

Article

Using Linkography and Situated FBS Co-Design Model to Explore User Participatory Conceptual Design Process

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Abstract: To unravel the complex challenges addressed by product innovation, it is oftentimes essential for users to participate in the design process. However, there is a paucity of research in terms of in-depth exploration of the cognitive patterns and dynamic design processes of co-design with user participation in the existing design cognition research. The current study aimed to investigate the cognition activities involved in the process of co-design between user and designer at both the individual and team levels. The combination method of linkography and the situated function–behavior–structure (FBS) co-design model was carried out to encode and analyze the protocol data. The results showed that, at the individual level, designers and users adopted different design strategies to promote the progress of the design. In addition, the interaction activities among users and designers varied in different co-design processes. However, at the team level, the collaborators showed systematic thinking modes, and each design move was two-way. This cognitive strategy of the innovation team ensured the continuity and effectiveness of the co-design process. Theoretically, these findings will bring new insights for studies on team cognition activities and contribute to building user-centric design theory by uncovering the dynamic design processes of co-design with user participatory. In addition, the study makes a methodological contribution by illustrating how linkography and the situated FBS co-design model can be utilized to analyze the team cognition during co-design activities.

Keywords: user participatory design; linkography; situated FBS; design cognition



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1. Introduction

User participation in design has become increasingly important with the growing individuation and heterogeneity of design requirements, higher demand for market response efficiency and product innovation. Design activities have gradually evolved into collaborative innovation between users and designers [1,2]. However, existing design research has emphasized the exploration of individual designers' cognitive activities, such as the ideation process [3] and design fixation [4] or the development of intelligent design methods [5–7] to cope with the uncertainty of ideation processes, ignoring the essential value of design innovation brought by users when they participated in the design.

There is a lack of in-depth exploration of the cognitive patterns and dynamic design processes of co-design between user and designer. Therefore, the present study intended to explore the cognition activities, such as the selection of design strategies and interactions between team members, involved in the process of co-design between the user and designer at both individual and team levels through a verbal protocol analysis. Linkography and the situated FBS co-design model were utilized to analyze the unstructured design protocols and the relationship between the co-design processes and interaction patterns among design participants.

Users deeply involved in the design process referred to the situation where users played the role of product design implementer, they discussed design problems and generated design solutions together with designers. Such a process is essential to co-design [8], collaborators shared the same design goal and worked together to construct design solutions. There have been numerous studies on the co-design process. Klimoski et al. [9] proposed a mental model to analyze the information-sharing mode among participants during the co-design process.

In the study of Masclat et al. [10], a real-time coding method based on augmented reality was proposed to study the information interactions between user and designer in the process of co-design. Wiltchnig et al. [11] explored the coevolution of problem space and solution space in the co-design process based on protocol analysis. Maier et al. [12] discussed the main factors that affected design communication in co-design, including information expression and understanding. These studies provide a theoretical foundation for a better understanding of co-design and support the practice of co-design. However, there is still a paucity of research on team cognitive patterns and design processes in user–designer co-design.

Protocol data plays an important role in the analysis of the co-design cognition process between users and designers, which can truly and completely record the interaction among participants and reasoning processes [13–15]. The encoding and analysis strategies of protocol data are often inconsistent due to different research purposes [16]. The present study aimed to explore co-design cognition between users and designers from the perspectives of design processes and interactions among participants. Three factors should be considered: the situationality of co-design, the dynamics of the design processes and the multi-dimensionality of design information.

Therefore, a combination of linkography and the situated FBS co-design model was adopted to analyze the protocol data of the user participatory design workshop qualitatively and quantitatively. Linkography is a verbal protocol analysis method originally established by Goldschmidt [17], and it can visually represent individual designers' reasoning processes based on protocol data in chronological order. With the further development of Goldschmidt [18], linkography can be effectively applied to represent the team ideation process.

A linkograph can directly exhibit the bidirectional movement of participants' thinking process and provides solid support for the quantitative study on the team cognitive process. The situated FBS co-design model provides a fine-grained representation of the co-design activity, each designer's interactions with other collaborators and their internal cognitive processes. The combined application of linkography and the situated FBS model aimed to deeply explore the co-design process with user participation and the interaction activities between collaborators and provide new insights into co-design cognitive patterns.

2. Background

2.1. The Situated FBS Co-Design Model

Translating and encoding the verbal data generated by completing the co-design task holds the key to the protocol analysis. The encoding scheme was often limited to certain research [19] because the encoding scheme adopted varied considerably according to the research tasks. The function–behavior–structure (FBS) model proposed by Gero [18,20], reveals the complete mapping relationship between functional (F) variables, behavior (B) variables and structural (S) variables during the conceptual design process. This model is generally applicable to design protocol analysis and has been widely used in many design research fields, such as engineering design [21], product service system design [22] and mechanical engineering [23].

As shown in Table 1, the FBS model states that functional variables contain the purposes of the artifact, behavior variables represent the expected interaction properties between artifacts and the environment, and structural variables describe the absolute composition of artifacts and their relationship. However, the FBS model was known to bear

some weaknesses because it did not cover the situational characteristics of design and was incapable of describing the dynamic design process [24].

Table 1. The FBS model and definitions of design variables [20].

Design Variables	Definition
Requirement (R)	R includes the design brief, client or regulation requirements.
Function (F)	F is the design object teleology i.e., what the design object is for.
Behavior (B)	B represent how the design object performs: it can be an expected behavior (Be) or a behavior derived from the structure of the design object (Bs).
Structure (S)	S is the description of elements or groups of elements of the design object and their relationships.
Description (D)	D represents externalizations representing the design object.

The situation in the design activity contains design information from both the current design environment and the designer's experience. The situated FBS model [24] combines FBS ontology with four cognitive processes: interpretation, constructive memory, focus and action (in which interpretation and constructive memory are regarded as push-pull processes), and describes how the individual designer deals with design information in the interaction between the internal experience and external environment in the process of conceptual design. This is independent of the design fields and has the adaptability of different design situations. The situated FBS model determines three different situational worlds: the external world, the interpreted world and the expected world. The superscripts x , i and e in the figure, respectively, indicate that the design issues are in the external, interpreted and expected world.

