# A systems thinking inspired approach to understanding design activity

**Gregory Litster**
University of Waterloo, *Canada*
*gmlitste@uwaterloo.ca*

**Ada Hurst**
University of Waterloo, *Canada*

**Carlos Cardoso**
Iowa State University, *USA*

Systems thinking is a popular approach for addressing complex problems. System mapping, a tool commonly used to facilitate systemic thinking, can be used to visualize the systems under consideration, and thus its complexity, which is useful in many design contexts. This paper aims to determine the extent to which systems thinking can be used to understand design activity. We review the literature on systems thinking and its relationship to design thinking. Building on this foundation, we introduce a new method for analyzing verbal protocols using system mapping and test it on eight protocols of participants engaged in design activity. Preliminary analyses of the generated maps point at the usefulness of the approach, especially for capturing problem framing. Areas of future research are proposed, including connections to design ideation and fixation, team collaboration in design, and using the approach for assessing systems thinking maturity.

## Introduction

As societal problems become more interrelated and interdependent, they manifest themselves at different levels of increasing complexity. As a result, designers are called to go beyond typical problem-solving approaches when designing and thus think more holistically about systems-level change [1], [2]. *Systems thinking*, sometimes referred to as *systems view* or *systems approach* – the ability to understand systems and their behaviour often with the aim of devising modifications that move them in a desired direction [3] – emerges as a critical approach.

Systemic design, an interdisciplinary approach that combines systems thinking and design principles, when trying to tackle problems in complex sociotechnical systems, is one example of the integration between these two disciplines [4]. We believe that systems thinking and design share similarities and complement each other. As such, similarly to the field of creativity research where systems approaches have been used to build a systems model of creativity [5], [6] and model the developmental patterns of creative individuals [7], [8], we set out to use elements of systems thinking as an approach for understanding design activity. In particular, we introduce a novel approach to analyzing design protocols by using *systems mapping*, which presents many useful properties for investigating design activity. The research question that guides this work is:

> *What can a systems mapping approach to analyzing design protocols tell us about design activity?*

The rest of the paper is organized as follows. We first provide an overview of systems thinking and its relationship to design. We then go on to briefly talk about systems mapping as a commonly used systems thinking tool and introduce our proposed approach for using it to analyze design protocols. Next, we present a proof of concept of the approach by generating maps of the systems for eight design protocols and explain how various features of the maps can be used to characterize design activity. We conclude with a discussion of the implications of our findings and propose a number of future analyses that can be employed building on this foundation.

## Background

### Systems and systems thinking

A *system* is a representation that describes how a set of component parts work together in an organized manner to accomplish a common purpose. These component parts, when arranged in a particular way, make up systems of various scales and purposes (i.e., the system does something) [9]. In other words, the system is more than just the sum of its components.

*Systems thinking,* the way in which we engage with and understand systems, emerged as a response to the century-long reductionist view of science, which relied on the analytical approach of taking things apart to understand living systems [10]. Biologists, realized at the beginning of the 20th century that such systems could not be studied through analysis. Thus, systems thinking surfaced as a new way of looking at the world, where the properties of the parts can only be studied within the context of the larger whole [10]. The approach has been adopted and adapted to fit a variety of contexts and articulated by various theorists such as Ludwig von Bertalanffy under the umbrella of General Systems Theory [11], and subsequently by Russel Ackoff [12], Barry Richmond [13] and Jay Forrester [14], among others.

### Systems thinking and design

Systems thinking has been a matter of discussion among designers who, albeit often not consciously, recognize that their products live in contexts outside of their own design practice [16]. Espejo [17] explains that systems are mental representations or ways of looking at the world, a view that gives designers the ability to determine a set of interrelated component parts that fit together. Though the language used in the bodies of literature describing systems and early-stage design thinking is different, these two approaches share striking similarities.

Many definitions of systems thinking have been proposed since the term's initial inception [13], [18], [19], [20]. Perhaps the most comprehensive and recent definition is articulated in Arnold & Wade [3], who synthesized the various definitions and determined that "systems thinking is a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviours, and devising modifications to them in order to produce desired effects" (p. 675). This definition of systems thinking also captures more recent thinking about what design is. While design has traditionally been viewed from a problem-solving lens, Dorst [2, p. 123] and Irwin [1], for instance, explain that as problems become truly complex, our understanding of design needs to shift such that it becomes not just the creation of solutions to problems, but rather "high-quality interventions" that move the system towards a more desired state.

