Using systems mapping to understand design framing

by

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AUTHOR'S DECLARATION

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

Gregory Litster was the sole author for Chapters 3, 4, 5 and portions of Chapters 1, 2, which were written under the supervision of Dr. Ada Hurst and were not written for publication.

This thesis consists in part of two manuscripts written for publication, with major changes to the material for the thesis. Exceptions to sole authorship of material are as follows:

Research presented in Chapter 1 & 2:

This research was conducted at the University of Waterloo by Gregory Litster under the supervision of Dr. Ada Hurst. Gregory Litster designed the literature review, completed the data analysis, and drafted the manuscript. Dr. Hurst provided intellectual input on manuscript drafts.

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Abstract

Design is a cognitive activity that involves an iterative process of problem definition, analysis, solution synthesis, and evaluation. These are necessary for grappling with the complex and ill-structured nature of design problems, that are shaped and focused by those who attempt to solve them. Early parts of the design process require designers to select into view elements of the problem that they deem important for generating solutions. These elements are interconnected and dynamic, shifting criteria and constraints that the designer must consider as they explore the design space. This exploration process is commonly referred to as problem framing, which is essential to the success of creating solutions to design problems.

One useful way that designers can understand the complexity inherent to design problems is by using systems thinking. Systems are commonly thought of as sets of components or parts with interrelations between them which, when arranged in a particular way, carry out a specific purpose. Systems thinking is the way that we understand those system components and the interrelations in order to create interventions, which are often used to move the system outcomes in a more favourable direction. As such, systems thinking has emerged as a promising approach to aid in designers' understanding of complex design problems.

This thesis proposes a novel research approach to understand design framing activity using a system thinking lens. In particular, I use a common system thinking tool – systems mapping – which is often used to visualize complex situations in order to gain clarity of the elements that are important. I use the systems mapping approach on verbal protocols of designers engaging with design problems in two separate design contexts, in order to retrospectively understand their framing activity. The system map visualizations are analyzed from a wide variety of perspectives, highlighting the novel approach's use to understand design behaviour.

The method and analyses conducted suggest that these system maps offer a representation of the design framing activity that occurs in each session. Furthermore, small communities of related nodes could represent design frames, used by the designers to create targeted solutions to the design problem. In addition, a temporal analysis on the development of nodes

and system dynamics indicates these elements are developed mostly in the early parts of the session, highlighting when framing of the problem occurs. Finally, by assigning ownership of each element added to the system map, the contributions made by each participant can be visualized and analyzed to demonstrate the group's collective understanding of the problem.

In conclusion, the efficacy of the approach for understanding design framing activity in particular stages of the design process is emphasized. That is, the system mapping approach is well suited to visualize the framing activity that occurs in open-ended problem contexts, where designers are more focused on problem finding and analyzing rather than specifying details of their solutions. Several future research avenues for which the approach would be useful are proposed, with the goal of testing systems mapping in a wider range of problem contexts.

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Chapter 1 Introduction and Literature Review

Design is cognitive activity which involves the creation of products, systems and services that will move society to a more desired state of affairs (Goel and Pirolli, 1992). Design researchers, since the 1960's, have interrogated the nature of design to determine the degree to which design is a science, a method, or process that might be codified (Cooper, 2019). Research with designers has received considerable attention from academics determined to extend the knowledge of the underlying cognitive processes of design practice (Cooper, 2019; Hay et al., 2020). Design practice is concerned with creating solutions to design problems, which inherently lack structure and are commonly ill-defined (Cross, 1982). The ill-defined nature of design problems requires that designers learn to define, redefine, and change the problem-as-given in the light of the potential solutions that emerge (Cross, 1982).

A similar conceptual framework for approaching problems is systems thinking. Like design thinking, systems thinking has become one way of looking at the world to understand its complexity (Checkland, 1999). Though the definitions vary in different contexts, in general a system is regarded as a set of connected elements that form a whole, and the properties of that whole are different than just a collection of those same individual elements without connections (Checkland, 1999). *Systems thinking* is the way we understand those elements, see interconnections between them, and ultimately ask questions about their future behaviour to inform system interventions when necessary (Meadows, 2008). Systems are important to design teaching and practice, as designers recognize their designed solutions exist as elements within systems or are systems themselves (Buchanan, 2019). Though there are recent examples of design and systems thinking being explored together (Buchanan, 2019; van der Bijl-Brouwer & Malcolm, 2020) these two approaches have largely been explored in isolation from one another (Greene et al. 2017).

The lack of research focus at the intersection between these two approaches is the motivation for this thesis. Inspired by the applicability of systems thinking to understand complex problems, this thesis proposes and explores a new research approach to understand design activity. I use a systems thinking tool – systems mapping – on verbal protocols of design activity to characterize the design process used by designers in two different design contexts.

I take particular interest in using the novel approach to make salient the design frames – ways of looking at a problem – designers develop in the early-stages of their design process. Throughout this work, I emphasize how the systems thinking literature offers appropriate language for exploring the complex phenomenon of design and how the proposed research approach offers a unique perspective on design processes.

The remainder of the thesis is structured as follows: Chapter 1, so far, has introduced the motivation for the work. The remainder of this chapter will explore, in more detail, the literature on design (section 1.1), problem framing (section 1.2), systems thinking (section 1.3), and protocol analysis (section 1.4) to contextualize the remaining chapters. In section 1.5, I will introduce the novel approach taken in this research. Chapter 2 will introduce the methodology, providing specific details of two studies that were conducted to create and test the method. Chapter 2 will also introduce and demonstrate what a system map is and how they were generated. Chapter 3 focuses on the results of the first study and includes details of several different analyses that the system map visualisations afford. Chapter 4 presents the results of the second study, highlighting the approach's use in a second design context. Finally, in Chapter 5 I will offer discussion, specifically focusing on how the visualizations and quantitative analyses can further inform our understanding of design framing and how the systems maps can detect design frames. This chapter will also provide commentary on the limitations of the method, but I will conclude the thesis by offering some suggestions for future research avenues and extended use of the method.

1.1 Design

To appropriately frame the methodology and discussion presented in later chapters, it is first important to understand the concept of design. A single definition of design, like many other phenomena, is difficult to articulate. Theorist and practitioners have been defining design for decades. Most notably the work of Herbert Simon in *The Sciences of the Artificial* (1969) and Donald Schön in *The reflective practitioner* (1984b) have provided a foundation for many of the discussions around the concept and practice of design.

1.1.1 Defining design

From Simon's view, design is a planned course of action aimed at changing existing situations into preferred ones (Simon, 1969). Simon believes that design is a rational problem-solving process where design artefacts (whether they are products, systems, or services) are created and used to attain goals (i.e., how things should be). In traditional problem solving, formal rules of logic are at the base of generating solutions (Simon, 1969, p. 114). If the designer's goal is to determine a solution given a certain set of conditions, they should devise the set of all possible solutions and select the one that optimizes those conditions. However, when dealing with a problem as complex as design problems typically are, in which all criteria and constraints cannot be known or there is not an objective measure of utility, devising an optimal solution is unrealistic (Jonassen, 2011, 142).

As such, Simon introduces the term "satisficing" to refer to solutions that are not optimal but are satisfactory under the circumstances (Simon, 1969, p. 119). To Simon, design solutions are the sequences of actions that lead to the desired situation under a certain set of conditions (p. 124). He recognizes that both alternative courses of action and the goals (the criteria and constraints to be satisfied) emerge in the design process (Simon, 1995). The search process for alternative courses of action, however it is structured, is generally understood as the way designers gather information about the problem and use it to create solutions.

Schön's writings (1984a, 1984b, 1987), focus more on how, through interaction with the problem, the designer shapes the problem. For Schön, the foundation of design practice is 'reflection-in-action'. Reflection-in-action occurs when a designer experiences surprise in their problem (i.e., something that fails to meet expectations), which diverts from their regular problem-solving activity (Schön, 1984a, p. 28). This surprise triggers feedback from the situation, a kind of 'talk back', to which the designer responds. A good designer is said to have a "reflective conversation" with the design situation in which they will consider and weigh a set of actions and the consequences of those actions. When actions are implemented, their consequences are observed which will later require more actions, which in turn will have their own consequences, and so the process continues. It is this reflective conversation with a problem situation that eventually leads to a solution.

This idea is echoed in writings by Maher & Poon (1996) and Dorst & Cross (2001), in which the design process is described as a co-evolution of problem and solution spaces. In this case, distinct problem and solution spaces interact over time. Evolution of the two spaces occurs simultaneously, each with mechanisms to inform and expand the other. For example, new information about a requirement or constraint in the solution space might help refocus the definition of the problem in the problem space. The reflective conversation that Schön describes is exactly the mechanism which might expand the problem or solution space, until a desired approach is reached.

In a recent review of the literature on problem-solution co-evolution, Crilly (2021) argues that the distinction between problem and solution elements are relative rather than absolute. He states that in general, people understand problems as description of unfavourable situations and solutions as the descriptions of those actions that will produce an improvement to that situation (p. 320). However, talking about problems and solutions as occupying separate "spaces" that co-evolve has marked them as different kinds of thing, rather than a different perspective on the same kind of thing. This is again echoed in recent writing by Nickel et al. (2022), whose framework for modelling interactions between parameters in the problem and solution spaces intentionally removes the distinction between the two. Following from this paper, I will use the term "design space" when describing elements of either problem or solution spaces.

1.1.2 Design as an approach for solving complex problems

One might also think of design as the way in which we approach design problems, that is, those steps that designers take to create solutions to design problems. What is not immediately evident are the criteria used to define a 'design problem'. Though there are likely many definitions of design problems, some of the most notable efforts to characterize them come from Goel and Pirolli (1992), Jonassen (2000, 2011), and more recently Dorst (2015).

Goel and Pirolli (1992) offer a set of characteristics to classify design problems. They note that information in design problem spaces; including the start state, goal state and function to move between these two states, is typically limited (p. 401). In the start state there exist several constraints which vary in nature (i.e., laws of physics are non-negotiable compared to political policy that can be negotiable). These constraints live in a problem space which is usually large and complex, leading to many components and interconnections between them (p. 401). As a result of this complexity, any change in the problem space that occurs as a result of a design decision has costs and consequences. This means that design problems do not have right and wrong answers, only better or worse ones depending on the consequences. Finally, Goel and Pirolli make the distinction between design specification of the thing being designed and the delivery of that thing in its intended form. In this case, design specification always comes before delivery of the designed product, system, or service.

Jonassen (2000, 2011) proposes a typology that can distinguish between different problem types along a few characteristics. Importantly for design problems, according to this typology, they are one of the most complex and ill-structured of any kind of problem, next to dilemmas (Jonassen, 2011, 138). In his view, complexity of a problem refers to how clearly and reliably components are represented in the problem and how stable those components are over time (Jonassen, 2007, 68). Ill-structured problems have unknown elements, multiple solutions, and multiple criteria for evaluating those solutions (Jonassen, 2011, 67).

In another, albeit broader, view Dorst (2015) describes design problems as open (the borders of the problem are unclear), complex (many elements and connections between them), dynamic (the problem situation changes over time), and networked (problems are related to one another). Design then is any such method, no matter how it is structured, for which problems with these characteristics (as described by Jonassen, Goel and Pirolli and Dorst) can be handled (i.e., a useful solution is created) with some level of sophistication and rigour.

1.1.3 Design as process

The consideration of design as a problem solving activity has prompted the development of phase-based models of the design process, which guide the designer through various stages - from problem definition to solution implementation – each with its own associated methods (Lawson & Dorst, 2009, p. 32). Several prescriptive models have been proposed, including those developed by Jones (1970), Pahl & Bietz (2007), and Cross (2000). For Jones (1970), as summarized in Evboumwan et al. (1996), core activities of designing are those associated with *analysis*, *synthesis*, and *evaluation*. In analysis, designers list all design requirements and then reduce them to a complete set of logically related specifications. During synthesis, designers find possible solutions for each of the specifications and build alternative designs from these. In the evaluation phase, designers evaluate the accuracy with which any one alternative fulfills the requirements determined in the analysis phase and a final design is selected. Building on previous models of design, an integrative prescriptive model is proposed by Cross (2000), who further breaks up the earlier stages of the design into clarifying objectives, establishing functions of the new design, which are specified in requirements, and determining the characteristics of the solution, such that they satisfy the requirements. The next phase, generating alternatives, maps on to the synthesis phase as described by Jones (1970). Finally, potential solutions are then evaluated and improved upon, in the final two stages, which map onto Jones (1970)' "evaluation" phase (Cross, 2000, pp. 57-58)[1].

These models generally assume that the designer has already been provided with a problem definition, with design goals that are often "explicit, clear and stable" (Lawson & Dorst, 2009, p. 32). They are therefore commonly used in technically oriented design professions (as exemplified by one of the most influential engineering design methods books - Pahl and Bietz (2007)) and in later stages of the design process. More recent models of design are more "inclusive" of design contexts in which the designer is provided with severely ill-defined problems, requiring the designer to spend much more time and effort in the activities of need finding and needs analysis. Building on the other models, the process is visualized by four alternating phases of divergent and convergent thinking, as also popularized in the Double-Diamond model of design (Design Council, n.d.), shown in Figure 1. Prompted by a challenge, need, or problem opportunity, in the early phases of the design process (i.e., first "diamond"), designers attempt to understand the real need (or client's problem statement), clarifying and establishing metrics for the objectives, all while imposing their own subjective lens to construct or *frame* the problem to be solved (Dym et al., 2009, p. 25). Problem framing

[1] I should note that the examples explained here are only a few of many prescriptive models of design that have been proposed. A more detailed summary of some of these models, as well as many others, can be found in Evboumwan et al. (1996).

is then a key component of the design process, which will be discussed in detail in the next section.

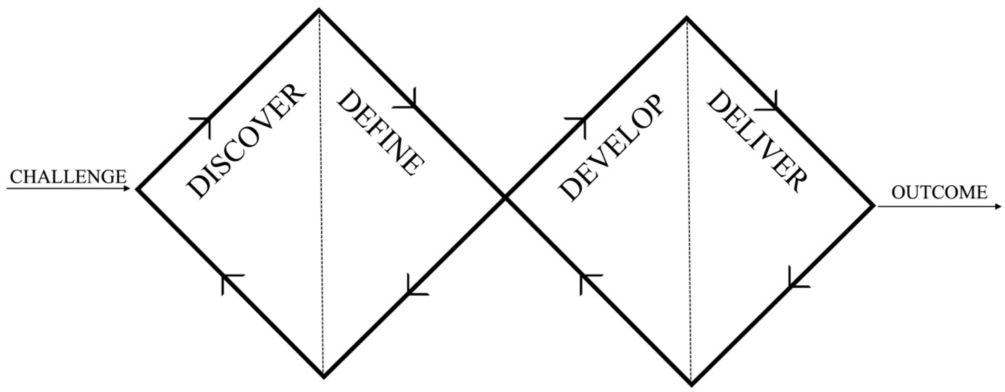

Figure 1 The Double-Diamond Design Process

1.2 Problem framing

The concept of problem framing in design theory is largely based on Donald Schön's (1984a, 1984b, 1987) work on reflective practice. Schön explains that problems rarely present themselves as given, and in practice are constructed from the materials of problematic situations which are puzzling, troubling, and uncertain (Schön, 1984b, p. 40). Schön's description of a "reflective conversation", as explained in section 1.1.1, between the problem solver and the situation forms the foundation of this construction (Schön, 1987). In this view, designers have a perception of their situation and are able develop a set of possible actions (using reasoning) which will have influence on the situation (Paton and Dorst, 2011). Described as a "web", the set of possible actions and their consequences, often lead to a restructuring of the initial understanding of the problem (Schön, 1987, p. 42). The reflective conversation forms the initial phase of exploration, where problem solvers select what will be treated as "things" of the situation and what boundary exists around those things (Schön, 1984b, 40). It is this work that lays the foundation for more recent accounts of problem framing in design.

Simon also provides commentary related to problem framing, though it is less specific than Schön's account, with particular focus on bounded rationality and limited human attention (Simon, 1995). Bounded rationality is the idea that our ability to understand the complexity of the world and make decisions in it, is limited (Simon, 1969). When trying to understand the complexity, designers seek out relevant information, which is often readily available. However, as we seek the information, only a small fragment of it can be in our focus at any one moment, hence the limit of human attention (Simon 1995). As design alternatives emerge throughout the design process, so do the criteria and constraints, meaning the design problem is continually reformulated (Simon, 1995). Simon says that "design is a process of forming, finding and solving problems" (Simon, 1995, p. 251)

The most comprehensive and recent work on problem framing in design contexts has been carried out by Kees Dorst and colleagues (Dorst, 2010, 2011, 2015; Valkenburg & Dorst, 1998). In his book, *Frame Innovation: Create New Thinking by Design*, Dorst (2015) outlines a process of design framing that he has developed based on many years of observations of framing activity. Using 19 case studies of designers working on design problems, Dorst demonstrates a set of nine common practices designers use to approach their problems in a productive way (Dorst, 2015). One of those cases, which I will paraphrase below, illustrates the fundamental nature of the framing process and how it tends to lead to positive outcomes for designers. The case is described as follows:

> "Kings Cross, the entertainment district in the City of Sydney has experienced continuous problems. The district attracts some 30,000 young people over the weekend and all their activity is concentrated in a short stretch of road filled with bars, restaurants, and clubs. As one might expect with that number of people, problems including drunkenness, fights, petty theft, and minor drug-dealing have become a common occurrence. As such, the restaurant owners and police have increased security presence, in an attempt, to mitigate these problems. A group of designers from the 'Designing Out Crime' center in Australia have framed this problem differently than that of the original law and order approach. Using a metaphor (in this case acting as the frame), the designers compared this situation to a large music festival. Designers then asked themselves 'How would one go about organizing a music festival?' First, the organizers would ensure that the attendees had ample opportunity to come and go as they please. In the entertainment district, people coming into the area often arrive at 1AM, and the lasts train to leave the

area departs at 1:20AM. Once they are in the district, it becomes very difficult to leave until trains start running later in the morning, which leads to boredom and frustration. Second, music festivals have 'chill out' spaces that offer extra attractions apart from the main stage. Interestingly, the street has a few big clubs that act as the main attractions, with little to do otherwise. Folks who leave one club might find that the wait time to get into another is quite long, again resulting in increased frustration, boredom, and aimless walking around the street. Finally, the extra security personal and bouncers used as part of the conventional approach to solving the problem contribute more to the poor atmosphere than to solving the problem" (p. 31-34).

Ultimately the designers sought out the best practices of music festival design, to mitigate some problems associated with the Kings Cross district. The designers first proposed the most obvious solution to the first problem (access to transit to and from the area) by providing more trains. As a secondary solution to this problem, they proposed a fallback system of temporary signage on the pavement, to help the partygoers reach a different station that had buses running throughout the night. For the second problem (bored people on the street that have just left one of the main attractions), the designers proposed a texting service or smartphone app that allows you to check the wait time of another one of the main attractions, to minimize the chance that you will leave the first establishment and begin wandering the streets. Finally, instead of increasing the presence of menacing looking security, the designers proposed a system of very visible young 'guides' in bright t-shirts, who help people find their way through the area and are approachable when help is required.

Dorst notes that the designers' choice to use a metaphor to frame the problem situation as a music festival, rather than a typical law and order problem, opened the solution space for more manageable, yet effective, solutions. Design framing is used as an effective method to pursue solutions to complex problems, but what are the underlying reasons designers must frame?

1.2.1 Why do designers frame problems?

When a designer is faced with the level of complexity inherent in design problems, they typically start with the identification of what they know about the problem and its elements.

From the vast amount of information that exists, designers select from their environment the information necessary to create an appropriate mental model of the situation (Simon, 1969; Matthieu et al., 2000). As discussed earlier, in an ideal (though completely unrealistic) problem-solving setting, a designer would have the ability to access all knowledge of relevant problem elements in order for a solution to be developed.

Acknowledging this limitation of information processing, it is people's attention, not information, that is ultimately what matters (Bardwell, 1991; Simon, 1978). Design framing occurs in part due to the fact that human rationality is bounded and shaped by the narrow focus of human attention (Simon, 1978). Framing then becomes a necessary activity for solution creation. As such, designers select into view those aspects they believe to be relevant to solving the problem. Designers' attention may be directed to form or to function, to the whole or the details, to technological issues, to ergonomic considerations or aesthetic values, and so on (Goldschmidt 2014, p. 43-44).

Another reason designers frame is due to the paradoxical nature of design problems. Framing in response to paradoxes, situations with two or more conflicting statements, is a key and rather special element of designers' problem-solving practices (Dorst, 2011). When designers are faced with this kind of paradox they can redefine (or reframe) the problem situation (Dorst, 2015), a process that may bring previously unseen variables and approaches to the designer's focus (Nickel et al., 2022). An alternative perspective has the potential to shift designers' views about core elements of a problem and may redirect them toward different solutions (Murray et al., 2019). Frames help to simplify and create alternative views of a problematic situation; which results in alternative outcome spaces that afford a wider range of responses (Paton & Dorst, 2011). This range of responses offers a means of approaching problems in ways that might have otherwise been avoided or overlooked (Bardwell, 1991).

1.2.2 Problem frames

With a brief understanding of why it is required to frame problems, it is also useful to provide an explanation of how problem frames have been conceptualized in the literature. First, it has been determined that problem frames are personal and social concepts. While a problem can be reframed in multiple ways, individuals' interpretations of a framing can vary considerably (Silk et al., 2021). This is a result of an individual's knowledge and experience being situated, that is, a person's standpoint (i.e., individual experiences shaped by socially structured systems) will enhance or limit the tacit and experiential knowledge they can have and understand (Wylie, 2003). As such, problem frames generated by the designer(s) are situated and depend largely on the experiences of those who frame the problem. For example, in group or team designing, problem frames change over time via social interaction as individual members impose their own experiences on the collective understanding of the problem (Hey et al., 2007). Social interaction does not make the frames observable, rather frames can be shared by a team or group only to the extent that the individual members' frames overlap or align (Hey et al., 2007). In design practice, a frame is the proposal through which, by first recognizing and then applying a particular pattern of relationships, we can create a desired outcome (Dorst, 2015). Although frames can sometimes be paraphrased by a simple and elegant statement, they are complex thought tools. Proposing a frame includes the use of certain concepts, which are assigned significance and meaning (Dorst, 2015).

In an investigation of the role of question asking in problem framing, Cardoso et al., (2016) provide a working definition of a problem frame. They state that a "frame is the perspective that is imposed by the designers on the design situation at a specific time during design activity" (p. 67). Such a perspective is fundamentally about how known problem and solution elements are characterized and related to each other (Cardoso et al., 2016). This may also be described as the "discovered problem" which is related to the problem's interpretation imposed by the designers (Studer et al., 2018). Designers search for and interpret elements of the design space and draw connections between them. Frames are then, the completed patterns of problem solution connections that are imposed on the situation at that point in time (Dorst, 2003). In this way, frames act as something to hold onto for the activity that occurs following their creation (Valkenburg & Dorst, 1998).

There are several criteria that have been proposed for defining problem frames. It is believed that design frames should have a desired end state or goal and include a boundary and criteria for evaluation (Hey et al., 2007). Frames should be actionable and ultimately, like many other thinking tools, whether something is a frame or not is determined by how useful it is. Some caution is presented in Dorst (2015) when he states “We must be careful and realize that ‘what’s in a frame?’ may not be the right question to ask – a frame is not a completely static concept. […] ‘When is something a frame?’ might be a better question to ask” (p. 65).

1.2.3 Frame making

As highlighted earlier, the complexity of design problems necessitates frame making. In traditional problem-solving people tend to find solutions by mirroring what has been done before. In general, this is a useful strategy and has been observed in the behaviour of experienced designers who are able to create simple frames quite quickly (Dorst, 2011). When the problem situation is familiar, a problem frame will be the designer’s way of reading the situation and will likely come to mind early in the process (Dorst, 2011). However, sometimes new problems may be incorrectly understood as similar to old problems and thus more effective solutions may be overlooked (Bardwell, 1991). As a result, a more methodical approach to problem solving (i.e., exploration of many problem frames) which refers to the effort put forth to focus one’s understanding of the problem, might be a better approach (Bardwell, 1991). When a design project provides creative freedom for the design, designers rely on their own interpretation to produce a result, which is especially true in the conceptual phase of the design process and is best described in terms of reflective practice (Dorst, 2003).

Pee et al. (2015) describes the process of problem framing as comprising of three activities: seeing, thinking, and acting. In this case, *seeing* is the act of structuring the problem so designers can adopt certain concepts to describe the situation. *Thinking* creates the proactive steps used to define new order on the situation which will, when implemented, move the situation to a more desired state. Finally, *acting* is the implementation of the frame to generate ideas and solutions to then be tested. The see-think-act phases are iterative and usually those iterations continue to occur until a desired problem frame is developed. Pee et al. (2015) emphasize that these phases are not linear and discrete. The activities rarely occur one after another, rather the flow between them happens simultaneously and in quick succession.

In a team situation, Hey et al. (2007) model framing as a four-phase circular process which begins with pseudo frames, providing an initial understanding of the design situation. As the team explores the pseudo frames in more detail, individual team members' frames (including their assumptions and expectations) become explicit and shared among all team members. This inevitably creates conflicts, which are debated and made salient in the third step. Finally, the team works to alleviate the conflicts and negotiates a shared frame which may, or may not, restart the process.

One of the most comprehensive accounts of the process of problem framing is described in Dorst (2015). Dorst has observed that during the early phases of a design project, designers focus on the depth of the apparent problem and begin to uncover what the core challenge of the problem is (i.e., asking "What makes this problem hard to solve"). Then using a series of research techniques, the designers parse out who the key stakeholders are and what they care about. Common themes begin to emerge out of synthesis of stakeholder desires/needs which lead to the development of frames usually phrased as statements of the form "If the problem situation is viewed like…then it might be solved by…" (e.g., Kings Cross as a music festival). These frames evolve into solutions that are then integrated into the appropriate settings to determine their effectiveness. In the same way that the problem framing process, as described by Pee et al. (2015) is not linear, Dorst emphasizes that these steps are also not linear. At any point, designers might return to earlier steps or move towards steps further down the list. The key point here is that designers are identifying early what makes the problem difficult and then explicitly moving away from that difficulty by imposing another perspective. To put it quite simply, Dorst quotes Albert Einstein who says 'A problem can never be solved from the context in which it arose' (Dorst, 2015, 55).

