What is happening when designers from different disciplines work together: Characterization of the design behaviors and design spaces of mechanical and electrical engineers working in teams

Authors: John Gero[1] and Julie Milovanovic[1]

[1] College of Computing and Informatics, University of North Carolina at Charlotte

Abstract: Multidisciplinary teams have become the norm in design and relates to the complexity of the artifact designed. In this article, we study multidisciplinary teams' design behaviors by combining protocol analysis, Natural Language Processing and network science. Three teams composed of professional mechanical and electrical engineers took part in this study. Designers engaged in the design activity with similar design processes and spend more cognitive effort on evaluating their design artifact when collaborating. Creating a network of the topic explored based on designers' disciplines produces their design spaces and illustrates the influence of context knowledge on the design situation. Mechanical engineers tend to tackle user-centered issues while electrical engineers focused more on product related one. For most of the topics covered like with the end users, the product in context of usage, and technological aspects of the product, we observed collaboration between disciplines. Using networks to represent design spaces and design processes could become a tool to support team design collaboration.

Keyword: design team, multidisciplinary, design cognition, design space, topic network, protocol analysis

1 Introduction

Design teams are more and more complex as they become more heterogenous, including designers from different backgrounds. Designers in a team work toward a shared and common goal (McGrath et al., 2000) to address the design task at hand. Compared to individual designing, co-designing is impacted by team members' interactions (Détienne et al., 2012; Valkenburg & Dorst, 1998), at both the design and social levels. Factors such as leadership and expertise (Cross, 2004; Gero & Kannengiesser, 2004) design background (Gero et al., 2014; Zimring & Craig, 2001) or gender (Laeser et al., 2003; Milovanovic & Gero, 2019) can have an effect on how co-designing unfolds in a team. Working in teams can be challenging as team members need to synchronize their ideas toward a common shared concept (Bierhals et al., 2007; Cash et al., 2020). Engineers from different disciplines hold similar yet different sets of design skills (Visser, 2009), that requires fine-tuning when co-designing. Teams' homogeneity related to their functional background can positively impact the team task performance as the team relies on a larger set of skills, cognitive patterns and expertise (Carter et al., 2019; Stewart, 2006). On the other hand, aligning viewpoints and ideas can be challenging in heterogeneous teams, and might delay the achievement of the task (Carter et al., 2019). Semantic coherence within a team tends to affect their creativity and performance positively (Dong et al., 2004) although micro-conflicts among team members can also have a positive effect on the team performance (Paletz et al., 2017).

In this study, we explore the effect of team members' discipline on design teams' cognitive behavior, design spaces and semantic topics explored while designing. To do so, we analyze a set of three design sessions of professional engineers grouped in teams of three. Teams were all composed of engineers from two different disciplines: mechanical and electrical. The protocol analysis methodology was used to analyze our protocols (Ericsson & Simon, 1984; Kan & Gero, 2017; Van Someren et al., 1994) with the Function Behavior Structure coding scheme (Gero, 1990; Gero & Kannengiesser, 2014) and a model of co-design (Gero & Milovanovic, 2019) to locate the teams' co-design processes.

Determining the design behaviors and design space exploration of mechanical and electrical engineers working in teams can provide new directions toward developing tools to support co-design by developing designer's awareness of the complementarity of their cognitive processes and skills while designing. Our findings provide a new perspective on design team interactions through co-designing by integrating the relationship between design solutions topics within the design space. It relies on an analysis of the semantics of designers' utterances, a common approach in design research (Dong, 2005, 2007), that has not been adequately explored. Design research could benefit from more semantic driven studies on design thinking.

2 Background: multidisciplinary design teams in design studies

Multiple factors influence team performance. In their meta-analysis, Stewart (2006) defined three main categories of factors: group composition, task design and organizational context. Group composition refers to the team size, structure, heterogeneity, and characteristics of team members (gender, personality, age). Task design relates to the task itself, and how the activities within the task are differentiated and integrated. It also includes intrateam organization and management, the team and sub-team autonomy and coordination. The last group of factors, organizational context, includes leadership and supervision through the interface of the team leader and the broader organization, such as a department or the company itself.

The assumption in team composition is that individual abilities grouped together provide more resources to the team. But specific skills from team members should combine in the 'right' way to increase team-level performance. Studies on teams' homogeneity or heterogeneity in relation to team performance provide insights to team composition (Carter et al., 2019; Stewart, 2006). On one hand, heterogeneity should enhance creativity in the teams as diverse skill sets are combined, but on the other hand, homogeneity should support fewer conflicts in the team as it includes similar team members (Stewart, 2006). For creative tasks, such as designing, heterogeneity tends to increase the team performance as it requires different expertise (Stewart, 2006). Team members with similar functional background, or discipline expertise, are more likely to identify problems in a similar way, and are less likely to propose a richer set of alternative solutions (Carter et al., 2019). Teams including team members with different functional skill sets will rely on more knowledge, cognitive patterns and cognitive styles, which can benefit solving tasks at the team level (Carter et al., 2019). It could also slow the team process as integrating different ideas and perspectives can be challenging.

