THE SITUATEDNESS OF DESIGN CONCEPTS: EMPIRICAL EVIDENCE FROM DESIGN TEAMS IN ENGINEERING

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ABSTRACT

Situatedness in design suggest that designing is situated within the design process or the cognitive actions taken by the designer, the designer's expertise and know-how, the designer's experience generally and the interactions in the specific design task being undertaken as well as the interactions with the design artefact generated. In this paper, we analyzed the situatedness of design concepts generated by teams of professional engineers during a design task. The method combines protocol analysis, Natural Language Processing and network theory to provide a representation and a measurement of design situatedness overtime. Providing empirical evidence of the situatedness of concepts has been overlooked in design research. The method and results presented in this paper outlines the foundation to empirically explore design situatedness.

Keywords: Design cognition, Design theory, Design process, Situatedness, Networks

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1 INTRODUCTION

Designing is a cognitive activity that relies on multiple reasoning processes like problem solving, evaluation and decision-making (Dorst, 2011; Simon, 1969). 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; Schön, 1983). Based on empirical observations, Schön (1983) defined designing as a reflection-in-action process, meaning that designers reinterpret their designs within their situation to advance in that activity. Designing is contextualized within the designer's situated view of the activity (Gero, 1998). Characteristics of design situations, related to the design process, the designers' experiences and the design artefact, shape cognitive activities while designing (Visser, 2006, 2009). Design situations make the process of designing unique compared to other types of problem-solving activities (Cross, 1982). This paper focuses on design situations, more specifically on the situatedness of concepts within design spaces generated by designers while designing.

Designers generate new concepts in the design space, which then have the propensity to change that space. The design space is inherently dynamic and evolves throughout the interactions between designers and their design space. We define the design space as the ensemble of situated concepts generated by a designer or a team while designing (Gero and Milovanovic, 2022). The design space expands over time (Gero and Kan, 2016), and its situation changes as the designing activity unfolds. In this context, design ideas evolve in relation to other concepts within the design situation.

In this paper, we introduce a method to track the evolution of concepts over time in the design space. This provides an opportunity to observe the situatedness of those concepts within the design space. This approach provides a simplify model to represent design concepts situatedness in relation to the design artefact. This method uses a semi-automated approach based on Natural Language Processing (NLP) of design protocols and automated graph generation, which allows for the analysis of large datasets. This alleviates a limitation of the manual coding often needed in design protocol analysis (Ericsson and Simon, 1984).

To exemplify this method, we analyzed the situatedness of design concepts from engineers design teams. Using a dynamic graph representation of design concepts over time, we capture the situatedness of design concepts in relation to other concepts formulated within one design session. We focused on two types of ideas: final concepts and transitory concepts. Final concepts are ideas that were included in the final design while transitory ideas were ideas generated but discarded and do not appear in the final design. To our knowledge, providing empirical findings of the situatedness of concepts has been overlooked in design research. This method and results presented here provide the foundation to empirically explore design situatedness.

2 BACKGROUND

2.1 Situatedness in design

Differences in design situations call for different forms of designing (Visser, 2009). Design situations broadly encompasses characteristics of the design process (cognitive actions taken by the designer), the designer's expertise and know-how, the designer's experience or expertise and the interactions in the specific design task being undertaken as well as the interactions with the design artefact generated. Design situations are key in reflection-in-action processes that designers engage in while designing (Schön, 1992). Designing develops as a conversation with the materials of the design situation (Schön, 1992), where a design situation encompasses physical design spaces (e.g., a site, a prototype), virtual design spaces (e.g., sketch pad, 3D models) and conceptual design space in the mind of the designer. In other words, designing occurs as an act of interaction between the designer and their design situation (Schön, 1992).

Design tools used and design representations impact how the design unfolds. Its evolution can be tracked by looking at how the design space changes over time. According to Goel and Pirolli (1992) the design problem space is shaped by features of the cognitive structure of the designers, features of the task environment and incremental development of the design artefacts. Design spaces provides a more tangible construct to observe elements of design situations.