Richmond [13] outlines how system thinking requires problem solvers to exercise different thinking skills simultaneously (e.g., dynamic thinking or operational thinking). This is echoed in other writings of systems thinking approaches; for example, Orgill *et al.* [9] outline that systems thinking involves visualizing relationships between parts of systems, examining how those behaviours change over time and drawing out phenomena from the interaction of system parts. Designers who do this well can anticipate unintended consequences that might emerge from the interactions among multiple parts of a system [21].

**Systems mapping**

Across different disciplines, people use a wide variety of visual diagrammatic representations to understand and/or communicate ideas. From a structural perspective, these representations come down to a small range of *map typologies*. These can be radial, hierarchical, tree structures, flow diagrams, Venn diagrams and feedback loops, sometimes combining several of these characteristics into one configuration. These *maps* are often used as tools for different purposes and at various stages of a design/engineering process.

In this research we use *system mapping*, more specifically a type of tool called *Causal Loop Diagrams* (CLDs). CLDs belong to a larger typology of tools called *Dynamic Thinking Tools* [22]. CLDs aim to make explicit the structure of the system(s) being studied as well as the *system dynamics* in place - relationship between parts of a system. Causal loop diagrams are made up of *core nodes*, which are things that can influence/be influenced by something else. Nodes, often named with nouns, are variables that can augment or diminish in terms of quality or quantity. The characteristics of these nodes change due to the transmission and return of information between nodes, also known as *feedback*. Feedback can be *positive* (more of A leads to more of B) or *negative* (more of A leads to less of B) and can sometimes be *delayed* (A changes B, but after some time), adding a timescale to the relationship. Causal Loop Diagrams present an effective way to represent complex systems in a succinct form, by making explicit the inherent dynamic interrelationships between its parts. For the remainder of the paper, we refer to *Causal Loop Diagrams* of the systems we are trying to visualize as *map(s)*.

### System mapping for analyzing design protocols: a novel approach

Over the last few decades, design researchers have sought to understand the mental processes and representations involved in designing, a research area called ‘design cognition’ [23]. Though a number of qualitative and quantitative research methods have been used in this endeavor, verbal protocol analysis [24] stands out as one of the dominant approaches [23], [25]. Designers’ verbal utterances are recorded, transcribed, and later coded, typically using a predetermined coding scheme, which results in a quantitative data set. These data points enable researchers to investigate many aspects of the design activity from which the protocols were collected.

In this paper, we propose a new way to analyze verbal protocols by creating maps from verbal utterances. Typically, system mapping is used to help the problem solver identify and visualize system components and their interactions as they work to understand the problem and identify interventions. In our study, we use such mapping as a research tool to *retrospectively* visualize designers’ evolving mental representations [17] through their verbal narratives while working on a design task.

The process of using system mapping for analyzing design activity differs from other protocol studies, in part because we do not use a pre-defined coding scheme. Instead, we follow a set of rules, or heuristics, derived from the literature, using nodes and arrows to depict relationships that describe the systems dynamics taking place (see section on systems mapping). As design conversations are changing and evolving (as the participants explore the problem and solution spaces), nodes and dynamics can be identified at any point in the session.

To our knowledge, this type of system mapping approach has not been previously applied to protocols in this way. To illustrate the use of the proposed method, and to provide a preliminary assessment on whether the approach can be useful for understanding design activity, we conducted an exploratory study using an existing data set collected by one of the authors.

## Method

### Data collection

The data studied in this research consisted of eight verbal protocol transcripts, originating from video recordings. In the study, eight groups of industrial design master students (three per group) were tasked with generating solutions to an open-ended problem. Students were randomly allocated across groups, though most had on average two students from an industrial design background and one from either mechanical or civil engineering backgrounds. The age of the participants ranged from 22 to 26 years old. Each group was provided the following instructions:

*"Different people have different waking up experiences in the morning. However, a great number of people consider this process as unpleasant. How might you improve the morning waking up experience? As a team of three, generate new and useful ways (a product/system/service) that provide people with a positive waking up experience. If you generate several ideas, make sure you choose one final concept, and make a clear sketch of it. You should spend approximately 30 minutes on this activity."*

The video recordings of the design activity were captured by the students themselves as part of an assignment in a graduate course about design methodology. Students were tasked with watching the video footage and searching for, as well as reflecting on, key moments in their idea generation session with an impact in their thinking and decision-making process. Transcripts from the videos were later generated by a research assistant, and not the students themselves. The eight transcripts each had, on average, 3637 words and ranged from 2090 to 5044 words.