The external world holds all design variables and their representations in the external design situation, including seven design issues: Requirement related to function (FR^x), Requirement related to behavior (BR^x), Requirement related to structure (SR^x), Function (F^x), expected Behavior (Be^x), Behavior from structure (Bs^x) and Structure (S^x). The interpreted world is constructed by designers based on their own experience and perception of the external world and current design concepts, including four design issues: the interpreted Function (F^i), expected Behavior (Be^i), Behavior from structure (Bs^i) and Structure (S^i). The expected world contains possible design actions build upon the designer's interpreted world, including three design issues: the expected Function (F^e), Behavior (Be^e) and Structure (S^e).

Multiple situated FBS models can be further linked to form a situated FBS co-design model [25]. The cognition activities of co-design contain two levels, including a personal level and team level. The personal level design process, such as constructing knowledge and reasoning about current design problems based on the designers' own experience and background, take place in the expected and interpreted world. The team-level design process, such as communicating and decision-making among participants to achieve cognitive synchronization of the team, take place in the external world [25]. As shown in Table 2, the situated FBS co-design model summarizes the co-design process into seven steps, taking both the internal cognitive processes of designers and designers' interactions with each other through external design representations into consideration, thereby, providing a solid body of knowledge for the present study.

Table 2. The situated FBS co-design processes [25].

Process	
Formulation	$FR^X \rightleftarrows F^i, BR^X \rightleftarrows Be^i, SR^X \rightleftarrows S^i, FR^X \rightleftarrows F^i, BR^X \rightleftarrows Be^i \dots$
	$F^e \rightarrow F^x, F^x \rightleftarrows F^i, F^i \rightleftarrows F^i, F^i \leftrightarrow F^e, F^e \rightarrow Be^e, Be^e \rightarrow Be^x$
	$F^e \rightarrow F^x, F^x \rightleftarrows F^i, F^i \rightleftarrows F^i, F^i \leftrightarrow F^e, F^e \rightarrow F^x$
	$Be^e \rightarrow Be^x, Be^x \rightleftarrows Be^i, Be^i \leftrightarrow Be^e, Be^e \rightarrow Be^x$
Synthesis	$Be^e \rightarrow Be^x, Be^x \rightleftarrows Be^i, Be^i \leftrightarrow Be^e, Be^e \rightarrow S^e, S^e \rightarrow S^x$
Analysis	$S^e \rightarrow S^x, S^x \rightleftarrows S^i, S^i \rightarrow Bs^i, Bs^i \rightarrow Bs^x$
Evaluation	$Bs^i \rightarrow Bs^x, Bs^x \rightleftarrows Bs^i, Bs^i \rightarrow Be^e, Be^e \rightarrow Be^x$
	$Be^e \rightarrow Be^x, Be^x \rightleftarrows Be^i, Be^i \rightarrow Bs^i, Bs^i \rightarrow Bs^x$
Reformulation 1	$S^e \rightarrow S^x, S^x \rightleftarrows S^i, S^i \rightleftarrows S^i, S^i \rightarrow S^e, S^e \rightarrow S^x$
Reformulation 2	$S^e \rightarrow S^x, S^x \rightleftarrows S^i, S^i \rightarrow Be^i, Be^i \rightleftarrows Be^i, Be^i \leftrightarrow Be^e, Be^e \rightarrow Be^x$
Reformulation 3	$S^e \rightarrow S^x, S^x \rightleftarrows S^i, S^i \rightarrow Be^i, Be^i \rightarrow F^i, F^i \rightleftarrows F^i, F^i \leftrightarrow F^e, Fe \rightarrow F^x$

\rightleftarrows Push–pull process; \leftrightarrow Focus process; and \rightarrow Action process.

In FBS ontology, the design issues related to design problems mainly involve Requirement (*R*), Function (*F*), and Expected Behavior (*Be*), while Structure (*S*) and Behavior from Structure (*Bs*) are design issues related to artifacts as design solutions. Therefore, design issues can be divided into problem-related issues (including *R*, *F* and *Be*) and solution-related Issues (*S* and *Bs*) [26]. The design activity is a process of co-evolution of the problem/solution space [27], for the situated FBS co-design model, it can be seen that the Formulation process takes place in the problem space, while Analysis and Reformulation 1 processes take place in the solution space. The transformation from problem space to solution space is accomplished through the Synthesis and Evaluation ($Be^x \rightarrow Bs^x$) processes, while the transformation from solution space to problem space is realized through the processes of Evaluation ($Bs^x \rightarrow Be^x$), Reformulation 2 and Reformulation 3.

2.2. Linkography and Its Application

In protocol analysis, design activities were first divided into numerous design moves. These design moves are simple thinking activities generated in accordance with the time series, which can be an action, behavior or operation, and which change the state of the design before this design move occurs [26,28,29]. The linkograph is constructed by linking these design moves according to their relationship with each other.

Linkography is an effective means to capture designers' cognitive activities because of its flexible analysis and multi-level coding as well as its ability to visually represent the design activities [18,30,31]. To explore whether the designer's selection of design information can effectively assist in solving design problems, Blom and Bogaers [32] used linkography to analyze the verbal data generated through a think-aloud experiment, and the preliminary experimental results showed that novice designers widely use external information sources to organize and solve current design problems.

Cai et al. [33] investigated design patterns among designers of different expertise levels and exposure to different inspiration sources before design activity by extended linkography. Linkography can also be effectively used to evaluate collaborative design thinking activities of product design and engineering design, Hatcher et al. [29] used linkography to identify the most prominent variations in performance concerning inter-connectedness, parallel thinking and idea diversity of team ideation when performing different creative methods. Kan and Gero [30] explored the contribution of individual designers in the process of co-design through qualitative analysis of linkography.

Jiang and Gero [34] explored intragroup communication in team design using data collected from a protocol study. They interconnected the conversational turns and design issues of team design activities using linkography, and the results showed that linkography combined with FBS ontology can be effectively used for content-based analysis on team design. These studies utilized linkography as a visual analysis tool combined with different coding methods and all promoted the in-depth study of design cognition to a certain extent.

3. Experiment

The objective of the present study was to explore the team members' cognitive activities and dynamic design processes of co-design through a think-aloud experiment. Combined with the linkography and situated FBS co-design model, the protocol data during the co-design processes were analyzed qualitatively and quantitatively. Following are the experimental details.