Modelling design situatedness is complex because numerous elements impact design situations. In this paper, we approach design situations through one of these elements: the design artefacts through designers' verbalizations. The focus is primarily on the design space of the artefact being designed. This design space captures all the design concepts generated by designers. The situatedness of design concepts changes as the design process unfolds, and the design space expands (Gero and Kan, 2016). By representing the design space as a dynamic component, we can represent design concepts' situatedness and account for their evolution across time. A situated design concept will change its relationships with other concepts based, in part, on what happens in the design space after it has been first introduced, i.e., later experiences in that design sessions will change its situation and hence potentially change its meaning in the design.

2.2 Using graphs to represent design situatedness

Graph theory provides topological measures for networks that we can apply and interpret in studying design thinking. Using graphical network-type representations serves to automate the visualization process of a design situation. Prior research used such representations to illustrate different cognitive styles of designers by tracking the ideas developed and their precedents (Kim and Kim, 2015). In their study, Kim and Kim (2015) used a Social Network Analysis tool to represent designers' cognitive maps while designing, with a force graph helping visualize adjacency between nodes intuitively. Aside from helping visualize information about designing, graphs can help elucidate structures, patterns and relationship between elements (Cash et al., 2014). In their research, Cash et al. (2014) explored the use of an organic information visualization to analyze the organization of information used during a design process. They tracked sources of information used as well as of design processes to reveal their connections. More interestingly, Cash et al. (2014) explored network dynamics by measuring network growth rates over time. In this paper, force graphs are generated from design protocols (Ericsson and Simon, 1984) as a representation of design teams' design spaces. Concepts' situatedness is tracked within the graphs through metrics related to the graphs' structural components. Using network metrics goes beyond the usefulness of its representation and provides ground for unexplored areas of design research.

3 METHODOLOGY

3.1 The dataset

This study is based on the analysis of empirical data from an earlier research project (Milovanovic, et al., 2021) and a subsequent dataset using the same design brief. In total, 57 engineers working in the two different companies participated in a think-aloud protocol experiment and were grouped into teams of three. The first company specializes in developing solutions for automotive safety. The twenty-seven engineers from this company were all males, and came from different background ranging from mechanical engineering, quality engineering to manufacturing. The second company is a leader in providing systems and products for the aerospace and defense industries. Thirty engineers from this company participated in the study, forming ten teams of three engineers formed randomly (5 females and 25 males). Most engineers from this group were electrical engineers, and others had backgrounds in mechanical engineering, computer science, and physics. All engineers were used to working together within each company as the companies implemented agile manufacturing and lean production processes.

Each team was given the same task, 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. The team had 60 minutes to propose a concept description and sketch it on a white board. All team members were collocated and a research assistant stayed in the room as participants developed their designs. Toward the end of the design session, the research assistant asked the design team to summarize their ideas for their final concept. Each design session was video recorded for later analysis.

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3.2 Analyzing design concepts situatedness using Natural Language Processing and force graphs

Verbal data has been used to study design cognition over the past decades (Ericsson and Simon, 1984). The assumption is that cognition is captured through designers' verbalizations. From the transcribed recording of the design conversations between these professional engineers, an automated method extracted design concepts using Natural Language Processing in Python with the NLTK package. The transcript of each 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. Using Natural Language Processing provides an automatic way to track the emergence of concepts in a design session. For example, an utterance from one of 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”.

Then, we generated a force graph of concepts where a node represents a concept and an edge between two nodes accounts for their syntactic link. Using the Networkx and Plotly package in Python, we can represent the design space network where nodes are concepts and edges are processes connecting concepts. In previous work, using a similar approach, we characterized the design space with graph representing design process, such as synthesis or analysis (Gero and Milovanovic, 2022).

In this paper, the focus is on concept situatedness overtime and rely on semantic similarity and syntactic connection between ideas. Edges' weights are defined by semantic similarity. In this analysis, we measured semantic similarity within the WordNet (Fellbaum, 1998) taxonomy using the Wu and Palmer similarity metric with the python package NLTK. With this metric, similarity values vary between 0 and 1. The similarity is based on how similar the word senses are and where the two words occur relative to each other in the WordNet hypernym tree.