While the length and contextual setting of this 30-minute activity is not a realistic simulation of real-world practice, the structure of these sessions shares a reasonable number of similarities with how students would approach this type of design brief in a studio setting. Therefore, and despite the brevity of these sessions, we consider this to be a plausible starting point to explore the use of systems mapping to analyze some aspects of design activity.

## Generation of maps

The following protocol was developed for generating maps of the systems in question from the transcripts. As the coders review the transcript line by line, they seek to identify nodes and system dynamics. A *node* is identified whenever a participant (*i.e.*, student) describes an entity that can influence or be influenced by other entities, and thus has a measurable quality or quantity. The coder then assigns the node a short label that captures its meaning. *System dynamics* describe how one node influences another and is here interpreted in three ways: positive (+), negative (-), or no evident increasing or decreasing effect but somehow related (+/-). As such, system dynamics labels indicate the nature of influence that one node has on another.

As the design activity unfolds, nodes and dynamics are recorded once only, when they first occur. It is helpful to conduct both the coding and visualization of these elements (*i.e.*, drawing the map) simultaneously. This process helps the coders connect nodes that were recorded earlier in the session to those that are identified much later. However, if a node or system dynamic is articulated in a different way or the group's understanding of that relationship between issues changes, this alteration may be reflected in the maps with the addition of new elements, but not the redefinition of existing elements.

Although all groups were posed with the same problem statement, each session produced a unique set of nodes and system dynamics. As the coders attempted to use the language of the participants as much as possible, to avoid subjective interpretation, no predetermined coding scheme (*e.g.*, by coding for common nodes) could be feasibly created beforehand. In most protocol studies, reliability of the applied codes is determined by an inter-rater reliability score calculated from an independent coding process between at least two coders. However, in this case, a lack of a predetermined codes prevents a reliability score from being calculated in this way. In our approach, the codes emerge from the verbal protocol and how certain verbal utterances are potentially interpreted by the researchers.

Despite efforts to follow the language of the participants, the interpretation of verbal utterances and the use of guidance to build the maps of the different systems [22] often resulted in different node names. Whereas we have no specific metrics to report, we have tested our overall process internally. Two of the authors independently generated maps for a subset of the groups. We observed that while the labeling of the nodes differed, different coders produced maps that were similar along the general patterns that drove most analyses (*e.g.*, number of nodes and interconnections between those nodes). However, it should be noted that when two independent coders create maps individually, though they may reliably identify entities in the same place of the transcripts, the resulting map may be different. It is possible to arbitrate between two sets of coders which would result in a single map used for the analysis, but given the exploratory nature of this work, this was beyond the scope of the project.

In Table 1, we present an excerpt from one of the groups' transcript to demonstrate how nodes and system dynamics were defined during the coding process. Consider the utterance by P3: *"I think we can start with defining what our problems with waking up [are]? And then we can work from there?*" A node is identified and labeled as "Quality of waking up experience". Now consider the next utterance by P1, who says "*Maybe also the sound…it is not a nice way of waking up. Like with stress*". Here, a new node is identified – "Amount of sound", as well as a new relationship (system dynamic): The new node has a negative (decreasing) influence over the previously identified "Quality of waking up experience". Finally, within that second utterance, another new node is also defined and given the name "Amount of stress". Another system dynamic is also inferred: the "Amount of sound" node has a positive (increasing) influence over the node "Amount of stress". The map generated from these nodes and system dynamics is visualized in Fig. 1.