One useful framework for analyzing these situations in order to change them into a more desirable problem-solving context is systems thinking. There is evidence that good designers exhibit the ability to think systemically (i.e., in systems) and effectively frame their problems (Cross and Cross, 1998).

1.3 Systems Thinking

A *system* is a relationship of parts that 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) (Orgill et al., 2019). Without this arrangement a system might not function as intended; or in other words, the system is more than just the sum of its components (i.e., there is something more than a simple collection of components). That is, a system's defining purpose cannot be carried out by any part of the system taken separately (Ackoff, 1994).

Systems thinking then becomes the way in which we engage with and understand systems. This approach 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 (Capra & Luisi, 2014). Biologists, in particular, 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 (Capra & Luisi, 2014). Once pioneered by biologists, systems thinking has been adopted and adapted to fit a variety of contexts; the approach has been articulated by various theorists such as Ludwig von Bertalanffy under the umbrella of General Systems Theory (1968), and subsequently by Russel Ackoff (1971, 1994), Barry Richmond (1993) and Jay Forrester (1994), among others. Often systems thinking is confused with systems design or systems engineering. Though they share many of the same principles, systems thinking and systems engineering are not the same (Monat & Gannon, 2018). Systems engineering is an interdisciplinary approach used to integrate many fields of engineering to design and implement systems.

Furthermore, systems thinking is a transdisciplinary research field that can contribute to meeting the need for improved problem framing and understanding of the engineering design process (Elsawah et al., 2015). The transdisciplinary nature of system thinking, like design, means that many definitions have been proposed since the term's initial inception (Richmond, 1993, 1994; Senge, 2006; Sweeney & Sterman, 2000). Systems thinking is also considered a conceptual framework, derived from patterns in systems science concepts, theories, and methods (Cabrera, 2006). Perhaps the most comprehensive and recent definition can be found in Arnold and Wade (2015), who synthesize many definitions and determine 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 it has traditionally been viewed from a problem-solving lens, Dorst (2019, p. 123) and Irwin (2019), for instance, discuss that as problems become truly complex, our understanding of design needs to shift such that design is not the creation of solutions to problems, but rather "high-quality interventions" that move the system towards a more desired state. The system thinking approach allows designers to distinguish areas of interventions more easily by making the components and their connections more explicit.

Richmond (1993) outlines how system thinking requires problem solvers to exercise different thinking skills simultaneously. For example, *dynamic thinking* involves the ability to observe patterns of behaviour rather than seeking to predict events. In this way, designers that can do this well can think about a process, and in turn the design solution, over time. Other useful kinds of thinking include closed-loop, structural, operational, continuum, scientific and generic thinking. This is echoed in other writings of systems thinking approaches; for example, Orgill *et al*. (2019) 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. As such a desirable quality of designers is to be able to anticipate unintended consequences which might emerge from an understanding of the interactions among multiple parts of a system (Dym et al., 2005).

As part of the systems thinking approach to problem solving efforts, and across different disciplines, a wide variety of visual diagrammatic representations are used to understand and/or communicate ideas. These representations come down to a small range of *map typologies* which include radial, hierarchical, tree structures, flow diagrams, Venn diagrams and feedback loops, sometimes combining several of these characteristics into one configuration. These *maps* are used as tools for different purposes and at various stages of a design/engineering process. For example, *process maps* or *flow charts* might help to visualize a specific order of actions and unfold graphically in a sequential layout (Sanders et al., 1999). M*ind maps* have a more organic shape and help the problem solver to think without much limitation to connect more ideas (Buzan, 2013).

One of the most popular systems thinking tools is *systems mapping*. Typically, system maps are tools devised to help the problem solver identify and visualize system components and their interactions as they work to understand the problem and identify interventions. As such, this tool is used to make explicit the important concepts and stakeholders of a problem situation, while drawing connections between them. A further description of systems maps, and in particular, a type of system map called Causal Loop Diagrams, which is of relevance to the approach developed in this thesis, will follow in Section 1.5.

1.4 Protocol analysis for understanding design behaviour

Protocol analysis (PA) (Ericsson & Simon, 1984) is one of the most popular and useful methods for studying cognitive processes, in particular designing (Blessing & Chakrabarti, 2009; Cross et al, 1996; Litster & Hurst, 2021). A large body of literature has used PA as a means to characterize design processes, see for example the work of Cynthia Atman and her colleagues (as recently summarized in Atman (2019)) and John Gero and his colleagues (Gero, 2010). Overall, these studies have explored the design cognition of designers with varying expertise and showed that PA can be a flexible method that can be adapted to each individual researcher's needs through variations of the approach and the application of different coding schemes to protocol data.

The method is motivated by a desire to derive a quantitative account from qualitative data (verbal reports), which "can be of the greatest value in providing an integrated and full account of cognitive processes and structures" (Ericsson and Simon, 1984, p. 373). Participants may provide verbal reports either *concurrently* or *retrospectively* (Ericsson & Simon, 1984, p. 16). In concurrent verbal reports (also known as talk aloud or think aloud reports), participants verbalize what they are doing as they complete a task. In contrast, retrospective verbal reports ask participants *after* they complete their task, sometimes with a video prompt of the activity, to describe exactly what they were doing at that moment.

Typically, a protocol analysis session is set up in a quiet room with minimal distractions (Ball et al., 2004). This ensures that participants can focus on the design task and the recordings are of sufficient quality for accurate transcription. Usually, multiple cameras, positioned at various angles, and individual microphones are used to gather the most comprehensive recording of the session (Kannengiesser & Gero, 2017). The study design may require participants to work on the design task individually or in groups.

The literature offers many examples of design tasks that have been used in previous protocol studies. For example, the Midwest Flood Problem asks participants to consider the factors they might consider in designing a retaining wall system for the Mississippi River, which commonly experiences flooding (Atman & Bursic, 1996). Another example is a playground design problem which has participants come up with a design of a fictional playground while meeting a number of requirements (like safety, city budgets, etc.) (Atman et al., 1996).

In concurrent protocol studies where participants are working individually, they are usually asked to first describe their actions as they complete a simple task (i.e., solving a puzzle or a simple mathematics problem), to familiarize themselves with the think aloud protocol (Dixon & Bucknor, 2019). When participants are working in groups, this step of familiarization is unnecessary as pairs and groups have been found to naturally promote authentic verbalisations among participants (Wells et al., 2016). Participants are then provided with the description of the design task and any other information (e.g., location of prototyping tools, information seeking procedures, etc.) they may need to successfully complete the task.

Once the tasks are complete and the transcripts are generated, the first step in the analysis is typically segmentation, which is the process of breaking the verbal text into units (or segments) that can be coded using a pre-defined scheme (Atman et al., 1996). Depending on the approach taken, segmentation can occur either before or in conjunction with the application of codes. Once segmentation of the transcripts is complete, the coding scheme can be applied to the data. Codes are usually assigned to the segments by two or more independent coders, but this task can also be completed by a single coder (e.g., as presented in Lane and Seery (2011)). Codes are then checked for reliability between coders (a specific agreement level is usually reached) and any discrepancies are resolved in an arbitration session, resulting in one final set of coded segments (Williams et al., 2012), where statistical analysis can be carried out to test a variety of hypotheses.

1.5 System maps for analyzing design protocols: a novel approach

It is evident from the discussion presented in this introductory chapter that design and systems thinking have provided great utility in our ability to engage with complex problems. In particular, understanding the design process and the products of design in relation to the social and physical systems they live in is an important endeavour as it will reveal the true functions of the designs (Buchanan, 2019). When designers look at interrelations between components in design spaces, which is usually inherent to their practice, the systems thinking lens offers opportunity to strengthen the overall approach (Espejo, 1994). It has been argued that systems thinking is positioned to address the challenges of problem framing because of the central focus of understanding complex problems (Elsawah et al., 2015).

This thesis explores how design activity, and in particular design framing, can be analyzed through the lens of systems thinking. Specifically, this inquiry is guided by the following research question: *What can a systems mapping approach say about design framing activity?* As introduced in Section 1.3, *system maps* are used to visualize and understand system components and their interrelations as designers work to understand the problem and identify interventions. In the proposed approach, I use system maps to retrospectively visualize designers' evolving mental representations (Espejo, 1994) through their verbal narratives while working on a design task. The objective of the research is to develop the system mapping approach for analyzing verbal protocols as a research tool, in order to gain further insight into design framing activity. As a new protocol analysis approach, I expect a systems mapping approach will offer a unique perspective of design activity.

I use a type of *system map*, called *Causal Loop Diagrams* (CLDs). CLDs belong to a larger typology of tools called *Dynamic Thinking Tools* (Kim, 1994). 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. CLDs include *nodes*, which are things that can influence/be influenced by something else. Nodes, often named with nouns are variables that can increase or decrease in terms of quality or quantity. The characteristics of these nodes/variables change via *system dynamics*. System dynamics 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). All dynamics are either *positive* or *negative*, and the *delay* just adds a timescale to the relationship. Positive does not mean 'good' and negative does not mean 'bad', it simply indicates the *direction* of the influence.

The process of creating system maps for analyzing design activity differs from other protocol studies, in part because I do not use a coding scheme. Instead, I 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. The design conversations are changing and evolving (as the participants explore the design space), and as such, nodes and dynamics can be identified at any point in the session.

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. These diagrams are often used to understand a system at its current state. For the remainder of the thesis, I will use the term system map(s) when referring to CLDs. 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, and in particular, problem framing, in the following chapters I describe two exploratory studies using existing data sets.

Chapter 2 Methodology

This chapter will provide detail on two studies that were conducted to develop and test the novel approach created for this thesis. The first study, hereafter referred to as 'Study A', was the initial implementation of the approach and was aimed at determining the effectiveness of system mapping to understand design problem framing. I sought out and tested several analyses that system maps afforded to determine how the system maps might be useful. The second study, hereafter referred to as 'Study B', was conducted to test the method in a different context. Study A was conducted beginning in June 2021 and Study B was conducted beginning in September 2021 after the completion of analysis for Study A.

2.1 Study A: The waking up experience

2.1.1 Study A data collection and design task

The data set used to create the first set of system maps consisted of eight verbal protocol transcripts, originating from video recordings. This study was conducted at the Delft Technical University in the Netherlands by Dr. Carlos Cardoso. The data set was used with permission. In the study, eight groups (each with three master's students in the Industrial Design program) were tasked with generating solutions to an open-ended problem. 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 problem statement is intentionally vague and open ended, because of the "How might you…" phrasing at the beginning of the design challenge statement. This type of problem statement is typically used to encourage further exploration of a given problem (Siemon et al., 2018). That is, designers tend to spend most of their time searching for elements of the problem which warrant a solution to be designed. As such, Study A was focused on design activity occurring mostly in the first ‘diamond’ of the Double Diamond design process, where the participants would need to conduct considerable problem finding and framing in order to identify a suitable and promising “area” of the problem for which they could begin ideating solutions. Therefore, this was a very well-suited context in which to develop the approach.

The video recordings were captured by the students themselves as part of an assignment in a graduate course about design methodology. Students were randomly allocated to groups of three, though most groups 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. As part of the assignment, students were tasked with watching the video footage and searching for, as well as reflecting on, key moments in their idea generation session, which had an impact in their thinking and decision-making process. As this was done earlier in the course, prior to students’ exposure to different theoretical aspects of design methodology, their reflection on the behaviours they exhibited was primarily intuitive. The transcripts from the videos were later generated by one of Dr. Cardoso’s research assistants, and not the students themselves. Eight transcripts make up the dataset used for the creation of the system maps. The average length of the transcripts is 34 minutes.

2.1.2 Study A Generating the system maps

As explained in Chapter 1, protocol studies typically begin with the collection of verbal reports that are then segmented. As I did not collect the dataset used in Study A, transcripts were already segmented based on who was speaking. Unfortunately, in protocol studies where participants are working together, segmentation can be a difficult process because team members may be talking over one another, and several incomplete sentences can be found in the transcripts.

The process for creating systems maps began with a review of each transcript line by line. Though most protocol studies set out to understand a single phenomenon in design (e.g., use of sketching in idea generation) using a predetermined coding scheme, this exploratory work had no coding scheme. In line with the systems thinking literature and using a subset (Groups 1-4) of the dataset, together Dr. Ada Hurst and I sought to identify nodes and system dynamics. A *node* is identified whenever the speaker describes an entity that can influence or be influenced by other entities, and thus has a measurable quality or quantity (Kim, 1994). Each node is assigned a short label that captures its meaning. *System dynamics* describe how one node influences another and can take three forms: increases (+), decreases (-), or no evident increasing or decreasing effect but somehow related (+/-). System dynamics were assigned to the transcripts where I could determine that participants were verbalizing a relationship between two or more identified nodes.

The process does not distinguish between nodes that are related to how the system currently works (i.e., problem understanding) and how the system ought to work (i.e., new solutions to improve the systems current state). These kind of nodes are coded and visualized equally throughout the process. This is intentional as it is in line with the most recent understanding that the distinction between problem and solution spaces is not clear (Crilly, 2021; Nickel et al., 2022).

In most protocol studies, the predetermined codes are usually assigned to the segments by two or more independent coders which help determine a level of interrater reliability. Though Dr. Hurst and I coded the first subset of transcripts together, checking reliability of the coding process was difficult. In this case, a lack of a common coding scheme prevents a reliability score from being calculated. The interpretation of verbal utterances often results in different node names or different system dynamic assignments (e.g., + or -). That is, though two coders will likely identify a similar set of nodes based on the verbal utterance, the coders' definitions of them can be different and thus result in an overall different system map.

Though there are no specific metrics to report, I was able to test this approach internally in two ways. The first way included an independent coding process between me and Dr. Hurst for the same subset of transcripts used for the initial map creation process. I observed that while the labeling of the nodes might differ between coders, general patterns (e.g., number of nodes and system dynamics) which are the drivers for most analyses, were detected to a similar degree. The second way to ensure reliability of the process for creating system maps was to complete the coding process for a subset of the groups on two separate occasions. That is, I individually coded three of the group's transcripts to ensure some level of reliability. In this instance, no significant deviations were observed between my first and second iterations, again with labelling of the nodes being the only major difference.

For the generated system maps, only the first occurrence of a node or system dynamic is recorded. It is helpful to conduct both the coding and visualization of nodes and system dynamics simultaneously, as they are identified. In the first pass of the transcripts, system maps were created using PowerPoint, creating a new slide each time a node or system dynamic was added. This approach to creating the system maps became useful in two ways; it afforded the connection of system dynamics to nodes that occurred earlier in the session to those that appeared much later, and assisted in keeping the labeling of the nodes consistent throughout the coding process. Although all groups in the individual datasets were posed with the same problem statement for their respective sessions, each group produced a unique set of nodes and system dynamics.

Once a transcript was coded and the initial system map generated, the data was manipulated into a format that could be read by an open-source network visualization and analysis platform called Gephi (Bastian et al., 2009). Gephi offers a variety of rendering and data analysis tools that are useful for understanding the structure of the system map by more clearly indicating the nodes and system dynamics that connect them compared to the PowerPoint versions.

In addition to the labelling of nodes and system dynamics, a short label was also assigned to the solution ideas generated by each group and were noted when they appeared in the transcript. The process of identifying the solution ideas was less straightforward compared to the labelling of nodes and system dynamics. One reason for this was the difficulty in distinguishing between a novel idea (e.g., an idea for a product or service that did not already exist) and products that are on the market which claim to improve parts of the waking up experience. That is, as might be expected, the participants frequently referred to previously designed products (i.e., a smart light bulb able to change the amount of light emitted based on schedule) that might have influence over the waking up experience. Nonetheless, an effort was made to track the emerging ideas and to provide a short label to them in a similar way to nodes. At the time of initial coding, there was no intention of analyzing solution ideas to place judgements on their novelty or usefulness and tracking them became a secondary task of the coding process. However, it was determined later that the solution ideas, in conjunction with another kind of analysis, might be useful when discerning framing activity.

2.1.3 Example of coding process

In Table 1, I present an excerpt from Group 1's transcript to demonstrate how nodes and system dynamics were defined during the coding process. The constructed system map of the verbal utterances can be found in Figure 2. For any given pair of nodes connected by a system dynamic, I assigned the relationship (either +, -, or +/-) with an assumption that the node attached to the tail of the arrow representing the system dynamic is increasing. To illustrate, consider the utterance by P2: "I just basically have like…6 alarms in my phone at different times. I do not wake up always. It's horrible." A node is identified and labeled as "number of alarms set". This node has a positive (increasing) influence on another node, labeled "ability to hear the alarm", which was identified in the preceding utterance by P1. In plain language, this pair of nodes and the associated system dynamic are read as 'an increase in the number of alarms set increases the ability to hear the alarm clock'. This example also illustrates the importance of the coder having a good understanding of the utterance in the context of the designers' conversation as the meaning of each node and system dynamic label depends on what was said both before and after a node is identified.

Table 1 Excerpt from transcript of Group 1

Verbal utterance	Coded nodes (N) and system dynamics (D)
G1P2: So 5 minutes research about waking up	
G1P3: Yeah 5 minutes on experience and brainstorming…Defining the problem	
G1P2: I have really a lot of experience about not waking up so I can write about that.	N1 = 'Ability to wake up'
G1P3: Okay, so we are already starting with… umm our waking up experience, okay I'll just take some notes.	
…	
G1P1: Okay, what do you have? Everybody has like pressing the snooze button, I guess.	N2 = 'Number of times someone snoozes' D1 = N2 **decreases** N1
G1P2: Uhm, yeah. I do.	
G1P3: Yeah, the alarm clock. Also, when I'm sleeping…It's just like…my phone shouldn't be near or next to me.	N3 = 'Proximity of phone to person in space' D2 = N3 **increases** N1
G1P1: I'm really short-sighted and when I use my phone without my glasses… (looks up shaking head) It's, it's like luck basically.	N4 = 'Ability to see alarm/phone' D3 = N4 **increases** N1
G1P2: (*Mimicking tapping the phone*) Shut up!	
G1P1: Yeah…also hearing the alarm clock…	N5 = 'Ability to hear the alarm clock' D4 = N5 **increases** N1
G1P2: I just basically have like…6 alarms in my phone at different times. I do not wake up always. It's horrible.	N6 = 'Number of alarms set' D5 = N6 **increases** N5
G1P1: Also, for me.	
G1P3: Yeah, still feeling sleepy	N7 = 'Level of tiredness' D6 = N7 **decreases** N1
G1P1: Oh yeah there's this room border. Room border with nothing coming [Inaudible]	
G1P3: Not wanting to wake up.	N8 = 'Desire to wake up' D7 = N8 **increases** N1
G1P1: And I hate it when it's winter and your bed is warm and outside it's so cold…I really don't want to get out.	N9 = 'Temperature differential' N10 = 'Desire to get out of bed' D8 = N9 **decreases** N10 D9 = N10 **increases** N1

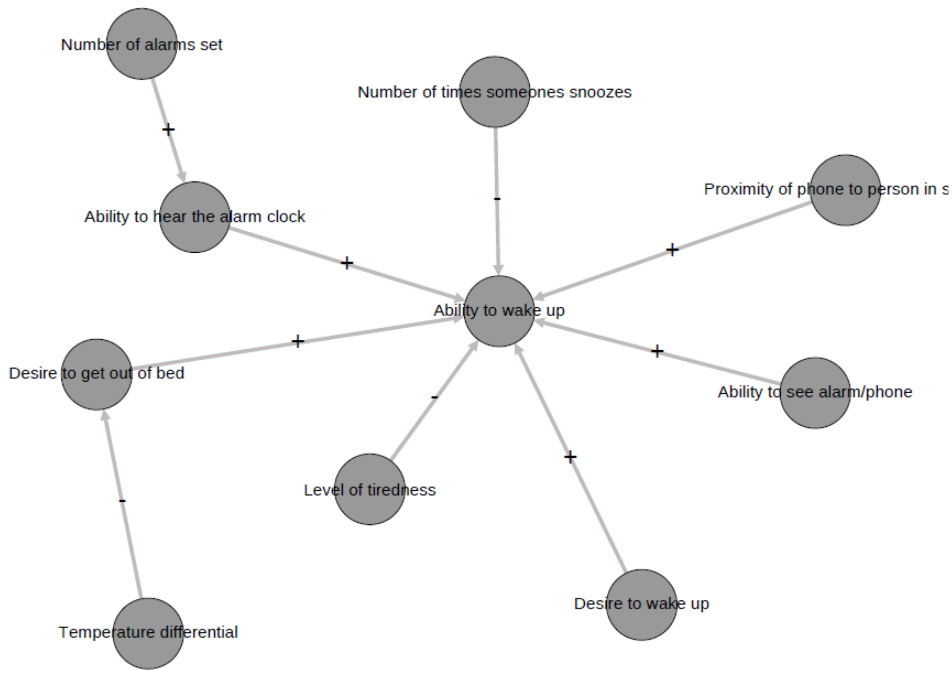

Figure 2 Partial system map generated from Group 1's excerpt (Table 1)

2.2 Study B: Design of assistive device

Study B had two primary aims. *First*, after the coding and analysis in Study A, it was determined that the system map coding and creation process could be overfit to the dataset. That is, it was unclear if the novel approach could be used for mapping relationships in another research endeavour of a different context (e.g., designers working on a different design problem). For example, a new study might follow the same steps outlined in section 2.1.2 and create visualizations that are not useful or provide much information. To further test and validate the method, another set of transcripts was coded, and system maps were created for analysis.

The design activity captured in Study A was mostly focused on the early stages of the design, capturing participants tackling a very vague problem prompt which required them to spend most of the design session exploring the need and figuring out the most promising aspects of the problem, on which they could ideate solutions. As such, Study A was focused on design activity occurring mostly in the first diamond of the Double Diamond design process. As a result, that dataset was very well-suited to be analyzed using the system mapping approach, because of the utility of systems thinking for understanding complex problems. In contrast, in Study B, participants were provided with a very detailed design brief, which presented a very well-defined problem with several requirements and constraints. As such, using this dataset allowed me to achieve a *second* aim: to test how the systems mapping approach would fare in analyzing design activity that occurred primarily in the solution ideation and evaluation phases, or the second diamond in the Double Diamond design process.

2.2.1 Study B data collection and design task

The verbal protocols analyzed in Study B were collected as part of a study conducted during a workshop at the DESIGN 2018 conference in Croatia (Nespoli and Isaksson, 2018). The purpose of the workshop was to share authentic and relevant design challenges in their contexts and to bring academics and practitioners together around these challenges for collaborative learning. The data was collected by Oscar Nespoli from the University of Waterloo and Ola Isakksson from Chalmers University of Technology. The data set was used with permission.

In the workshop, the participants addressed a real design challenge based on a case study created by the Waterloo Cases in Design Engineering group at the University of Waterloo (MacDonald et al., 2015). Participants were introduced to the design challenges via a video and reading of the case study. They were also given an opportunity to ask the facilitator questions related to the case. The case study challenges the designer with creating conceptual designs for a mechanical device that would enable an artist, named Lois, to sculpt glass vessels of a variety of shapes, sizes, and weights using her existing tile cutting saw and the technique she currently used. The brief that was provided to the participants explained that Lois had suffered a shoulder injury because of a minor automobile accident, which prevented her from working for long periods of time carving glass (especially when the vessels were particularly large) in the way that she was normally used to. The case included a full description of Lois' workshop, photos and videos of Lois working, and responses from an interview with Lois where she explained some of her requirements and desires. The descriptions also included details of the equipment, measurements of the work area, and a maximum estimated budget.

In total, four groups participated, of 4 participants each: two groups were made up of participants who identified as "academics", one group was made up of participants who identified as "practitioners", and a fourth group comprised of participants that considered themselves 50% each academic and practitioner (Nespoli & Isaksson, 2018). Participants were asked to audio record their discussions as they worked on the design challenge. Those recordings were later transcribed using a professional transcription service. Other material related to the design challenge created by the participants (e.g., written and sketch data) was collected as well. Only the transcripts of protocols from two groups were used for the purpose of the thesis, one of the academic groups and the practitioner group, each 46 minutes and 1 hour 18 minutes in length, respectively.

2.2.2 Study B example

The same process explained in section 2.1.2 for coding transcripts and solution tracking was carried out for both transcripts in Study B. As such, no explanation of that process is provided here. However, Table 2 does present a sample of the coding process taken from the academic transcript to provide some context for how the system visualizations were created. Figure 3 represents a systems map visualization of the generated nodes and system dynamics presented in Table 2.