In the study presented here, teams are composed of mechanical and electrical engineers. Mechanical and electrical engineers tackle different design problems within the same design task (Riboulet et al., 2005). In practice in industry, both can work in isolation in product development, although collaborative optimization beforehand helps avoid long development loops between designers (Riboulet et al., 2005). A case study of product development at Microsoft highlights that communication and understanding of each engineer's expertise favor the decision-making process, boost innovation and helps keeping the timeline of the project development (Li et al., 2017). For example, for the development of a scrolling wheel for a mouse, the mechanical engineer would focus on the physical component, the electrical engineer would tackle how to transmit data to microcontrollers while software engineers would define how to communicate the data from the scrolling wheel to the computer (Li et al., 2017). Problems are tackled at the team level to decide on possible adjustments dealt individually by each engineer. A holistic understanding of the product was key in developing better products (Li et al., 2017).

Even though factors such as the task, designers' expertise or disciplines affect designers' approach, designers display similar cognitive behavior while designing (Akin, 2001; Gero et al., 2014; Visser, 2009). Design is a cognitive activity that is not defined through a professional status (Visser, 2009). Designers usually tackle design problems through the relationship between sub-problems or subsystems. The approach to designing can vary depending on the discipline. For instance, designers with industrial or architectural background usually adopt a more intuitive approach to problem solving, whereas engineering disciplines tend to be more analytical and knowledge driven (Akin, 2001; Roozenburg & Cross, 1991; Zimring & Craig, 2001).

When entering the workforce, designers rely on the skills they acquire during their education. Discipline differences are rooted in pedagogical approaches to teaching designing and to professional cultures. Engineering education shapes future engineers' models of designing, technical skills and capabilities for collaboration (Dym et al., 2005). In engineering, capstone design courses were implemented to bring the practical side of engineering into engineering curriculums (Froyd et al., 2012). Today, teaching design through studio is common across disciplines. But, learning objectives of project-based courses tend to differ depending on the discipline. For example, industrial and architecture studio courses tend to be innovation driven compared to mechanical engineering design courses that are performance driven (Goldschmidt et al., 2014). Learning goals set within design courses impact future professionals' approach to designing. Empirical studies in design suggest that these different approaches to designing can lead to exploiting diverse design patterns and processes (Gero & Jiang, 2014; Kan & Gero, 2011). Mechanical and electrical engineers possess different ranges of skills and expertise related to their discipline, yet as designers, they mobilize similar cognitive design processes

(Gero et al., 2014). In fact, their approach to designing is similar. In multidisciplinary design teams, they are perceived as system thinkers and problem solvers (Li et al., 2017).

3 Research question

In this study, mechanical and electrical engineers worked in teams on a design task. We explore the effect of team members' discipline on design teams' cognitive behavior and their exploration of the design space. Through design processes, designers advance in the design activity by structuring the design space based on the design situation and their expertise (Cross, 2004; Gero, 1990). 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). Disciplinary backgrounds shape technical knowledge that can influence how designers explore and expand their design space. The research questions are as follows:

1) What is the effect of discipline expertise on design teams' cognitive behavior?
2) What is the effect of discipline expertise on semantic topics explored while designing?

Based on findings from prior studies described in section 2, we expect to find more differences in the type of topic each engineer explored than in the cognitive design processes they engaged in. Semantic topics are likely related to each engineer's functional professional skills and should reflect that expertise. Mechanical and electrical engineers' approach to designing is considered similar, compared to other designers (i.e., architects, industrial designers). Hence, we expect participants to display similar cognitive design patterns.

4 Methodology

4.1 Data collection

Engineers participating in the study worked at a company providing systems and products for the aerospace and defense industry. Thirty engineers (5 females and 25 males) randomly formed ten teams of three engineers. Most engineers from this group were electrical engineers, and others had backgrounds in mechanical engineering, computer science, and physics. Each team was given the same task, to design a next-generation personal assistant and entertainment systems for the year 2025 (see Appendix). 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 define 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 design. The company requested the experiment to be done outside of the work environment for privacy reasons. Each design session was video recorded to be analyzed (Figure 1). No incentives were given to participants.

This dataset of 10 design teams was collected in research that looked at the effect of the working environment on design teams' behaviors (Milovanovic et al., 2021). In the exploratory study reported here, we selected a subset of 3 teams composed of mechanical engineers and electrical engineers. The remaining teams from the dataset that were not composed of both mechanical engineers and electrical engineers were not selected as they did not fit the scope of the research. Here the analysis focuses on analyzing results related to participants' engineering discipline, mechanical or electrical. All team members of the three teams were male engineers. All engineers were used to working together as the company uses agile manufacturing and production processes. Even if team members have not previously been part of the same team, they are used to working in the same organization environment. This way, although the experiment was carried out in vitro to better control the setting, the interpersonal interactions among members reflected their normal work behavior. All the participants were experts in their domains and had around ten years of expertise in their fields.