**Table 1** Coded transcript excerpt from design protocol of Group 2

| Verbal utterance by participants (P) | Generated nodes (N) and system dynamics (D) |
|---|---|
| P3: I think we can start with defining what our problems with waking up [are]? And then we can work from there? | N1 = Quality of waking up experience |
| … | |
| P1: Maybe also the sound…it is not a nice way of waking up. Like with stress. | N2 = "Amount of sound"<br>D1 = N2 decreases N1<br>N3 = "Amount of stress"<br>D2 = N2 increases N3 |

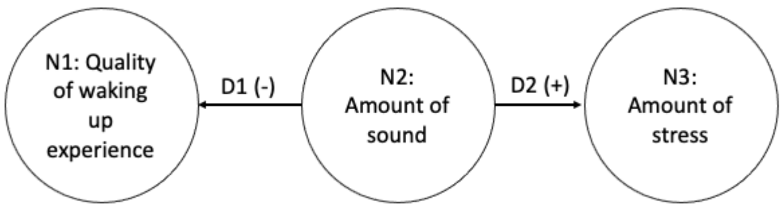


**Fig. 1** Nodes generated from excerpt in Table 1

Once we coded all transcripts, the data was formatted in order to be read by an open-source network visualization and analysis platform called Gephi [26]. Gephi offers a variety of rendering and data analysis tools that are useful for understanding the structure of the maps of the systems being portrayed.

## Results

Using the protocol described above, we generated maps from all eight transcripts, as presented in Fig. 2. The generated maps vary both in size (*i.e.*, the number of nodes and system dynamics) and structure (*i.e.*, patterns of interconnections between nodes as determined by the system dynamics). In this section, we describe some preliminary analyses conducted on the maps, along three main aspects: size of the maps, evolution of the maps overtime, and discernable patterns in those maps related to their structure. Their potential significance, extensions as well as other approaches for analyzing the maps are presented in the Discussion.

### Size of the map

The number of nodes and system dynamics provide two simple attributes by which to characterize a map. Fig. 3 presents the total number of nodes and system dynamics (labelled "elements") in each of the maps generated from the eight protocols. There is a notable variation between groups, even though all groups worked on the design task for approximately the same amount of time (average 34 minutes across groups). At the extremes, the largest contrast is observed between the number of map elements generated from the design activity of Group 3 and that of Group 7. The map of Group 3 is also notable because it is the only one in which the number of system dynamics is larger than the number of nodes. We also note that except for Group 4, there is a positive relationship between the protocol length (in words) and the size of the map.

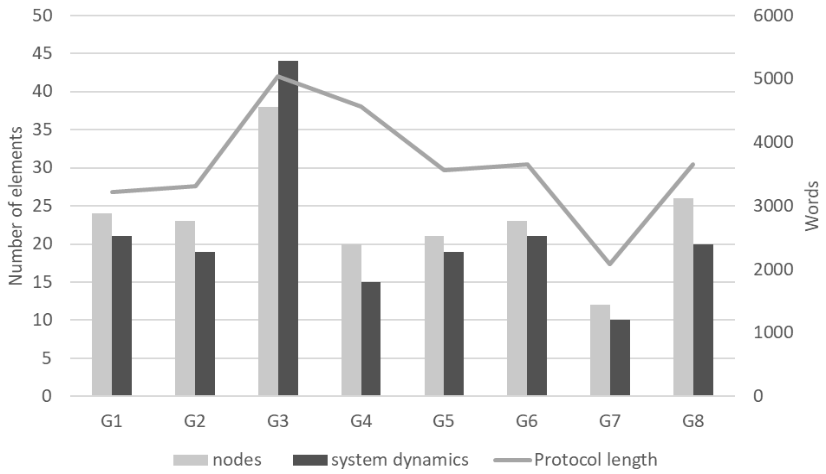


**Fig. 3** Frequencies of identified nodes and system dynamics (left axis), and protocol length (in words - right axis), by group

