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Creation and Characterization of Design Spaces

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Abstract: Designers advance in the design processes by creating and expanding the design space where the solution they develop unfolds. This process requires the co-evolution of the problem and the solution spaces through design state changes. In this paper, we provide a methodology to capture how designers create, structure and expand their design space across time. Design verbalizations from a team of three professional engineers are coded into design elements from the Function-Behavior-Structure ontology to identify the characteristics of design state changes. Three types of changes can occur: a change within the problem space, a change within the solution space or a change between the problem and the solution spaces or inversely. The paper explores how to represent such changes by generating a network of design concepts. By tracking the evolution of the design space over time, we represent how the design space expands as the design activity progresses.

Keywords: design space; protocol analysis; networks; design concepts

1. Introduction

Designing is a cognitive activity that relies on multiple reasoning processes like problem solving, evaluation and decision-making (Dorst, 2011; Simon, 1969; Visser, 2009). Designing is also a situated activity (Clancey, 1997) which implies that the outcome of the design process is context-based, in relation to the designer and the design situation (Bucciarelli, 2001; Gero & Kannengiesser, 2004; Schön, 1983). Design problems are not well defined and structured (Rittel & Webber, 1973; Simon, 1973). Therefore, designers advance in the design process by structuring the design space based on the design situation and their expertise.

The design space is a representation of the ideas and concepts that designers develop over time to propose a design solution that materializes into a design artifact (i.e., a product, a building, a service). The design space can be characterized through two subspaces encompassing the design problem space and the design solution space (Goel & Pirolli, 1992; Jiang et al., 2014). Design space expansion is common along the design activity as new concepts emerge (Gero & Kan, 2016). Changes in the design space relate to design processes designers engage in to structure the problem space while developing potential solutions (Dorst & Cross, 2001; Maher & Poon, 1996). Understanding the structure and evolution of the design space and its expansion is relevant for design thinking research. Indeed, structuring the design space as a network of concepts offers metrics to quantify and qualify concepts within the design space. Creativity is claimed to be correlated with the novelty, quantity, quality and unexpectedness of the ideas present in the design space (Gero & Kan, 2016; Shah et al., 2003), therefore its representation as a network of ideas provides a way to assess ideas within it.

In this paper, we characterize how the design space is structured through design processes that connect unique concepts formulated during a design session. The Function-Behavior-Structure (FBS) ontology serves as a framework (Gero, 1990) to analyze design protocols and identify the design processes that structure the design space of a team of three designers. This exploratory work offers a methodology to characterize the design space and provides a novel way to measure and represent it using Natural Language Processing and network science. The design session analyzed is used as an example of how the method works. It illustrates the type of result one can get from applying this approach.

Design teams adopt a wide array of methodology to track and assess their process and performance (Škec et al., 2017). With the method presented in this paper, teams could visualize in near to real time, the design space they explored. That representation could serve as a design tool to reduce cognitive load in recalling past ideas. Moreover, visualizing concepts already mentioned could lead to new ideas by combining existing elements from the design space.

In the following section, we present some salient features of design thinking and the design space. Then, in Section 3 we describe how the method serves to measure and represent the design space. Section 4 provides an illustrative example of the type of information we can extract from a design protocol while the remaining sections discuss the implications of the work presented, its limitations and future work.

2. Characterizing the design space using the FBS framework

The design space is commonly described by two subspaces, the design problem space and the design solution space. The problem space is defined by design problems states or situations as well as the processes or operators allowing a change of states (Goel & Pirolli, 1992). Designing was primarily understood as a linear process of decomposition and analysis of the problem space followed by a synthesis of sub solutions into an overall one (Alexander, 1964; Goel & Pirolli, 1992). But, the unstructuredness (Rittel & Webber, 1973; Simon, 1973) and situatedness of design problems (Gero, 1990; Schön, 1983) require the co-evolution of the design problem and solution spaces (Dorst & Cross, 2001; Maher & Poon, 1996). Early solutions or primary generators (Darke, 1979) help designers structure design problems by testing early solutions (Lawson, 1993, 2006).

Empirical studies show how designers navigate the design problem and solution spaces while designing (Jiang et al., 2014; Milovanovic & Gero, 2018). The FBS ontology provides a suitable framework to identify design processes structuring the design problem and solution spaces, although other frameworks could be used. It accounts for a set of six design issues as well as transitions between issues that define specific design processes (Gero, 1990; Gero & Kannengiesser, 2004) as illustrated in Figure 1. The function (F) of a designed artifact is defined as its intended purpose or teleology; the behavior of that artifact is either derived (Bs) or expected (Be) from the structure, where structure (S) represents the components of an object and their relationships. The requirements (R) are set by the clients and are formalized through a design brief while the descriptions (D) are externalized representations of the structures (S) defining the proposed solution.