3.1. The Experimental Task and Procedure

Considering the requirements of the protocol study for each participant to think aloud, the difficulty and workload of the design task should be appropriate. Therefore, the design task was to design a household air purifier that meets the needs of target users. To ensure the users' deep participation in the design, the researchers first recruited target users with the purchase intention of a household air purifier through the internet. The experiment was conducted in the form of offline design workshops. Each target user cooperated with two to three postgraduate students majoring in design to finish the design task.

A pre-experiment was conducted for each participant to help them become familiar with the think-aloud experiment. They were all required to describe and draw their route to the experimental site simultaneously. After the pre-experiment, they were introduced to the requirements and precautions of the design task in detail. Participants expressed their design ideas and design solutions through face-to-face communications, gestures, texts and sketches. They were required to express their views as much as possible to seek more possibilities of design solutions.

To prevent achieving abhorrent results due to the long experimental time, the experimental time was limited to 60 min. When the time reached 60 min, participants were informed of the progress of the experiment but not forced to end the design task. The verbal data, body movements and sketching processes of all participants were videotaped during the whole experiment.

3.2. Segmentation and Encoding Scheme of the Protocol Data

At the end of the experiment, the verbal data were extracted and converted into transcription reports, which were then segmented and coded. Segmenting refers to the segmentation of transcribed reports according to changes in the design moves and intentions expressed, and coding refers to transforming each segment into a series of codes that can represent design behavior, the reasoning process or other design features according to semantics and independent topics.

The present study segmented and encoded the protocol data strictly according to the situated FBS co-design model, and each segment contained a situated FBS code. The behavior of sketching is thought to be related to generating solutions. To ensure objectivity [18] and avoid the impact of cooperative coding on the accuracy [35] of the coding results, the segmenting and coding of protocol data was conducted independently by two coders. To ensure coding consistency, when judging whether the two design moves were linked, the two coders were required to follow the guidelines listed below [29]:

- (1) When the participants' ideas or actions are directly related to the earlier ideas in the verbal data, it means that the two design moves are linked.
- (2) When the semantic contents of two design moves are similar in structure, function or behavior domains, and no new design elements are generated, it means that the two design moves are linked.

- (3) When participants' ideas or actions are related to early visible body movements, sketches or written instructions, it means that the two design moves are linked.

The Cohen's Kappa coefficient was used to check the consistency of the two coders' coding results.

3.3. Linkography Production Process

Before producing the linkograph, the unstructured verbal data were first converted into structured data according to the coding results. According to the link relationship between design moves [18,26,30] and referring to the transformation method of El-Khouly and Penn [36], each design move was encoded. For any design move i , when it was linked with other design moves, it was encoded by 1; otherwise, it was encoded by 0. Therefore, the linkograph can be transcribed into a link matrix with the following expression:

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

where n is the total number of design moves. l_{ij} represents the link relationship between design moves i and j , if the two design moves are linked, its value is 1; otherwise, its value is 0. When $j = i$, it means the design move itself and will be set to zero. After coding, each design move can be represented by a link vector with length n . The combination of link vectors of all design moves is the complete link matrix $L_{(n \times n)}$. This step is the basis for realizing the subsequent visualization of the linkograph and further quantitative calculation.

The linkograph is formed by connecting all design moves with link relationships directly, as shown in Figure 1. The link relationship can be divided into two types: forelink and backlink. Forelink shows the design move related to the subsequent design moves and indicates the contribution to the new move to occur. Backlink shows the move related to the move that already happened and records the path that led to the current design move [28]. A chunk is a triangular cluster of links in the linkograph, which indicates that a certain number of continuous design moves have high connectivity and reflects the thinking period or the verification of subproblems [18,29].

Critical Moves (CMs) are design moves that are rich in links and represent influential design actions produced by team members in the process of co-design. The threshold of CMs varies according to different design tasks, and the number shall generally not exceed 10–12% of the total number of design moves [18]. According to different link types, CMs can be divided into Critical Forelink Moves (CMs>), Critical Backlink Moves (<CMs), and Two-Way Critical Moves (<CMs>) [18,37,38].

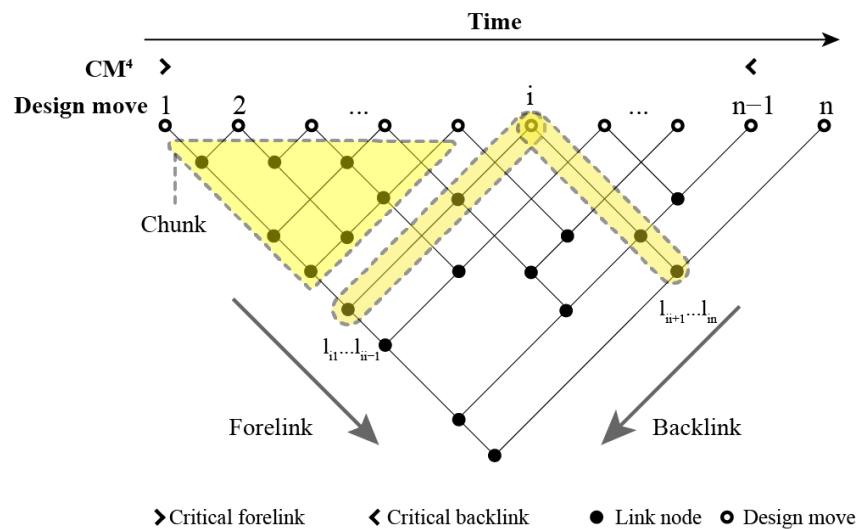


Figure 1. The linkograph production process and its common structures.

A CM> contains a large number of forelinks, which indicates that this design move has inspired many future design moves, A <CM contains a lot of backlinks, indicating that the design move draws on or integrates many previous design moves, showing the convergence of thinking. A <CMs> contains many forelinks and backlinks at the same time, indicating that the designer plans the subsequent design steps while ensuring the continuity of the previous design moves [18].