Figure 1. Experiment setup and organization with examples of discussion between team members. Teams were composed of either two mechanical engineers and one electrical engineer, or one mechanical engineer and two electrical engineers.

4.2 Describing design processes and collaboration

In this study, we utilized the Function-Behavior-Structure (FBS) ontology to describe design knowledge and processes (Gero, 1990; Gero & Kannengiesser, 2014). Many frameworks have been used in the past decades to describe design processes (Lawson, 2006), for example the C-K theory (Hatchuel & Weil, 2013) the reflective practice (Schön, 1983; Valkenburg & Dorst, 1998) or designers' cognitive actions (Suwa et al., 1998; Suwa & Tversky, 1997). Most integrate concepts related to synthesis, analysis and evaluation as three main design processes (Lawson, 2006). Using the FBS ontology to explore design cognitive process is relevant as its descriptions of function, behavior and structure do not require additional ontological concepts. Moreover, it has been used in empirical studies analysis in diverse domains (Bott & Mesmer, 2019; Hamraz & Clarkson, 2015; Sakao et al., 2020). The FBS framework represents six design issues:

- Requirement (R) includes the design brief and is outside of the designer
- Function (F) is what the design object is for
- Expected Behavior (Be) represents an expected behavior of the design object
- Structure (S) represents elements and their relationships that go to make up the design object
- Structure Behavior (Bs) is behavior derived from a structure
- Description (D) is an external representation of the design object.

The FBS framework also describes a total of eight cognitive design processes as a consequence of transitions between the six design issues, as shown in Figure 2:

- Formulation, a transition from a requirement (R) to a function (F), or from a function (F) to an expected behavior (Be)
- Synthesis, a transition from an expected Behavior (Be) to a design structure (S)
- Analysis, a transition from a design structure (S) to a behavior from structure (Bs)
- Evaluation, a transition from an expected behavior (Be) to a behavior from structure (Bs) and inversely
- Documentation, a transition from a design structure (S) to a description (D)
- Reformulation 1, a transition from a design structure (S) to a different design structure (S)
- Reformulation 2, a transition from a design structure (S) to an expected behavior (Be)
- Reformulation 3, a transition from a design structure (S) to a function (F).

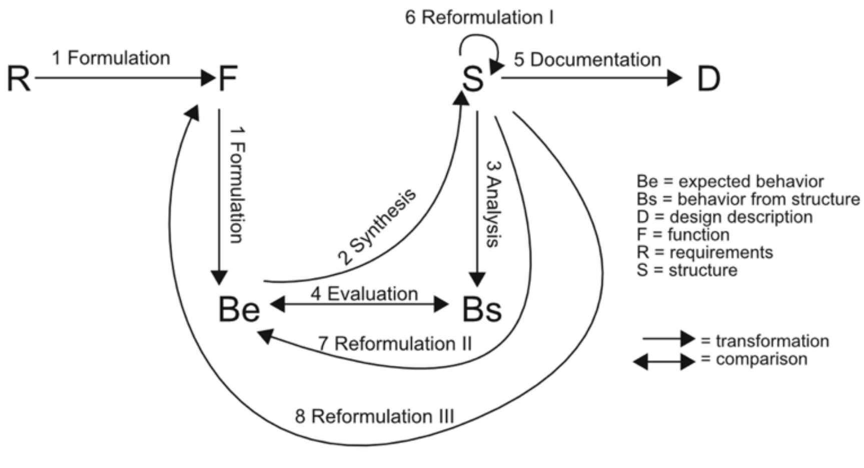


Figure 2. FBS design knowledge and process framework (Gero, 1990; Gero & Kannengiesser, 2014)

4.3 Coding the design protocols to obtain information on collaboration and design processes

The protocol analysis methodology was applied to analyze the design sessions. Video protocols were transcribed, segmented and coded using the Function-Behavior-Structure framework represented in Figure 2. In this study, we analyzed collaborative interactions between team members based on their engineering discipline. Each segment was coded with the engineer's discipline, mechanical or electrical. Two teams comprised two mechanical engineers and one electrical engineer whereas the other team was composed of one mechanical engineer and two electrical engineers.

As explained above, FBS design processes are identified as transitions from a specific design issue to another specific design issue (Figure 2). A process formulated by a single engineer, implies that both design issues forming a design process are verbalized by the same engineer. We identified a co-design process as an FBS design process where a first engineer formulates the first design issue, and the second designer verbalizes the following design issue (Gero & Milovanovic, 2019). With a dual coding scheme, we were able to identify dominant design processes for mechanical engineers, electrical engineers and collaborative processes between mechanical and electrical engineers. Processes and interactions are based on a syntactic model, looking at the activity in a temporally linear manner, not based on semantic associations or turn taking (see Table 1 for an example of protocol coding).

Each session 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. The average coder agreement for all sessions is 80%, which ensures the reliability of the data analyzed.