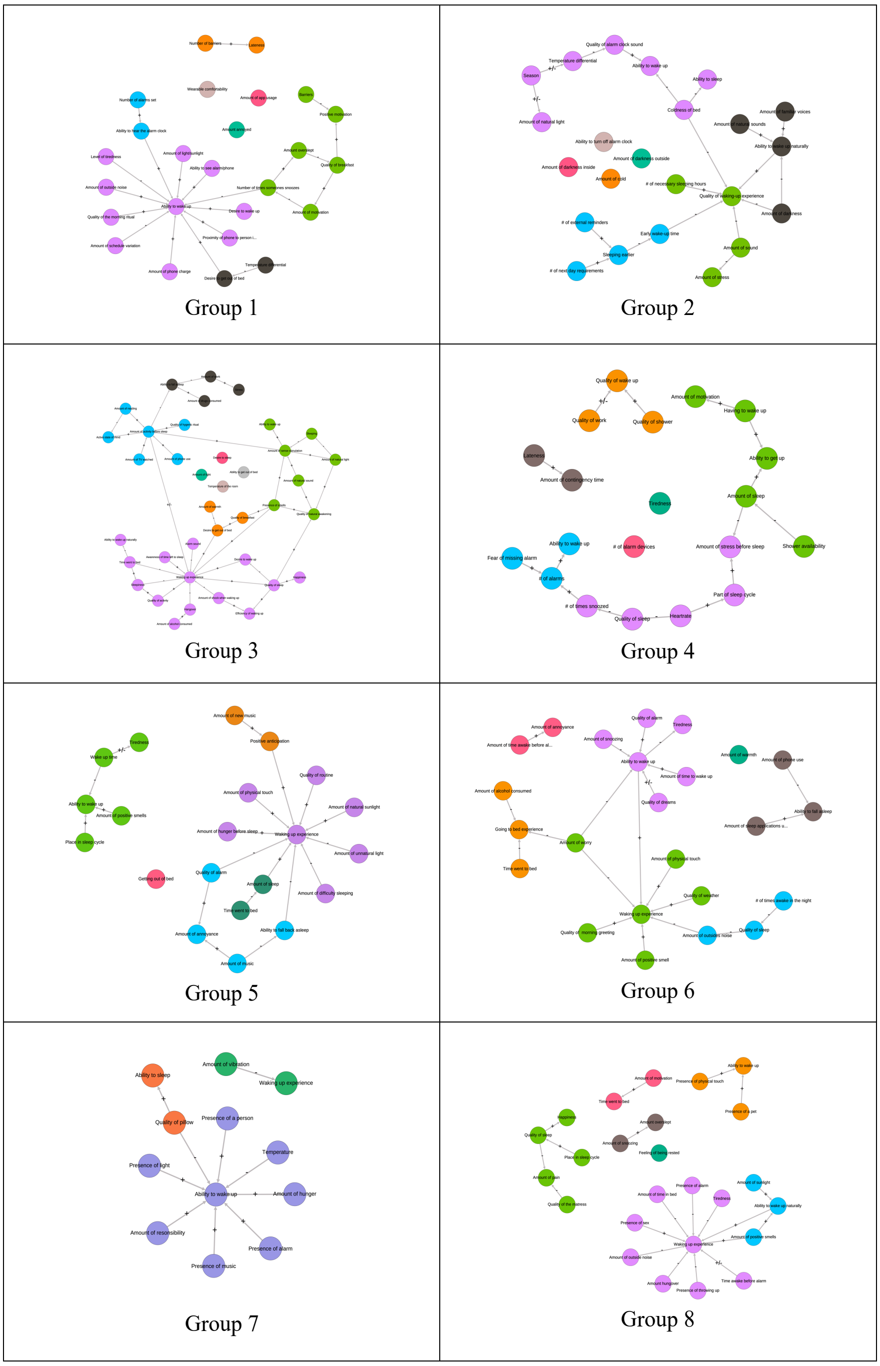


**Fig. 2** Generated maps for all eight groups with modularity analysis

## Maps over time

The approach also facilitates analyses in the temporal dimension. To observe how the maps evolved over time, we divided each protocol into 20 equal segments and counted the nodes and system dynamics that emerged in each ventile. Fig. 4 presents a cumulative graph of these occurrences, for each group.

A clear general pattern can be observed: in the early parts of the sessions there is a rapid emergence of new nodes and dynamics, as participants begin to analyze the problem. For most groups, new additions to the map taper off about halfway through their design session. At this point, the designers' conversation shifts focus from framing the problem to generating solutions or continuing conversations about topics which were already previously captured by certain nodes and dynamics.

Different groups vary in terms of the rate at which they produce new nodes and system dynamics throughout their session. For example, while Group 7 produces no new additions to the map after the 10th ventile, other groups continue to add new elements in the second half of the session (albeit at a slower rate), and as late as the 19th ventile.