3.4. Entropy Measures of the Linkograph

The production of linkography realizes the transformation from unstructured verbal data to structured data and the visual display of cognitive processes. The entropy of the linkograph was proposed by Kan et al. [39] based on Shannon's information theory [40] to quantitatively describe the creative thinking process of designers. The calculation formula of Shannon entropy (H) is as follows:

$$H = -\sum_{i=1}^n p_i \log(p_i) \quad (2)$$

where, p_i refers to the probability that the system is in i state. The selection of the base depends on the unit used to measure the information. When the base number is 2, the unit of information is a binary number (bit).

The calculation formula of entropy (H) of each design move in the linkograph is:

$$H = -p(ON)\log_2(p(ON)) - p(OFF)\log_2(p(OFF)) \quad (3)$$

where, $p(ON)$ is the probability that there is a link relationship in the linkograph, and $p(OFF)$ is the probability that no link relationship is formed, $p(ON) + p(OFF) = 1$.

The design moves in the linkograph are $1, 2, \dots, N$, and the maximum number of links that can be formed is:

$$N = \frac{n \cdot (n-1)}{2} \quad (4)$$

$N(ON)$ represents the number of design moves that form a link relationship, and $N(OFF)$ represents the number of design moves that do not form a link relationship in the linkography. Then,

$$p(ON) = \frac{N(ON)}{N} \quad (5)$$

$$p(OFF) = \frac{N(OFF)}{N} \quad (6)$$

Entropy can also be distinguished into two types: forelink entropy and backlink entropy. The forelink entropy measures the opportunity for the generation or launch of new ideas, and the backlink entropy measures the opportunity corresponding to the current design moves and the previous design activities [30]. In the present study, both the forelink entropy and backlink entropy of each design move in the linkography were calculated and analyzed according to the above formulas.

3.5. Protocol Data Segmentation and Encoding

According to the segmentation and coding scheme described in Section 3.2, the design activities and protocol data of each participant were mapped to the corresponding design issues in the situated FBS model shown in Figure 1, and the co-design processes of each group of participants were mapped to the situated FBS co-design process shown in Table 2.

Table 3 shows the coding results when a group of designers and users co-design and complete the experimental task. The Kappa coefficient is 0.73 ($\eta = 0.73, p < 0.05$), which indicated that the two coders have high consistency and confirms the reliability of the coding results. The co-design processes of this group of participants were divided into 240 design moves. The link node column listed the previous design moves linked to the current design move.

Table 3. The coding results of the protocol data.

Time	Design Move	Utterance	Role	Situated FBS Co-Design Code	Link Node
0:01:50	1	I think, first of all, the purification effect of it (air purifier) needs to be very good.	Target User	FR^x	—
	2	Well, you want the air purifier to have a high purification effect.	Designer 1	F^i	1
...	
0:07:50	77	In terms of the use environment, I hope the function and appearance can adapt to the environment.	Target User	S^x	50, 51, 52, 64
...	
0:14:50	117	Movable, you mean that when cleaning this room, it (air purifier) cannot move, but after cleaning this room, it can move to another room according to the planned route, right?	Designer 2	Be^e	14, 27, 28, 34, 59, 60
...	
0:19:50	143	By the way, you just said that there are three filter modes, which means I should choose each filter. Is there any difference between each filter?	Target User	S^i	72, 75
...	
0:34:50	238	There are many tall and thin ones. However, if it is higher, it may have higher requirements for its bottom area, otherwise, it may appear unstable.	Designer 1	BS^i	161, 162, 167, 168, 235, 237
	239	One of the key points of the air purifier is stability. In this solution, the bottom area of it will change, and the whole may be more stable.	Designer 1	BS^x	163, 165, 166, 235, 237, 238
	240	Well done, I think it's very good and I choose this solution.	Target User	BS^i	238, 239

$FR^x F^i S^x Be^e S^i BS^i BS^x BS^i$ After completing the segmentation and encoding of protocol data, according to formula (1), the link relationships of each design move in Table 3 can be transformed into the following 240×240 matrix $L(240 \times 240)$:

$$L_{(240 \times 240)} = \begin{bmatrix} 0 & 1 & 1 & 1 & \cdots & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & \cdots & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & \cdots & 0 & 1 & 1 & 0 \end{bmatrix} \quad (7)$$

Then, the link matrix was imported into MATLAB to generate the linkograph as shown in Figure 2. This operation realized the visualization of co-design processes between users and designers.

4. Results and Discussions

First, the overall co-design processes and cognitive activities of collaborators were analyzed based on the structures of the linkograph. On this foundation, the CMs, the entropy of each design move and the cumulative entropy of each collaborator were analyzed, and the details of the co-design process were explored. Then, the analysis of protocol data encoded based on the situated FBS co-design model was conducted to make further efforts to explore the relationship between interaction activities among collaborators and co-design processes.

4.1. Analysis of the Linkograph Structure

Figure 2 shows the structures, the distribution of chunks and CMs of the linkograph. By examining these structures of the linkograph, the reasoning and interaction processes during the co-design could be told.

Chunks The linkograph shown in Figure 3 contains a series of separate or overlapping chunks. Chunks were considered to be related to a more efficient creative thinking process [18], and the interconnected design moves in chunks showed the designer's in-depth examination of the relevant elements of the design idea, indicating that designers paid almost all their attention to the current design idea. By analyzing the chunks, the collaborators completed the design task by solving subproblems step by step in the process of co-design.

For instance, the purification effect was discussed in design moves 8–15, the function of removing droplets and sterilization in the air was proposed in design moves 14–19 and the expected behavior of self-planning mobile route was raised in design moves 19–26, etc., so as to gradually conceive of the complete design solution. The overlaps between chunks showed that when collaborators were solving the next subproblem, they were also considering the solutions of the previous subproblem at the same time.