Table 1. Example of coded protocol with design processes and interactions

Utterance	FBS code	Design process	Designer	Interaction
It's got to be able to connect to	Be	-	Mech. Eng.	-
all the in-home, you know.	S	Synthesis	Mech. Eng.	Mech. Eng. > Mech. Eng.
So, if you have a Wi-Fi. The Wi-Fi stuff…	S	Reformulation 1	Elec. Eng.	Mech. Eng. > Elec. Eng.
or Bluetooth	S	Reformulation 1	Elec. Eng.	Elec. Eng. > Elec. Eng.
or whatever features	S	Reformulation 1	Elec. Eng.	Elec. Eng. > Elec. Eng.
and be able to network with all of them.	Be	Reformulation 2	Elec. Eng.	Elec. Eng. > Elec. Eng.
And then you got to have, you know, with the TVs	S	Synthesis	Mech. Eng.	Elec. Eng. > Mech. Eng.
and then connecting	Bs	Analysis	Mech. Eng.	Mech. Eng. > Mech. Eng.
to your entertainment things.	S	Synthesis	Mech. Eng.	Mech. Eng. > Mech. Eng.

4.4 Measuring design space exploration with NLP and networks

Tools from network science provides a new perspective on studying design teams, design tasks and design spaces (Adolphe et al., 2020; Leenders et al., 2016; Parraguez & Maier, 2016). To measure the design space explored by engineers during the design sessions, we created a graph to represent the entire design space produced by all the designers through the topics mentioned by them. Elements within the design space are concepts or ideas that are formulated by designers. The graph also accounts for relationships between concepts and their frequency of occurrence. To build the graph, the input data was prepared using a Natural Language Processing (NLP) script in Python (nltk package) and the Gephi software to visualize the graphs (Bastian et al., 2009). We used a python script to clean the design protocols with NLP tokenization. Doing so, punctuation and stop words were removed from the protocol, and we selected tokens tagged as nouns (nltk.pos_tag() function in the nltk package). To create the graph, we considered each token (i.e., "home", "people", "concept", "app") as a node. Edges between nodes are created when both tokens appear in the same protocol segment. The frequency of the co-occurrence of tokens provides the weight to graph edges. As each segment is assigned to the speaker, we were able to track who established a relationship between tokens, a mechanical engineer or an electrical engineer.

Figure 3 illustrates an example of the entire design space for this specific task for all three sessions combined, represented by the network of topics explored by all the engineers. 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. Such networks provide a relevant visual tool to better understand the design space explored by engineers based on their discipline. In Figure 3, blue edges represent connections made by mechanical engineers and pink edges represent connections made by electrical engineers. A node, such as “people”, is connected to other nodes with blue and pink edges, meaning that both groups of engineers mentioned “people” but with different connections to other topics. Nodes connected to other nodes by edges of a single color imply that these topics were covered by only one type of engineer. Node size represents the node degree (number of connections with other nodes) while edge width accounts for co-occurrence frequency of concepts.

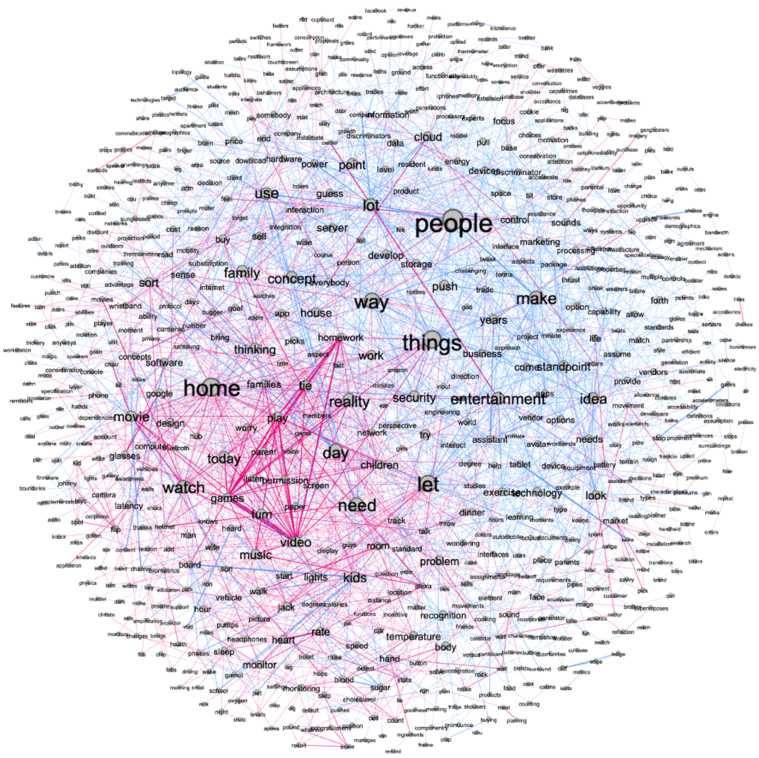


Figure 3. Graph example of the entire design space represented as topics explored by all the engineers in all the teams designing a personal entertainment system. Blue edges represent connections made by mechanical engineers and pink edges represent connections made by electrical engineers.