The network representation chosen is based on a force directed graph (Fruchterman and 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 two other concepts. Using a force graph provides a way to represent the connectedness of concepts (Gero and Milovanovic, 2022). Figure 1 represents the design space as a force graph of the design concepts for the design session of a team.

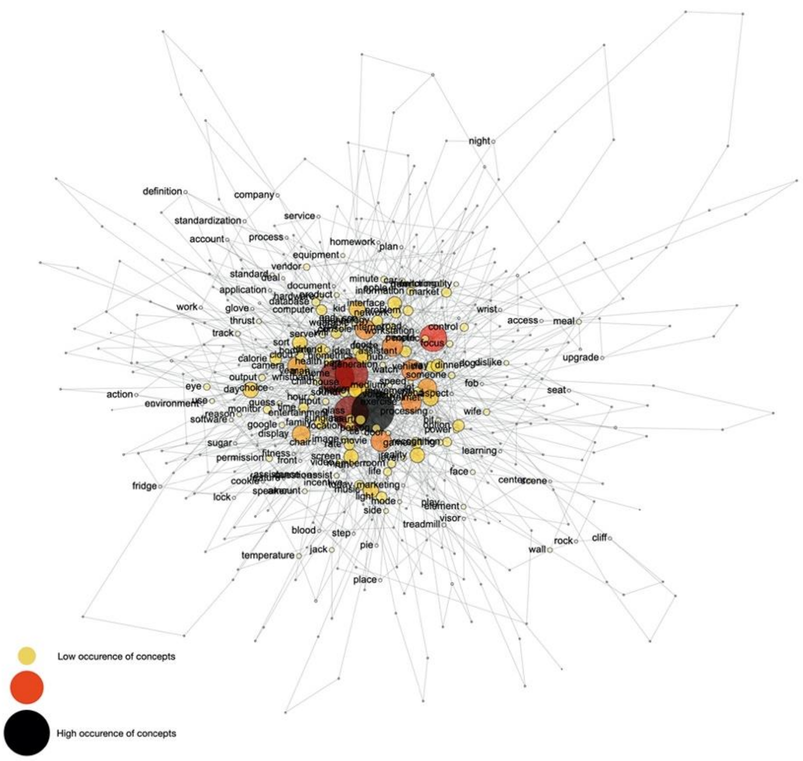

Figure 1. Force graph representation of the concepts generated by one team of designers during a one-hour session. Concepts in the center of the graph occurred more frequently and are more connected to other concepts in the design space compared to concepts at the periphery of the graph.

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To track the evolution of the situation of concepts over time, the session was segmented into temporal quartiles. This arbitrary division of design protocols serves to provide a sense of concepts evolution over time. For each quartile, a force graph was generated in order to monitor the evolution of concepts. To determine the position of each concept for each quartile, a separate force graph was produced at each stage. The graph from the first stage is generated based on the concepts and links from the first quartile. The graph from the second stage is based on the concepts and links generated during the first two quartiles. The same technique is applied for the subsequent quartiles. This way, at each stage, concepts are represented based on the state of the design space based on everything that occurred in the past, since the beginning of the session. Doing so, we capture the situatedness of concepts across time based on the re-occurrence of concepts and the introduction of new ones (Figure 2).