Requirements (R), Functions (F) and expected Behavior (Be) are situated within the problem space while Structures (S), Behavior from structures (Bs) and Descriptions (D) are situated within the solution space. Therefore, design processes describe three types of processes within the design space: a change of design state within the problem space (purple arrows in Figure 1), a change of design state within the solution space (blue arrows in Figure 1) or a change of design state between the problem space and the solution space or inversely (yellow arrows in Figure 1). These three types of transitions account for processes identified in problem-solution co-evolution models (Dorst & Cross, 2001; Gero, et al., 2022; Maher & Poon, 1996). For instance, synthesis (process 2) and evaluation (process 4) are processes illustrating a transition from one subspace to the other. Analysis (process 3) on the other hand, is only situated within the solution space.

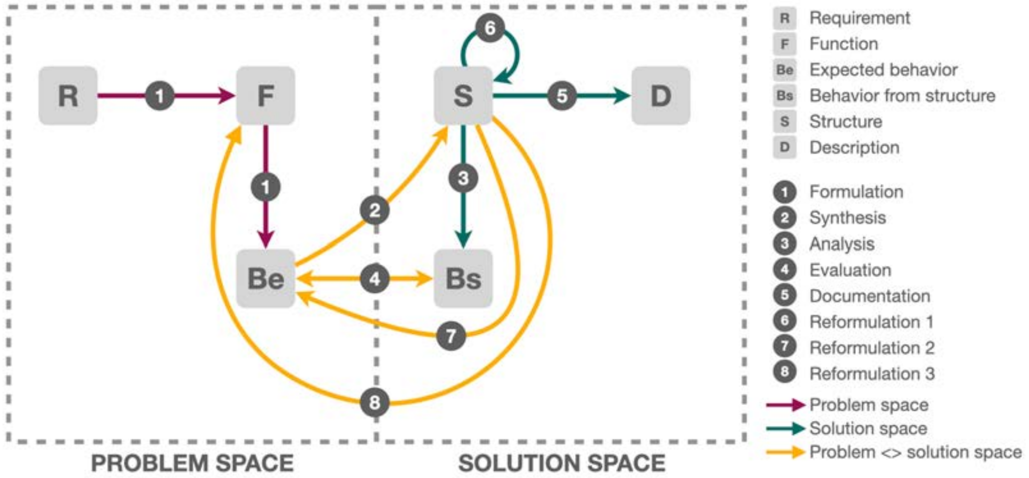


Figure 1 Representation of the Function Behavior Structure framework based on (Gero, 1990). Half of the FBS design issues are situated in the problem space while the others sit in the solution space. Design processes represent change of state from one design issue to another. Design processes either account for a change of state within the problem space (purple arrow), within the solution space (blue arrow) or between the problem space and the solution space (yellow arrow).

FBS elements are generic definition of ideas and concepts introduced along the design activity. The structure of the design space is characterized by first occurrences of ideas and their relationships. A concept is labelled as a first occurrence the first time it is introduced into the current design session. In this work, first occurrences are also FBS design issues (Gero & Kan, 2016). By representing first occurrences of ideas in a design session, we can visualize what is in the design space and the interactions that occur over time between the elements within the design space. In the following section, we will develop a methodology to create a visual representation of a design space as a network of concepts and its evolution across time.

3. Methodology

In this study, we exemplify our method by representing the design space of one of 19 teams of three professional engineers that were given a brief to design a next-generation personal assistant and entertainment systems for the year 2025. They were invited to focus on "what this system would be, how this system works and interacts with people, and what the personal assistant and entertainment system would provide to end users". Each team had 60 minutes to propose a concept description and sketches on a white board. The team members for each team were collocated and a research assistant stayed in the room as participants developed their design. The design session was video recorded to be analyzed. No incentives were given to participants. Prior analysis of this data set is found in (Milovanovic et al, 2021a, 2021b).

To visualize the design space, we used a network representation to highlight concepts as nodes and relationships between concepts as edges to account for the design space structure. The methodology consists of 1) defining the nodes of the design space network that are the first occurrences of design concepts and of 2) qualifying the relationship between design concepts with FBS design process. The protocol analysis methodology (Ericsson & Simon, 1984; Van Someren et al., 1994) was used with the FBS framework (see Figure 1) to code the verbal transcript from the design session and infer the nature of the connection between first occurrences of concepts.

3.1 Natural Language Processing to identify first occurrences of processes

We used an automated method to generate the first occurrence of concepts using Natural Language Processing in Python with the NLTK package. The transcript of the design session is first cleaned and tokenized. Words are stemmed based on the Porter Stemming Algorithm from the NLTK package to obtain the root of the concepts. Only the first occurrence of concepts is kept for the next steps of the analysis to structure the design space. First occurrences are a key element in the structure of the design space as they can set a conceptual frame for design solutions to develop. Using Natural Language Processing provides an automatic way to track the emergence of new concepts in a design session. For example, one of the first utterances from the design teams was "Is there any constraints on size and cost? We get to set that?". With the NLP script used, the concepts returned include "constraint", "size", "cost" and "set". Any later occurrences of these words were not kept for the rest of the analysis.