Graph theory provides topological measures for networks that we can apply and interpret in studying the exploration of design spaces. Here, we looked at network density and modules within the graph. Network density is the ratio of the number of edges within the network to the number of possible edges in the network. It provides an idea of how well nodes are connected to each other, in this case, how well topics are connected to each other. Modularity provides an estimation of how a network breaks into smaller sub-networks or communities (Newman, 2006). Using Gephi's clustering function for modularity (Louvain method), we are able to define modules within the network that corresponds to a chunk of the design space explored. Modules have dense connections between the nodes within the module and sparse connections with nodes in the other modules. Modules are "small worlds" in social networks. Defining such modules can help us determine groups of topics where engineers collaborate or if some modules are discipline-specific.

5 Results

5.1 Designers display different design behaviors based on discipline

The results indicate differences in the cognitive effort expended by engineers in designing, based on their engineering discipline. The average distribution of FBS design processes for all three sessions, for electrical engineers, mechanical engineers and the collaborative processes between them is presented in Figure 4. Electrical engineers tended to put more effort into analysis compared to mechanical engineers. They spent 38.6% of their cognitive effort on analysis. Mechanical engineers put more emphasis on reformulating design solutions, reformulation 1 design process, as such a process represents 43.2% of all their FBS design processes. The distribution of evaluation design processes is twice as large for collaborative design processes between mechanical and electrical engineers than for discipline-specific design processes. For other processes like synthesis and reformulation 2, the distribution of processes is similar for all types of interactions.

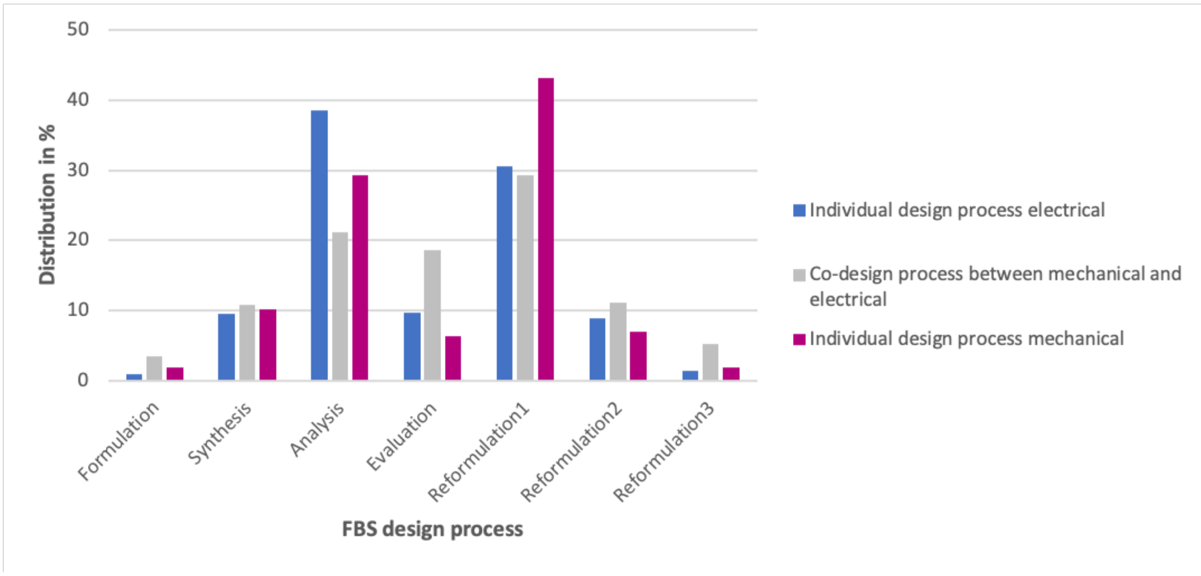


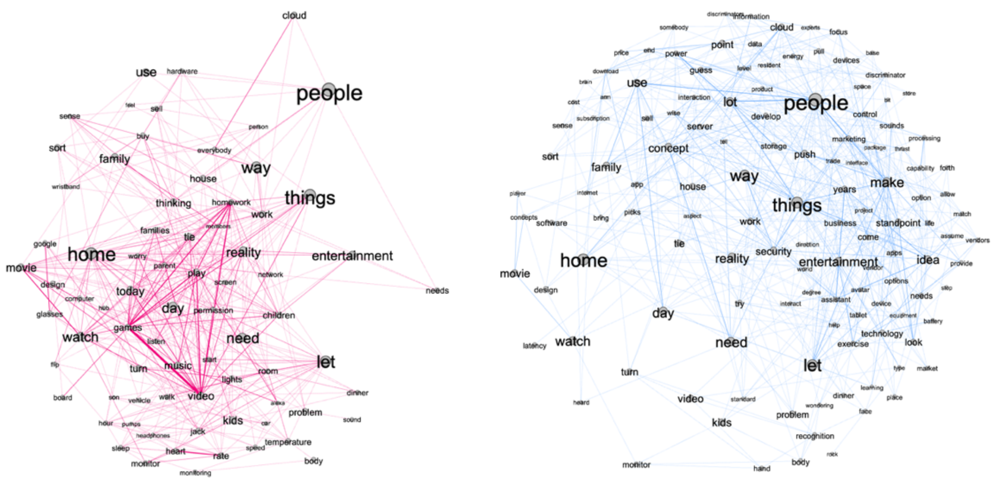
Figure 4. Average distribution of individual and collaborative design processes based on design discipline