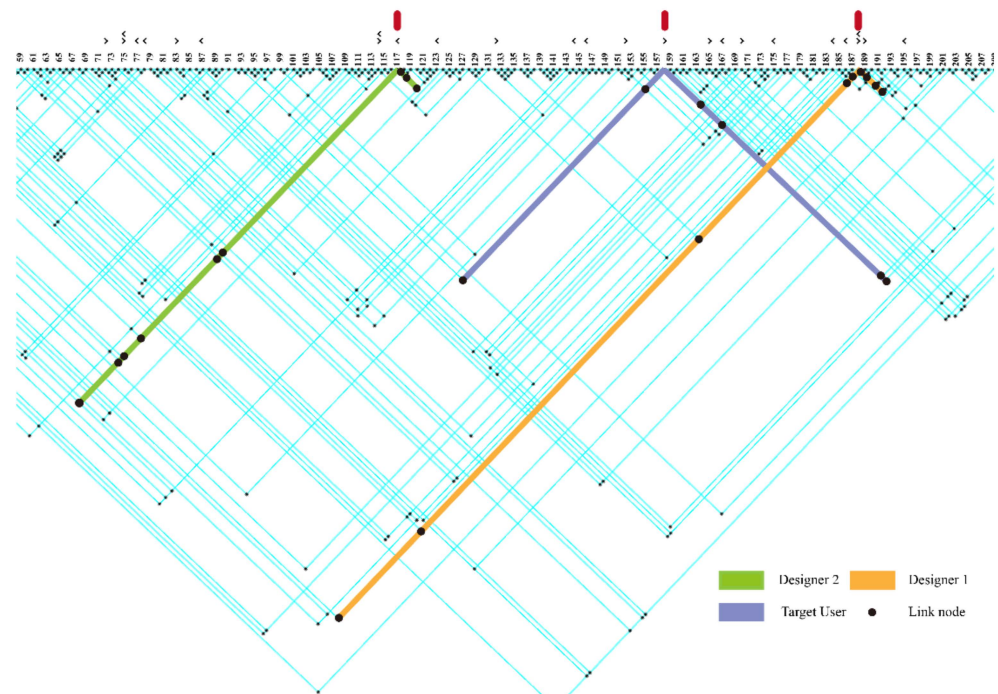


Figure 3. Link nodes included in <117, 158> and <188>.

CMs CMs represent a high degree of interconnection between a series of design moves and are of great significance. CMs> and <CMs were, respectively, regarded as the indicators of divergent and convergent thinking. Consequently, the design thinking patterns of users and designers in co-design processes can be quantified through the analysis on CMs>.

<CMs and <CMs>. The present study selected 4 link nodes as the threshold of CMs. As can be seen from the linkograph shown in Figure 3, CMs contained not only a large number of link nodes in the dominant direction but also some link nodes in the opposite direction. Take <117 as an example, it included 6 backlinks and 3 forelinks at the same time.

Referring to the utterance, Designer 2 made a preliminary plan for the air purifier's moving route on the basis of confirming its movable function discussed above. Another example, 158> included four forelinks and two backlinks at the same time. The Target User first decided on whether it was necessary to display harmful gases on the screen, and then put forward the expectation that the air purifier could have the function of self-purification of air, and <188> included four forelinks and two backlinks at the same time.

Based on determining to retain the lightweight and movable characteristics of the air purifier, participant Designer 1 proposed that the air purifier can start the corresponding purification mode according to the air detection results when moving to each room. The above results revealed that when generating new ideas and promoting the co-design processes, the collaborators still retained some attention and inheritance to the previous design activities to ensure the continuity of the design process. The design collaborators also paid some attention to planning future design activities when they verified, analyzed or reflected on previous design activities to ensure the effectiveness of design processes.

Figure 4 recorded the ratios of various CMs generated by each participant during the co-design process. The ratio of CMs> to <CMs of the Target User were significantly higher than that of the other two participants. The Target User participated in the co-design process and expressed his/her requirements as comprehensively as possible and was not limited by any design constraint. Therefore, the Target User showed the most active divergent thinking among all participants.

While the differences between CMs> and <CMs of Designer 1 and Designer 2 were relatively smaller, which indicated that they conducted more balanced divergent and convergent thinking during the co-design process. Throughout the whole co-design process, the total number of CMs> produced by collaborators was slightly higher than that of <CMs (the ratio of CMs> to < <CMs was 30:20). This result is consistent with the findings of Goldschmidt [37] regarding effective creative thinking processes during conceptual design, designers' divergent thinking and convergent thinking exist at the same time, and divergent thinking is a little more active.

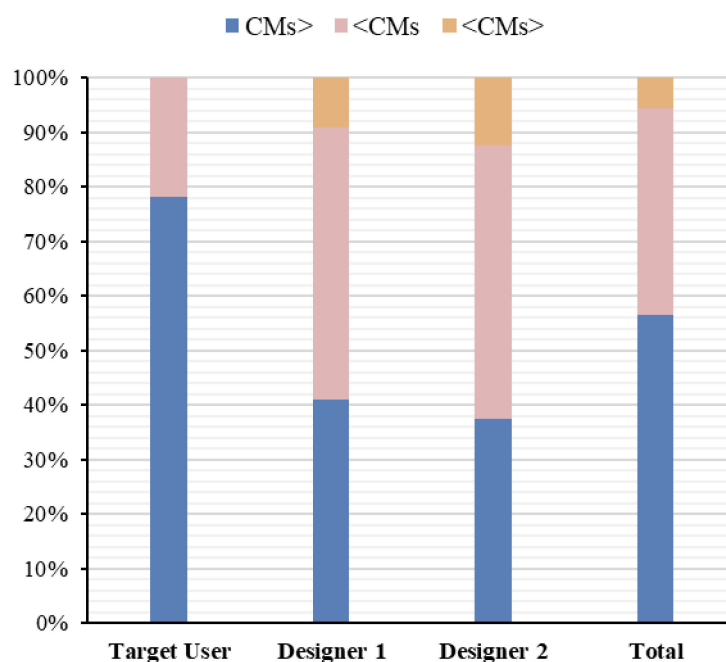


Figure 4. The ratios of various CMs generated by each collaborator during the co-design process.

4.2. Entropy of the Linkograph

Entropy measures the probability of occurrence. Forelink entropy measures the probability of new ideas, and backlink entropy measures the response of current design move to previous ideas [30]. The forelink and backlink entropies of each design move in the co-design process were calculated by Formula (4), and the results were shown in Figure 5. From the figure, it can be seen that the entropy of design moves fluctuated continuously as the design process progressed. Figure 5a showed the fluctuation of forelink entropy of each design move.

The peak of forelink entropy appeared at the very early stage of co-design and then decreased gradually. This indicated that the generation of new ideas was more active at the beginning of design, and the probability of the generation of new ideas decreased gradually as the design process progressed. This result was consistent with the study of Blazhenkova and Kozhevnikov [41]. Combined with the intensive long forelinks that appeared at the early stage of design in the linkograph shown in Figure 2, it can be concluded that the new ideas generated in this period largely inspired the subsequent design processes.