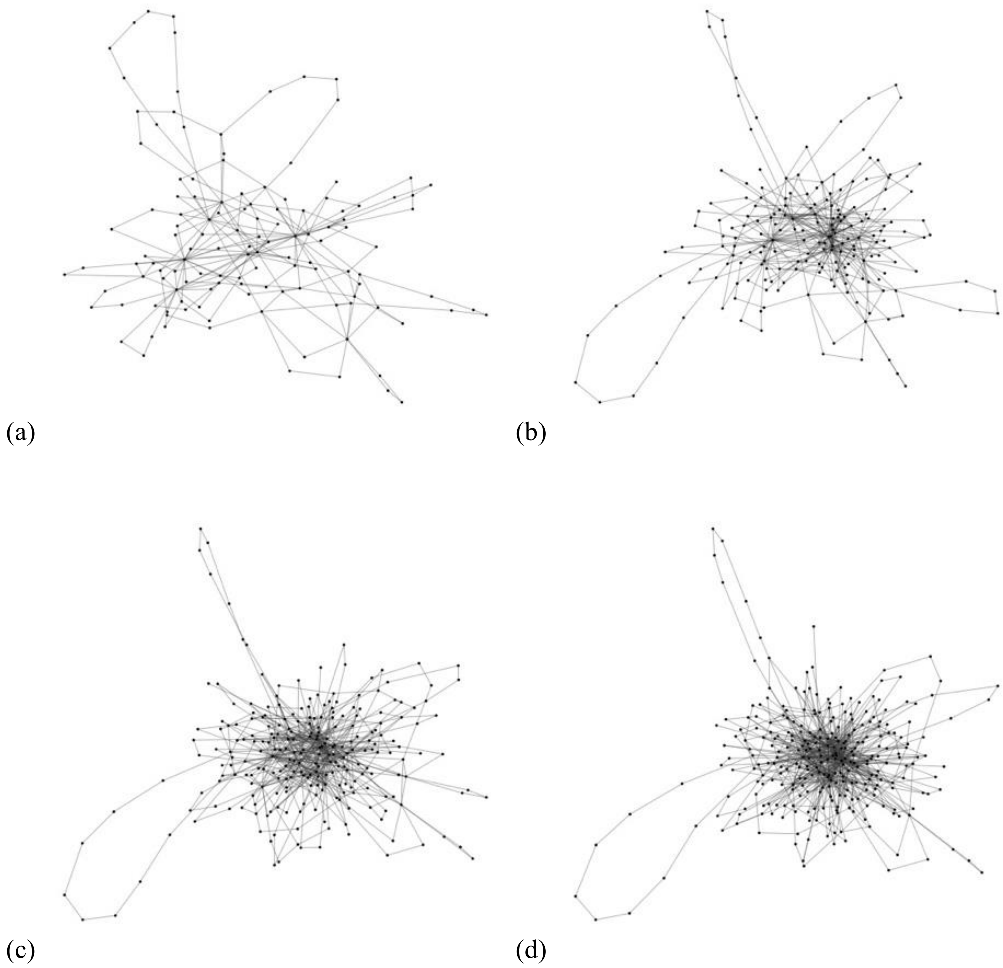

Figure 2. Force graph representing the design space for each stage for one design session: (a) First stage (concepts from 1st quartile), (b) Second stage (concepts from the 1st and 2nd quartiles), (b) Third stage (concepts from the 1st, 2nd and 3rd quartiles), (c) Last stage (concepts from the whole session)

In Figure 3, the movements of three concepts for one design session are represented using the same session data as in Figure 2. Over time, the concepts' positions change as designers formulated new ideas that relate to previous ones. Figure 3 illustrates this movement across time for three concepts: 'access', 'software' and 'device'. Applying this method to represent concepts within each team's design space helps track changes in the positions of concepts. These changes indicate the evolution of their situatedness.

For each team design session, we are able to extract concepts that appear in the final design description from transitory concepts, i.e., concepts that appear in the design session but do not appear in the final design. Transitory concepts have value as they support design thinking (Sosa and Gero, 2013). They help define the limits of the design space and structure the design space which affects the situatedness of the final concepts. In the next section, we explore the situatedness of both types of concepts.

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Figure 3. Representation of the movement of three concepts across time (quartiles) for a design session. The concepts move based on their relationships to other concepts at each stage of the design session. Edges are not represented for visualization purposes.

4 FINDINGS AND DISCUSSION

To illustrate the method described above, we looked at the situatedness of concepts in the final design. One session from our dataset was used as an example (Figure 4). To extract the concepts in the final solution, we applied the same NLP approach to the final summary of the solution verbalized by the teams. The movement of the final concepts, represented by colored path in Figure 4, demonstrates the situatedness of these final concepts. Final concepts were verbalized at different point in time. We see that the general movement of the final concepts is to move toward the center of the graph. This movement implies that these concepts occurred more frequently over time and that they are more and more connected to other concepts. Concepts represented in grey are the concepts not found in the final design. Their role remains key as they structure the design space and have a direct impact on the situatedness of all the concepts represented.