5.2 Designers explore different design topics in the design space based on discipline

5.2.1 Results based on discipline expertise

The network of concepts is built from the segmented protocols as described in the methodology section. In total, 2,536 segments were used as input (1,115 for mechanical engineers and 1,421 for electrical engineers). Nodes represent concepts discussed by engineers during the design session while edges show the relationship between concepts based on the protocols. In order to visualize highly connected topics, we used a threshold based on node degree to select nodes with a higher node degree than the average. Since, on average, nodes have 15 connections to other nodes, the threshold was set at 15, and only nodes with 15 or more connections are represented in the networks shown in Figure 5. Figure 5 illustrates subgraphs of dominant concepts for mechanical engineers (Figure 5(a)) and electrical engineers (Figure 5(b)). The mechanical engineers' subgraph comprises fewer nodes (393 nodes) than the electrical engineers' subgraph (602 nodes). However, the mechanical engineers' subgraph has a higher network density (0.027), than the electrical engineers' subgraph (0.018). This suggests that mechanical engineers explored fewer topics than electrical engineers but made more connections between the topics explored.

The analysis of the design space for the design teams shows some overlap of the topics that designers focused on. For instance, "people", "home", "entertainment" and "need" are key nodes in each sub-network (see Figure 3). Each cohort also discussed topics specific to their discipline. For example, mechanical engineers explored concepts related to the category of users (e.g., "parent", "family", "children") and user wearables (e.g., "glasses", "watch", "wristband", "monitoring" "heart rate" and "sleep") (Figure 3(a)). On the other hand, electrical engineers expended cognitive effort in exploring product-related concepts (e. g., "marketing", "package", "energy", "processing").



(a) (b)

Figure 5. Subgraphs representing relationships between topics explored by engineers based on their discipline: (a) mechanical engineers and (b) electrical engineers. A threshold based on node degree was applied to highlight prevalent topics explored by engineers. The node degree threshold of 15 is selected, which is the average node degree for the entire network of topics.

Using Gephi's clustering tool with network modularity, 5 main modules were identified (Figure 6). Those 5 modules represent 90.5% of all the nodes in the network. In most modules, both mechanical engineers (pink edges) and electrical engineers (blue edges) made connections between nodes (see Figures 6 (a), (b) and (c)). For two of the modules, we obverse the dominance of electrical engineers' connections (blue edges in module 4 in Figure 6(d)) or the dominance of mechanical engineer's connections (pink edges in module 5 in Figure 6(e).

Module 1, representing 40.1% of the network of concepts, relates to the end users with topics like "people", "families", "need", "use", "assistant", "avatar" and more. Module 2 representing 20.2% of the network of concepts describes the product in context with topics like the "home", "cameras", "monitor" for a specific usage related to measuring data ("heart rate", "sleep", "temperature"). Module 3, representing 11.6% of the network of concepts, focuses on a function of the product's technological aspect that deals with "technology", a "server", "internet", and a "cloud". For all these modules, mechanical engineers and electrical engineers brought complementary ideas, using similar ideas (nodes) and connecting (edges) them to different other ideas.

Module 4, representing 10.7% of the network of concepts, is dominated by blue edges illustrating connections made by electrical engineers. In this module, the focus is on one of the requirements for the product "entertainment". It relates to some uses for the product like "exercise" to the components of the product, for instance the "apps", the "software", "data". The last module, representing 8.0% of the network of topics, is dominated by pink edges showing connections established by mechanical engineers. In this module, the concepts represent features offer by the product designed, as "games", "music", "video", "movie", "homework" that connects to users ("families" and "children").