3.2 Using protocol analysis and FBS ontology to identify relation between concepts

The example used in this paper to present the methodology is taken from a larger study involving 57 professional engineers broken into 19 teams of three. Only one team I used in the study used here (Milovanovic, et al, 2021a, 2021b). The protocol collected in the study was segmented and coded with elements within the FBS ontology. Therefore, each of the first occurrence concept is associated to one single design issue. Each session from the whole dataset (19 sessions in total) was coded by two different trained coders. When a disagreement occurred, coders arbitrated each segment together, and relied on an external coder’s input if they could not reach an agreement. In total, three coders worked in pairs to code the data (19 one-hour long protocols). Agreement between coders was measured with Cohen's kappa. It reached 0.79 for the FBS design issue codes (before agreeing on final codes), which ensures the reliability of the data analyzed.

Earlier, we exemplified the process of extracting concepts from verbal utterances. The utterance “Is there any constraints on size and cost? We get to set that?” was defined as an expected Behavior (Be). Each concept from that utterance, namely “constraint”, “size”, “cost” and “set”, are then characterized as expected Behaviors (Be). The relationship between concepts is determined syntactically. For example, if a first occurrence concept is identified as structure (S) and is followed by an expected Behavior (Be), the concepts are connected by a link characterized as a Reformulation 2 process (see Figure 1). This type of process accounts for a design state transition from the solution space to the problem space. As an example, consider the following in one of the sessions, the utterance “If it's an assistant,” is identified as a structure (S) and the NLP script extracted the concept “assistant”. The next utterance is “you should be able to maybe make some phone calls with it, right?” which is identified as an expected Behavior (Be). The concepts from this utterance are “phone” and “call”. The script developed would account for a connection between those concepts and characterize it as a Reformulation 2 process.

3.3 Representing the design space as a structured network

The first steps of the analysis identify the elements that constitute a network: nodes are first occurrence concepts while edges are syntactic design processes illustrating a transition from one FBS design issue to another FBS design issue. In other words, for each segment of the design protocol, first occurrences of concepts are extracted and represented as nodes. Those nodes are connected to nodes representing concepts from the next segment in the design protocol. Using the Networkx and Holoviews package in Python, we can represent the design space network where nodes are unique concepts and edges are processes connecting concepts. The network representation chosen is based on a force directed graph (Fruchterman & Reingold, 1991). The concepts that are highly connected appear in the center of the network while concepts at the outskirt of the network usually connect to only one other concept. To provide a better readability of the graph, edges are bundled so that there are no edges crossing each other. We created an interface to select different design processes and visualize how each process structures the concepts within the design space for two time periods, the first half and second half of the design space (Figure 2). Visualizing different time periods allows for the analysis of the design space structure over time. In the example in Figure 2, two time periods are presented, the first half and the second half of the design session. The interface provides a way to identify the characteristics of the links between concepts. The links represent design processes like evaluation or synthesis. This features help visualize the relation between concepts based on the process engaged by designers when using those concepts.