The higher the backlink entropy, the higher the response of the current design move to previous design activities. Figure 5b showed the backlink entropy changes of each design move in the co-design process. It showed relatively stable fluctuations at the early stage and reached the peak at the end of the co-design process, indicating that as the design process advanced, the probability of correlation between the design moves and the design ideas generated at the early stage was increasing.

Lee et al. [42] held the idea that the high backlink entropy was related to active evaluation activities. According to the backlink distributions in the linkograph shown in Figure 2, it showed that in the early and middle stages of the co-design processes, while maintaining the continuity of the design proceeding, the collaborators also conducted phased evaluation and summary of the subproblems. At the end of the co-design process, collaborators made overall summaries of the previous design activities, which were reflected in the peaks of backlink entropy and the intensive long backlinks at this stage.

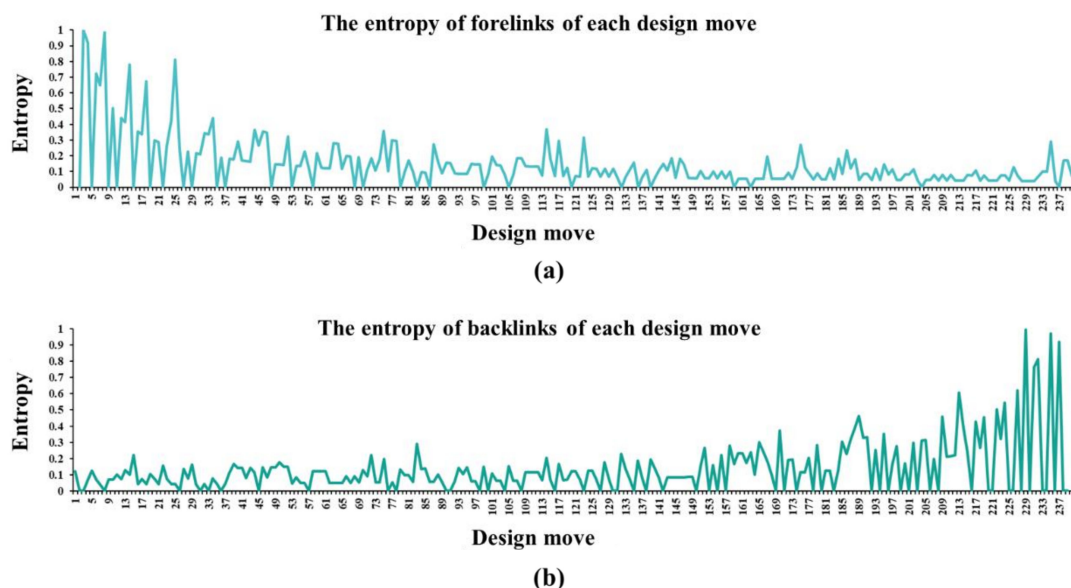


Figure 5. (a) The entropy of forelinks of each design move (b) The entropy of backlinks of each design move.

The cumulative entropies of forelinks and backlinks of each collaborator were shown in Figure 6. Polynomial fittings (as shown by the dotted line in Figure 7) were used to further reflect the entropy variation tendency of forelinks and backlinks of each participant. Among them, at the beginning and end of the design stages, the forelink entropies of

Designer 1 increased the fastest. The backlink entropies of Target User maintained a relatively uniform growth trend throughout the co-design process. At the end of the design stage, the backlink entropies of Designer 1 showed a rapid growth trend.

At the middle stage of design, the forelink and backlink entropies of Target User and Designer 2 maintained uniform growth, and the growth trend of Target User was faster, while the forelink and backlink entropies of Designer 1 has no growth trend. Kumar et al. [43] found that the high value of cumulative forelink and backlink entropies meant that design participants generated a great number of new ideas and later verified and reconstructed these ideas. In the present experiment, a similar situation was observed. Take Designer 1 for example, he/she generated a lot of new ideas at the early stage, then developed these ideas, and finally integrated the complete design solutions to the Target User.

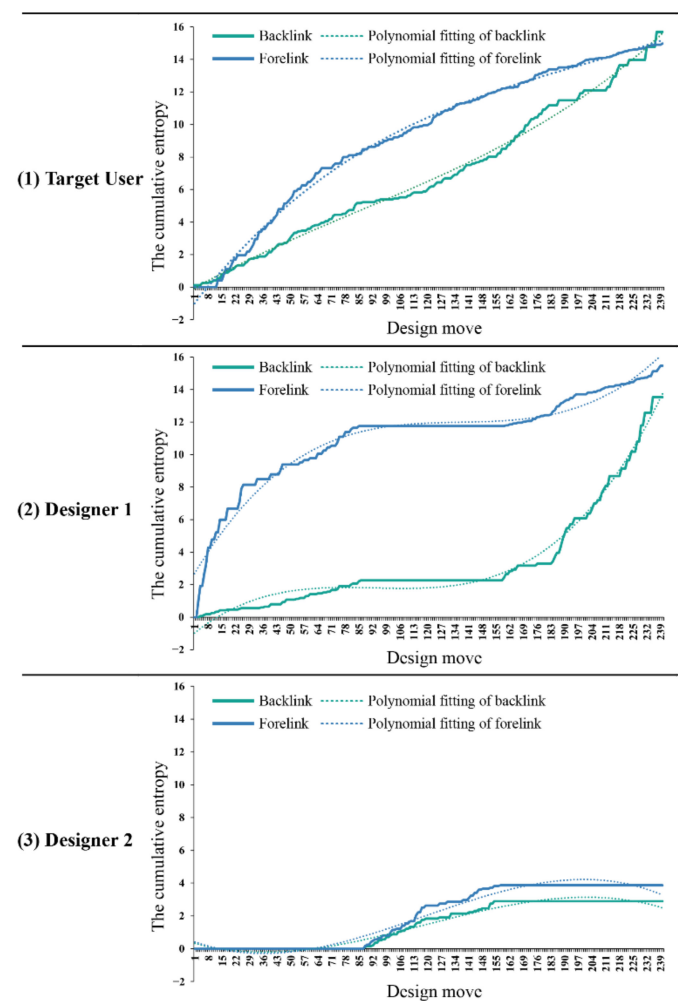


Figure 6. The cumulative entropies of forelinks and backlinks of each collaborator.