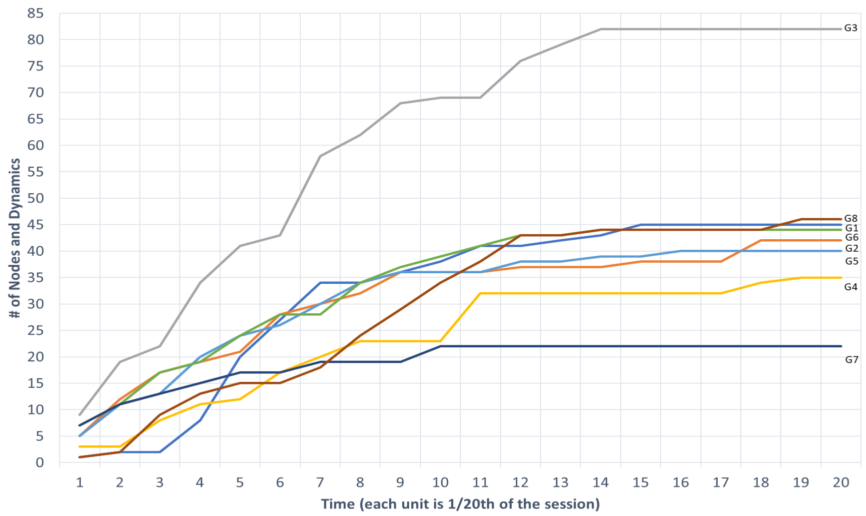


**Fig. 4** Cumulative graph of nodes and dynamics emerging over time, by group

## Patterns in maps

The overall structure of the maps may also tell us something about the designers' approach. Visually, we observe that nodes can be organized in various clusters, especially those organized in a "hub and spoke" configuration. To detect these clusters in the maps, we use the modularity function in Gephi, which uses a community detection algorithm [27]. The detected node clusters for each group are color-coded in the maps presented in Fig. 2. When considering clusters of at least two nodes, the eight maps each have three to six clusters.

We take the example of Group 3, which produced the largest and most complex map (Fig. 5), to explore the significance of the detected clusters. In our analysis, we take advantage of both the nodes' labels and the solution ideas that the groups generate that are related to those nodes. The latter are noted in the transcript by the coders, and included in the map in Fig. 5 labelled in red, but are not part of the standard protocol introduced in this paper.

Group 3's map has five clusters of three or more nodes each. The largest cluster (in purple) centers on the "waking up experience" node; but in this case it is hard to detect a clear focus. The nodes in this cluster represent several under-developed threads that capture the entire time window from "before going to bed" to "waking up the next day". The idea that the group discusses, as the nodes in this cluster emerge, is that of a "sandwich" alarm, one that both reminds the user to go to bed (thus allowing for a sufficiently long sleep) and wakes the user up in the morning.

The other three distinct clusters have a clearer focus:

- The nodes in the blue cluster center on the activities one engages in before going to sleep (*e.g.*, watching TV, reading, and using the phone). Solution ideas are targeted at making these activities "dull" and relaxing, for example by having the user exposed to nature images and listening to audio-novels.
- The nodes in the black cluster relate to one's ability to actually fall asleep once in bed, which might be affected for example by stress, drugs, and anxiety about work to be done. The ideas that emerge in response are, for instance, a mattress that massages the user to sleep and stress-reduction activities like meditation.
- The nodes in the orange cluster focus on one's desire to get out of bed, particularly in relation to the temperature of the bed and and the quality of the breakfast. There were limited solution ideas related to this cluster.
- Finally, the nodes in the green cluster focus completely on the awakening processes, especially with regards to the role of the senses (*e.g.*, smells, lights). Accordingly, related solution ideas focus on engaging with the senses, for instance through an automatic curtain that allows natural light to come in when it is time to wake up.

This analysis supports the idea that clusters represent different aspects of the problem that the designers are thinking of and paying attention to at different moments during the design session. The significance of this analysis and possible extensions are further addressed in the Discussion.