Table 2 Excerpt from transcript of academics

Verbal utterance by participants (P_)	Generated nodes (N) and system dynamics (D)
PB: Too robotic. [crosstalk 00:01:10] You can now have ... But you can now [inaudible 00:01:15] the cost. So, we're stuck with the device there as far as I understand. Is that correct? So, that's one of the constraints?	N1 = Cost
PA: Yeah	
She said she wants to [crosstalk 00:01:26]	
The one thing we might have to change to that is the way we handle the water.	
Yeah. The water…some way to [inaudible 00:01:35] since it can be quite heavy [inaudible 00:01:38]	N2 = Weight of piece
PA: Interesting that she's basically describing a contradiction because she wants to have the flexibility of movement to have the feel for the process with the body, with the same time she has ... It's very ... So, she needs to be flexible when she's moving and then at the same time it has to be safe, which is basically not when you are [inaudible 00:02:01]. So, she is basically describing a contradiction.	N3 = "Movement flexibility" N4 = "Feel for the process" D1 = N3 **increases** N4 N5 = "safety" D2 = N3 **decreases** N5
…	

PA: It's really like when you drill, you want to have a feeling because then you can moderate [inaudible 00:02:46].	N6 = "ability to moderate movement" D3 = N4 **increases** N6
PC: So, probably a robotic solution would be ... It's not giving to her the feeling of what she's doing so she can modulate the-	
PB: That's really why it's great also where we have [inaudible 00:03:03] engineering and [inaudible 00:03:04]. We have a tough budget here.	
PC: Yeah, short budget. So, eventually, the problem with the weight is when she's actually not carving it. So, the moment she is carving the glass, she does not already care what she wants to feel the weight, but as soon as she move away from that, she doesn't want to feel it.	N7 = 'Distance from saw' D4 = N6 **decreases** N4

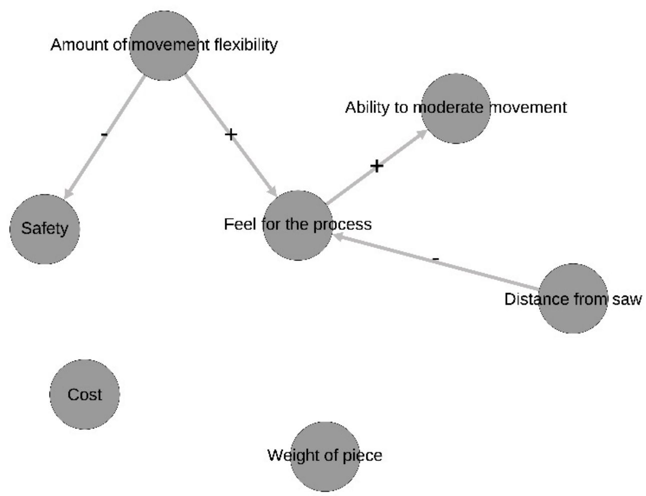

Figure 3 Partial system map generated from academic's excerpt (Table 2)

2.3 Summary

This chapter has presented the details of two studies, Study A and B, carried out to develop a novel approach to understanding design framing activity. For Study A, descriptions of the participants and the problem they were posed with were provided and the process of constructing system maps was explained in significant detail. In section 2.2, I provided the details of Study B, which uses two transcripts collected from a workshop with both academics and practitioners. The purpose of this study was twofold: to test many of the assumptions and overall coding process used in Study A and to test the applicability of the approach in a design activity context that is primarily focused on solution generation and evaluation. In the next chapter, a full description of the completed systems maps and following analyses will be explored, providing the evidence of the systems maps ability to capture the cognitive activity involved in framing.

Chapter 3 Results – Study A

This chapter will present metrics and insights that can be derived from the system maps as discovered during Study A, explaining the structure and patterns observed and highlighting how they can be used to gain insight into design framing activity. Section 3.1 will present map size metrics, including the number of nodes and system dynamics identified in each transcript. Section 3.2 will describe the contents of the system maps, highlighting two groups' maps to demonstrate the diversity of nodes, dynamics, and resulting structures between groups. Section 3.3 will discuss how the system maps evolve over time, by describing the rate in which new contributions to the system maps are added over the design session. Section 3.4 will explain how a community analysis algorithm provides one attempt to categorize the structure of the nodes and system dynamics. This provides more specificity and insight into aspects of the design space that come into focus. Finally in section 3.5, I present the results of the system map from a perspective of individual contributions. Here the maps visually highlight which nodes and system dynamics are created by each participant, to demonstrate who contributes to the development of the system map.

Although every transcript from study A was used to create a system map, only a selection of them will be displayed throughout this chapter. Those that are not used can be found in the appendices. Specifically, Appendix A holds the most generic version of the systems maps, as they are coloured in grey. The system maps coloured by the community detection algorithm and general summaries of nodes grouped in each community can be found in Appendix B. Finally, the system maps coloured by the individual team member contributions can be found in Appendix C.

3.1 Number of nodes and system dynamics

The number of nodes and system dynamics provide two simple attributes by which to characterize the system maps. Figure 4 presents the total number of nodes and system dynamics (or "elements") in each of the maps generated from the eight protocols. Though all groups worked on the design task for approximately the same amount of time (on average 34 minutes), there is a notable variation in the number of elements identified in each group. At the extremes, the largest contrast is observed between the number of nodes and dynamics 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 system map where the number of system dynamics is larger than the number of nodes. A simple linear regression model between the number of elements added and the number of words spoken indicates a positive relationship ($\beta = 0.726,\ p$-value < 0.05). This means that, in general, the longer a group discusses the problem, the greater the size (i.e., number of nodes and/or system dynamics) the system map will have.

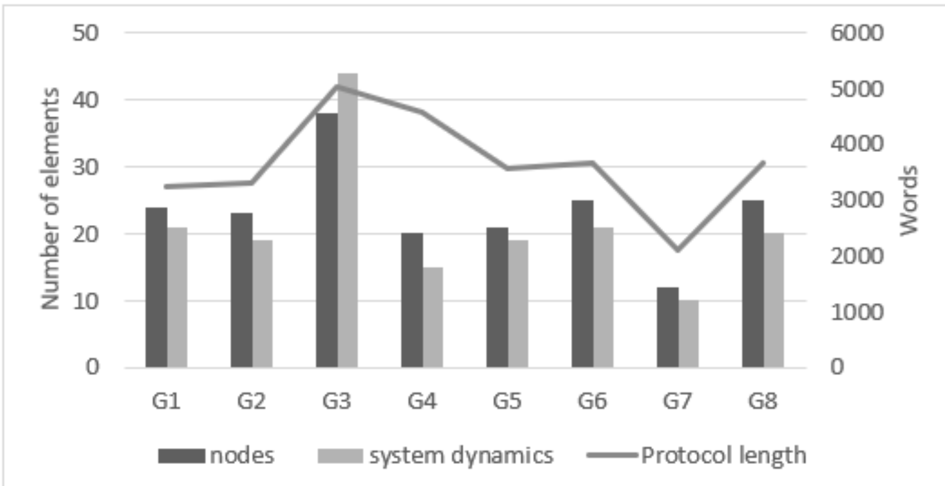

Figure 4 Number of nodes and system dynamics (elements)

3.2 The contents of the system maps

Figure 5 presents the system map generated from Group 1's transcript. Examples of nodes identified include the "amount of motivation", "quality of breakfast", and "number of alarms set". Looking at the system map, one is able to see what the group has focused on during their design activity.

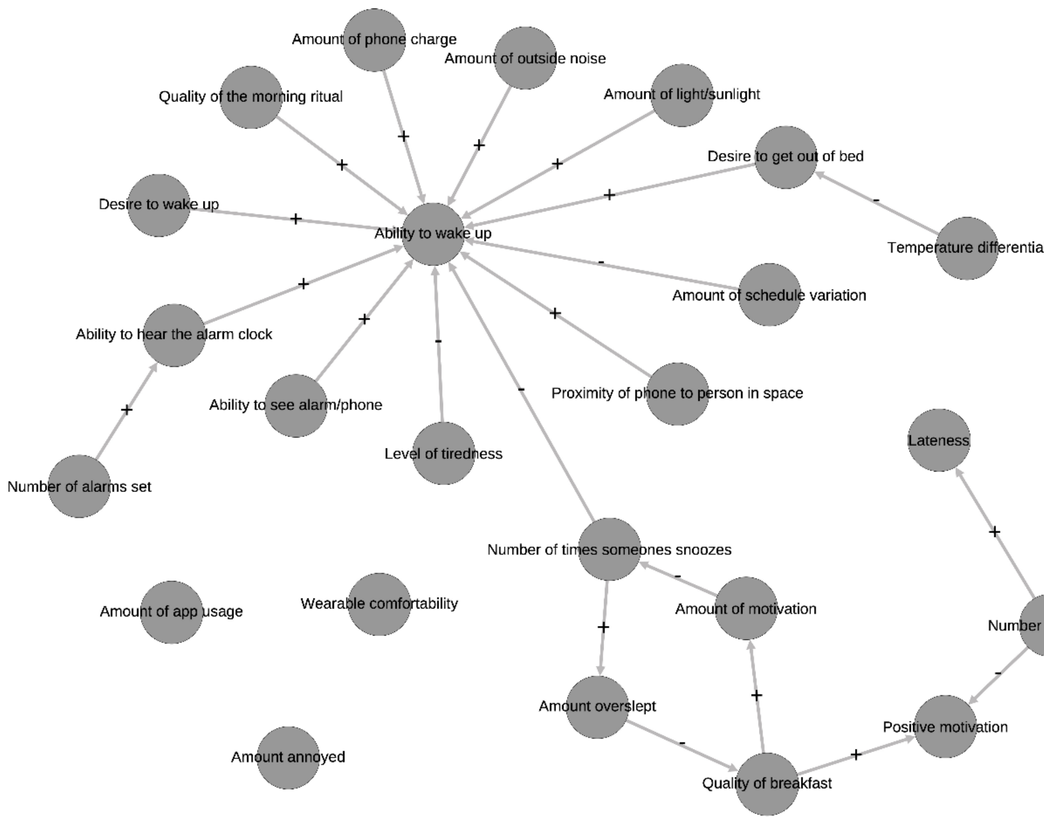

Figure 5 Group 1's system map

I then compare the system map seen in Figure 5 to the system map generated from the transcript of Group 4, shown in Figure 6 . One can observe the overall structural differences between them; in particular, Group 1's system map has many nodes connected to a single node, while Group 4's has a more linear structure. The content of the nodes highlights the similarities and differences between the two groups' system maps. For example, both Group 1 and Group 4's system maps include nodes labelled 'Ability to wake up', 'Temperature', 'Number of alarms set' and 'lateness'. In contrast, the system map for Group 1 includes nodes related to the 'quality of breakfast', 'amount of motivation', and 'amount of light", which are not contained in the map of Group 4. This demonstrates that there are nodes related to the problem that are identified by one group and not by another.

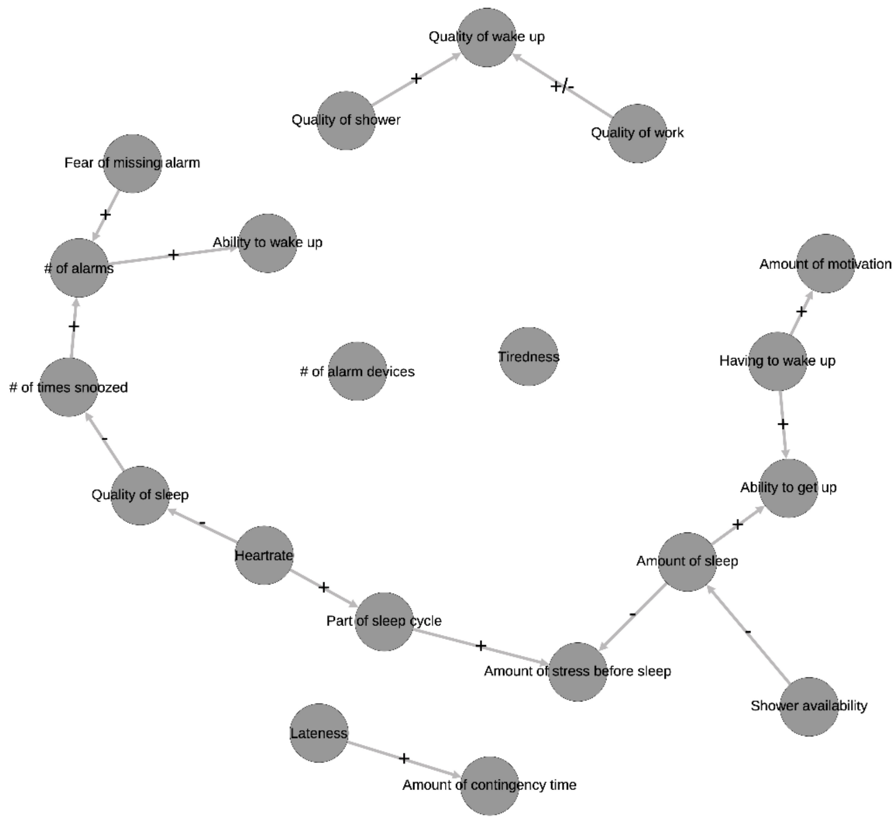

Figure 6 Group 4's system map

This observation provides evidence for a difference between the two groups in terms of how they work through their problem prompt. The system map visualizes one operationalization of their problem framing, displaying all nodes and system dynamics that designers have brought into focus as important to the design task at some point during the design session. The system maps used throughout the thesis are static windows into the design framing of each group, as observed at the conclusion of the design activity and do not show the order in which the different nodes and system dynamics are added to the map.

3.3 System maps over time

To observe how the system maps evolved over time, I divided each protocol into 20 equal segments (called ventiles) based on the number of lines in the transcripts and counted the number of new elements that emerged in each ventile. Figure 7 presents a cumulative graph of these occurrences for each of the groups, distinguished by colour.

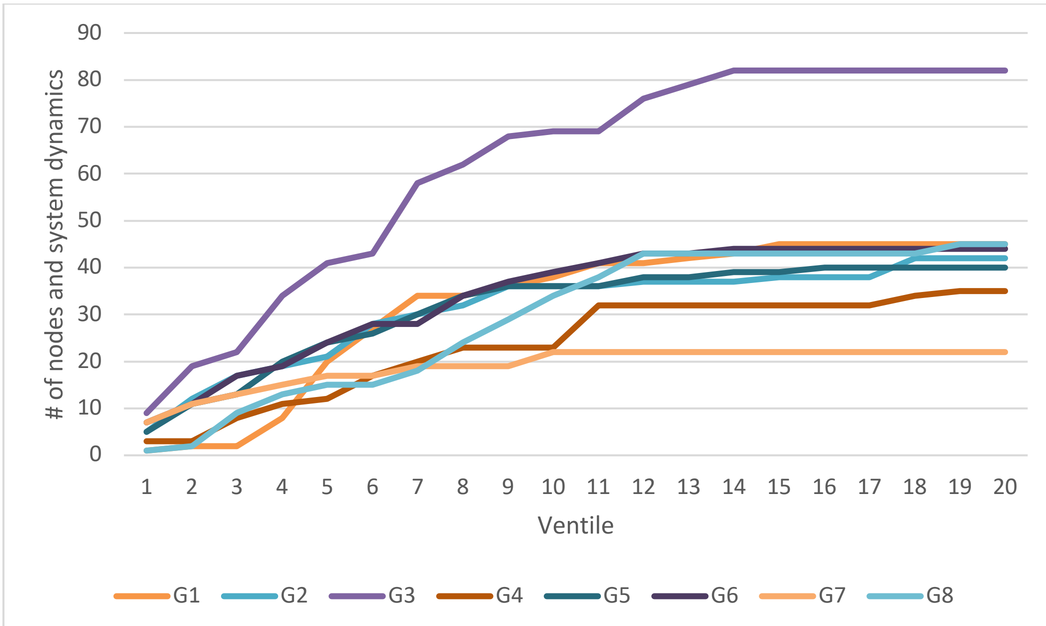

Figure 7 Cumulative added elements to the system maps

A clear general pattern can be observed: in the early parts of the sessions there is a rapid emergence of new nodes and system dynamics, as participants begin to explore the problem. For most groups, new additions to the system map plateau about halfway through their design session. I observe that, typically, at this point the participants' utterances change in focus to the generation of solution ideas or revisiting of previously identified nodes and dynamics, rather than an indication of the generation of new nodes and system dynamics. Any discussion by the designers about previously identified nodes is not captured in this analysis because only the first occurrence of new nodes and systems dynamics are coded.

The rate at which each group produces new nodes and system dynamics varies throughout the session. This rate is represented by the slope of the line between ventile segments – a steep line indicates rapid development of nodes and system dynamics while a flatter line indicates minimal contributions during that time. 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 compared to the first half of the session), and as late as the 19th ventile.

3.4 Community detection

Visual inspection of the maps reveals that the nodes are organized in "hub-and-spoke" and other structured clusters (hereon referred to as "communities"). A modularity algorithm, built into the Gephi program, can computationally determine the boundaries of communities of related nodes based on map structure. The Gephi modularity clustering algorithm utilizes the Louvain method (Blondel et al. 2008). An explanation of the mathematical details of the algorithm are unnecessary for the purpose of the thesis but a brief overview will provide some context for how the algorithm works. The algorithm uses a modularity score throughout the process. Modularity is a score (between -1 and 1) that assesses the density of links inside a community compared to those links outside the community. The process is divided into two phases. In the first phase, each node in the network is assigned to a community of their own. Then each nearest neighbour is iteratively added to each community until a local maximum of modularity is determined. Once this local maximum is identified, those communities then become a node in a new network and the process is repeated until modularity is optimized.

As a result of this algorithm, there are some instances where nodes in the system maps are counted as a single community at the termination of the algorithm. This is because all nodes are initially assigned to their own community, and because these nodes are not connected to other nodes through any system dynamics, their modularity score never changes. Table 3 shows the distribution of the number of communities with at least a certain number of nodes for each group. In this table, it is clear that there are significant number of communities with each community only has a single node. The number of communities per system map is typically reduced when the threshold of nodes per community is increased.

Table 3 Distribution of the number of communities with particular number of nodes

Communities with at least…	G1	G2	G3	G4	G5	G6	G7	G8
1 node	8	8	9	8	6	7	3	7
2 nodes	5	4	5	6	5	6	3	6
3 nodes	3	4	5	5	3	5	1	4
4 nodes	2	4	5	1	3	3	1	2
5 nodes	1	2	3	0	2	2	1	2
6 nodes	1	1	3	0	1	1	1	1
7 nodes	1	0	1	0	1	0	1	1
8 nodes	1	0	1	0	0	0	1	1
9 nodes	1	0	1	0	0	0	0	1
10 nodes	1	0	1	0	0	0	0	0
11 nodes	0	0	1	0	0	0	0	0
12 nodes	0	0	1	0	0	0	0	0
13 nodes	0	0	1	0	0	0	0	0
14 nodes	0	0	1	0	0	0	0	0

Observing the individual nodes in each community, it was hypothesized that nodes might be related in a semantic way rather than simply by the structure detected by the algorithm. That is, one could use the labels of the nodes within a community to infer a common theme or meaning for that community. To investigate this, I selected a subset of communities and qualitatively evaluated the nodes present in each system map. This evaluation was exploratory in nature, as described below.

The first step in this process was determining which communities to investigate. I discovered early that there was limited focus that could be derived from communities composed of a single node, so these communities were not investigated. Similarly, those communities that had only two nodes provided weak evidence of any specific focus. When two nodes are connected through a system dynamic, by definition, it means those two nodes have a relationship. Therefore, no further interpretation of that relationship can be inferred, beyond what is already described by that system dynamic. Therefore, I determined that only those communities that met or surpassed a threshold of at least three nodes would be included in this investigation.

Inspection of the detected communities in the system maps showed that each focused on a particular aspect of the problem, each prompting different kinds of solutions. To demonstrate this finding, I consider the following two maps, Group 3 (Figure 8A - left) and Group 6 (Figure 8B - right), which each had a total of 5 communities that matched the threshold inclusion criteria. The average number of nodes per community is 6.8 and 4.2 for Group 3 and Group 6, respectively. This means that a community found in Group 3's map will have, on average, two more nodes than any community found in Group 6's map. The figure also illustrates the 'community of one' concept discussed above, which is especially evident in Group 3's map. There are four nodes (e.g., the single pink node in Figure 8A) that would be considered a community of their own, as they received no system dynamic connections throughout the session.

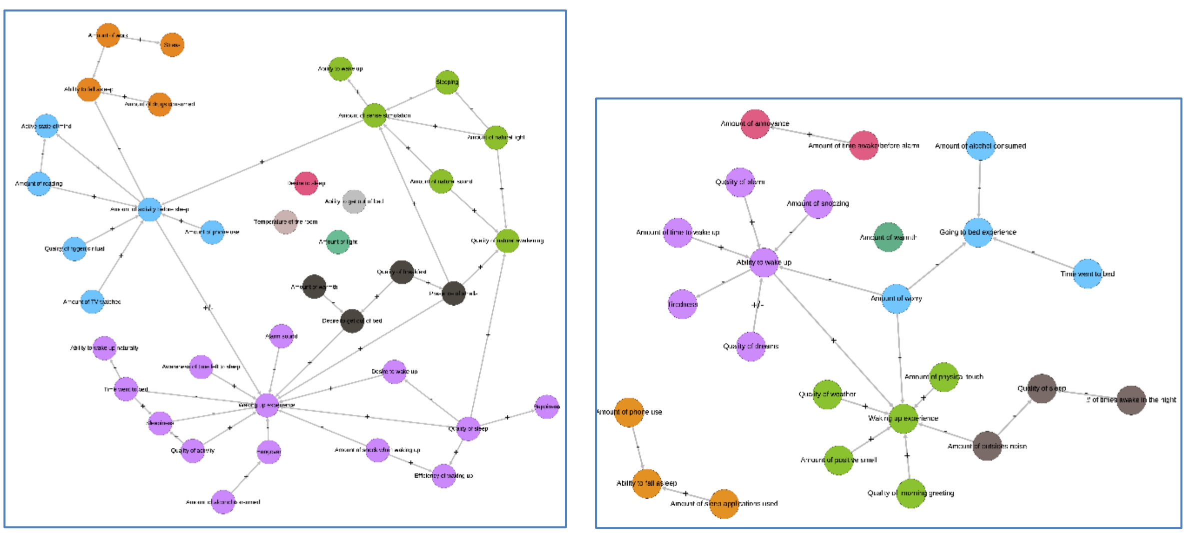

Figure 8 A) Group 3's system map with communities (left); B) Group 6's system map with communities (right)

Table 4 presents a list of the communities (and respective nodes) in Groups 3 and 6 that share a common theme. For each community pair, a label describing the inferred theme is provided in the left column. Further, for each community, the colours are provided so that the reader might identify the communities on the system maps themselves. These colours are assigned arbitrarily in Gephi and do not carry any significance between the two maps.

Table 4 Common communities and associated nodes

Community label	**Group 3**	**Group 6**
Activity before going to sleep	**Blue** • Amount of activity before sleep • Quality of hygienic ritual • Amount of phone use • Amount of reading • Amount of TV watched • Active state of mind	**Orange** • Amount of phone use • Ability to fall asleep • Amount of sleep applications used
Factors that influence the ability to wake up	**Green** • Ability to wake up • Amount of sense stimulation • Sleeping • Amount of natural light • Amount of natural sound • Quality of natural awakening	**Purple** • Amount of snoozing • Ability to wake up • Quality of dreams • Tiredness • Amount of time to wake up • Quality of alarm
Factors that influence the ability to fall asleep	**Orange** • Amount of work • Ability to fall asleep • Stress • Amount of drugs consumed	**Blue** • Amount of worry • Going to bed experience • Time went to bed • Amount of alcohol consumed

There are noticeable similarities and differences associated with each of the communities found in the two system maps presented here:

- The two communities that fall under the "*Activity before going to sleep"* theme only have one common node, 'Amount of phone use'. Compared to Group 3, the nodes that comprise this community in Group 6's map do not provide as clear a picture of activities one might complete before going to bed.
- The two communities that fall under the "Factors that influence the ability to wake up" theme include nodes that involve the role of the senses ('amount of sense stimulation', 'quality of alarm', 'amount of natural sound') during the waking up experience.
- Finally, both groups have a community that falls under the "*Ability to fall asleep"* theme, including common nodes such as the 'amount of substance use', and the amount

of ‘stress’ or ‘worry’. In this case, the nodes in the community have a focus on those factors that might prevent a person from sleeping.

In addition to the generation of nodes and system dynamics the groups’ solution ideas were tracked throughout the coding process. A summary of the ideas that targeted each of the above communities can be found in Table 5.

Table 5 Solution ideas for common communities in Group 3 and Group 6

Community label	Group 3 solution ideas	Group 6 solution ideas
Activity before going to sleep	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.	**No solution ideas related to this community.**
Factors that influence the ability to wake up	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.	Solution ideas are targeted at mindful ways of waking up including, stories and motivational words. They also discuss a text messaging service that matches you with people who have similar interests as you to spark conversations.
Factors that influence the ability to fall asleep	The ideas that emerge in response to this are, for instance, a mattress that massages the user to sleep and stress-reduction activities like meditation.	The solution idea related to this community was introduction of bedtime stories.

Each of Groups 3 and 6 system maps also have two other communities that are omitted from Table 4 because they did not share a theme between the two groups. Their nodes, inferred theme, and the solution ideas associated with each community are summarized in Table 6 for Group 3 and Table 7 for Group 6.

Though the purple community found in Group 3’s map centers on the waking up experience, it is hard to detect a clear focus; instead, the community includes several under-developed threads that capture the entire time window from ‘before going to bed’ to ‘waking up the next day’. The final three communities did however have a clearer focus. For example, the brown community from Group 3’s system map focuses on a desire to get out of bed, while the remaining two communities from Group 6's system map focus on the factors that influence the waking up experience (green) and the quality of a person's sleep (brown).

Table 6 Communities, nodes, and solution ideas for Group 3

Community Label	Nodes	Solution ideas
No discernable focus (Purple)	• Ability to wake up naturally • Time went to bed • Sleepiness • Quality of activity • Awareness of time left to sleep • Amount of alcohol consumed • Hangover • Waking up experience • Alarm sound • Desire to wake up • Amount of shock when waking up • Efficiency of waking up • Quality of sleep • Happiness	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.
Desire to get out of bed (Brown)	• Desire to wake up • Amount of shock when waking up • Efficiency of waking up • Quality of sleep	**No solution ideas related to this community.**

Table 7 Communities, nodes and solution ideas for Group 6

Community Label	Nodes	Solution ideas
Factors that influence the waking up experience (Green)	• Waking up experience • Amount of physical touch • Quality of weather • Amount of positive smell • Quality of morning greeting	As such, the idea that surfaced from this cluster was a projection on the wall to include, sounds, stories and light as a service used by people to wake up.
Quality of the sleep (Brown)	• Amount of outside noise • Quality of sleep • Number of times awake in the night	**No solution ideas related to this community.**

In Tables 4-7 above, I have demonstrated a useful approach for highlighting the focus of each community found in the two system maps. To ensure that this result could be extended to produce some other useful insights, communities across all groups were analyzed in the same way. A full account and details of this analysis can be found in Appendix B. After identifying a theme for each community across all groups, it was determined that many of the communities were similar between groups. Table 8 summarizes the results of all groups' communities. The most common communities that were developed during the exploration of this design space, as indicated by more than one group considering that theme, are marked with an (*) in the table.