4.3. Situated FBS Co-Design Process

By analyzing the interaction patterns between collaborators in the process of co-design, their roles at each stage can be qualitatively explored. Six interaction patterns existed in co-design, namely U-U, U-D1, U-D2, D1-D1, D1-D2, and D2-D2 (U-Target User, D1-Designer 1, D2-Designer 2). Among them, the interactions between two collaborators are regarded as co-design processes, while the interactions of transition of collaborator him/herself are regarded as the individual design processes. Correspondence Analysis (CA) can reduce the dimension of categorical data and describe the correlation between categorical data in a two-dimensional graph.

The distribution of different categorical variables in the two-dimensional graph and the distance between variables can show the correlation among them. To highlight the relative differences of each collaborator's roles in the present study, CA was first carried out to qualitatively explore the relationships between interaction patterns among collaborators and the situated FBS co-design processes.

The results are shown in Figure 7. As can be seen from the figure, interaction patterns involving users (U-D1, U-D2 and U-U) and interaction processes involving only designers (D1-D1, D1-D2 and D2-D2) were distributed on both sides of Dimension 1. In the processes of Formulation, Analysis and Evaluation, the interaction patterns between the user and designers were relatively dominant. While, in the processes of Synthesis Process, Reformulation 2 and Reformulation 3, the interaction patterns among designers were relatively dominant.

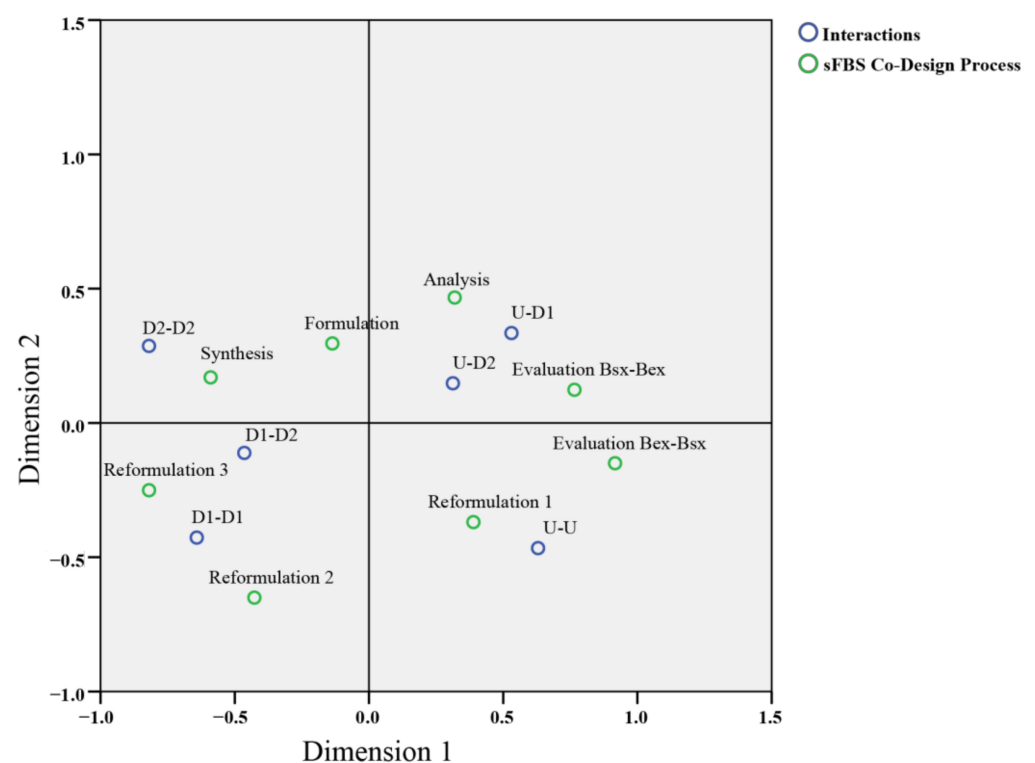


Figure 7. The results of the correspondence analysis between the situated FBS co-design processes and interaction patterns among U-Target User, D1-Designer 1 and D2-Designer 2.

The results of the correspondence analysis indicated that there were differences in the interaction patterns for different co-design processes. To further explore the roles of collaborators in the co-design process, all interaction activities were visually represented using the situated FBS co-design model. Figure 8 shows the representation of the situated FBS co-design processes between users and designers (a) and designers (b). As seen from the figure, the co-design with user participation can be summarized as follows:

(I) The target user involved in the conceptual design process expressed his/her requirements to the designers and explored the problem space to conceive the design scheme jointly with the designers (Formulation Process).

(II) Then, the designers discussed and communicated with each other to synthesize design solutions (Synthesis Process), and this realized the transformation from the problem space to the solution space.

(III) The user and designers analyzed the design solutions (Analysis Process).

(IV) They collaboratively explored the solution space and made evaluations of the design solutions and newly introduced requirements and constraints [44] (Evaluation

Process), thus, promoting the iteration and coevolution of the solution space and the problem space.

(V) While interacting with designers, the user expressed the evaluation of the design solution structure (Reformulation 1), and this process took place in the solution space.

(VI, VII) Then, the designers collaboratively reconstructed the design intention (Reformulation 2 and Reformulation 3) according to the user’s evaluation results, and this led to the iteration from the solution space to the problem space and the coevolution of the two spaces.

The iteration and evolution of the problem space and the solution space are the characteristics of conceptual design [27]. In the processes of co-design, the collaborators have different roles, experiences and backgrounds; therefore, they affect the iteration and coevolution of the problem space and the solution space in different ways and to different degrees.