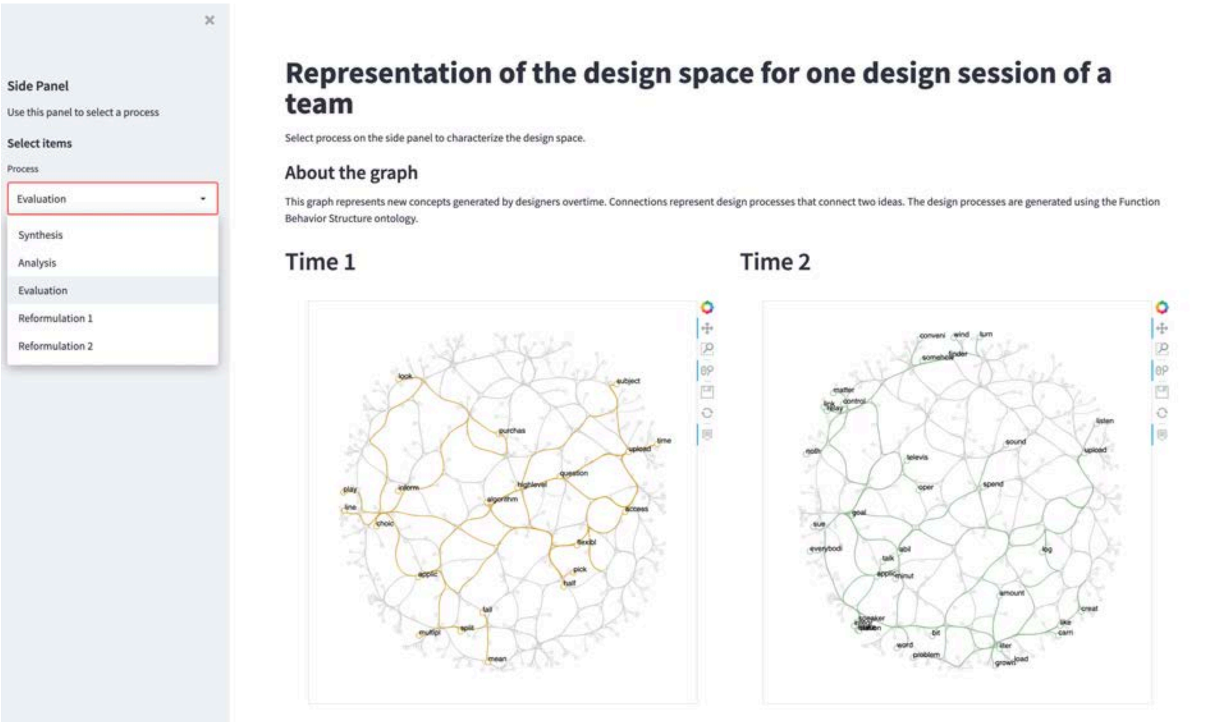


Figure 2. Interface to select the design processes to visualize as a characterization of the design space (see Python script in GitHub https://github.com/Julie-Milovanovic/design-space-map). The side panel serves to select the design process to represent on the two networks. Here, Evaluation is selected and represented on the network for the first half (left) and the second half (right) of the session. Colored edges and nodes represent the process selected and related concepts. The grey edges and nodes represent the entire design space.