## Discussion

At a high level, we set out to study design activity from a systems perspective, under the assumption that such a viewpoint would provide a general framework to understand design activity. The contribution of this paper is the introduction and preliminary evaluation of a novel protocol analysis approach that uses system mapping as a visualization to code verbal protocols of design. Our research was guided by the following research question: *What can a systems mapping approach to analyzing design protocols tell us about design activity?* The results support our assertion that the contents of the protocols could be approached as a complex network of nonlinear dynamics where groups of interconnected and interrelated 'parts' can be studied as a system. Given the exploratory nature of this work, our study raises questions that prompt future research directions. Below, we summarize our contributions and their implications for future research. We also propose areas of inquiry that prompt new ways in which the maps can be further analyzed.

### Contributions and significance

System mapping are a useful thinking tool to help make explicit the structure of the system being studied, including the various "parts" and their interrelationships. In the design context, a system mapping serves to uncover and visualize the designer's understanding of the complex problem being defined and analyzed, with the aim of identifying leverage points where interventions (or solutions) can be designed [28]. It then follows that maps generated retrospectively based on transcripts of design activity would best capture designers' work in the problem space.

#### *Tracing co-evolution and maturity of design process*

The temporal analyses on the eight generated maps provide further support for the assumption that these can effectively capture the designer's activity in the problem space. For all groups, most of the nodes and dynamics were generated in the first half of the session, when the participants were mostly identifying what affected their waking up experiences. Any new additions to the maps tapered off in the second half once their attention turned to ideating and refining generated solution ideas.

One potential implication of this finding, is that cumulative graphs that maintain an increasing slope for a longer portion of the design session indicate that the designers engage in a process of problem-solution co-evolution [29], [30] for longer, demonstrating a more mature design process and higher design expertise [31]. The approach thus has the potential to be used as a means to compare designers across disciplines and/or levels of expertise, as has been previously done with other verbal protocol analysis approaches (*e.g.*, [32], [33]).

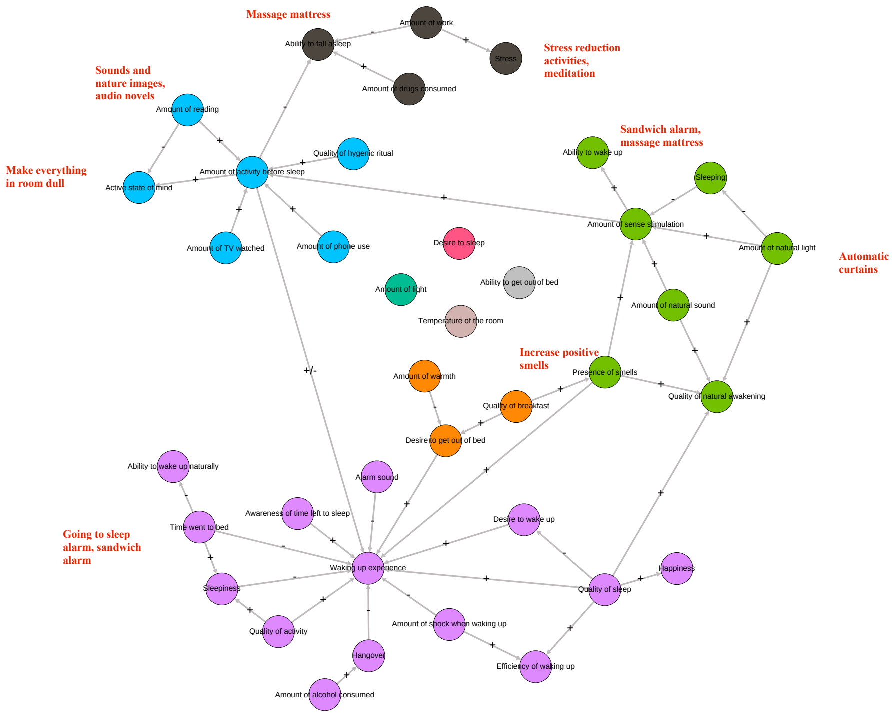


**Fig. 5** Map of Group 3 with nodes color-coded according to clusters and ideas highlighted in red

***Bigger maps, better designs?***

If the system mapping captures the designers' activity in the problem space, then the structure of the generated maps can provide a useful way for characterizing the designers' problem analysis activity. Comparing the maps of the eight groups, we found they varied in the number of nodes and system dynamics generated.

The question that emerges is whether groups whose protocols produced larger maps explored the problem space to a greater extent, and whether this points to a higher-quality design outcome. The approach does not presently provide any objective assessments of the quality of the nodes themselves, other than their location in the map, relative to the other nodes. This point is further elaborated on in the next section.

