analysing an experiment. The theme of the experiment is the design of bicycle locks. The design team would give different proposals during the process and evaluate all the ideas to choose the final one.

3.1 Results & Analysis

The process-link helps to show the design process graphically. The linkograph is generated from the protocols as shown in Figure 7. From the linkograph the dynamic situation can be easily seen from the density of links during the whole period.

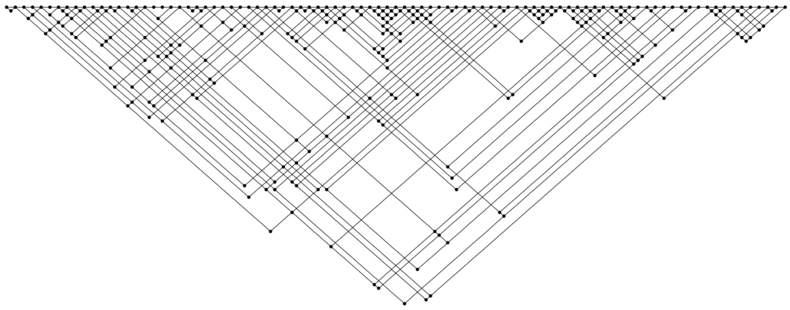

Figure 7. Linkograph of the bicycle lock experiment

Ml storing the digital information can also be generated including the role matrix and link matrix. $R_{91\times5}$ is the role matrix of the design team. The math-link realizes the change from unstructured data to digital information. $l_{91\times91}$ is the link matrix and the block matrix $B_{5\times5}$ can be operated from the formula: $B_{5\times5} = R_{91\times5}^{T} \cdot (l_{91\times91} \cdot R_{91\times5})$. The block matrix stores the number of self-links and inter-links.

$$R_{91\times5} = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ \cdots \\ 87 \\ 88 \\ 89 \\ 90 \\ 91 \end{array} \begin{array}{c} \begin{array}{ccccc} T_1 & T_2 & T_3 & T_4 & T_5 \end{array} \\ \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix} \end{array} \qquad (4)$$

$$l_{1\,(91\times91)} = \begin{bmatrix} 0 & 1 & 0 & & \cdots & \cdots & & 0 & 0 & 0 \\ 1 & 0 & & & & & & & & \\ 0 & 0 & 0 & & & & & & & \\ & & & & & & & & & \\ \cdots & & & & \cdots & & & & & \cdots \\ & & & & & \cdots & & & & \\ & & & & & & & & & \\ & & & & & & & 0 & 1 & 0 \\ & & & & & & & & 0 & 0 \\ 0 & 0 & 0 & & \cdots & \cdots & & 0 & 0 & 0 \end{bmatrix} \qquad (5)$$

This matrix helps to store all the linking information and can be the basis of further computation.

$$B_{5\times5} = \begin{bmatrix} 20 & 16 & 12 & 26 & 12 \\ 16 & 22 & 5 & 12 & 23 \\ 12 & 5 & 2 & 16 & 7 \\ 26 & 12 & 16 & 26 & 10 \\ 12 & 23 & 7 & 10 & 36 \end{bmatrix} \qquad (6)$$

When it comes to the concept-link, the relationship and development process can be explored. $N(91, l)$ is the concept-link. Thus the social network can be easily got according to the relationships. It helps to see the space relationship of different nodes while turning the order in time into space. The clustered social network is generated according to team members which extracts information by person and shows both the concept evolution process of everyone himself and interaction with others. Figure 8 shows the clustered social network.

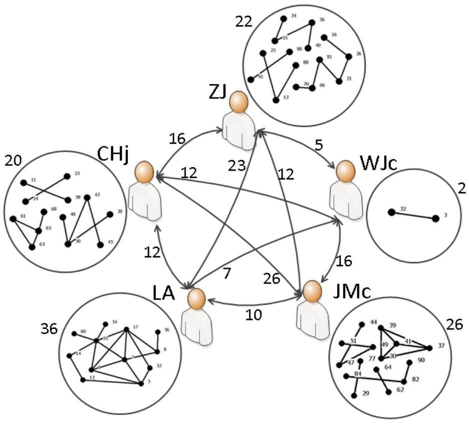

Figure 8. Clustered social network

From Figure 8, the team member WJc only have two self-links while LA got 36. For WJc the proportion of self-links and inter-links is 5%, but for LA the number grows to 69%. That means WJc mainly relies on discussing the others' ideas while LA doing both. This is the example of how clustered social network can help to explore the deep characters and relationship of the team members. The clustered semantic network as Figure 9 shows aims at exploring the structure of design concepts. The internal links and bridge links are of different importance. Concept blocks can be constructed and the relationship between these blocks can also be seen. This helps to see the whole design process in a more detailed way and deeper analysis can be conducted by the clustering.