Table 8 Summary of all communities detected in systems maps for Study A

Community	G1	G2	G3	G4	G5	G6	G7	G8
No clear focus* (no common theme could be determined from the nodes)	✓	✓	✓		✓		✓	✓
Factors that prevent punctuality and the influence of motivation	✓							
Oversleeping and the influence on subsequent tasks	✓							
Factors that influence a person ability to wake up naturally*		✓	✓			✓		✓
Ability to fall asleep*			✓			✓		
Factors that influence the amount of sleep one will need				✓				
Quality of wake up				✓				
Physically getting out of bed*			✓	✓				
Activity influences before someone goes to bed*		✓	✓			✓		
Quality of sleep*				✓		✓		✓
The ability to wake up*		✓			✓	✓		✓
Alarm efficacy*				✓	✓			

As was demonstrated in the example above with Groups 3 and 6, it should be emphasized again that though the communities share a similar focus and are labelled with the same name, the contents of each community can vary between groups. For example, as seen in Table 8, Group 2 and Group 5 have a community that focuses on the users' 'ability to wake up'. However, Group 2's community has a node labeled 'quality of the alarm clock' whereas Group 5's community with the same label does not include a similar node. Overall, Table 8 demonstrates that some groups cover a wide variety of communities which highlight more exploration of the problem and diversity in overall themes. For example, Group 6 above, has covered five out of the seven most common communities with a clear focus, while Group 7 has covered none of them. Given the size of its system map, as identified in section 3.1, it is surprising that Group 3's did not contain the greatest number of communities and had an equivalent amount compared to Group 4 and 6. This is likely a result of the single community in Group 3's map with a population of 14 nodes, which made it difficult to determine a clear focus.

3.5 Collaborative designing

As explained in Chapter 1, it is very rare that designers work alone to generate solutions to design problems. Therefore, I sought to understand how the system maps might help determine the contributions of individual participants to the group's problem exploration. That is, the following system maps and associated contribution analysis shows the role each group member plays in expanding the system map by adding nodes and system dynamics. This is demonstrated in the systems maps using colour to depict each participant's contribution. For example, Figure 9 presents the system map for Group 4, with the individual contributions colour coded as follows: the green, orange, and purple colours represent P1, P2, and P3 respectively. The same convention is used in all team system maps presented in this subsection as well as those found in Appendix C. In the remaining sections of this chapter, individual team members will be referred to using their participant ID's which consist of the group number they are a part of (1-8) and their assigned participant number (1-3). For example, participant 3 from Group 7 will be referred to as G7P3.

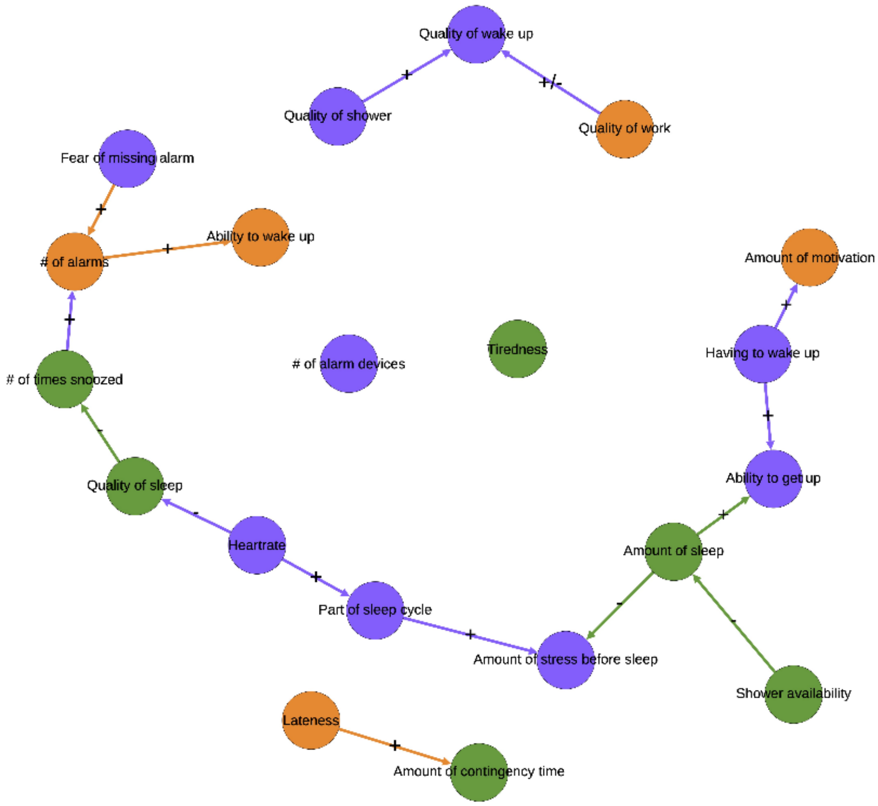

Figure 9 Group 4's system map coloured by individual contributions

3.5.1 Individual contributions to the system map

To determine how much a participant was contributing to the overall system map, participant IDs were assigned to each node and system dynamic based on the utterance in the transcript from which the system map element was created. Intuitively, if a participant speaks more during the session, then one might expect that they contributed more to elements that are present on the map. In general, this relationship is true as seen in Figure 10 which displays the portion of new additions against the portion of words spoken during the session. This graph demonstrates a weak positive relationship between the number of new additions to a system map (i.e., a new node or system dynamic is developed) and the number of words spoken.

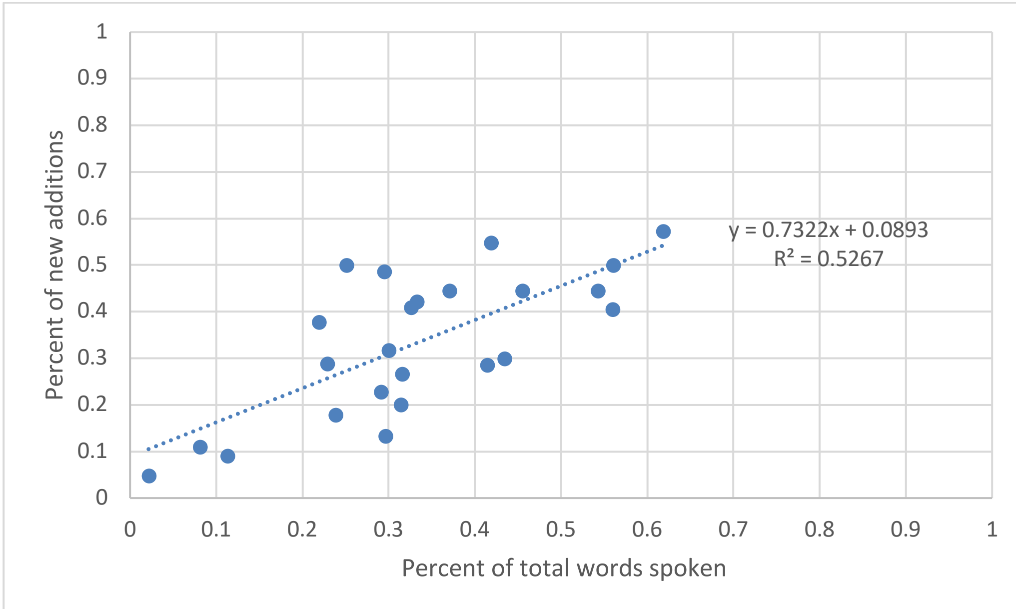

Figure 10 Scatterplot of the percent of total words spoken against the percent of new additions

Figure 11 displays the percentage of the total number of words spoken (W) compared to the number of contributions (C) - nodes and system dynamics - added to the system map by each participant for each group.

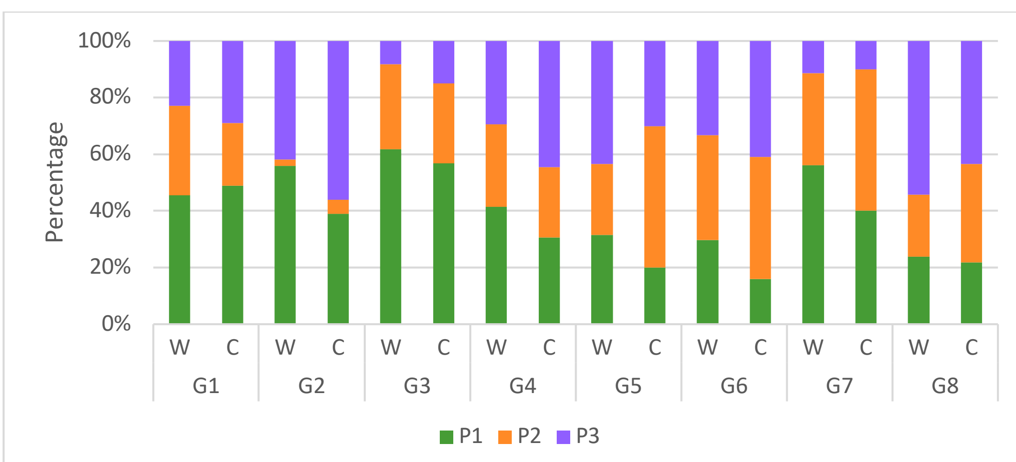

Figure 11 Percentage of total words spoken and percent of contributions made by each participant in Study A

What is interesting to note about this comparison is the relative importance of words spoken for creating nodes and system dynamics. That is, this graph identifies when some group members contribute significantly to the creation of the system map elements compared to their peers. For example, the number of words spoken relative to the overall contributions of Group 6 provides an interesting case to demonstrate the potential differences between team members. In this group, the number of words spoken by each participant resulted in an almost even distribution of speech with G6P1 contributing 30%, G6P2 contributing 37% and G6P3 making up the remaining 33%. However, the number of nodes and system dynamics contributed by each participant's utterances is not uniform, with G6P2 and G6P3 making almost equivalent contributions (44% and 42% of the total elements respectively) while G6P1's utterances only resulted in about 13% of the overall contributions. That is, though the group members might have participated equally in conversation, their individual contributions to the system map elements did not carry over in the same way. Another pattern is observed in Group 5. Here G5P2 participated in the conversation with about 25% of the total words spoken. However, G5P2 makes up a total of 50% of the contributions to the system map. Though they spoke less than the other two group members, what they said resulted in the generation of half of the system map elements.

Individual group members' utterances may contribute different elements to the system map. That is, one team member's segments may add more nodes than system dynamics or vice versa. Figure 12 presents the percentage of total number of nodes (N) and system dynamics (SD) contributed by each participant for all groups.

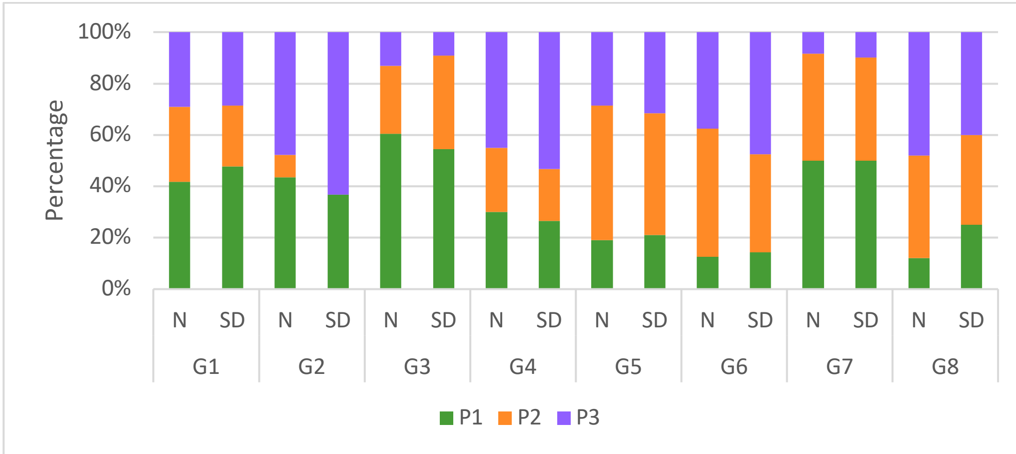

Figure 12 Percentage of nodes and system dynamic contributions made by each participant in Study A

I observe that in general the participants contribute a similar percentage of nodes as they do system dynamics, except for one of the participants. G2P2 contributed only 2 nodes (9%) to their group's overall system map and no system dynamics.

3.5.2 Individual node contributions to communities

Comparing the system maps which depict the design communities, and the individual contribution maps one can visually determine which nodes in the frame are contributed by each participant. For example, Figure 13 shows the system map of Group 6 with the communities differentiated by colour (A - left), as well as the system map with individual contributions (B – right). As can be seen in the two system maps, there is considerable diversity in ownership of nodes belonging to each community. For example, the purple community on the left is the theme that focuses on the factors that might influence the ability to wake up. In this community, three of the nodes are identified in G6P3's utterances, two by G6P2's utterances and one by G6P1's utterances. This is an example of a community that has all participants nodes contributing to a particular theme.

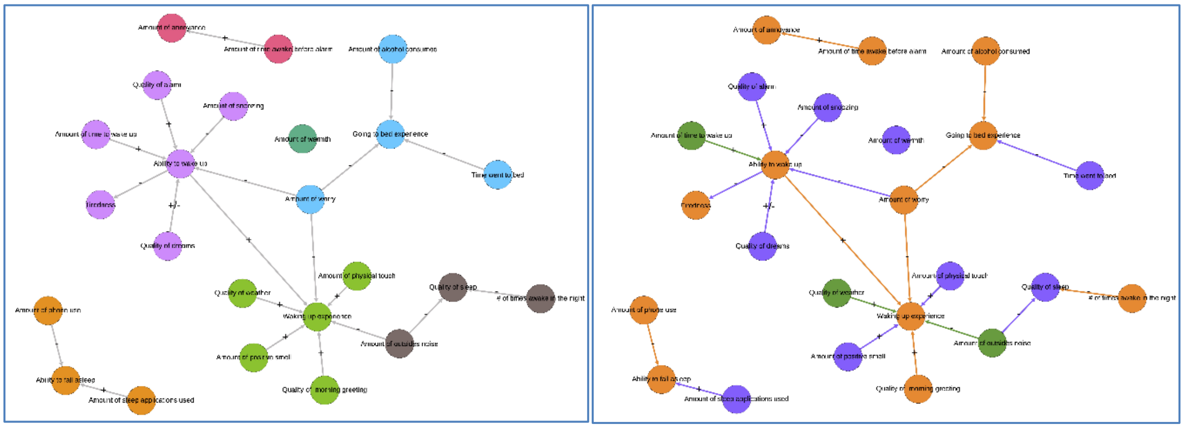

Figure 13 A) Group 6's system map with colour indicating communities (left); B) Group 6's system map with colour indicating individual contributions (right)

Figure 14 offers a more detailed breakdown of the individual contributions for each of the participants in Group 6 in relation to the five communities considered. Noticeably, 3/5 communities include nodes from all participants in the group, while the other two communities only include contributions from G6P2 and G6P3. A detailed breakdown for all groups' individual contributions to the group's communities can be found in Appendix C.

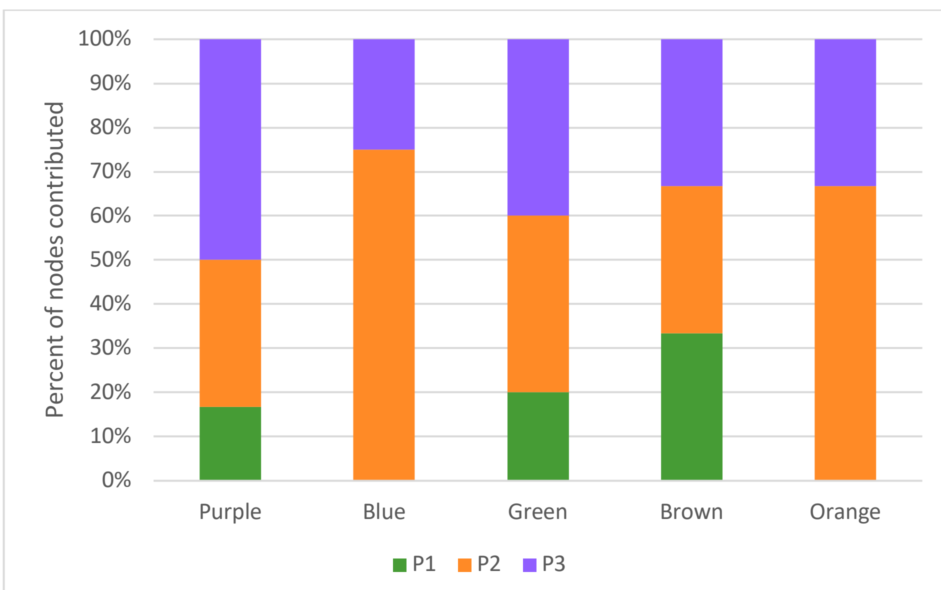

Figure 14 Participants of Group 6 percentage of contributions made to each community

3.5.3 Types of system dynamics

In addition to the nodes of each participant contributing to individual communities, the ownership of system dynamics can also be analyzed to demonstrate whose speech connects nodes in the system. There is considerable diversity in the types of system dynamics, depending on the ownership of the system dynamics itself and the nodes it connects. I observe that three different types of system dynamics are possible:

- Type I, occurs when a participant's system dynamic connects two nodes generated by that same participant. The pair of nodes 'place in sleep cycle' and 'ability to wake up' in Figure 15 (left) provide an example of this type of connection, as both nodes and the system dynamic connecting them was generated by G5P2.
- Type II, occurs when a participant's system dynamic connects one of their own nodes to or from a node generated by another participant. One example of this occurs in Figure 15 (center) where the 'amount of natural sunlight' and the system dynamic are generated by G5P2 and the 'waking up experience' is generated by G5P1.
- Type III, occurs when a participant creates a system dynamic that connects nodes that were not generated by that participant. An example can be seen in the Figure 15 (right) between the 'amount of music' and the 'amount of annoyance' nodes that were generated by G5P2 and G5P3 respectively, while the system dynamic is generated by G5P1.

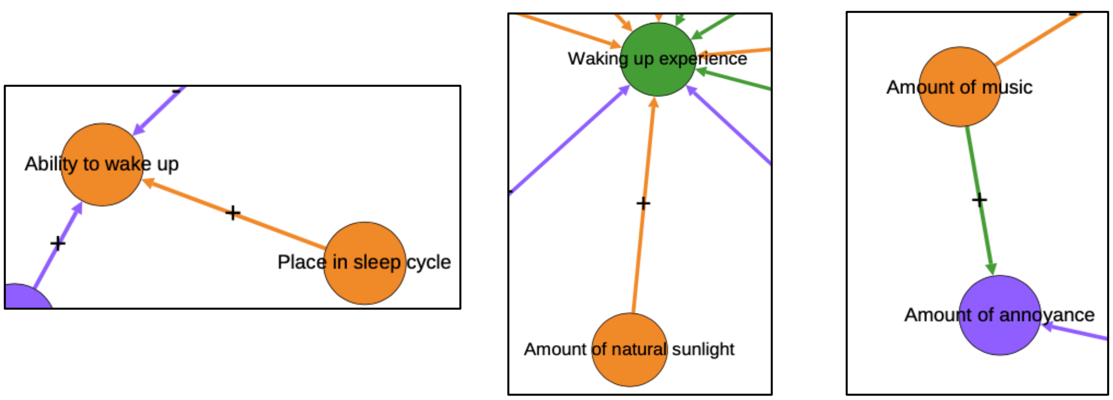

Figure 15 Types of system dynamics from Group 5's system map (Type I - left, Type II - centre, Type III - right)

To explore if these observed patterns carried any significant meaning, I calculated the frequency of system dynamic types created by each participant. Figure 16 includes the totals of those frequencies across all groups.

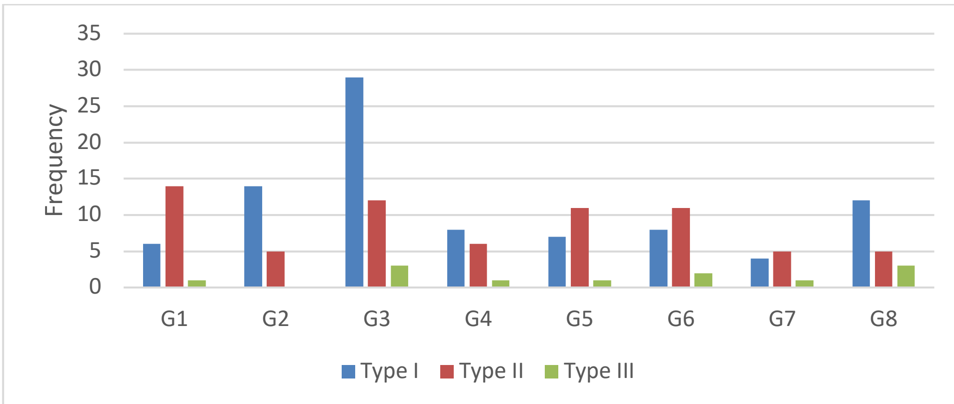

Figure 16 Distribution of system dynamic types

There are a few clear patterns that emerge from this graph. First, the transcripts of Groups 2, 3, 4, and 8 contain more Type I system dynamics compared to the other two types. The second pattern emerges from the other groups (i.e., 1, 5, 6, 7), where more of the identified system dynamics are Type II. Finally, the last observation from this data is the limited number of Type III system dynamics. Though almost all groups (except for Group 2) had instances of this type of connection, it only occurred a maximum of 3 times for two of the groups. This is the case for Group 3 and Group 8, where the utterances from G3P2 and G3P3 combine for 3 Type III system dynamics and G8P1 generated 3 system dynamics of Type III alone.

It should be emphasized here again that the system maps only provide a static view of the participants framing activity, because the temporal evolution of the maps cannot be seen. That is, a system dynamic that is found early in the session is no different, visually, than one that is found later. This carries significant implications for how each type of system dynamic (I, II or III) appears in the transcripts temporally. In particular, a Type III system dynamic can only occur after two nodes of other participants are identified in the transcript and a connection between them is made. This differs from Type I and Type II because these system dynamics can be, and often are, identified at the same time. That is, a line in a transcript can result in more than one element, usually a node and system dynamic pair, being identified by the same participant.

3.6 Summary

The system mapping approach created for this thesis provides several useful lenses to analyze design activity. This chapter has demonstrated how the system maps can be used to carry out a variety of analyses, including the size of the system maps and how they evolve over time. A community detection algorithm also demonstrates how the structure of the system maps can assist in distinguishing themes among structurally related nodes, which are useful in highlighting more specific areas of focus in the problem framing activity. Finally, a collaborative designing approach highlighted the differences in participants tendency to create nodes and system dynamics, proposing three types of system dynamics that are possible to observe in the system maps. These analyses are evidence of the efficacy of the system mapping approach for understanding the design framing activity that occurs during the early phases of the design process. In particular, these groups were presented with a highly ill-defined and open-ended problem, which necessitate problem scoping activities in order to find a suitable area of the problem for which a solution should be generated. In the next chapter, transcripts of designers working on a problem which predominately focuses on the latter half of the design process (i.e., solution generation and evaluation) is considered.

Chapter 4 Results – Study B

As briefly mentioned in Chapter 2, after completing the analysis for Study A there was potential for the process, including coding and map creation, to be biased towards that dataset. The primary goal of Study B, then, was to test the method in another problem context to observe how the approach performs on a dataset different from the one on which it was initially developed. In Study B, I tested the approach on verbal protocols collected from two groups of designers working in a different design problem. The design brief presented the participants with a detailed mechanical engineering design problem, with well-defined requirements and constraints. Because the problem was already well-defined, participants needed to spend little time on problem finding and could spend more of the design session on generating conceptual designs that could be potential solutions to the problem. As such, Study B also served the purpose of testing the approach on a design activity that was very different from the challenge presented to participants in Study A, which required more of the session to be spent on problem finding and analysis.

This chapter is structured in a similar way to Chapter 3, with section 4.1 focusing on the number of nodes and system dynamics found in the maps and how the system maps evolved over time. Section 4.2 will provide more detailed descriptions of the structures of the system maps and the content of the nodes in relation to community detection and collaboration.

4.1 Nodes, system dynamics, and maps over time

The total number of nodes and system dynamics generated from the two transcripts, the length of each transcript in words, for both groups, and the average for the groups in Study A can be found in Figure 17. The first group, made up of 4 participants that self-identified as design “practitioners” had a system map with 25 total elements The second group, comprised of 4 participants that had self-identified as “academics”, had a total of 28 elements that were detected. In Study A, across all eight teams, the ratio of transcript length (in words) to generated system map elements was on average 86. This was significantly lower than the ratio found in the two groups of Study B, which was on average 231.

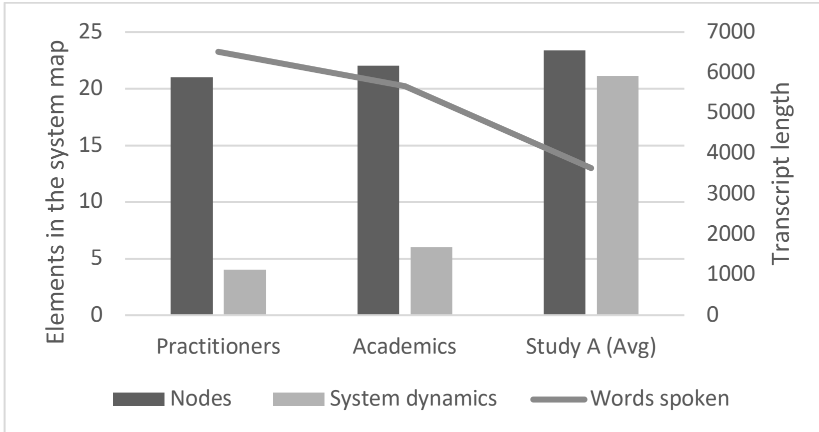

Figure 17 Number of nodes and system dynamics (elements)

The transcripts were divided into 20 equal portions, or ventiles, based on the number of lines in the transcripts. Figure 18 presents the cumulative number of elements that were identified in both the academic and practitioner transcripts, in each ventile, as well as the average number found in Study A. A similar pattern emerges, with both curves having a rapid increase in node and system dynamic identification early in the session, with new additions plateauing about halfway through the session.