4. Representing and analyzing the design space with networks

Using this methodology, we can generate a network of all the unique concepts that were formulated by the designers. In this particular session, the team generated 363 unique concepts connected through 1,466 links. The entire network for this session is illustrated in Figure 3 with bundled edges to help visualize the concepts. The network encompasses all the concepts that emerged during that design session. The structure of the design space is unique to this team.

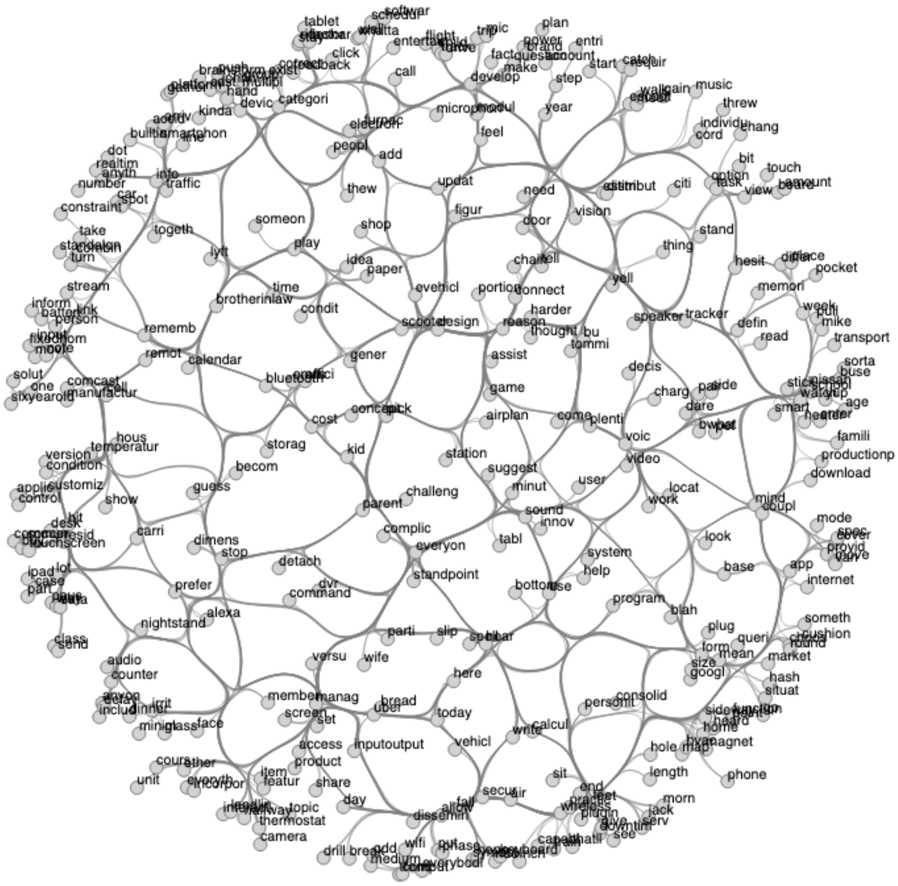
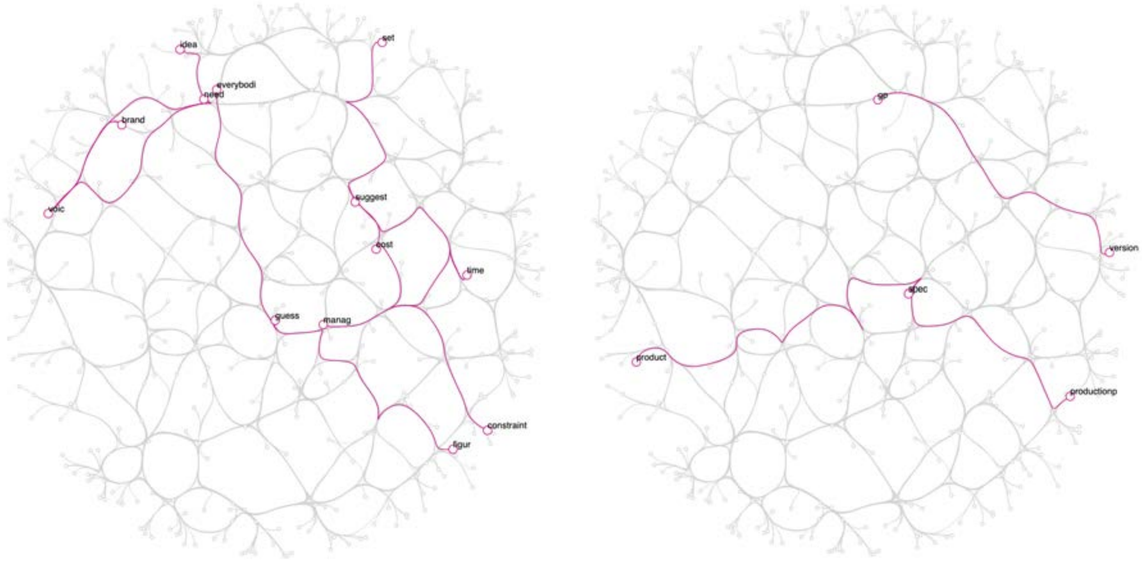