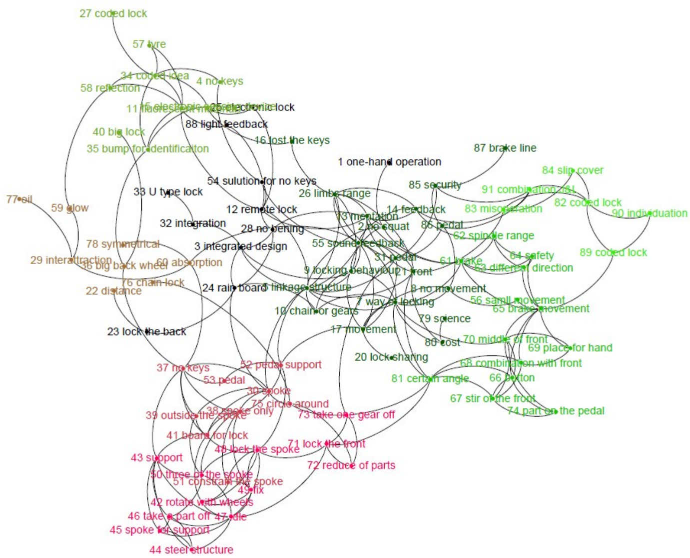

Figure 9. Clustered semantic network showing concept blocks in different colors

By clustering the concepts in Figure 9, the theme of each group can be known. Concept group 1 colored in black are mainly talking about the humanization ways for locking while concept group 2 in dark blue discussing about the forms of locks. This shows how clustered semantic network help to analysis the main points and concept groups.

Computational methods for the network are also useful. The properties of the net can be computed as the following Table 1 shows. Figure 10 shows the rank of nodes by centrality in the net.

Table 1. Centrality of nodes

Centrality	Node											
	1	2	3	4	5	...	86	87	88	89	90	91
C_{RDi}	1.11	5.56	5.56	2.22	13.33	...	4.44	1.11	2.22	3.33	2.22	4.44

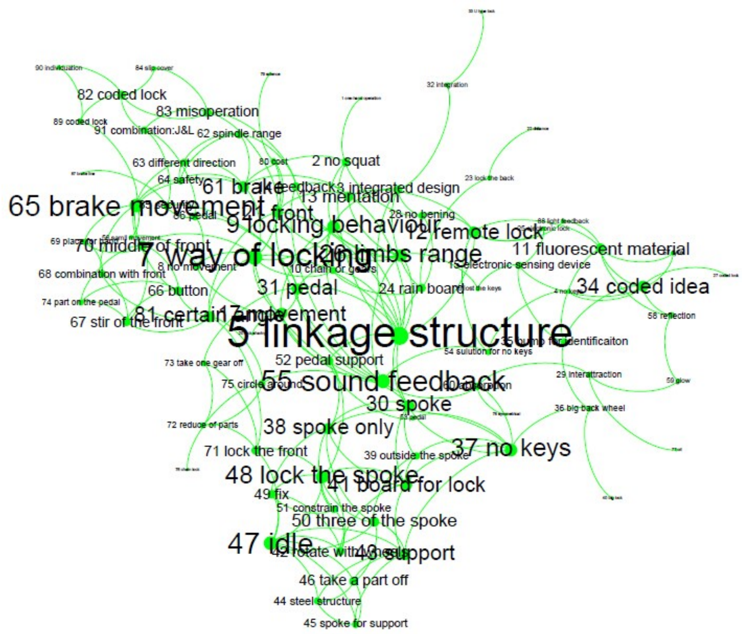

Figure 10. Node ranks by three centrality measures

4 DISCUSSION

Linkage realizes the multi-dimensional representation of the design process. Primarily, basic applications of this new tool can be generated from three aspects of design cognition: design process, design content and design team. Design process contains information about developments and conditions which can help to understand design from an overall perspective. Linkage can be used to represent the design process and compute typical characteristics. Concept-link reflects the space relationship of concepts, thus parameters from concept-link help to show characteristics of all the concetps. In this paper, the design content was analysed in two respects: the evolution process of concepts and the structure of content. By separating the design process into blocks, it is easier to get the basic structure of design. Representing the whole design process in space dimension also helps to see the evolution path of concepts. Study on team membership can also be conducted. Clustering concepts according to designers and computing the inter-links and self-links can reflect not only thoughts of designers but also relationship among them.

However, this paper mainly emphasizes on defining the new Linkage model rather than showing lots of applications. More applications can be carried on in further exploration. The Linkage tool finishes the transformation from primary verbal records to computable data and visual representations, thus providing the basis for further application and explorations.

5 CONCLUSION

A comprehensive tool has been developed in this paper to study design cognition. The Linkage was divided into three parts, the math-link, process-link and concept-link. Basic definition was made on these three parts including parameters, formulas and graph generations. The case illustration helps to explain how the representation of the form of Linkage is conducted including data processing, computations and visualizations. Preliminary applications on design process, design content and team members have also been explained. However, it is believed that various kinds of applications can be explored further on the basis of Linkage.

Linkage can realize the digital simulation in multi dimensions in the space of design cognition. It can provide a new way to deal with the unstructured verbal data in design cognition. It can also be a new rapid visualization tool which can provide good ideas and inspirations on the semantic-drived innovation design. New contributions can be made on the effective extraction of concepts, evaluation in design teams and capture of deep information.

In addition, in the experiment, protocol records are used. In the future, larger scale records will be necessary to explore the capability of processing big data in design cognition. Specific applications on design process, design content and team members will also be conducted.

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