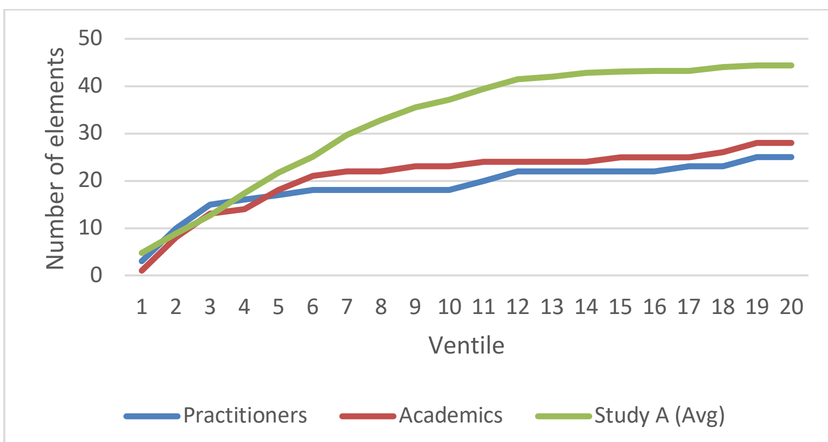

Figure 18 Cumulative added elements to the system maps

4.2 Communities and collaboration

Not only were the number of nodes and system dynamics similar between both groups, but the contents of the nodes were also similar. Figure 19 is the system map generated for the practitioner group and Figure 20 is the system map generated for the academic group.

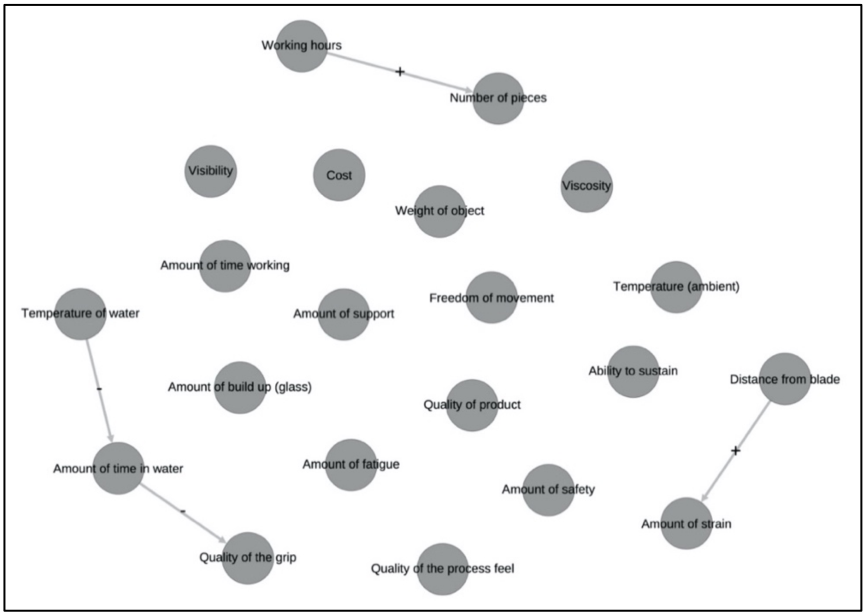

Figure 19 Practitioner's system map

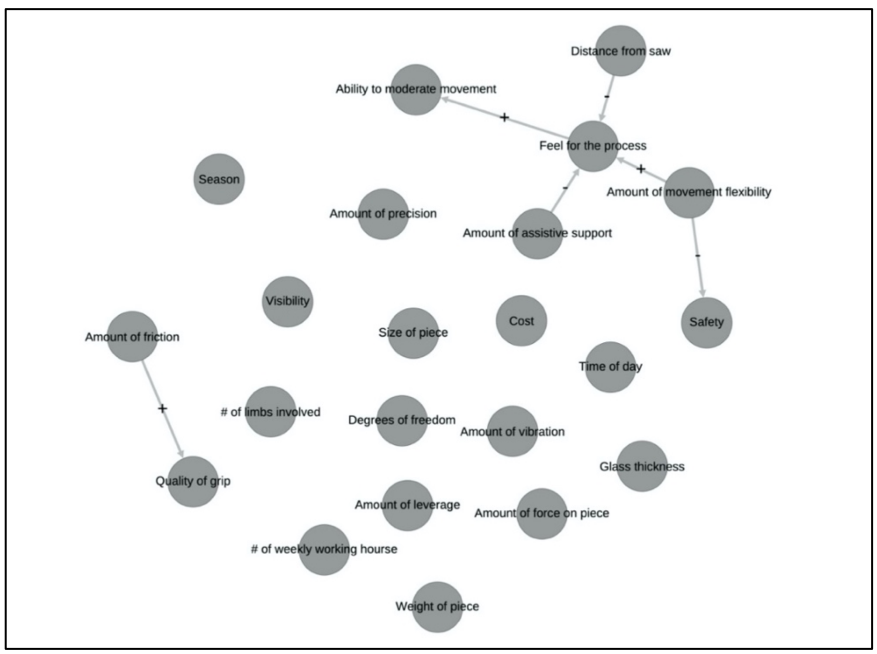

Figure 20 Academic's system map

Comparing the contents of the nodes between the two system maps, they share a total of 9 nodes with similar labels (i.e., they have the same meaning for both groups). Table 9 presents a summary of those nodes, as well as those nodes that are found only in one system map and not the other. Those nodes that are directly tied to the information in the design brief are marked with an (*) in the table. The system maps do not share any common system dynamics.

Table 9 Summary of nodes found in academics and practitioners groups' system maps

Nodes found in both groups	Nodes found only in practitioner system map	Nodes found only in academic system map
Cost*	Quality of product	Amount of movement flexibility*
Weight of piece*	Number of pieces*	Ability to moderate movement*
Distance from saw*	Temperature of water*	Degrees of freedom*
Safety*	Ability to sustain	Amount of precision*
Amount of time working*	Amount of time in water	Time of day
Visibility	Amount of fatigue	Season*
Amount of support*	Freedom of movement*	Glass thickness*
Quality of the grip	Amount of strain*	Amount of vibration
Feel for the process*	Viscosity	# of limbs involved
	Amount of build-up (glass)	Amount of leverage
	Temperature (ambient)*	Size of piece*
		Amount of force on piece
		Amount of friction

Due to the limited number of system dynamics, the community detection algorithm provided little information in the analysis of these maps. Figure 21 presents the system maps generated from the transcripts of the practitioner (A – left) and academic groups (B – right), both with the community detection filter applied to highlight communities using colour.

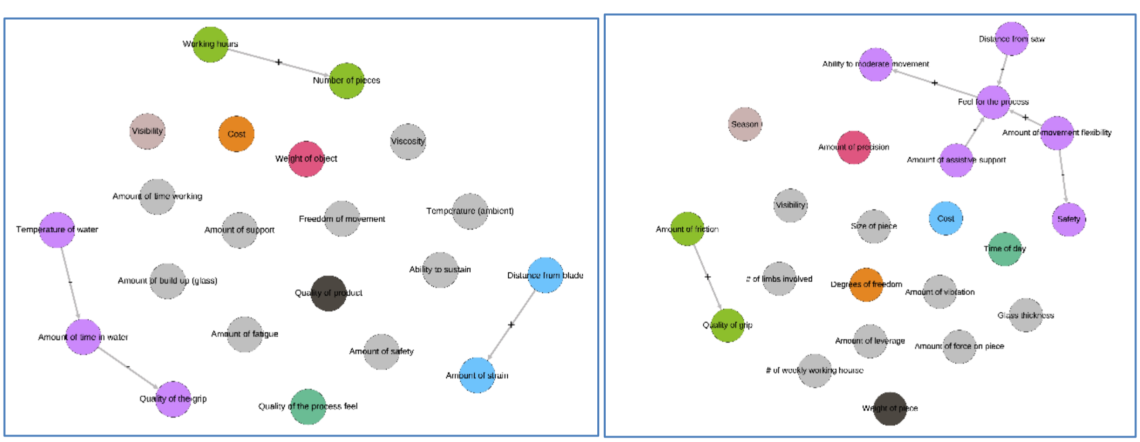

Figure 21 A) Practitioners' system map with colour indicating communities (left); B) Academics' system map with colour indicating communities (right)

Visual inspection indicates that there is only one community (colour-coded in purple) in each of the system maps with a population of three or more nodes. For the community found in the academic system map, which is composed of six nodes, the focus seems to be related to those elements (e.g., 'the ability to moderate movement') that would influence the overall feel for the process of glass carving. This was reflected in the solution ideas developed by the group, as they focused on a system that was able to support the piece of glass, while having the ability to move the piece with some level of precision. The community found in the practitioner map, which is composed of three nodes, seems to focus on the water used in Lois' process and how this might influence the quality of the grip. Not all the solutions ideas directly mapped to this central focus, though there was discussion of some kind of sling that could be used to support the weight of the piece.

Nodes and systems dynamic ownership were assigned in the same way as in Study A based on which participant's utterance added the nodes or system dynamic to the map. Figure 22A (left) is the system map for the practitioner group and Figure 22B (right) is the system map for the academic group, both with the team filter applied to distinguish participant contributions based on colour. I note that although both groups had a total of four participants, one of the participants in the academic group did not contribute to the conversation and was not included in the transcript. This observation is reflected in the system maps and analysis.

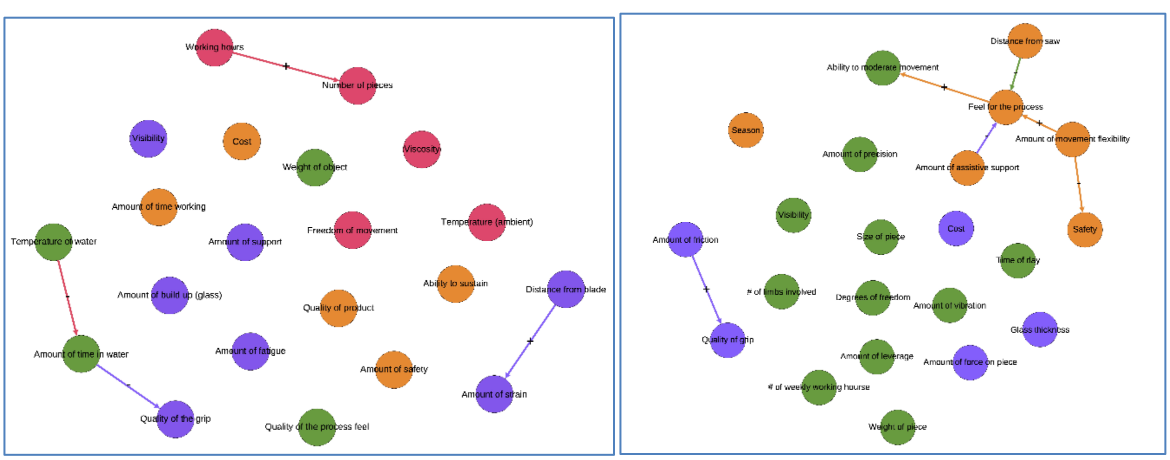

Figure 22 A) Practitioners' system map with colour indicating individual contributions (left); B) Academics' system map with colour indicating individual contributions (right)

Figure 23 provides insight into the percent of the total number of words (W) spoken by each participant compared to the percent of contributions (C) each participants speech made to the system map. Both groups had a similar distribution in the number of word spoken by each participant and the amount their speech contributed element to the system map.

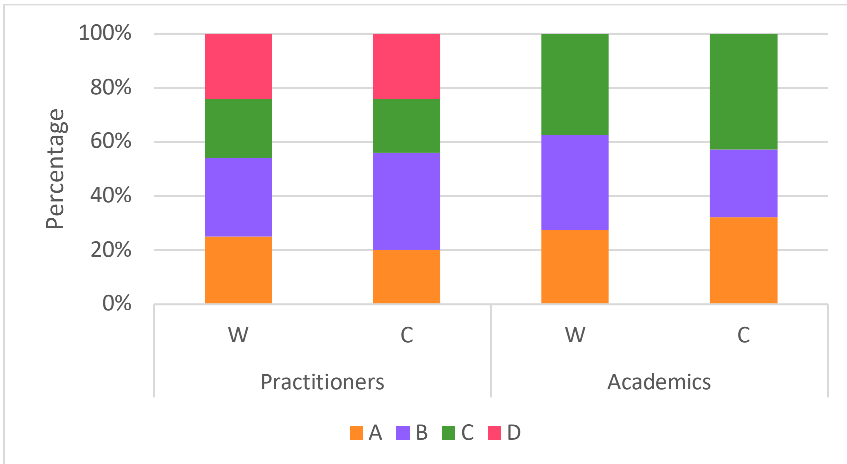

Figure 23 Percentage of total words and percent of contributions made by each participant in Study B

Figure 24 presents a comparison between the number of nodes and system dynamics generated from each participant's speech found in both groups. Noticeably, though all participants' speech in the practitioner group generated at least a node, only two of the participants' utterances (B and D) contributed a system dynamic. The academic group has many of the nodes (11/22) attributed to participant C, while that same participant only contributed a sixth of the team's system dynamics.

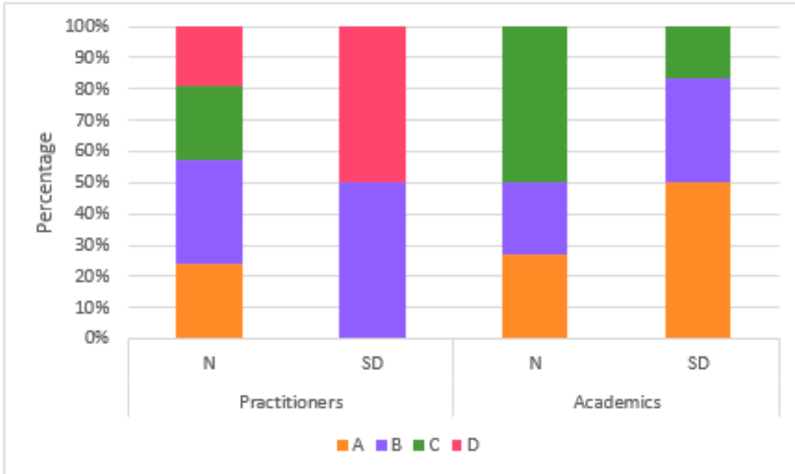

Figure 24 Percentage of node and system dynamic contributions made by each participant in Study B

As previously defined in Section 3.5.3, system dynamics are one of three types. Figure 25 presents the frequency of occurrence of each system dynamic type for each group. Due to the small overall number of system dynamics identified in the two protocols, limited inferences can be made to compare the two groups based on this characteristic. However, it is noted that one of the general pattern holds as found in Study A; that is, system dynamics of Type I are the most dominant.

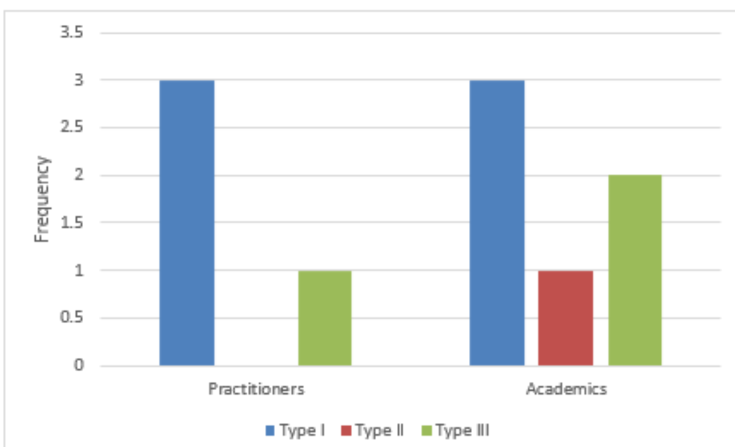

Figure 25 Distribution of system dynamic types in Study B

4.3 Summary

Study B was motivated by two goals. The first was to test if the system mapping method was overfit to the dataset used in Study A. By detecting nodes and system dynamics in the system maps, as presented in section 4.1 and 4.2, it was determined that the method was capable of detecting elements of design conversations, indicating that the method can be used in another problem context. The second goal was to determine if the systems mapping approach would be useful when analyzing design activity that occurred primarily in the solution ideation and evaluation phases of the design process. Though nodes were detected in participants' speech, a limited number of system dynamics were detected between the nodes. This result is not completely unexpected, as designers during the solution ideation and evaluation phases of the design process are focused on rapidly proposing and testing new ideas, rather than determining aspects of the problem to consider. As such, though the method was capable of detecting these elements, this finding highlights the limited suitability of the approach in all problem contexts.

Chapter 5 Discussion

This thesis was guided by the research question: *What can a systems mapping approach say about design framing activity?* To answer this question, I proposed and tested a novel protocol analysis approach, using concepts and tools from systems thinking, aimed at understanding design framing. What follows is a discussion of the contributions in relation to the findings presented in Chapters 3 and 4.

5.1 Contribution

Design is cognitive activity which involves the creation of novel solutions that tend to move society to more desired situations (Goel and Pirolli, 1992). Design problems, which inherently lack structure and are commonly ill-defined, require intentional design practice to define and redefine the criteria and constraints in order for novel solutions to emerge (Cross, 1982). Systems thinking has become useful for defining such problems because the approach focuses on understanding complex situations (Checkland, 1999). It is one of the ways designers can understand elements of a problem and see interconnections between them (Meadows, 2008). Designers should be aware of the importance of systems thinking, as design shifts into a new paradigm of activity that focuses on interventions that cause desired system change (Dorst, 2019).

Unfortunately, design and systems thinking have been explored in isolation of one another (Greene et al., 2017). As such, this thesis has aimed to fill this gap by introducing a system thinking inspired approach for understanding designers' activity while designing. In particular, this novel research approach utilizes systems mapping, a visual representation tool commonly used to identify and visualize elements of a problem and the interconnections between them. Verbal protocols of design activity are retroactively "coded" to identify system nodes and dynamics to generate a system map that characterizes the designers' discourse.

This thesis has demonstrated how the method was applied to create systems maps from verbal design protocols collected in two different studies. The generated system maps were analyzed from a variety of perspectives and the metrics derived from the maps (e.g., the number of nodes and system dynamics, communities, etc.) highlight the usefulness of the approach for understanding design framing activity. The generated system maps offer unique visual representations of the designers' framing, providing evidence for the utility of the system mapping approach. Further discussion of these aspects will follow in the remaining sections.

5.1.1 Capturing design framing using systems mapping

In Chapter 1, viewpoints from a wide variety of design researchers, including Donald Schön and Herbert Simon, were provided to highlight how and why design framing occurs. Emphasis is placed on the early phases of design activity, when designers construct their problem situations by focusing on the information, often limited, necessary for formulating solutions (Simon 1969; Schön, 1984a, 1984b).

Based on the results from Study A and B, the system maps generated from verbal protocols of design discourse show promise in their ability to capture the activity associated with framing as is described in the design literature. That is, the nodes and system dynamics that can be identified in participants' speech, and visually represented in a unique system map, provide insight on which aspects of the design problem are brought into focus and how those aspects might be connected. In other words, *the system map provides a lens (or representation) to describe what is brought into the designer's frame during the design activity*.

From the systems thinking literature, we know systems set limits on what is and is not included inside the system under analysis. For the system maps presented in Chapters 3 and 4, all nodes and system dynamics that are identified in the transcripts are considered to be within the designers attention at some point during the session. That is, nodes and system dynamics are not added to the system maps all at once, indicating an open and flexible quality to their design space. This quality is shared with design frames, which only represent a perspective that is imposed by the designers on the situation at a specific moment in time (Cardoso et al., 2016) and as such the system map can be seen as a representation of the design framing activity. If the design conversations were not time limited, as they were in both Study A and Study B, it is possible that new nodes and system dynamics would be added to the system maps, expanding the understanding of the current system. As designers learn about new information, they will revisit their structuring of the design space throughout the design process (Goel and Pirolli, 1992).

If the systems map is a representation of framing, then it follows that these maps can be used to draw insight on the framing activity. Therefore, *the quality of a designer's framing could be determined by characteristics of the system map.*

The number of nodes and system dynamics provide useful metrics for characterizing the size of the system map and by extension the designers' framing activity. One of the key findings from Study A was the detection of considerable differences between the number of elements on the system maps when comparing the groups (e.g., between Group 3 and Group 7). I believe that a system map with more nodes and system dynamics (e.g., Group 3 in study A) is an indication of greater exploration of the design space, and therefore *better* framing. However, though system maps with more elements might be indicative of better framing, this does not consider the quality and role played by individual nodes and system dynamics. It may be the case that there are some nodes and system dynamics that have greater importance than others and thus become more influential in the design process. In the results presented in Chapters 3 and 4, there are no clear metrics that support claims of a particular element being important, though there are some tools that could be used to determine this. Specifically, the relative importance of nodes in large network analysis is often determined by how central a node is in a network (Grando et al., 2018). A more thorough discussion of these tools can be found in the Section 5.3, where future research directions are discussed.

Another measurable characteristic of the system maps are the detected communities. Communities are sets of related nodes as detected by a modularity algorithm (as used in sections 3.4 and 4.2), based on the arrangement of nodes and system dynamics in the network. Based on the content (label) of each node in the community, a theme can be qualitative inferred for the community. For example, five communities were detected in the systems map of Group 6, including "activities before going sleep", "factors that influence the ability to fall asleep", and "factors that influence the ability to wake up". These themes present different aspects of the design space that had come under focus during the framing, offering different ways to look at the problem that prompt different types of solutions. Therefore, *each community could represent a design frame*. Across different groups' systems maps, communities of similar themes were identified. In Study A, across all eight groups, a total of nine communities with an identifiable theme were detected, with seven of them being common between at least two of the groups. This demonstrates that different groups' framing varies in the quantity and range of frames considered. Therefore, the number of detected communities could be used as an indicator of the quality of the group's overall framing, with more detected communities indicating a better exploration of the design space.

If the quality of framing can be assessed using the diversity of frames considered, as detected by the communities, then one must also determine whether quality differences between two communities that represent a similar frame can be measured. This brings into question how the "quality" of communities (or frames) might be assessed. It is not clear whether more nodes and system dynamics in a community are indicative of a better frame. For example, both Group 3 and Group 6's maps had a community with a focus on the activities one does before they go to bed (see Table 5 in section 3.4). Group 3's community had more nodes and system dynamics covering a wider variety of activities (i.e., reading or TV watching) compared to the community in Group 6's map, which only considered the amount of phone use. Given the assumption that was made previously in this section that a larger system map is indicative of a better overall framing activity, then it could follow that the quality of a design frame can be assessed in a similar way; that is, a community with more system nodes would indicate a more thorough investigation (or better exploration) of that particular frame. In this case, one would conclude that the frame found in Group 3's map is better than Group 6's.

The central idea of framing is that designers spend time reasoning about their desired outcomes and create possible design solutions via their frames (Dorst, 2015, p. 54). In other words, frames must be actionable, capable of leading to realistic solutions (Dorst, 2015, 63). However, like design solutions, the quality of a design frame is determined how useful it is (Dorst, 2015, 65). By noting the solution ideas generated by each group throughout the transcript, I was able to infer which solutions were derived from particular frames. This might help determine the quality of the design frame by assessing its utility in relation to generating solutions (e.g., more solution ideas could mean a better frame). Though the number of solution ideas related to a particular frame might be useful in determining that frame's quality, a more rigorous metric is likely required. That is, both an assessment of the quality of the final solutions and a metric assessing a frames causal influence for creating that solution would be necessary for determining the frame's overall utility. Though it is possible that this analysis could be conducted on this data set, it was determined that this endeavour was outside the scope of this thesis.

5.1.2 System maps over time

Design framing is an evolving activity, as new information will prompt exploration of avenues not previously considered (Simon, 1969). The temporal analyses plots (as presented in section 3.3 and 4.2) demonstrate this evolving process and a clear general pattern emerged. Specifically, significant framing of the problem occurred early in the session, as was evident by the rapid identification of nodes and system dynamics during that time. In general, observing this result in the system map analyses is interesting but unsurprising. Nodes, by definition, are concepts that have a measurable quantity or quality. This is also a characteristic of many design requirements and constraints that are identified early in the design process. This is especially evident in both maps from Study B, where many of the nodes identified in the transcripts, and later visualized on the map, are requirements or constraints that were identified in the brief provided to the participants. For example, of the nine nodes identified in both systems maps (see Table 9 in section 3.2), seven mapped directly to details (requirements) already provided to the participants in the design brief (case study). It is unsurprising then that these requirements became the basis for early discussions within both the academic and practitioner groups, resulting in a significant accumulation of nodes and system dynamics early in the sessions.

This finding is also evident in all timelines presented in Chapter 3, where there is identification of nodes and system dynamics mostly in the first half of the sessions. The nature of the design challenge prompt (i.e., “How might you…?”) helps to generate novel approaches to a problem (Siemon et al., 2018), in this case an unpleasant waking up experience. Therefore, participants were likely identifying a suitable area of this problem in the first half of the session for which ideation of a solution could follow. After the midway point of the sessions new additions begin to plateau, however some groups were observed to continue adding nodes and system dynamics up until the last ventile of their session, highlighting the iterative nature of the framing process.

5.1.3 Understanding team designing

Design frames are socially constructed, as individual interpretations of the frame can vary considerably (Silk et al., 2021). As such, the frame that is shared by all group members is changed via the group members' interactions with each other (Hey et al. 2007). The system mapping approach proved to be useful for analyzing individual contributions by assigning 'ownership' to both nodes and system dynamics to the participant whose verbal utterance generated that element. With this analysis, the system map visualizations became useful in detecting a team's ability to create a shared understanding of the problem (Mathieu et al., 2000).