***Maps as signatures of frames***

The maps show promise as a means to capture related cognitive activities such as problem framing [34]. Visual inspection of the maps reveals that the nodes are organized in "hub-and-spoke" clusters, the boundaries of which can be computationally determined through modularity algorithms, which can determine "communities" of related nodes. Inspection of the detected clusters in the map of one of the groups in our study showed that each focused on a particular aspect of the problem, prompting different kinds of solutions that addressed it. We thus believe that the maps provide insight on which aspects of the problem the designers choose to focus on - that is, which problem frames. When combined with temporal analyses of the creation and evolution of these communities over time, the maps have the potential of providing a window into the designers' framing and reframing activity throughout the design session.

When exploring the meaning of the node clusters for one of the groups, we made use of the solution ideas that the group generated to better understand the theme (or frame) of nodes in a cluster. In this preliminary work, we did not devise a systematic way for coding, tracking, and "placing" solution ideas in the maps. However, we believe it would be worthwhile to investigate the relationship between solution ideas and nodes and system dynamics in the map.

In particular, we expect that our approach can shed light on the quality of idea generation. If each cluster of nodes captures a different frame, a question that arises is whether there is a relationship between the characteristics of a cluster (*e.g.*, size and structure) and the quality of the frame in terms of the generated solutions that it prompts. One may hypothesize that a map with many highly populated clusters might be indicative of more *flexibility* [35] during idea generation (the ability to devise ideas that diverge into new and unusual directions) and thus more promising solutions compared to a map with few and/or small clusters. We might also be able to identify which nodes become essential when designers generate solutions.

## Future research

Below we describe a number of future directions for further improving on the approach and expanding on the range of analyses it can afford.

### *Centrality and design fixation*

Network analysis methods can be useful for drawing further insights from the maps. For example, centrality metrics can describe the extent to which any node can influence or be influenced by other nodes in the system. Combined with temporal analyses, centrality measures can be used to indicate if, for instance, design fixation is occurring. The approach as described in the Method section only keeps track of when a node or system dynamic is first identified in the transcript. Therefore, all analyses described in this paper are based on the first occurrence [36] of those elements. However, one could also keep track of subsequent occurrences of those nodes and system dynamics; participants sometimes mention the same concepts/topics again later in the session, so subsequent occurrences of previously identified map elements could be noted and tracked.

### *Mapping shared understanding*

The approach can also be used for analyzing team collaboration by assigning 'ownership' of a node and system dynamic to the participant from whose verbal utterance it was generated. With this approach, using the map visualizations it may be possible to detect a team's ability to create a shared understanding, or mental model [37], of the problem. The maps might reveal each team member's contribution to building the team's understanding of the problem and the extent to which they build on their own or other team members' ideas. We expect that for those groups who are able to build on each other's nodes and system dynamics, will collectively reach a more comprehensive problem understanding.

### *Systems thinking maturity*

Finally, the approach offers appropriate language and tools that can be used to characterize designers' ability to think systemically, by considering the wider complexity of the system and interconnections between parts/issues, a skill highly relevant and useful when solving wicked problems [38]. Given our dataset and the maps generated from the design activity of the eight groups, a question that arises is whether the groups with more nodes and system dynamics might be better able to think systemically. It would be useful to compare and contrast this approach with, for instance, recent research on assessing *systems thinking maturity* through the use of new and improved assessment rubrics [3].

## Conclusion

In this paper we have introduced a new approach for analyzing design activity that is inspired by systems thinking approaches. In most protocol analysis studies codes applied to transcripts are typically determined before the process begins. In contrast, our exploratory work uses system mapping as a diagrammatic notation of design conversation that evolves as designers continue to work on the problem.

The approach we have proposed was developed on the basis of an existing body of literature that has been used in many different contexts, like living systems and social networks research. These perspectives offer useful frameworks and metrics for understanding the generated maps of the different systems being portrayed. We have provided a proof-of-concept demonstration of the approach by testing it on verbal protocols collected from eight groups engaged in an early problem analysis and ideation activity. A preliminary analysis of the eight generated maps provides promising results about the usefulness of the approach, especially in capturing a designer's activity in the problem space, and points at an exciting array of research directions for capturing other design processes and phenomena.

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