The graph in Figure 4 shows that design concepts do not occupy a static position in the design space but are situated concepts whose position is a function of both themselves and what is happening around them. It provides empirical findings that aligns with viewing designing as a conversation with the materials of the design situation (Schön, 1992). We observe how the incremental development of the design artefacts structure the design space, echoing Goel and Pirolli's (1992) definition of a design space. Concepts formulated by designers captures parts of design situations, which comprises the design artefacts and its relation to its context (Visser, 2009). The illustration of concepts' situatedness over the time of a design session represented here provides empirical support for these previous researches.

The situatedness of these concepts are accounted for by two measurements: the change of distance to the center of the graph and the distance concepts travel over time. The change of distance to the center represents the situatedness of design concepts in relation to key concepts structuring the graph. As concepts get closer to the center of the design graph, they become key concepts in this design situation. Those concepts are repeated by designers, connect to more and more concepts, and become grounded in the design space. Concepts might be repeated because designers expand on this idea, evaluate it in relation to other concepts, or in team design, discuss this concept to reach a consensus.

For each stage of the design sessions, we computed the distance of the concepts to the center of the graph for all the sessions within this dataset. The average distance of final concepts and transitory concepts for all the design sessions from the dataset is represented in Figure 5(a). The final concepts move closer to the center as the design session unfolds. Similarly, transitory concepts also move closer to the center of the design space as the design session unfolds. We see that final concepts are on average closer to the center of the graph, compared to transitory concepts. Final concepts are often discussed in depth by the team to reach an agreement on the solution to adopt and develop in the design process (Valkenburg and Dorst, 1998). It implies that final concepts might have a higher connectivity to other concepts. It is expected to visualize such concepts at the center of the force graph. On the other hand, transitory concepts are not verbalized as often as final concepts as designers move along in their design process. They are expected to gravitate on the edge of the design space, further away from its center.