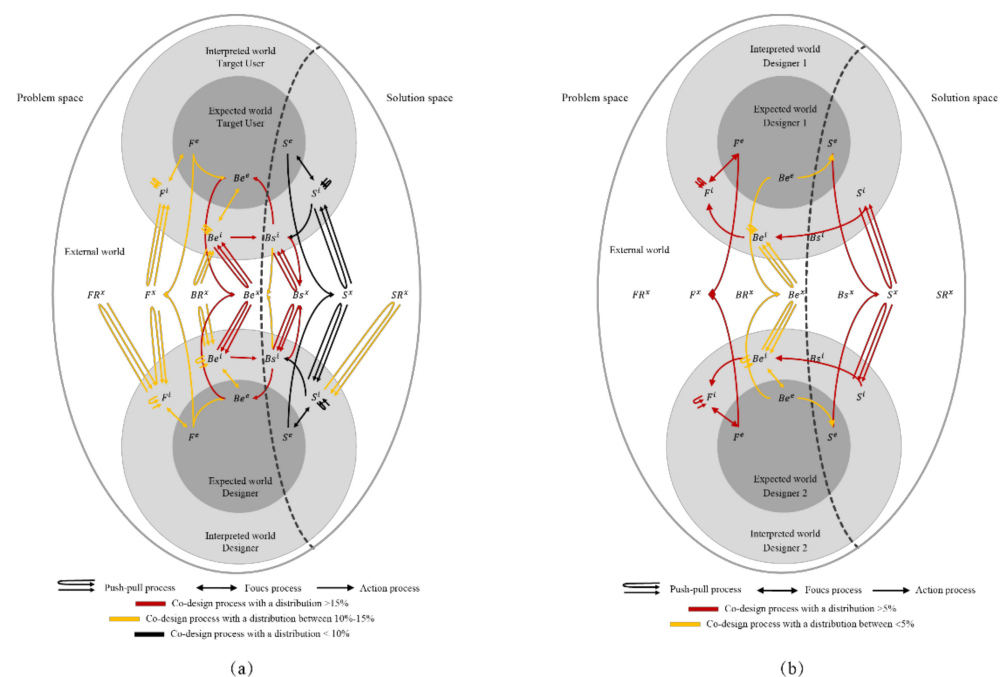


Figure 8. (a) Representation of the situated FBS co-design processes between users and designers. (b) Representation of the situated FBS co-design processes between designers.

5. General Discussions

The present study adopted the combination method of linkography and the situated FBS co-design model to explore the design cognitive activities at the team level from the aspects of co-design processes and design contents. The analysis results on the linkograph structures showed that the co-design process among users and designers was complex and nonlinear, and each design move of design activities was two-way: participants were also verifying the previous work while advancing the design process, and they were also conceiving the next design activity while focusing on the current work. These showed the complex nature of conceptual design from the team level [45] and showed that designers reasoned systematically about successions of subproblems or the whole issues [18].

In addition, divergent and convergent thinking, which were essential for effective creative thinking and are seen as occurring in cyclic phases within the design process [37,46], were observed at both the individual and team levels throughout the co-design process. This confirmed the effective creative thinking process of collaborators during the co-design experiment. Combined with the dynamic changes in forelink and backlink entropies, we can see the dynamic processes of the generation and synthesis of creative solutions throughout the co-design process.

During the divergent phase of co-design, the collaborators negotiated in a manner that allowed for differences and disputes, aiming at exploring a wider range of creative design possibilities for the design team. This was consistent with the findings of Björgvinsson et al. [47]. While, during the convergent phase, the collaborators evaluated and validated the diverse solutions of subproblems or problems and finally achieved a degree of conformity to form consensus design solutions. Our findings corroborated the claim of Leonard and Sensiper [48] that the generation of creative ideas in innovation groups was the transformation of knowledge, information and resources from divergence to convergence of all group members.

That users actively participated in the design and explored design problems and conceived solutions together with the designers was a key feature of the user participation innovation [49,50]. Although users and designers have common characteristics in the reasoning and processing of design information, their concerns regarding design problems and solutions were different.

Design strategies can therefore be divided into problem-driven and solution-driven [51]. The users' design behaviors are mainly to express requirements, evaluations and decisions for the purpose to design satisfactory products, showing the problem-driven design strategy. While the designers adopt the solution-driven design strategy, their behaviors are mainly to excavate the user's requirements and needs for the aim of generating solutions that meet the user's requirements. Through the analysis of co-design cases in real life, Pedersen [52] found that collaborators with different roles planned, negotiated and reconstructed repeatedly in the process of co-design.

Collaborators undertook their division of roles, through interactions and negotiations, they also influenced the design team's reconstruction of design problems and design solutions. This was also found in the present study. Goldschmidt [17,18,28] utilized linkography to emphasize the similarity between individual design and co-design. During the individual design processes, designers implemented a broader range of design activities, while in design teams, they tended to take on specific roles related to their expertise. In the present study, we found that, in addition to experience, background and personal goals also influenced the designers' design strategies and behaviors.

Our results revealed some interesting insights into the design cognition activities at the team level. However, several limitations should be considered. First, the protocol data was segmented and coded manually in the present study, which was very tedious work that took a great deal of time for coders to learn the coding scheme and finish their work, and greatly reduced the efficiency of research. This led directly to the second limitation that only one design session was conducted in our study.

It should be acknowledged that this is a preliminary and limited study based on only one design team. Our near-future work will focus on the development of automated segmenting and coding methods for protocol data, which will improve the efficiency of protocol data processing to a large extent. Furthermore, it will be helpful for us to conduct more in-depth and detailed research on cognitive patterns during the co-design processes with user participation. Finally, this research mainly focused on the exploration of co-design processes; therefore, the novelty of the design solutions generated was not considered—future research can make profound studies considering this aspect.

6. Conclusions

With the deep participation of users in product design and development, design activities gradually evolve into collaborative innovations between users and designers. The present study explored the team cognition activities of co-design processes based on protocol analysis and the combination methods of linkography and the situated FBS co-design model were utilized to segment and code the unstructured protocol data and visually represent the whole co-design process. The qualitative and quantitative results showed that, as collaborators in an innovation team, designers and users adopted different design strategies to promote the progress of co-design.

Designers played a leading role in guiding users to express their requirements and needs accurately and thoroughly, thereby, steering the co-design process. From the visual display in the linkograph, we found that, at the team level, the collaborators showed a systematic thinking mode, and each design move was two-way. This cognitive strategy of the innovation team ensured the continuity and effectiveness of the co-design process. These results provided new insights for studies on team cognition activities and the dynamic co-design processes. In addition, the utilization of the situated FBS co-design model in the present study made the encoding results universal, which is helpful for the comparison and analysis of other related studies.

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