Figure 3. Representation of the structure of the design space for the entire session of the design team. Nodes represent first occurrences of unique concepts while edges represent syntactic connections between concepts.

In Section 2, we identified three types of structural links between concepts: a change of state within the problem space, a change of state within the solution space and a change of state between the problem and the solution spaces and inversely. Based on the FBS design processes, we are able to discriminate the type of changes illustrated in Figure 1.

In Figure 4, the change of state within the problem space are represented for one design session for the first (Figure 4(a)) and second half of the design session (Figure 4(b)). In this session, state changes in the problem space occur more frequently in the first half of the session than the second. In the first half, the problem space is structured by 13 concepts (e. g., “manage”, “cost”, “brand”) and 26 connections between those concepts. In the second half, only five concepts structure the problem space (e. g.., “production”, “version”). State changes in the problem space tend to decrease overtime.

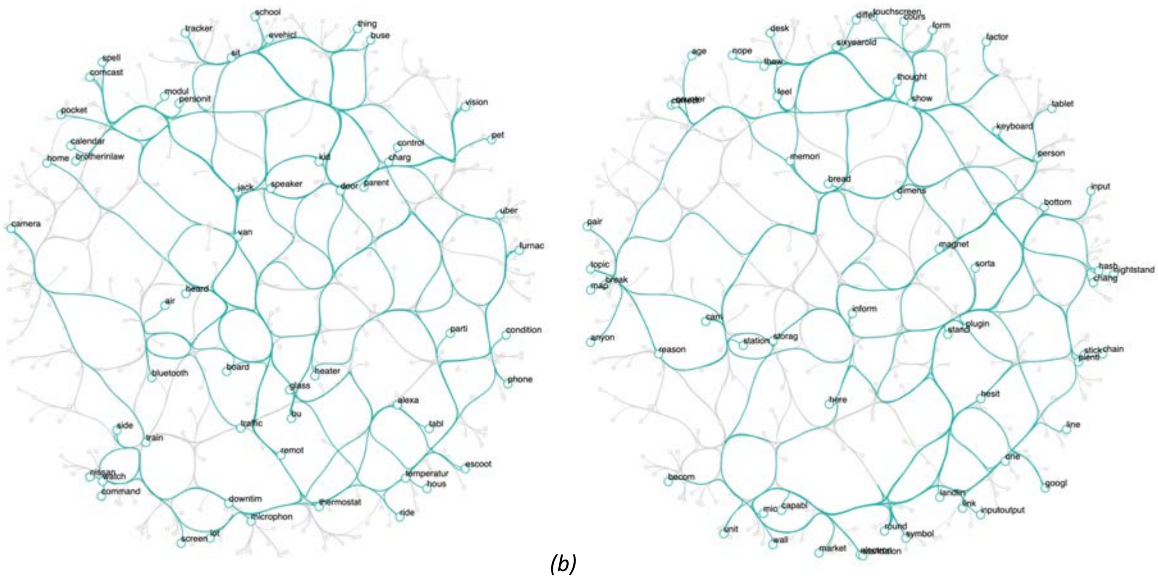


(a) *(b)*

Figure 4. Representation of the structure of the design space for processes situated in the problem space at two different periods of the design session, (a) first half and (b) second half. The grey edges and nodes represent the entire design space.

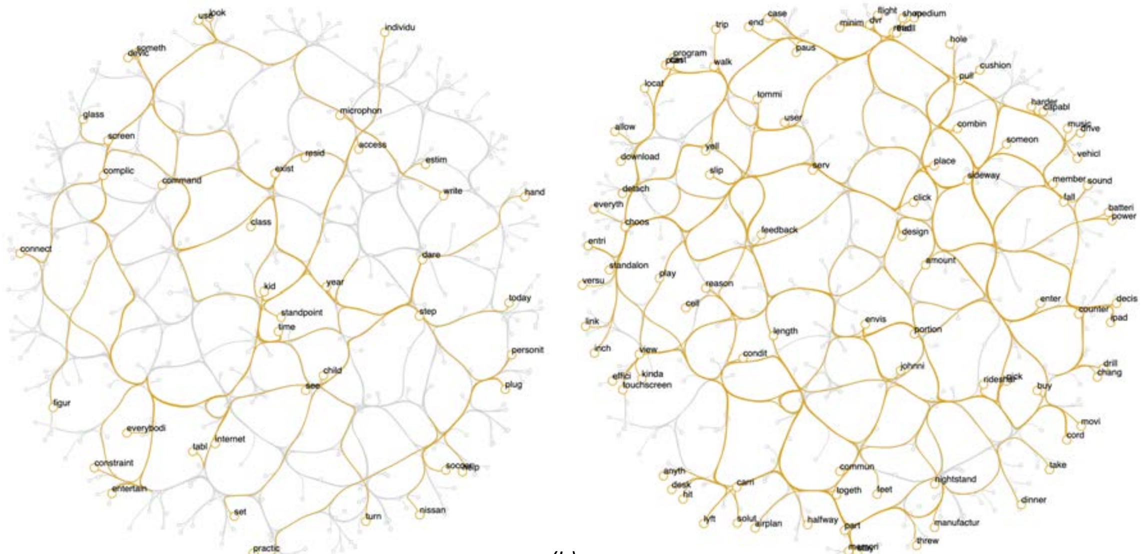
In Figure 5, we can see changes of state within the solution space. The number of concepts in each half is similar (55 in the first half and 61 in the second half) and the number of connections (edges) between concepts is 149 for both halves of the design session. Concepts in each half are unique as are their connections to other concepts. The number of changes of design state in the solution space remains the same over time for this session. The topics are different between for each half. They can be related to users like "kid" and "parent" in the first half, and "person" and "age" in the second half. Topics also encompass the products' attributes like "camera" and "microphone" in the first half and "keyboard" and "touchscreen" in the second half.

Some of the FBS design processes account for a state change between the problem and the solution space or inversely (Synthesis, Evaluation, Reformulation 1 and Reformulation 2). Those transitions are represented in Figure 6 for the first half (Figure 6(a)) and the second half of the session (Figure 6(b)). The number of state changes between the problem and the solution space increases over time for this session. The number of first occurrence concepts more than doubles between the first half of the session and the second half, going from 41 concepts in the first half to 94 in the second one. The number of connections also increases proportionally.