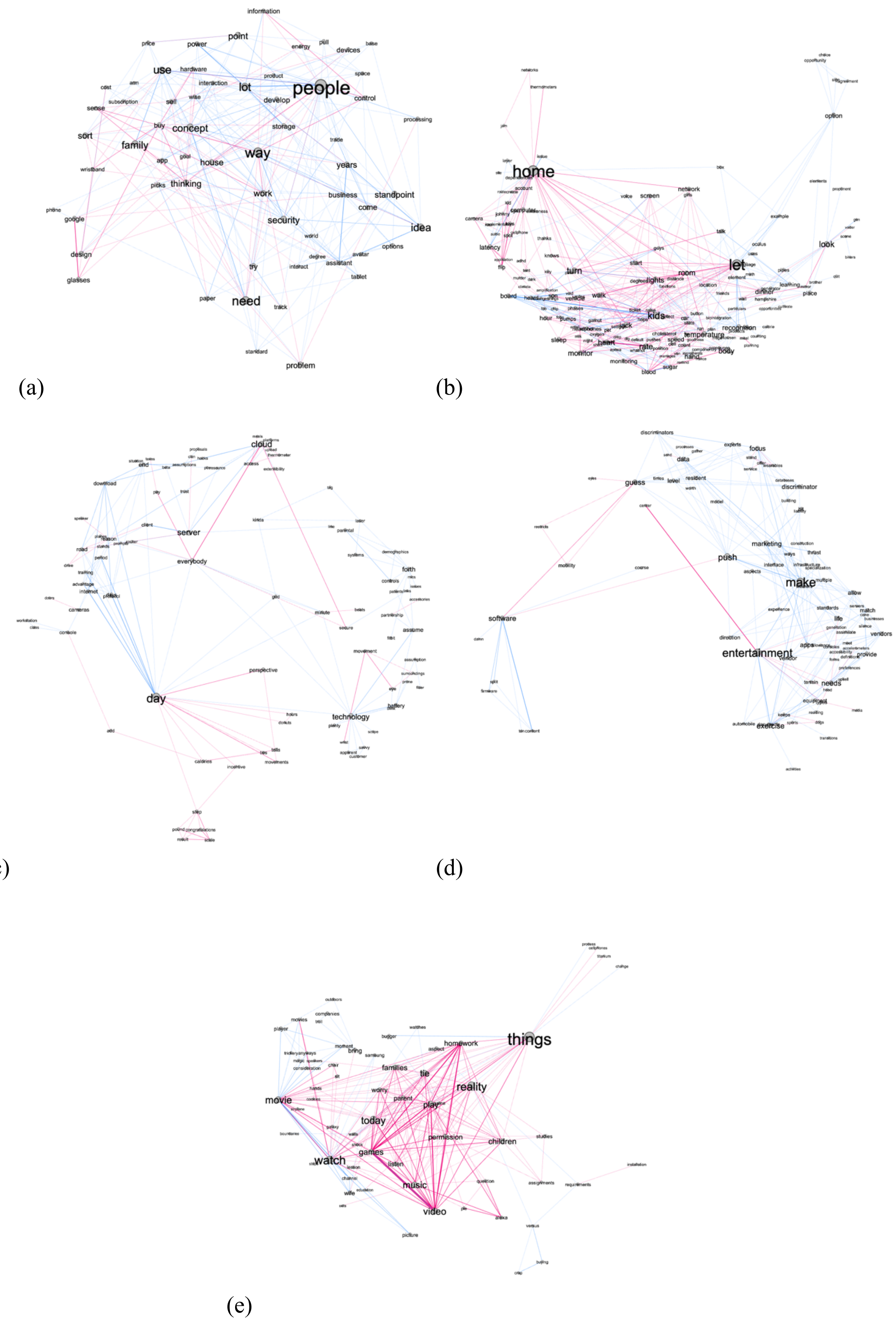


Figure 6. Subgraphs representing relationship between topics explored by engineers within modules: (a) module 1 representing 40.1% of topics, (b) module 2 representing 20.2% of topics, (c) module 3 representing 11.6% of topics, (d) module 4 representing 10.7% of topics, (e) module 5 representing 8.0% of topics. Edges in pink represent relationships from mechanical engineers. Edges in blue represents relationships from electrical engineers.

6 Discussion

In this study, we explored whether the disciplines of team members impact design behaviors, design spaces and design space exploration for teams of electrical and mechanical engineers. We observed differences in design behaviors and in the part of the design space covered by designers based on their discipline.

The divergences in the distribution of design processes based on discipline highlights slightly diverse cognitive design styles. Mechanical engineers put more cognitive effort into Reformulation 1 processes, whereas electrical engineers put more cognitive effort into Analysis. Both types of process focus on the design solution itself. While Analysis infers behaviors from design structures, Reformulation 1 processes implies rethinking design structures. Both types of designers display a design behavior focused on the solution, which agrees with previous empirical findings (Jiang et al., 2014). Mechanical and electrical engineers are both defined as analytical, system thinkers (Akin, 2001; Li et al., 2017) which provides an explanation for the dominance of Analysis and Reformulation 1 design processes. When collaborating, Evaluation processes become dominant compared to individual design processes. This finding supports the relevance of collaboration between disciplines as it triggers more evaluation between the current solution and design expectations. In the Microsoft project case study, communication between engineers from different disciplines was key when identifying problems and laying out possible adjustments for the product solution (Li et al., 2017). Navigation between problems and solutions is at the core of the Evaluation process, which echoes these previous findings on multidisciplinary team members communication while designing.