There are at least two ways in which this lens can be applied to determine the degree to which the framing activity was shared among all participants. First, when a frame includes contributions from all participants, it might suggest that the frame is shared by all team members. The results indicate that there are some design frames comprised of nodes generated by all group members, some frames from only two members, and some frames created by a single participant (see Appendix C). Therefore, *the degree to which a frame is shared by group members could be measured by the degree to which all members have contributed nodes to the community that represents that frame.*

Second, one could look at the prevalence of different system dynamic types (as defined in Section 3.5.3). As a reminder, Type I system dynamics occur when a participant's speech creates a connection between two of their own nodes, while Type II and Type III system dynamics occur when a participants speech creates a connection between two nodes, of which at least one belongs to another participant. Given the nature of the system dynamic types, *the degree to which the framing is shared among all group members could be measured by the number of Type II and III connections found in the system maps*. For example, in half of the groups in Study A, participants were found to create more system dynamics to or between nodes of other participants (more Type II and Type III) than connections to or between their own nodes (Type I). This provides one example of how the degree of shared problem understanding could be measured using the system map. However, this result also does not consider the number of times a particular relationship is revisited or debated once the connection is made on the system map, as the coding process only tracked the first occurrence of an element. Further discussion of this observation will follow in section 5.2.

5.1.4 Appropriateness of approach in different stages of the design process

Systems mapping is a system thinking tool that the problem solver (or designer) uses to understand and visualize the components (and their interactions) of a system under study, a very useful approach for understanding the problem and determining promising areas of focus for generating solutions (i.e., framing). It then follows, that when using system maps retroactively to code protocols of design activity, the tool would be better able to capture framing activity, which is typically the main activity in the early stages of the design process, as described by Jones (1970) and Cross (2000).

The differences observed between the system maps created in Study A and B provide strong evidence for the above. In Study A, across all eight teams, the ratio of transcript length (in words) to generated system map elements was on average 86, which is significantly lower compared to the two groups of Study B, where the average was 231. Both studies had participants designing, but the problems requires that designers work in fundamentally different stages of the design process. As explained in Chapter 2, in Study A, participants were provided a very short, open-ended, and ill-defined problem statement, a prompt that comprised of a vague goal about improving the waking-up experience. As such participants needed to spend much of the time engaged in problem searching or scoping processes, identifying which aspects of the problem offer the best opportunity for a designed solution – that is, framing. Accordingly, the system maps in Study A were dense with nodes and system dynamics, providing rich representations of the groups' framing activity. The design brief in Study B, however, was a detailed and well-defined mechanical engineering design problem, which required little task clarification and problem definition on the part of the participants. Instead, they could spend more of their time generating, evaluating, and explaining the details of solutions that would satisfy the requirements and constraints clearly set out in the design brief. Therefore, as expected, fewer system nodes were generated from this transcript, and even fewer system dynamics, which limited the detection of communities (or frames).

5.2 Limitations

In essence, this exploratory research project was focused on learning and understanding how systems mapping might be useful for research on design framing activity. The number of research avenues considered in the development of this thesis prevented any in depth analysis on two key components, which would provide further justification for the use of a systems thinking approach to understand design activity. The first is a lack of comparison between the systems mapping approach and other protocol analysis approaches used for studying design activity. The results presented in Chapters 3 and 4, though they provide evidence the approach shows promise in understanding design framing behaviour, they do not demonstrate that this approach is better than another protocol analysis approach. Though this comparison is theoretically possible, it seems difficult to do in practice because, to my knowledge, there are no other protocol analysis methods similar enough that a suitable comparison could be made to test the approach for validity.

The second main limitation is in validating the relationship between the system mapping approach (and its associated metrics) and the outcomes of design activity, for example, the quality of designed solutions. Though the designed solutions were captured in the transcripts, only preliminary steps were taken towards any comparison between the quality of the systems maps and the final solutions. In particular, the solutions were used in the community analysis to provide some validation for the themes in each community (see section 3.4 and 4.2) but no in-depth comparison between those community and the associated ideas was carried out. However, the results highlight the promise of the approach for future work in this area of inquiry. Further discussion of this idea can be found in the next section.

The coding processes used in protocol analysis studies are subjective in nature. A common approach to minimize the effects of this subjectivity is to have multiple coders code the protocol, aiming for significant agreement between coders. In the case of the method described in this thesis, coding of the protocols entails identifying systems nodes and dynamics in the participants' speech. This is unlike typical protocol analysis studies, where protocols are coded according to a pre-determined set of codes. Though Dr. Hurst and I coded a portion of the verbal protocols together, I completed the coding of the remaining protocols alone. This made providing coding reliability metrics impossible because no interrater reliability score could be calculated. In general, the nature of the coding process prevents any reliability scores from being calculated because any differences in the identification of a node could result in a completely different system map. That is, though two coders might agree that an utterance is an indication of a node, the way in which that node is defined on the system map by the independent coders would influence how any future nodes and system dynamics might be related to that node. Thus, common reliability metrics used in protocol analysis would not be meaningful, and in general, coding reliability in this context would be very difficult to calculate. However, there is opportunity to determine if two system maps are similar by comparing the various metrics that can be derived from them. Gephi offers a variety of system map metrics (i.e., the number of edges going to or from a node, the average distance it takes to each a node in the system) to be calculated. These can determine the extent to which maps share similar properties, and thus have the potential to be used for reliability metrics. That is, two independent coders could create system maps and a comparison of these properties could determine how reliable the coding process was.

5.3 Future research directions

The process of validating new research approaches involves building confidence in the usefulness of the approach with respect to a purpose (Pedersen et al. 2000). In this case, my purpose was to develop and assess a novel method, inspired by systems thinking, for understanding design framing. As this chapter has suggested, the approach has proven useful for understanding design framing by analyzing the created system maps from a variety of perspectives. However, to build more confidence in the findings, the most important future direction for this research is the repeated implementation of the approach in other problem contexts. That is, to claim that a method can be used more widely it must be rigorously tested.

Protocol analysis is one of the most popular research methods for understanding design behaviour. As such, there exists a large corpus of previously conducted studies on design protocols (e.g., Atman, 2019), used to study various aspects of design behaviour, for example, the differences between novices and experts (Song and Becker, 2014) or differences in idea generation techniques (Gero et al., 2013). This offers a unique opportunity to validate the systems map method by triangulating results from established protocol studies. Studies whose focus are on the early phases of the design process (where significant design framing occurs) would be most appropriate to validate the method. An early attempt at this kind of validation was conducted as part of this thesis to compare the results in Study B to those of a protocol study reported in Hurst et al. (2019), which analyzed the same dataset using the Function-Behaviour-Structure (FBS) ontology (Gero, 1990; Gero & Kannengiesser, 2004). However, given that participants in Study B mostly spent time in the solution ideation and testing phases of the design process, a kind of activity that cannot be suitably captured by the novel approach (as explained in Section 5.1.4), this attempt was unsuccessful. As such, careful consideration of the stage in the design process would be required for future comparisons of the system map method to any previously published protocol studies.

Throughout the development of this approach, several insights about the process of creating the system maps and the visualizations themselves have been gained. In section 5.1.1, I claimed the system maps offer one representation of the group's design framing. In the current implementation of the approach, the presented system maps present a retrospective view encompassing all nodes and dynamics generated by the participants throughout their design activity. This is a "flat" view and doesn't show any of the movement/changes that occur with time. However, the design literature on framing suggests that frames are not static entities. The way in which the method is currently applied, there is no way to demonstrate the dynamic nature of framing. Two improvements/extensions to the approach can be envisioned to address this.

First, while the approach currently tracks when a node of system dynamic is first generated in the design session, and cumulative graphs of the emergence of the elements have been provided, this temporal dimension is not visualized in the maps themselves - one cannot tell from looking at the map in which order the elements or communities emerged. Further, the approach currently only codes the first occurrence of new nodes and system dynamics rather than highlighting every utterance in the transcript that matches that element. Future implementations of the approach could track all instances of nodes and system dynamics regardless of when they are detected in the design session. This would offer one way to highlight the importance of the nodes and relationships found in the system maps. In the system map visualization, these results could be represented by increasing the size of nodes or the thickness of system dynamics, allowing for quick identification of elements that were discussed more often in the design conversation.

The analysis above could also be combined with centrality metrics, which can describe the extent to which any node can influence or be influenced by other nodes in the system. Gephi offers calculations for a variety of centrality scores that can be calculated for nodes. By identifying any correlations between frequently revisited nodes and the centrality scores for each node, one might be able to determine if a group is fixated on any one node or system dynamic. Design fixation refers to when designers become ‘set’ or ‘blinded’ by a particular solution or inadvertently carry over specific and unhelpful features from previous examples (Crilly, 2015). Rather than capture solution fixation, the approach described here provides an exciting avenue for exploring how designers might fixate on frames.

A second aspect of the dynamic nature of frames is that the nodes themselves could change meaning, break up, or combine with other nodes over the design activity. For example, in Study A, Group 1 discussed the concept of motivation early in their session. Later, they started to distinguish between different kinds of motivators that can be either positive (e.g., the quality of one’s breakfast) or negative (e.g., being shamed by a friend for waking up late). This conversation is only captured in the “motivation” node in the system map, though in reality, the motivation node was split into two nodes – positive and negative motivation. Future implementations of the method could more clearly track and visualize such changes that might occur to the design frame. The approach could be able to redefine a node and apply visual effects (e.g., animations or incremental additions) for a reconceptualization of nodes to better capture the new meaning.

One useful direction the approach offers is the appropriate language and tools that can be used to characterize designers’ ability to think systemically. Thinking systemically, by considering the wider complexity of the system and interconnections between parts/issues, is a skill highly relevant and useful when solving design problems (Checkland, 1999). Given the datasets and the maps generated from the design activity of the ten groups presented here, one may wonder if the groups with more nodes and system dynamics were better able to think systemically. It would be useful to compare this approach with more recent research on the assessment of systems thinking skills (Arnold & Wade, 2015).

Finally, as mentioned previously, an interesting avenue for future research would be to investigate if there is a stronger relationship between the final solution ideas and the quality of the system maps, as detected in section 3.4. The quality of the system maps might be assessed by building on the metrics (e.g., number of nodes and system dynamics, number of frames, quality of frames, etc.) presented in Chapters 3 and 4. An evaluation of the solution ideas could follow using existing solution evaluation techniques, like the Analysis of Exploratory Design Ideation (AEDI) found in Hay et al., (2019), which provides a framework for assessing the quality of ideas in the face of different problem interpretations. The frames identified by communities in the system maps could act as the "problem code descriptions" used in the AEDI framework, to assess the quality of solution ideas. I would expect that those groups with higher quality maps produce better final solutions.

5.4 Conclusion

Design is cognitive activity which deals with complex problems that must be structured in a way that allows solutions to be developed for those problems. Systems thinking offers one useful frame for approaching these problems and has similar characteristics to design thinking. This thesis proposed a method for generating systems maps from verbal protocols to analyze design framing. The system maps are unique visual representations of an entire design session and the analyses that are performed on them provide insight into those elements that designers bring into focus as they work on generating solutions to the problem. The results indicate that the system maps can act as representations of the groups' framing. Furthermore, a community detection algorithm can be used to identify communities of related nodes, which are akin to design frames as they are described in the literature. The method is most appropriate when analyzing design activity in the early stages of the design process, when framing is more common. This new way of coding verbal protocols, inspired by the tools used in systems thinking practice, can be used in a variety of research contexts. Several research directions have been provided, highlighting the usefulness and significance of this approach. Repeated implementations of this method with different protocols will ultimately determine its usefulness in our ability to extend our knowledge of design thinking, learning, and practice.

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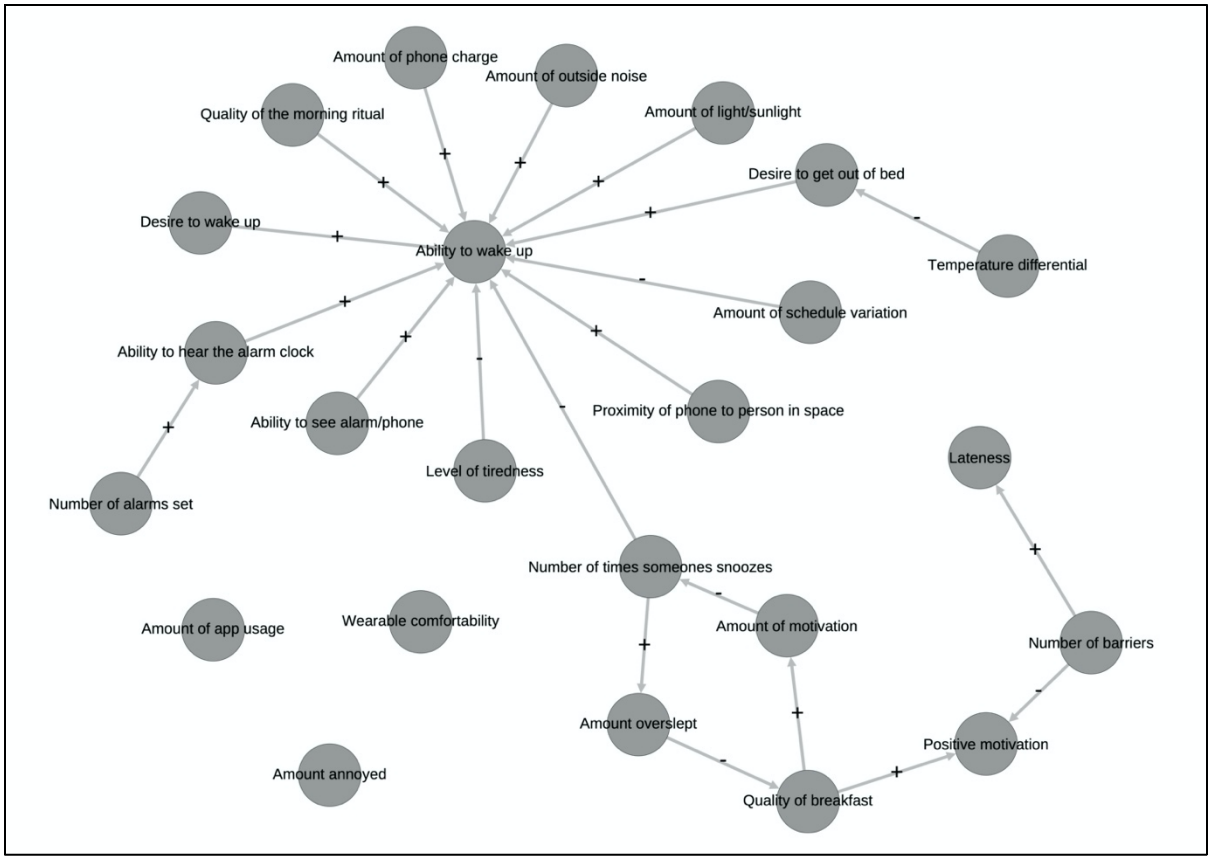
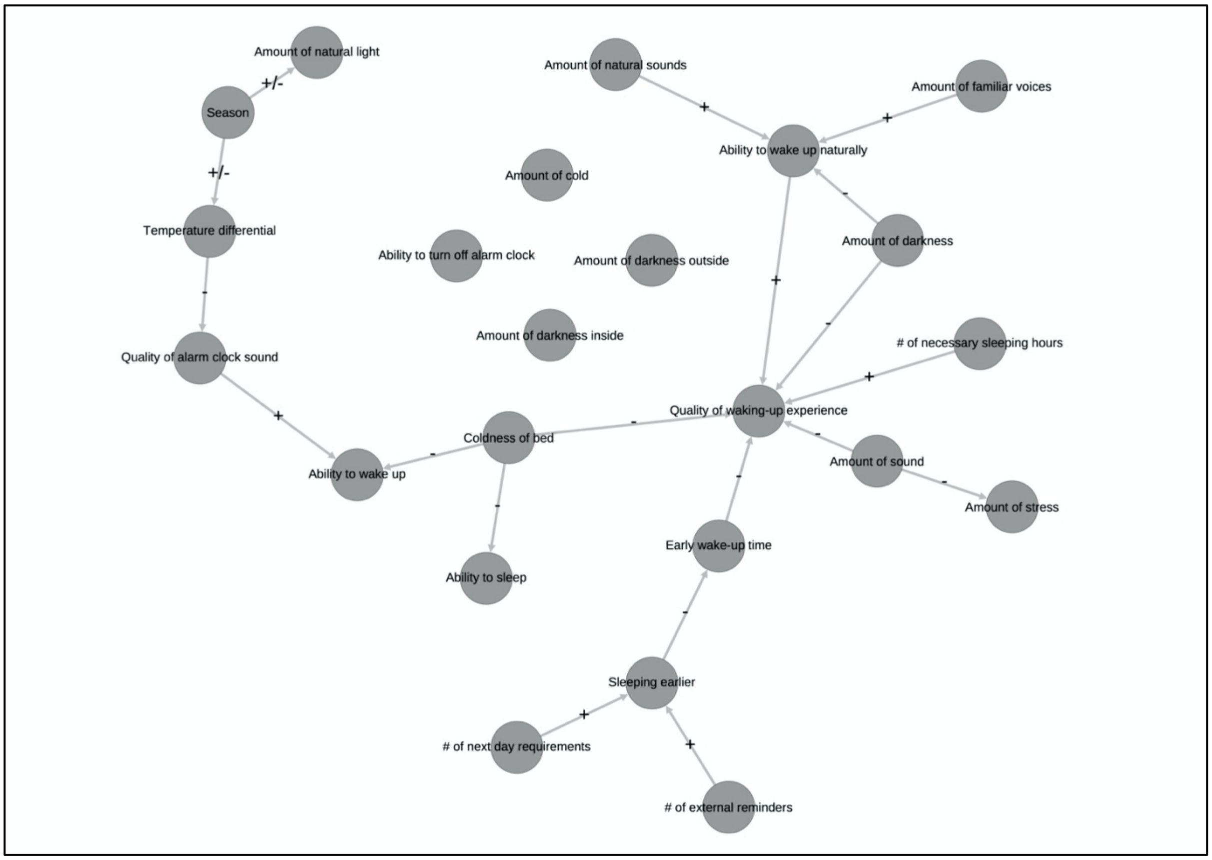
Appendix A Grey system maps Study A

Group 1

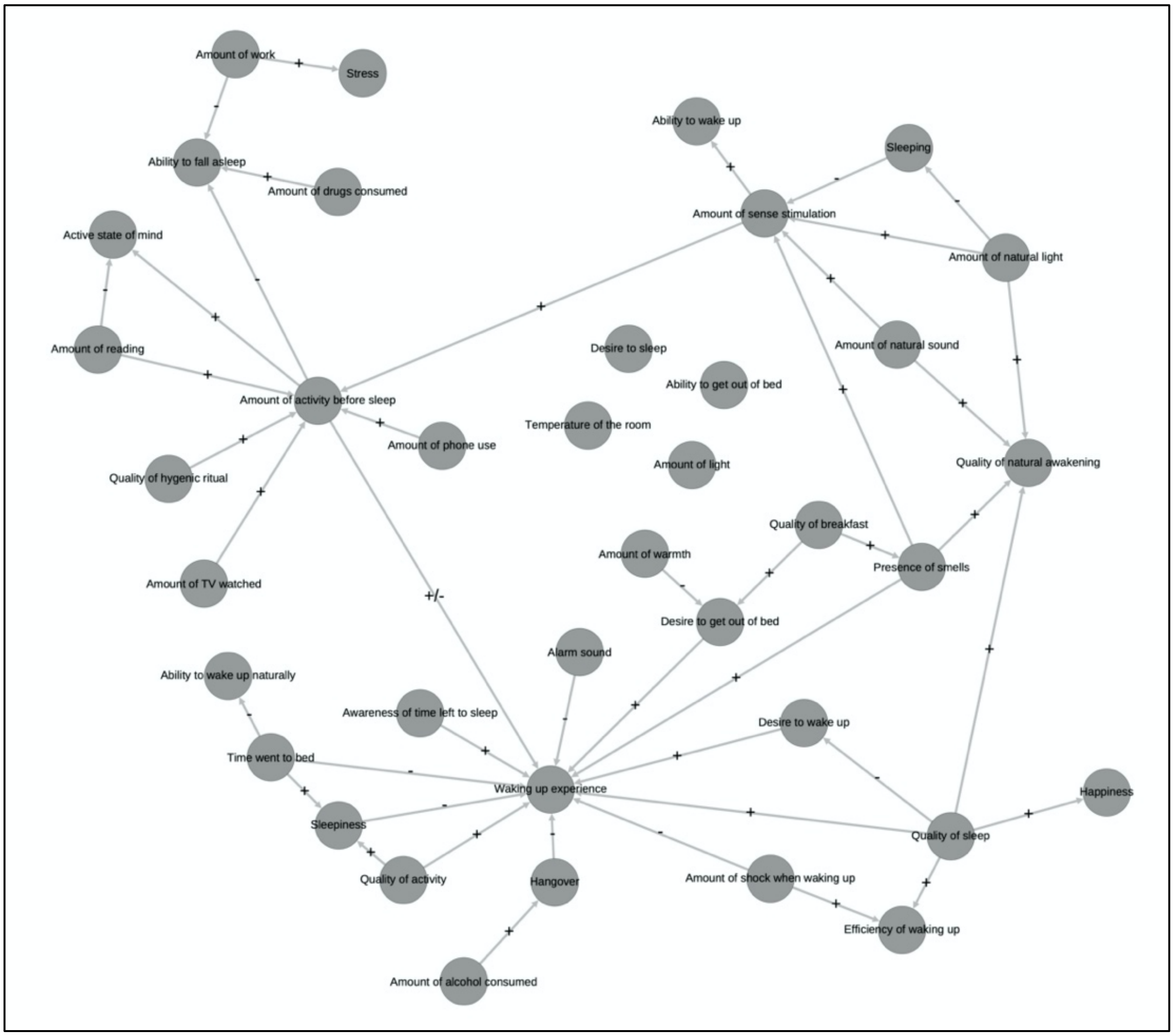


Group 2



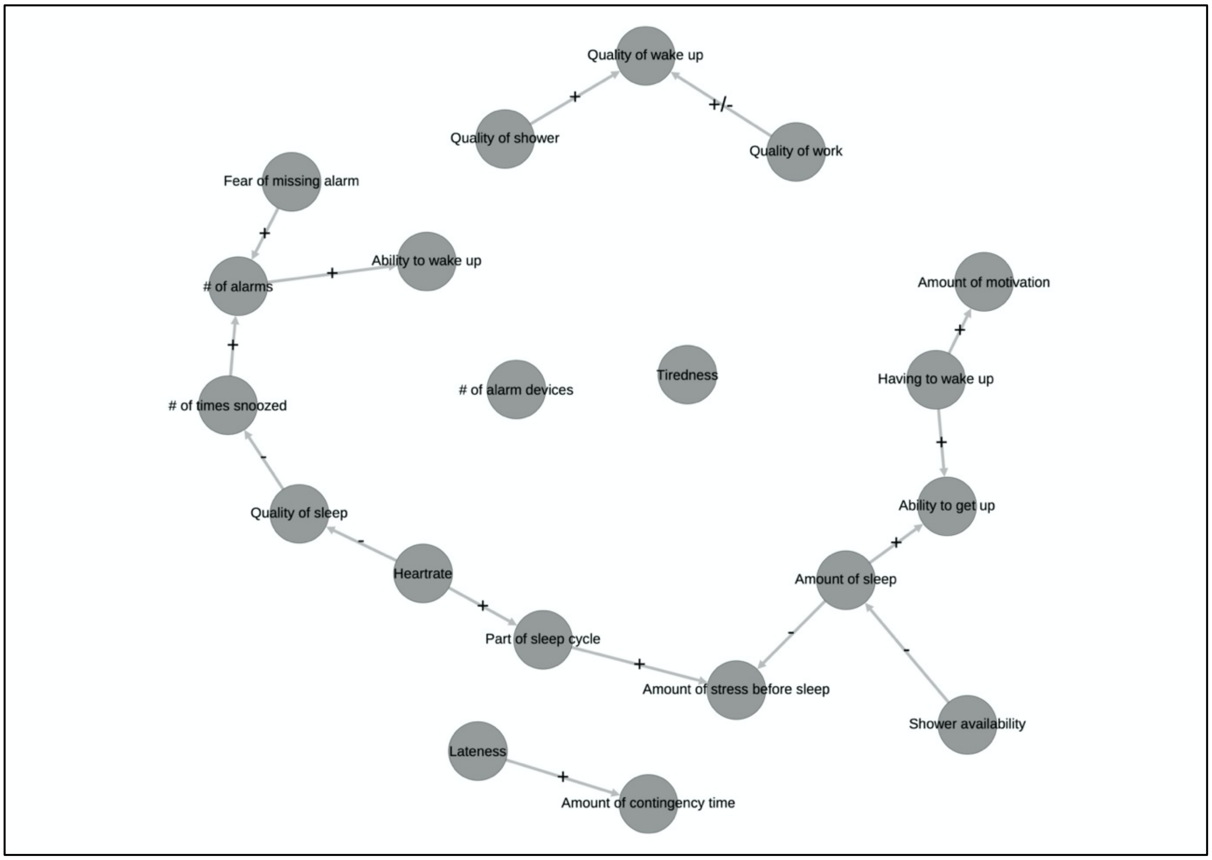
Amount of natural light
+/-
Season
+/-
Temperature differential
-
Quality of alarm clock sound
+
Ability to wake up
Amount of natural sounds
+
Amount of familiar voices
+
Ability to wake up naturally
Amount of cold
Ability to turn off alarm clock
Amount of darkness outside
Amount of darkness inside
Amount of darkness
-
+
-
# of necessary sleeping hours
+
Quality of waking-up experience
-
Coldness of bed
-
-
Ability to sleep
Amount of sound
-
-
Amount of stress
Early wake-up time
-
-
Sleeping earlier
+
# of next day requirements
+
# of external reminders