(a) *(b)*

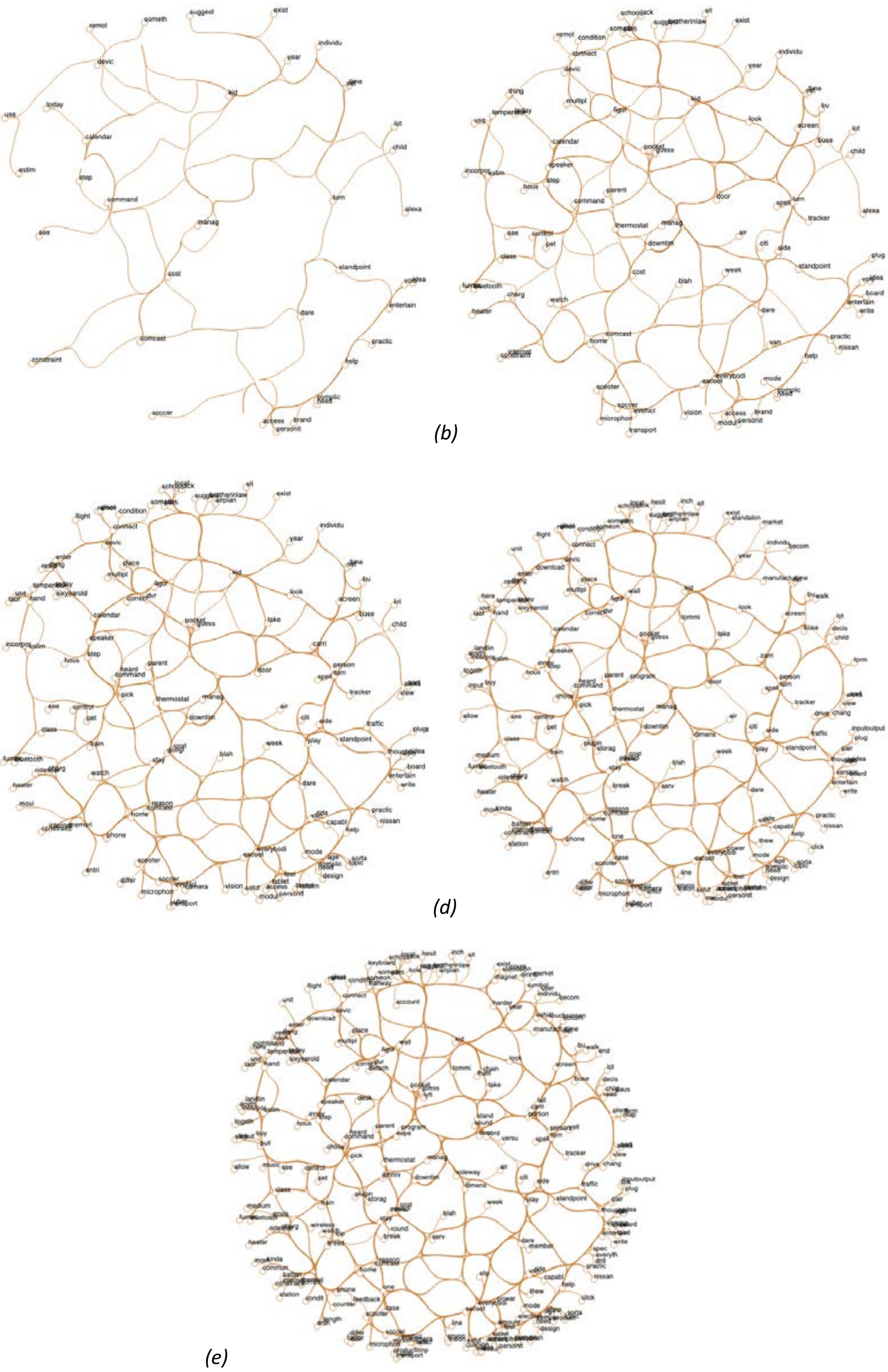
Figure 5. Representation of the structure of the design space for design processes situated in the solution space at two different periods of the design session, (a) first half and (b) second half. The grey edges and nodes represent the entire design space.



(a) *(b)*

Figure 6. Representation of the structure of the design space for processes connecting the problem and the solution space at two different periods of the design session, (a) first half and (b) second half. The grey edges and nodes represent the entire design space.

This approach provides the possibility to change the time granularity to represent the growth of the design space in more detail. In Figure 7, we can see how the design space expands over 5 time periods. The number of concepts per period tends to increase slightly over time from 38 in the first period to 68 in the last one.



(a) (b) (c) (d) (e)

Figure 7. Illustration of the expansion of the design space as the team progresses in their design activity. The design session was divided in 5 time periods: (a) time 1, (b) time 2, (c) time 3, (d) time 4 and (e) time 5. New concepts and edges for each time period relative to the previous ones appear in dark orange.

5. Discussion

In this paper, we presented a method to visualize the design space generated by a team of designers during a 60 minute long design session by representing unique concepts formulated and their relationships. The illustrative example shows the type of representation and metrics one can get from using this approach. The implications of the work presented in this paper are threefold: theoretical, methodological and practical.

The theoretical implication of this methodology relates to studying the design space. In the example presented, we reveal elements of team behavior by illustrating how the team navigates within the design space. This team tends to focus more on design state changes in the problem space at the beginning of the design session, which agrees with previous findings (Jiang et al., 2014). On the other end, their focus of transitions within the problem space remains the same across time, while the expectation was to observe an increase focus on the solution part of the design space. Interestingly, the transition of states between both subspaces (problem and solution) largely increases over time. This suggests that the co-evolution of the problem/solution space increases as the design activity progresses. Visualizing the design space as a network of concepts through nodes and edges brings information about the structure of the design space that can provide a new way to interpret designers' behaviors.