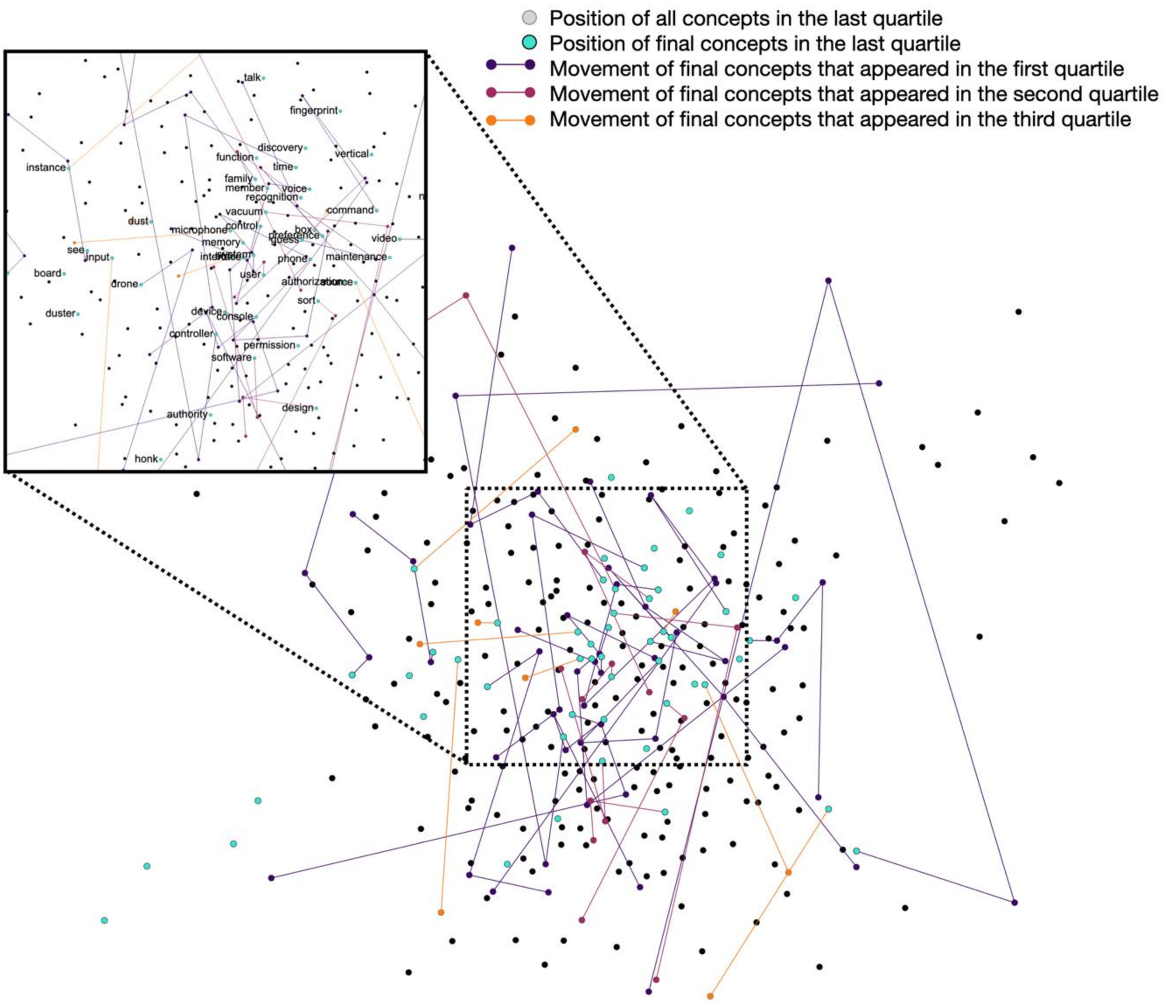

Figure 4. Representation of the situatedness of design concepts included in the final design of a design session. Grey nodes represent all the concepts that were not included in the final design but helped structure the design space. The blue nodes represent the positions of the final concepts in the last stage of the design. The paths represent the movement of the concepts across time.

The distance of the movement of concepts is another measurement of the situatedness of the design space. We computed the distance travelled by concepts between each phase. The average distance travelled by each concept between the four phases is represented in Figure 5(b) for all the design sessions from the dataset. A common trend appears across the concepts: the distance travelled reduces as the design session unfolds. It could be explained by the increasing stability of the force graph as key concepts become more and more grounded. Even though, across time, the design space expands as designers introduce new concepts (Perisic et al., 2021), concepts start to be more and more connected which reduces the propensity for movement. It also suggests that concepts become more and more grounded as the design advances. On average, transitory concepts tend to move more than final concepts. It aligns with the findings on the evolution of concepts distance to the origin of the graph