Group 3

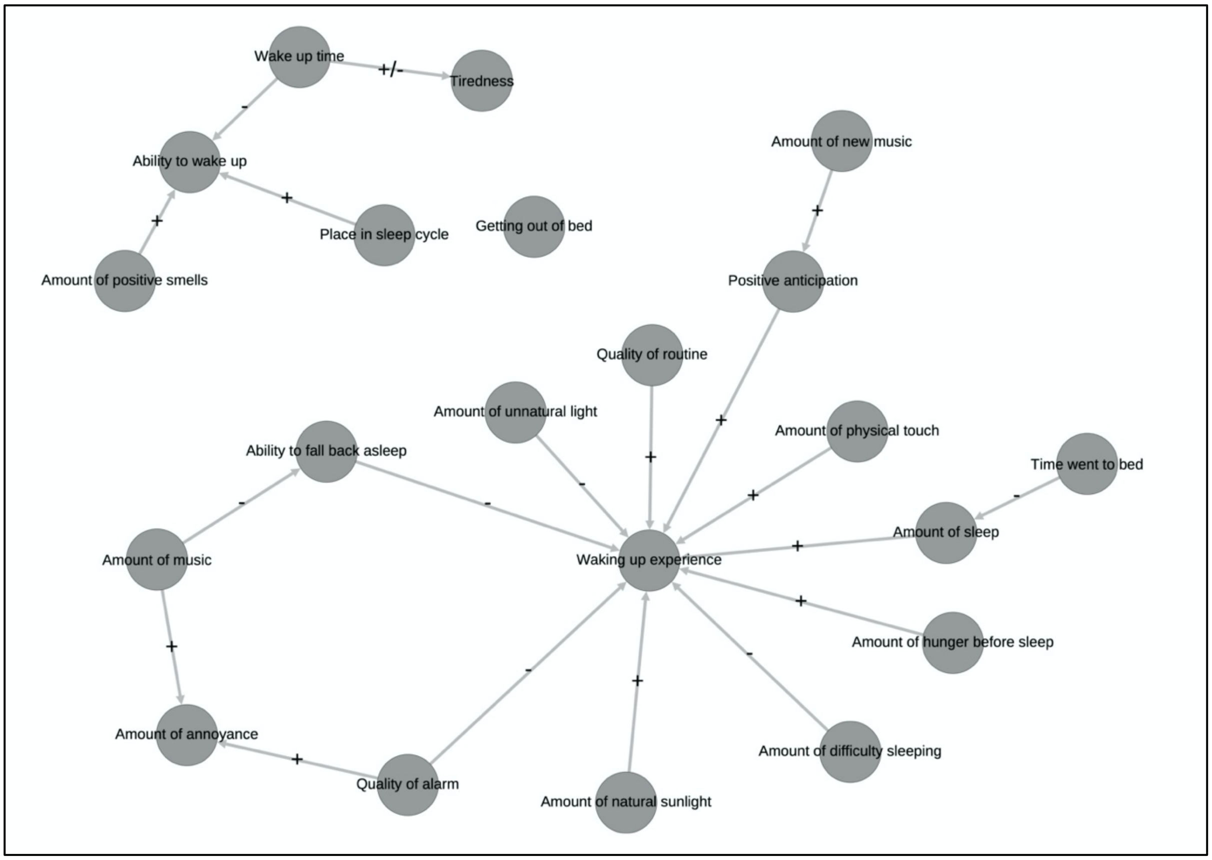


Amount of work
Stress
Ability to fall asleep
Amount of drugs consumed
Active state of mind
Amount of reading
Amount of activity before sleep
Amount of phone use
Quality of hygenic ritual
Amount of TV watched
Ability to wake up
Sleeping
Amount of sense stimulation
Amount of natural light
Amount of natural sound
Desire to sleep
Ability to get out of bed
Temperature of the room
Amount of light
Quality of natural awakening
Quality of breakfast
Amount of warmth
Presence of smells
Desire to get out of bed
Alarm sound
Ability to wake up naturally
Awareness of time left to sleep
Desire to wake up
Time went to bed
Waking up experience
Sleepiness
Quality of activity
Hangover
Amount of shock when waking up
Quality of sleep
Happiness
Efficiency of waking up
Amount of alcohol consumed

Group 4

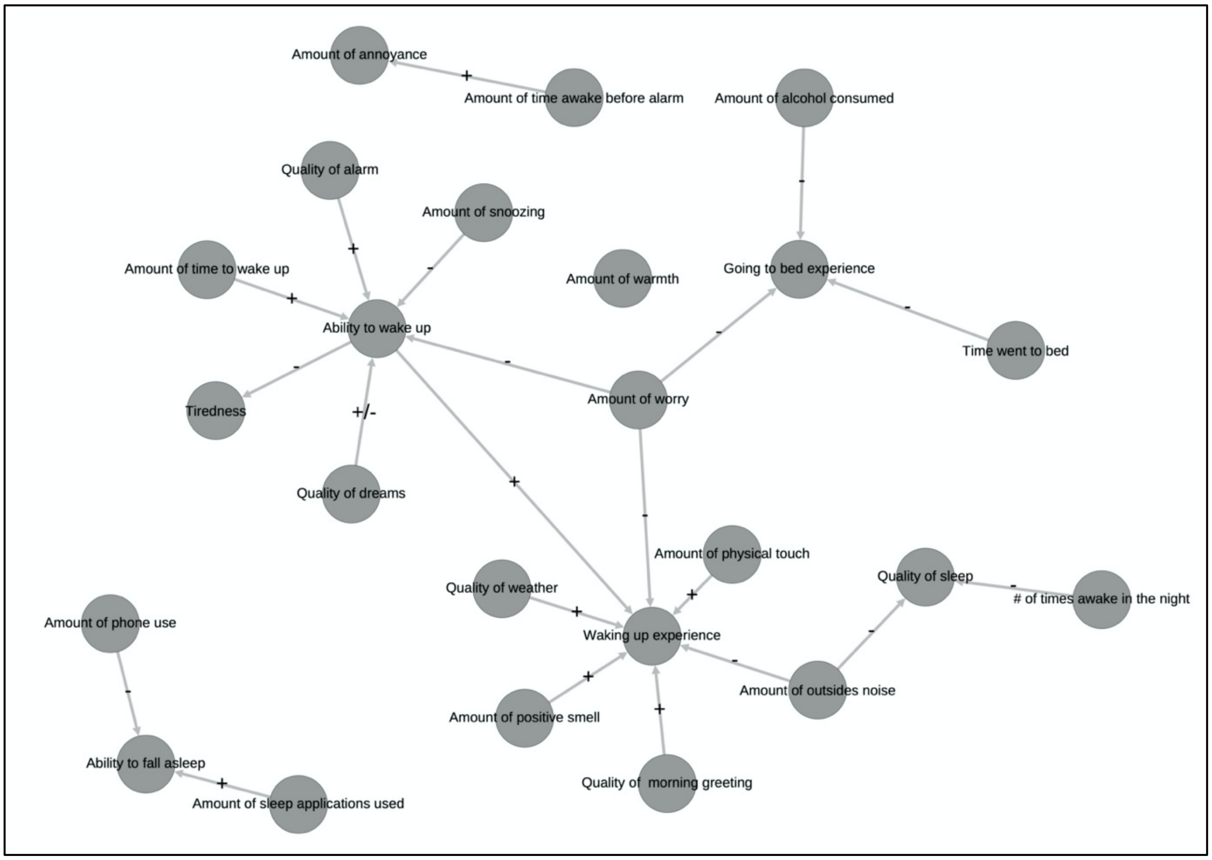

Quality of wake up
+
+/-
Quality of shower
Quality of work
Fear of missing alarm
+
Ability to wake up
+
# of alarms
Amount of motivation
+
+
# of alarm devices
Tiredness
Having to wake up
# of times snoozed
-
+
Quality of sleep
Ability to get up
-
+
Heartrate
Amount of sleep
+
-
Part of sleep cycle
+
-
Amount of stress before sleep
Shower availability
Lateness
+
Amount of contingency time

Group 5



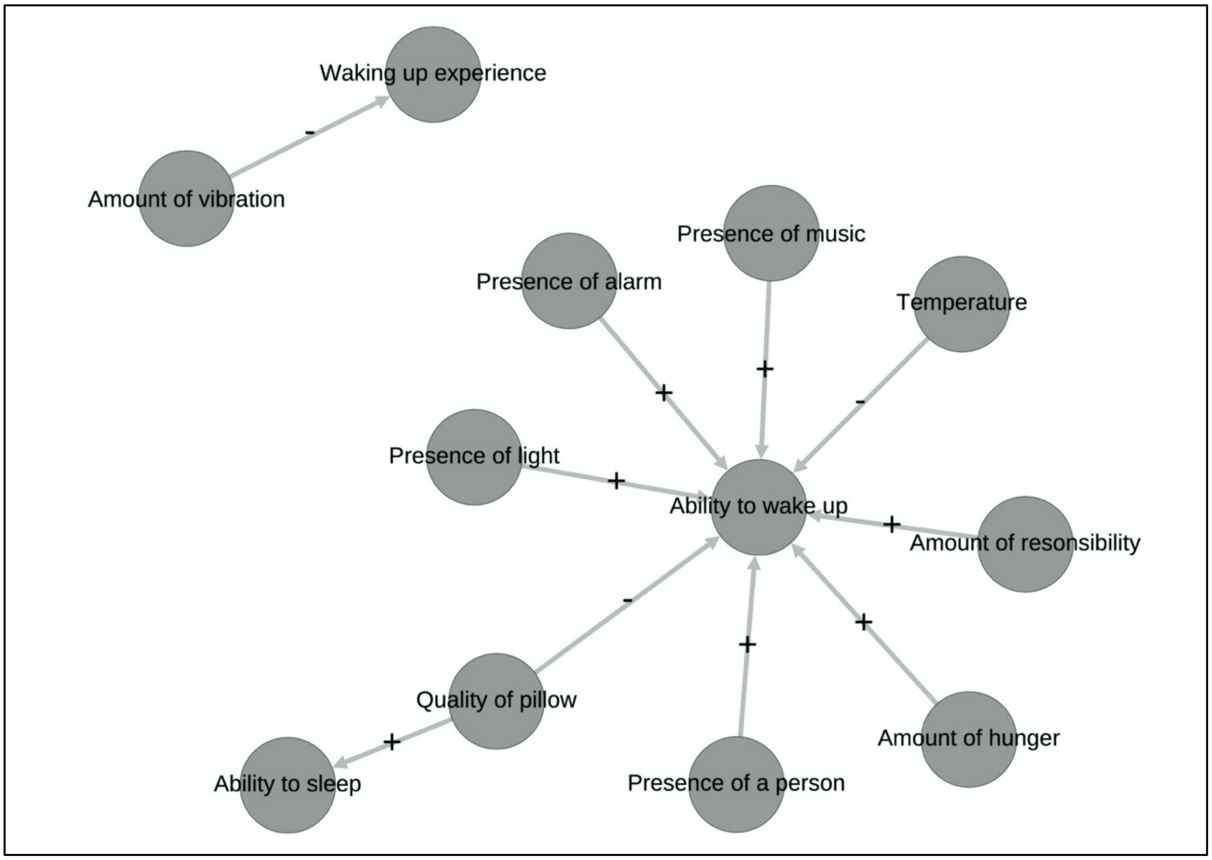
Wake up time
+/-
Tiredness
-
Ability to wake up
+
Place in sleep cycle
+
Amount of positive smells
Getting out of bed
Amount of new music
+
Positive anticipation
Quality of routine
Amount of unnatural light
+
Amount of physical touch
Ability to fall back asleep
Time went to bed
-
-
+
+
-
Amount of sleep
-
Amount of music
Waking up experience
+
+
Amount of hunger before sleep
+
-
-
+
Amount of annoyance
+
Amount of difficulty sleeping
Quality of alarm
Amount of natural sunlight

Group 6

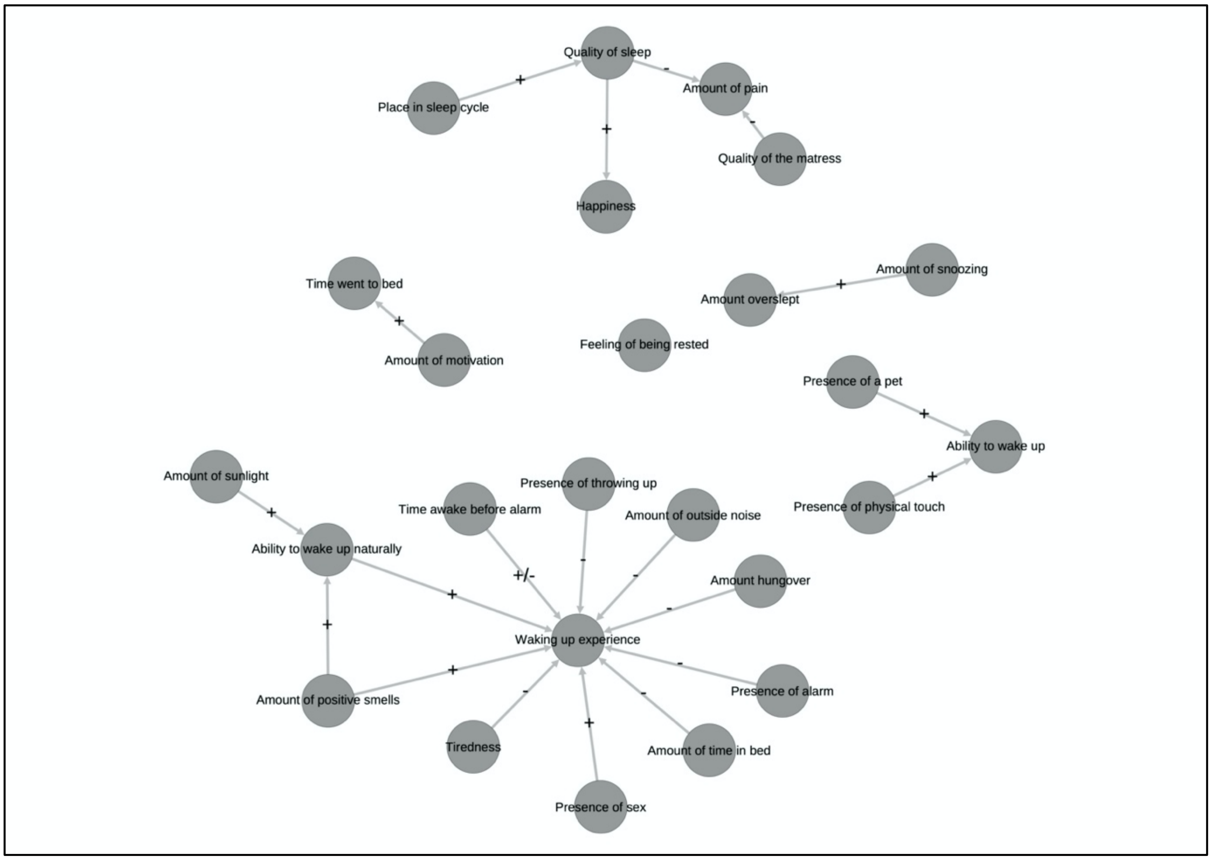


Amount of annoyance
+
Amount of time awake before alarm
Amount of alcohol consumed
Quality of alarm
Amount of snoozing
-
+
-
Amount of time to wake up
+
Amount of warmth
Going to bed experience
-
Time went to bed
Ability to wake up
-
-
-
Tiredness
+/-
Amount of worry
Quality of dreams
+
-
Amount of physical touch
Quality of sleep
-
# of times awake in the night
Quality of weather
+
+
Amount of phone use
Waking up experience
-
-
-
+
Amount of outsides noise
Amount of positive smell
+
Ability to fall asleep
+
Quality of morning greeting
Amount of sleep applications used

Group 7


Waking up experience
-
Amount of vibration
Presence of music
Presence of alarm
Temperature
+
+
-
Presence of light
+
Ability to wake up
+
Amount of resonsibility
-
+
+
Quality of pillow
+
Amount of hunger
Ability to sleep
Presence of a person

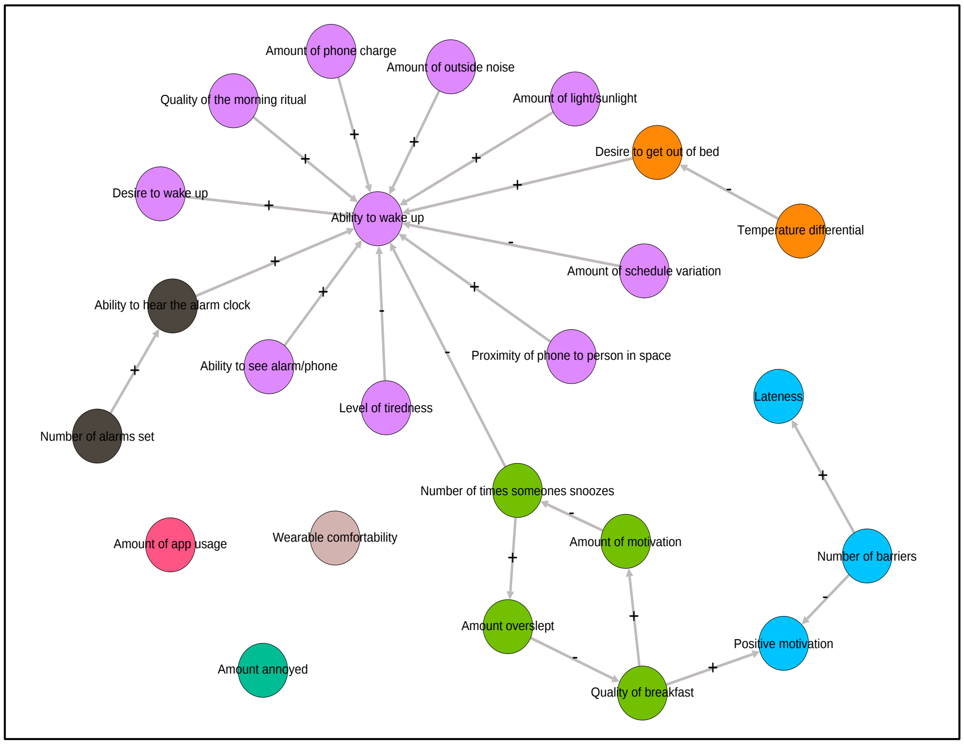
Group 8



Quality of sleep
Place in sleep cycle
Amount of pain
Quality of the matress
Happiness
Time went to bed
Amount of motivation
Feeling of being rested
Amount of snoozing
Amount overslept
Presence of a pet
Ability to wake up
Presence of physical touch
Amount of sunlight
Ability to wake up naturally
Time awake before alarm
Presence of throwing up
Amount of outside noise
Amount hungover
Waking up experience
Amount of positive smells
Presence of alarm
Tiredness
Amount of time in bed
Presence of sex
+/-

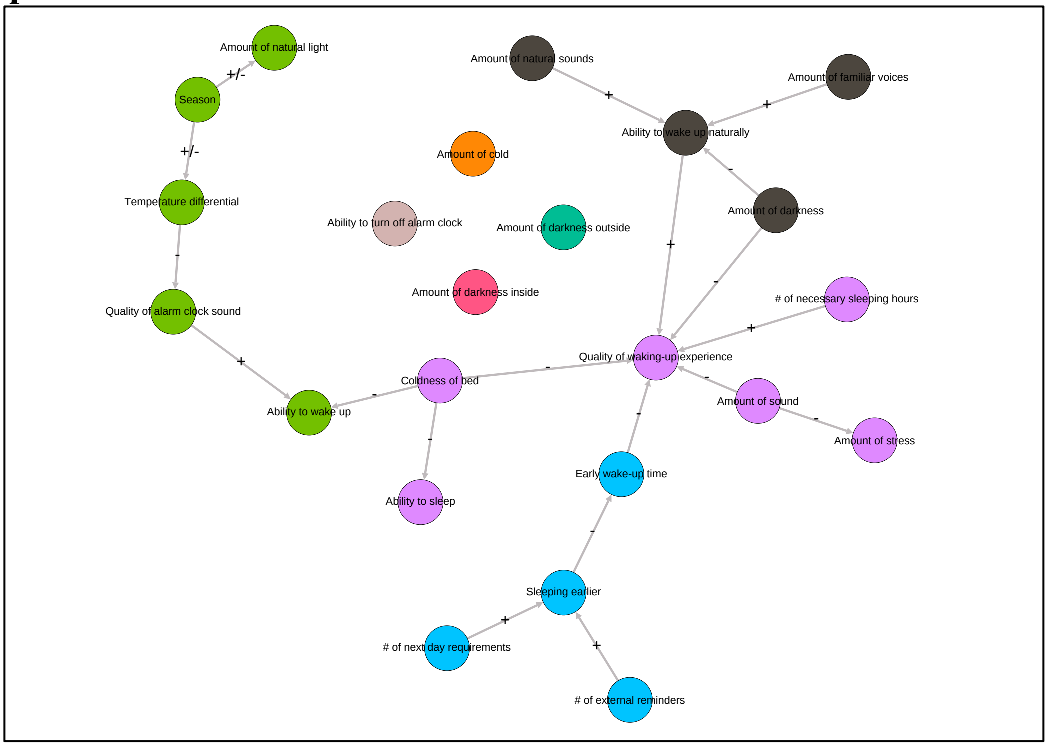
Appendix B Community analysis Study A

Group 1 communities



- The purple community, which is the largest community made up of ten nodes focuses on the factors the influence one's waking up experience. There is however no real discernible theme that can be gathered from the nodes belonging to this community. Some of the ideas that the group generated was a smart home system that would have the ability to change the temperature of the blanket and open windows.
- The blue community focuses on factors that would prevent punctuality and decrease the amount of motivation. Ideas targeted towards these nodes include an automated alarm setting application which might have a social feature to connect with friends.
- The green community focuses on the potential for oversleeping and its impact on subsequent activities like creating a quality breakfast. Ideas targeted towards these relationships include a coffee maker alarm clock or one that includes voice. There was also the idea of an alarm silencing task, like retrieving a token that is thrown across the room to turn off the user's alarm.

Group 2 communities



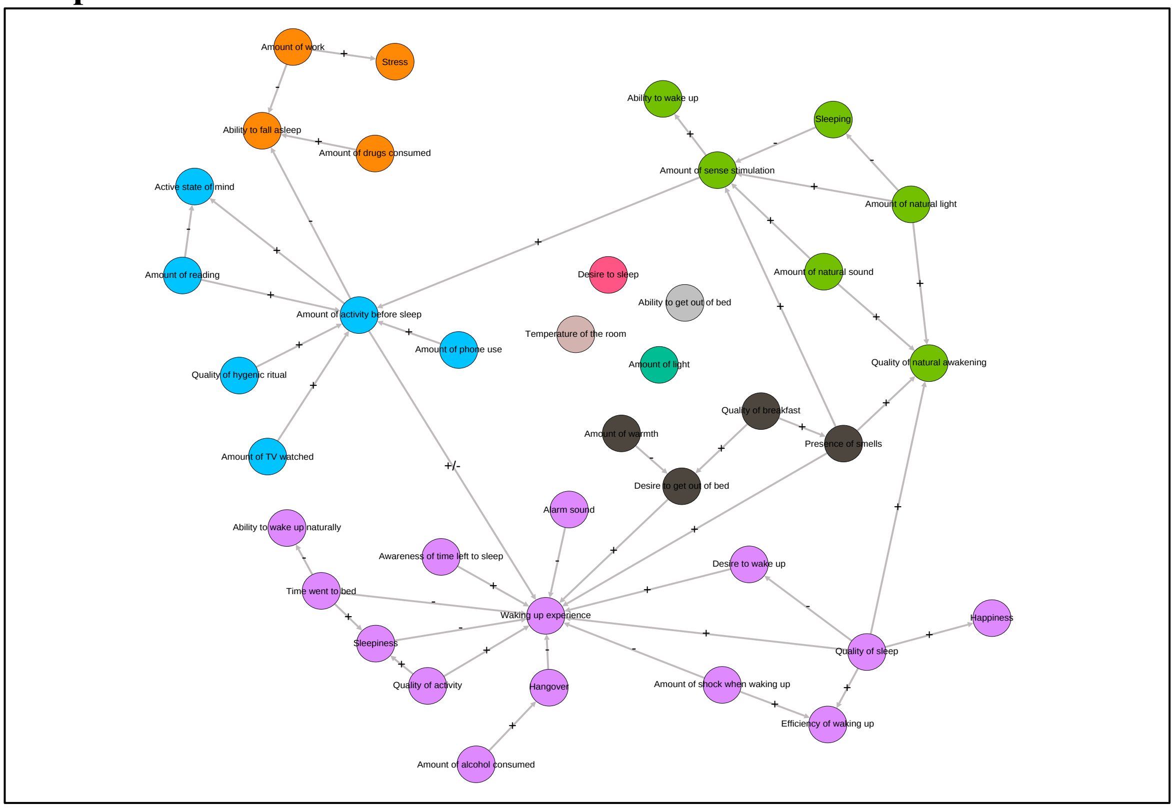
- **Error! Reference source not found.**The purple community is comprised of nodes that focus on the factors that influence the waking up experience. The solution idea that is related to this cluster was a countdown time, which provides a prompt for how much time you have left before you should sleep. There other three remaining clusters have a clearer focus:

- The blue community focuses on going to bed at an appropriate time and the factors that might cause a person to go to bed. Ideas included a device capable of providing reminders to a user throughout their house to remind them how many hours they have left to sleep.

- The green community focuses on the environmental factors that effect a person's ability to wake up. Ideas here include a light producing alarm clock and a bed that can gradually change temperature to wake the user up.