The methodological implication of the work is that with one representation through a network, we are able to capture quantitative and qualitative information about the structure and characterization of the design space. In prior work, we analyzed co-evolution processes in the design space through a quantitative metric (Jiang et al., 2014; Kan & Gero, 2017; Milovanovic & Gero, 2018). The Problem-Solution index used in those studies provided indications on the cognitive focus of designers (Jiang et al., 2014) and accounted for cyclical switch of focus between the problem and solution spaces over time (Milovanovic & Gero, 2018). In the method presented in this paper, the quantitative metric of the cognitive focus of designers is provided by network metrics (e.g., number of nodes and edges). Moreover, the identification of the concepts provides qualitative information about the specific elements in the design space that captured designers' focus. Network metrics like network density or centrality could provide further quantitative information about designers that is yet unexplored.

The tool presented can also have practical implications for designers. The network representation of the design space captures all the unique concepts and ideas that the designers generated in the design session. It provides feedback about the structure of the design space explored. It could act as a memory concept map created automatically after design meetings that could reduce cognitive load. Tools based on this approach could become design management tools to accompany designers or teams of designers in their process.

The design space graph could serve as a base network for a design collaboration with intelligent agents who could provide other concept stimuli that are not present in the design space. Expanding the design space through such collaboration could support the generation of creative ideas (Gero & Kan, 2016; Shah et al., 2003).

6. Limitations and future work

The method presented only offers a semi-automatic way to create a network of the design space. The coding of the design protocols requires manual coding which is time consuming. This step is necessary to determine the relationship between design concepts and identify in which subspace there is a change in design state. With further advances in Natural Language Processing, we might have access to automatic ways to encode verbal utterances into design elements. Automating the classification of concepts into design elements would improve the method presented here and could result in real-time feedback to designers.

A limitation of the method is related to the identification of concepts. The reliability of the script to identify relevant concepts is affected by the quality of the input data. In this case, the transcriptions were produced manually ensuring accuracy in the input data. However, the transcription of verbal utterances is time consuming. To increase efficiency, we plan to implement an automated transcription process for design discussions between designers and use it as an input for the extraction of unique concepts and ideas. In future work, we plan to test the robustness of automating the entire analysis process from verbal transcript to identifying unique concepts and assigning design elements to each concept.

In this study, we only scratched the surface regarding the type of metrics a graph provides. For instance, graph density provides information about how well nodes are connected to each other. Applied to the design space network, it would account for the connection between concepts. Using network metrics to measure and analyze the creation and characterization of design spaces brings new research questions. What does a change in network density over time mean in terms of design behavior? The relevance of pursuing research in that direction is to explore whether such metrics about the structure of the design space can reveal new knowledge about designers' navigation of the design space while designing.

The links identified between concepts are based on a syntactic approach. Other methods like linkography (Goldschmidt, 2014, 1990) account for semantic connections between concepts. Using linkography, we can capture designers parallel thinking processes (Lawson, 1993). Indeed, analyzing design processes in a syntactic way is a simplification of idea generation processes. While designing, ideas are evoked and then sometimes disregarded for a while but then resurface in a later design discussion. The current method fails to capture such process. In future work, we will explore automatic ways to generate semantic connections between concepts using semantic distance metrics. Doing so could provide a more accurate representation of how the design space is structured over time. The aim is to keep track of designers' use of concepts over time, that could correspond to grounding or fixation processes.

7. Conclusion

In this paper, we presented a method to create a network that represents the structure and the characteristics of the design space generated in a design session. This semi-automatic method provides a quantitative and qualitative way to analyze how designers build their design space. In designing, unlike other types of problem-solving activity, designers need to refine the problem space to define a possible solution. The method used tracks this process as it captures state transitions within the design problem space. A common understanding of design thinking is that it requires transitioning from the problem space to the solution space that co-evolve over time. These concepts can be illustrated in the networks generated by the method we presented.

By combining methods from Natural Language Processing and network science, we highlighted how to apply a method to capture fundamental characteristics of design thinking. The design session used as an illustrative example provided insights on how a design team structured their design space. For example, in this specific case, transitioning from the problem space to the solution space or inversely increased over time. In future work, we plan on applying this method to the entire dataset of design teams (19 sessions) to explore if the preliminary insights from this first example are confirmed.

Using such method to analyze, measure and represent design space expansion over time could have practical implications. For design teams, it could serve as a feedback tool on their design process. This first proposition could develop into an intelligent co-design agent to accompany designers in their exploration of the design space.

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Author 2 Dr. Milovanovic's research focuses on design cognition, design neurocognition and design learning. Her research aims at bridging design science and neuroscience to explore novel ways to teach design.