We expected few differences in design cognition based on discipline as both mechanical and electrical engineers tend to hold a similar approach to problem solving. Looking at the overall distribution of design processes, the data analysis provides indications of similar design behaviors although some divergence appeared as well. Interestingly, design behaviors were different for interdisciplinary codesign processes. Collaboration tends to co-opt a larger the array of design patterns designers engaged in during the design activity, which could lead to a richer outcome in terms of the design artifact.

Exploring the use of NLP and network science to study the extent of the design space explored depending on the discipline helped visualize the functional expertise of each type of designer. The design processes analyzed and discussed above act as a vehicle for concrete elements discussed by the participants. Mechanical engineers and electrical engineers explored complementary parts of the design space while designing. Some concepts overlapped between engineers including "people", "home", "entertainment" and "need". Concepts specific to disciplines were more user related for mechanical engineers and more product related for electrical engineers. When looking at clusters of topics based on network modules, we observed that the three main modules (covering the larger number of topics) contained a high participation from both types of engineers. It suggests that for this task, multidisciplinary collaboration helped cover more of the design space within modules. Those modules dealt respectively with the end users, the product in context of usage, and technological aspects of the product.

As more disciplines come into design, combining expertise is key to improving the design process and its outcomes. This study looked at two disciplines and could be applied to any number of disciplines in a team. Revealing how designers interact and the amount of design space they cover could benefit team organization and management. Engineers bring specialist knowledge to interdisciplinary teams, hence need to put effort into communicating their design language and context knowledge to other designers from different backgrounds. Such efforts could enrich the design artifact produced. In this study, we showed that the design space covered was extended based on the collaboration between engineering disciplines. We could argue that covering more of the design space could lead to more design alternatives and a better end product.

In this study, we focused on cognitive processes of the design teams but other factors such as social interactions impact how the design activity unfolds in a team. Teams can divide into subteams based on different characteristics. Subteams emergence within teams is shaped by faultlines, hypothetical dividing lines based on attributes of diversity, that are embedded in the situational and social context of the team environment (Carton & Cummings, 2012; Thatcher & Patel, 2012). The social organization of the team through leadership, project and conflict management can impact how the team progresses in their design activity. In future work, we plan to integrate such factors into our analysis.

In this study, one limitation is that the performance of the artifact is not evaluated. In our future work, we will include such metrics to better understand the relationship between the amount of design space explored and the design artifact quality. More metrics can be added and represented from the topics network. Through analyzing concepts that are first occurrences (first concept for one topic) in the protocol data (Gero & Kan, 2016), we can define the size of the design space and the semantic distance between concepts. Such metrics can provide a proxy to measure divergent thinking and creativity, which could complement subjective outcome evaluation, for instance with the Consensual Assessment Technique (Amabile, 1982).

7 Conclusion

Working in multidisciplinary design teams has become the norm with the increasing scale and complexity of designs. It requires a synchronization between designers from different discipline backgrounds, which can be challenging. The potential of interdisciplinary design teams is to increase performance by designing better products more effectively and efficiently. In this study, we analyzed the design behaviors of teams composed of mechanical and electrical engineers. Using protocol analysis, we were able to determine similar and different design behaviors between mechanical and electrical engineers. More importantly, when codesigning, engineers from different disciplines engaged in processes that were not dominant for discipline-specific processes. The extent of topics covered within the design space was extended based on discipline-specific context knowledge. The richness of design processes and potential for design alternatives in these design teams show the relevance of multidisciplinary teams.

This study was a testbed to integrate new design cognition metrics using NLP and network science. The tools used provide an automated way to study semantic relationships within design protocols. Network representations based on word co-occurrences provide an additional dimension of design thinking analysis. Networks representing relationships between ideas and concepts while codesigning could help the design team in their process (Gyory et al., 2021). Other forms of expression embedded within the design activity such as gestures (Kang & Tversky, 2016), physiology and neurocognition (Borgianni & Maccioni, 2020; Gero & Milovanovic, 2020) are additional area of focus in order to broaden the characteristics of designing that are studied. Considering all these characteristics in design research will enrich our understanding of design cognition, and can benefit team design through developing real-time tools to assist designers.

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Appendix

Personal Entertainment Systems (PES) is one of the most comprehensive entertainment companies in the world. In order to keep its leading position in the industry of entertainment, PES cooperates with many agents to explore the possibilities of new types of entertainment. Your design team has been invited to help in designing the next generation of a personal assistant and entertainment system suitable for family use in the year 2025.

Concept Design

In the context of engineering, a characteristic feature of the product design-related function is the description of products. Concept design includes a thorough roadmap from concept generation to production to product launch. See figure below:

The aim of concept design is to prepare for concurrent engineering by specifying the fundamental solution to the design problem.

Task

Your team is tasked with producing concept designs of a personal assistant and entertainment system suitable for family use for the year 2025.

For this project, your team should 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.

Your goal is to produce a number of concepts and then develop one of those concepts into a detailed design. At the completion of the session, please present sketches (using the whiteboard) and a verbal description of your solution. Your team will have 60 minutes to complete this task.