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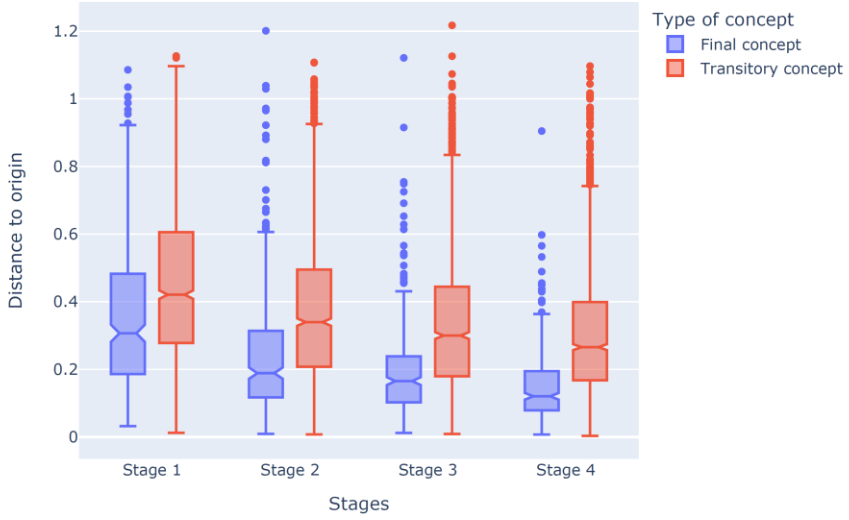
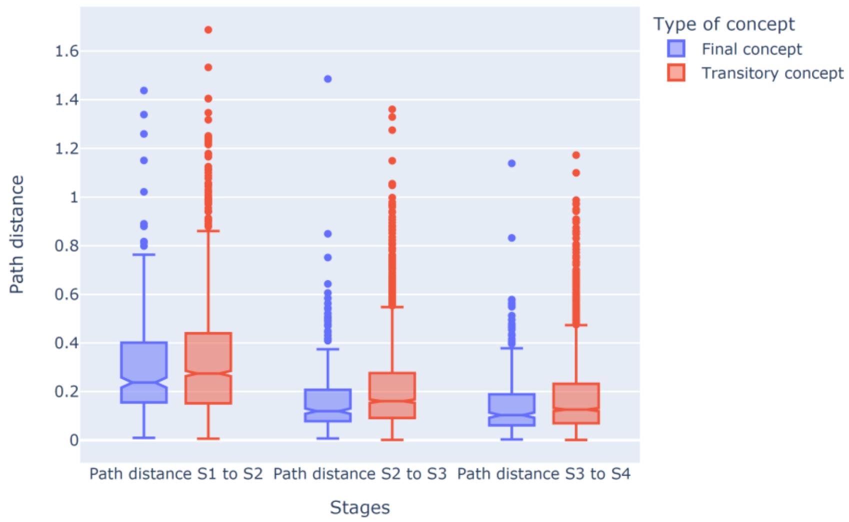
(Figure 5(a)). The situatedness of final concepts tend to be less affected by the evolution of the design space across time. It suggests that final concepts become grounded in the design space faster. We can hypothesize that they become structuring elements of the design space with less propensity to be affected by the occurrence of new concepts later in the session.



(a)



(b)

Figure 5. (a) Average distance of concepts to the center of the force graph for each phase of the design session. (b) Average distance travelled by concepts between two phases of the design sessions.

5 SUMMARY AND PERSPECTIVES

Designing is embedded within design situations. Design situations shape designers' cognitive activities while designing. Design situations are characterized by the incremental development of the design artefact, the designers' expertise, the designers' interaction with the artefact and the context of the design (e.g., social context, requirements). Design situations formalize within the design space which evolves over time. During design sessions, designers formulate concepts structuring the design space. They are situated within that space in relation to each other. In this paper, we measured and represented the situatedness of two types of concepts: final concepts and transitory concepts. Final concepts are ideas included in the final design while transitory concepts are ideas that were formulated but that were not part of the final design. The method developed to track concepts' situatedness is

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semi-automated, and can be applied to large datasets. It uses Natural Language Processes to extract concepts from design protocols. The design space is generated as a force graph where concepts are nodes, connected to each other based on how the design session unfolds. Concepts at the center of the graph occurred more frequently and are more connected than concepts on the periphery of the graph.
Final concepts and transitory concepts had similar yet different situated behavior. All concepts' situatedness changes over time. Concepts tend to move closer to the center of the design space as the design progresses. Final concepts appear closer to the center of the graph compared to transitory ones. Concepts at the center of the design space are key ideas. As concepts move toward the center of the design space, it implies that they become more grounded in the design space. Final concepts toward the center of the graph support that they structure the design space and are key elements defining the design situation.
Findings are limited to the model used to represent design situatedness. It only encompasses some of the aspects of design situatedness but fails to provide a holistic representation of all the elements that impact design situatedness. Moreover, time is accounted here through an arbitrary division of design protocols into quartiles. These findings are preliminary and stand as a first exploration of an underexplored area of design cognition research. Despite these limitations, this approach captures an essential component of design situatedness: concepts are situated in relation to each other which affect their trajectory within the design space. Findings support the application of this method to measure and represent the situatedness of design concepts. Using network metrics to measure design cognition provides opportunities to tackle for underexplored areas of design research through a new lens.
Future work will expend this first modelling of design situatedness by exploring semantic modeling instead of syntactic modeling to generate the design space. We will also explore what graph metrics can reveal about design situations and design processes.

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