- Finally, the brown community focuses on the factors that affect one's ability to wake up naturally. There were no ideas that specifically targeted at the nodes of this community

Group 3 communities

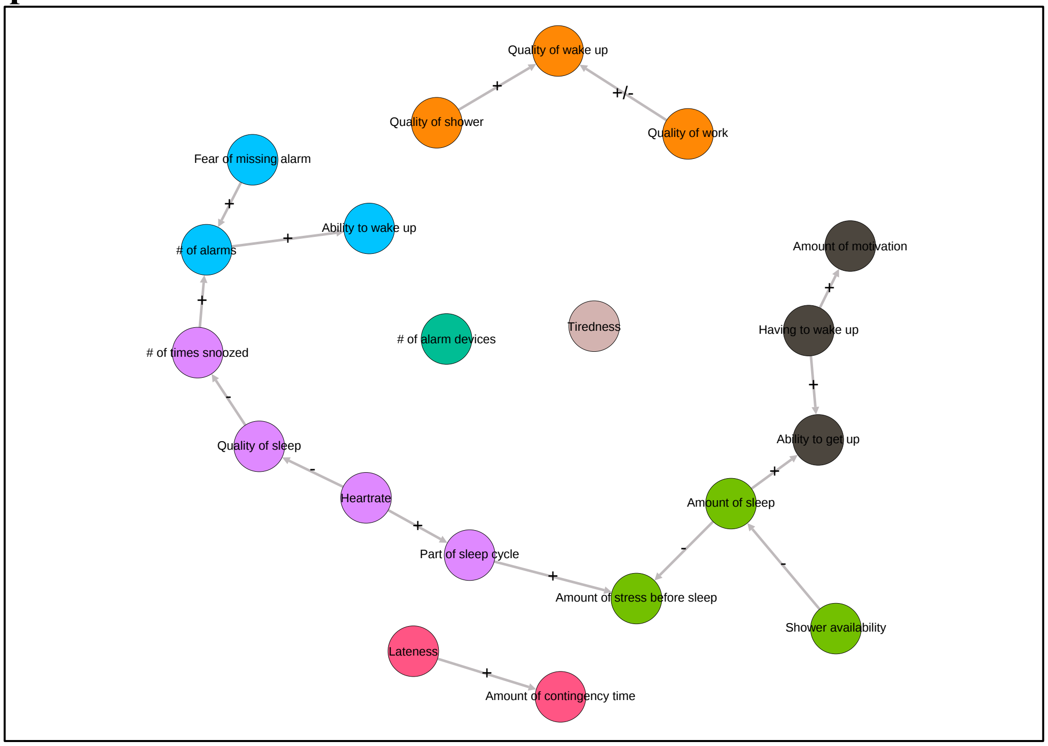


- The purple community centers on the "waking up experience" node, but in this case it is hard to detect a clear focus; instead, the cluster includes a number of under-developed threads that capture the entire time window from 'before going to bed' to 'waking up the next day'. The idea that the group 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 blue cluster centers on the amount of activity one engages in before going to bed (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.

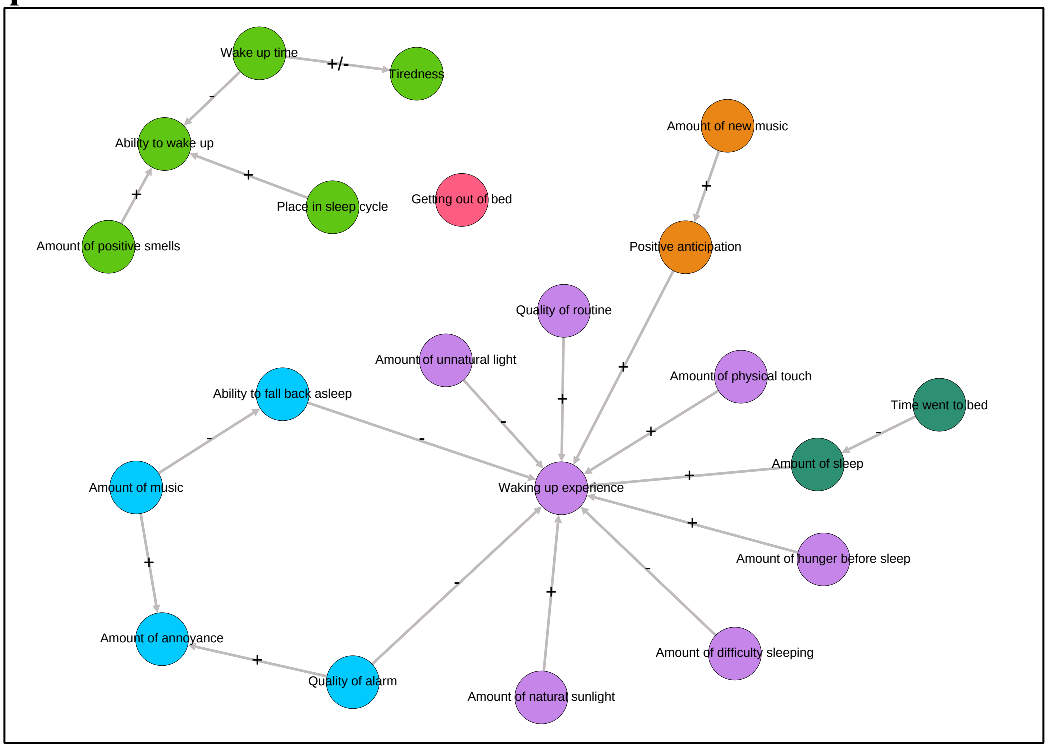
- The black cluster relates to one’s ability to actually fall asleep once in bed, which might be affected for example by stress, drugs, and anxiety about work to be done. The ideas that emerge in response to this are, for instance, a mattress that massages the user to sleep and stress-reduction activities like meditation.
- Finally, the green cluster focuses completely on the awakening processes, especially with regards to the role of the senses (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.

Group 4 communities



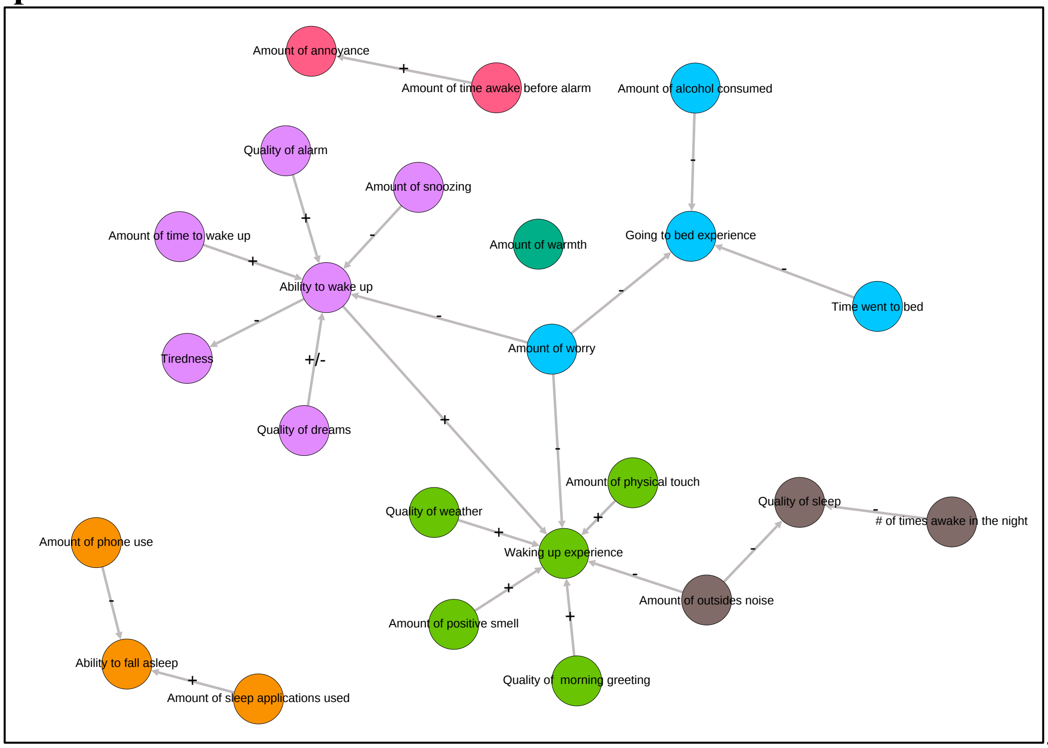
- The purple community focuses on the quality of one's sleep. No solution ideas associated with this community.
- The blue on the factors that influence alarm efficacy and need. No solution ideas associated with this community.
- The brown on the process of waking up and physically getting out of bed. No solution ideas associated with this community.
- The orange on the quality of the waking up experience. No solution ideas associated with this community.
- The green community focuses on the factors that will affect the amount of sleep a person will get, with the ideas focusing on a before bed alarm clock with an associated activity tracker. This product will also schedule sleep based on the sleep cycle, waking the user up at the 'optimal' time.

Group 5 clusters



- The purple community focuses on the factors that influence a person's waking up experience but do not form a common theme. There is one idea which emphasizes an increase in the amount of physical touch a person would receive to wake up.
- The blue community emphasizes the ability of the alarm to reduce the change of a user falling back to sleep. The discussion is about the method and type of noise that alarm uses. The idea is to increase the variety of noises the alarm uses, so as to prevent a user from getting used to a sound.
- The green community focuses on a user's ability to wake up, specifically focussing on the time they wake up and the place in the sleep cycle. The idea the group generates is that of a wake-up service that one might find use at a hotel.
- The idea of bed with multiple functions including detecting when a user has gone to bed and analysis of the body movement to reliably detect sensible points on the body that would most pleasantly wake a person up was not specically connected to a community.

Group 6 communities

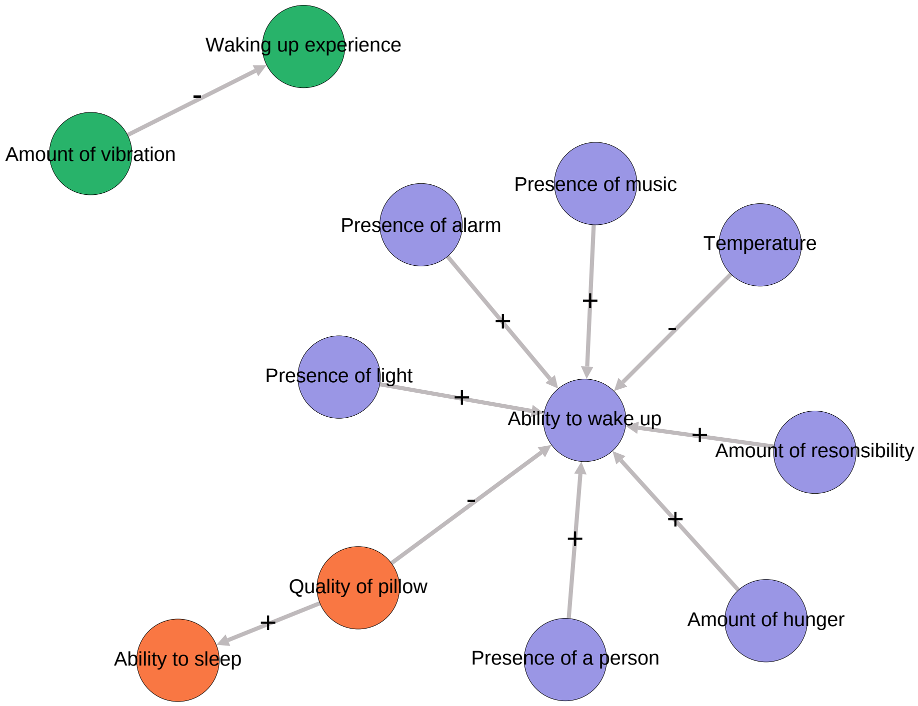


- The purple community focuses on the factors that influence a person's ability to wake up. The group generates ideas for a mindful way of waking up including some stories or motivation words that would play at a particular time. They also discuss a text messaging service that matches you with people with similar interests to start conversations in the morning. Pre-made breakfasts was also an idea associated with this community. A final, less realistic, idea includes waking a person up with crowd of puppies.
- The blue community has many nodes associated with the factors that influence a person's experience going to bed including stress or worry, the amount of alcohol consumed and the time the person went to bed. Interestingly there were no ideas associated with this community.
- The green community focuses on the factors that influence a person waking up experience. Though this is like the purple cluster, this community has a more refined outlook on the *experience* and pays particularly close attention to the

senses. As such, the idea that surfaced from this cluster was a projection on the wall to include, sounds, stories and light as a service used by people to wake up.

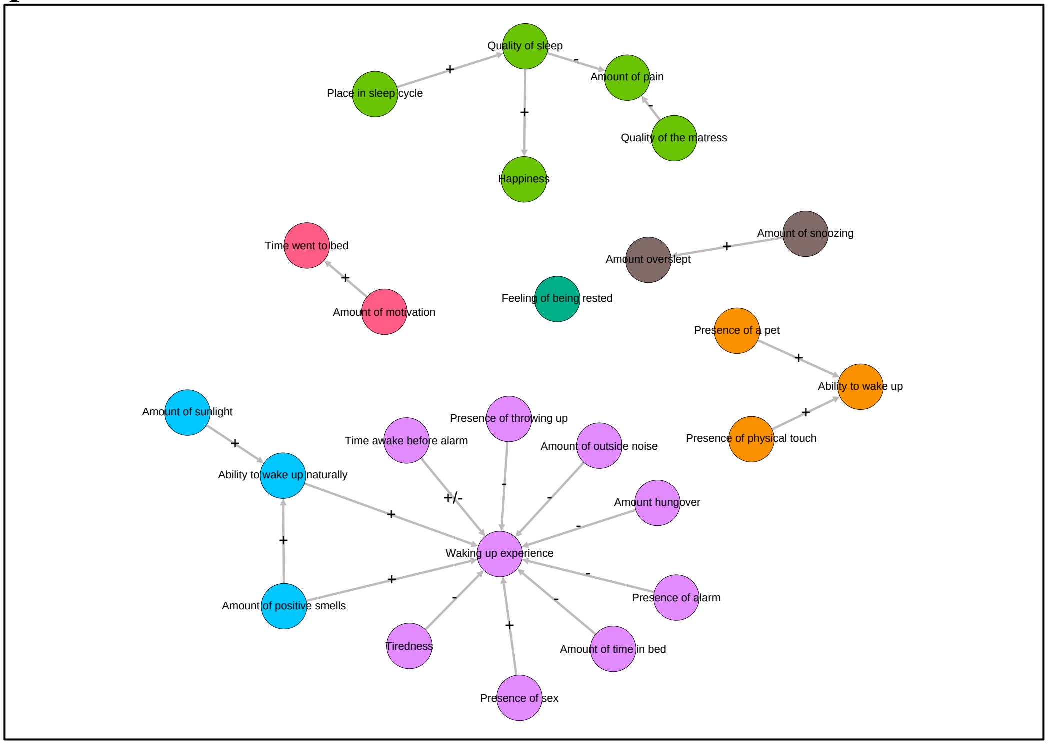
- The brown community is composed of nodes that relate to the factors that might influence the quality of someone's sleep. No solution ideas associated with this community.
- The final orange community is made up of nodes that affect a person's ability to fall asleep. The only idea related to this node was the idea of introducing bedtime stories.

Group 7 communities



- The single community focuses on the factors that influence the ability to wake up. Ideas included a hotel wake up call, a multifunctional experience like a smart home system and finally a smart pillow. This smart pillow would include functions like changing temperature and shape, vibrate, make phone calls, tells you the weather and spreads the smell of breakfast around.

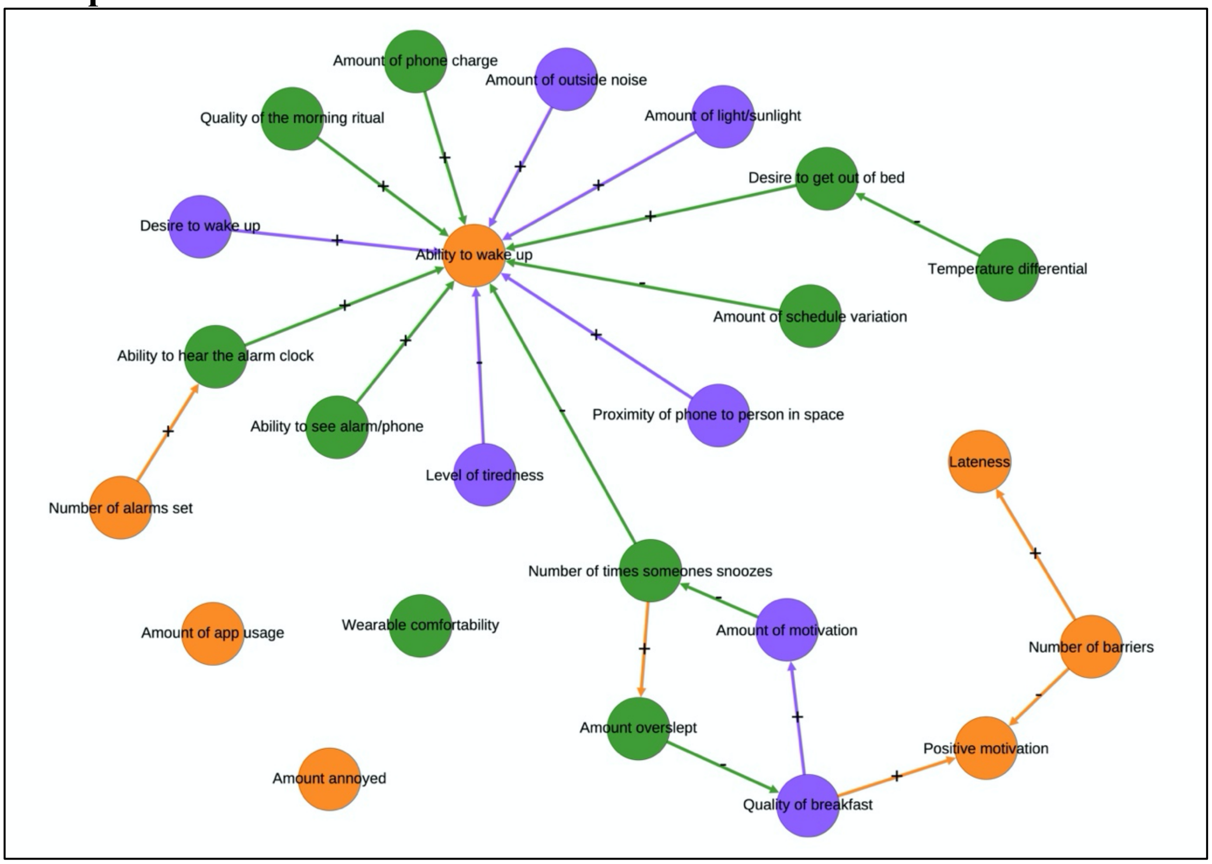
Group 8 communities



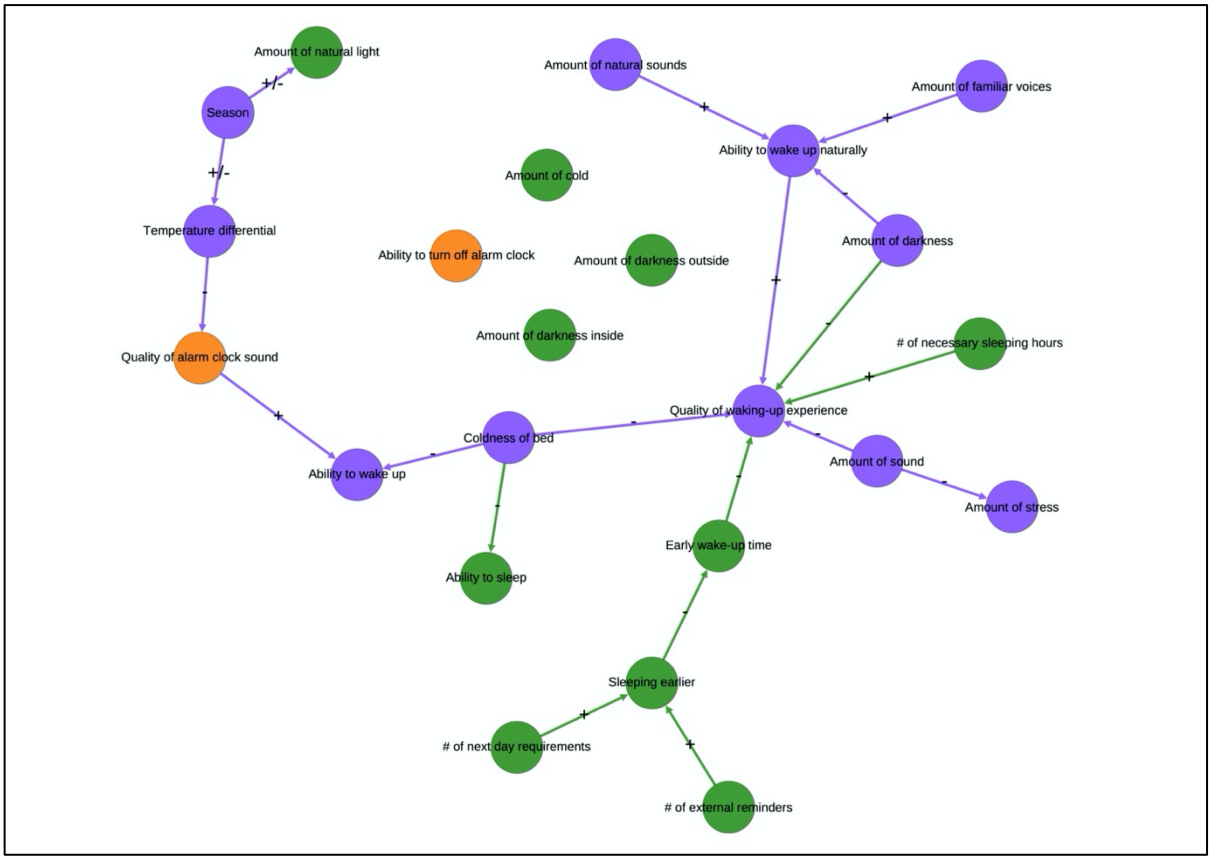
- The purple community has no easily identifiable theme. The nodes are related to the factors that influence the waking up experience. The ideas include an interactive bed, ear plugs with noise cancellation and an application device pair. The application device pair would have a sensor for messing the stage of the sleep cycle, a selection of sounds, ability to learn more about the user and a method for soliciting feedback from the user in the morning.
- The blue community focuses on factors that influence a persons ability to wake up naturally. This includes an idea for an air freshener with a collection of nice smells to induce natural waking processes.
- The green community is created with nodes that influence the quality of one's sleep and the implications of the quality of sleep. This community has no associated ideas.
- The orange community is created with nodes that affect a person's ability to wake up. No solution ideas associated with this community.

Appendix C Individual contribution maps and analysis Study A

Group 1

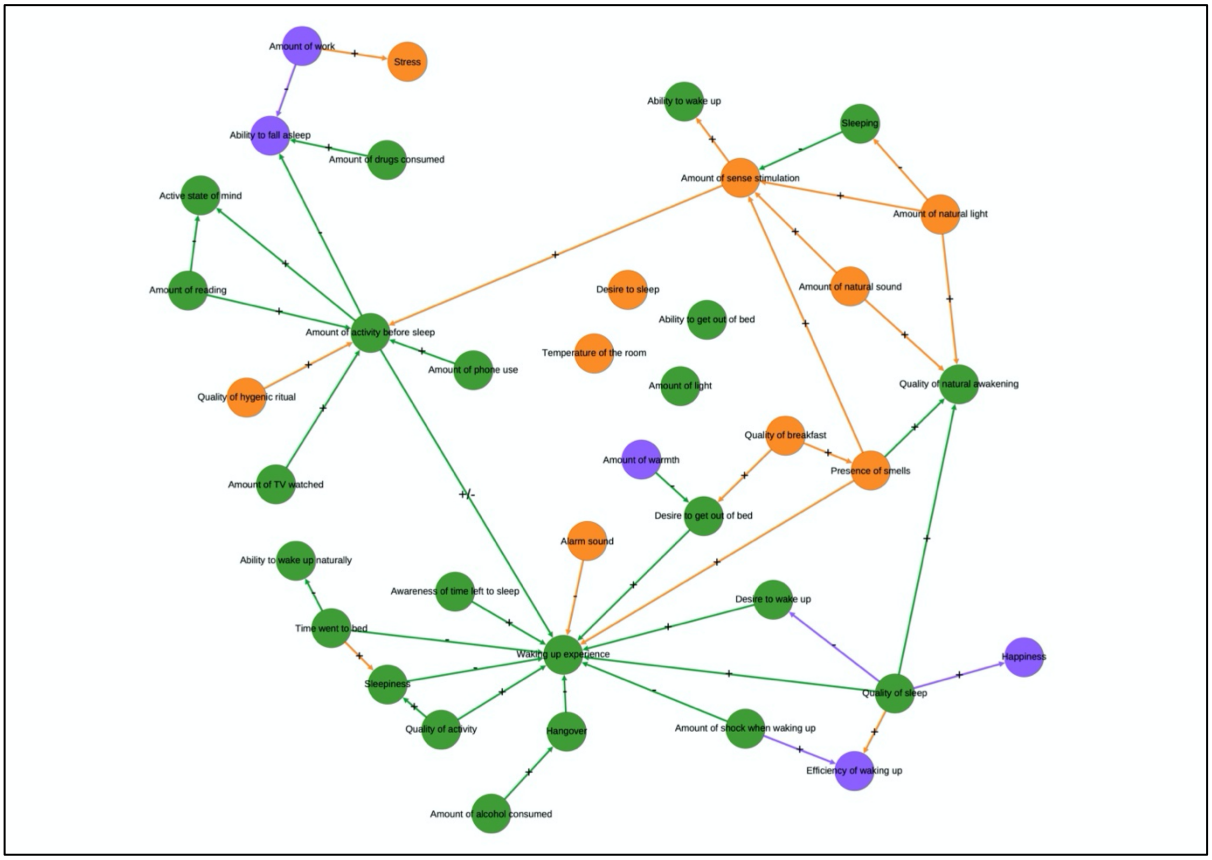


Group 2



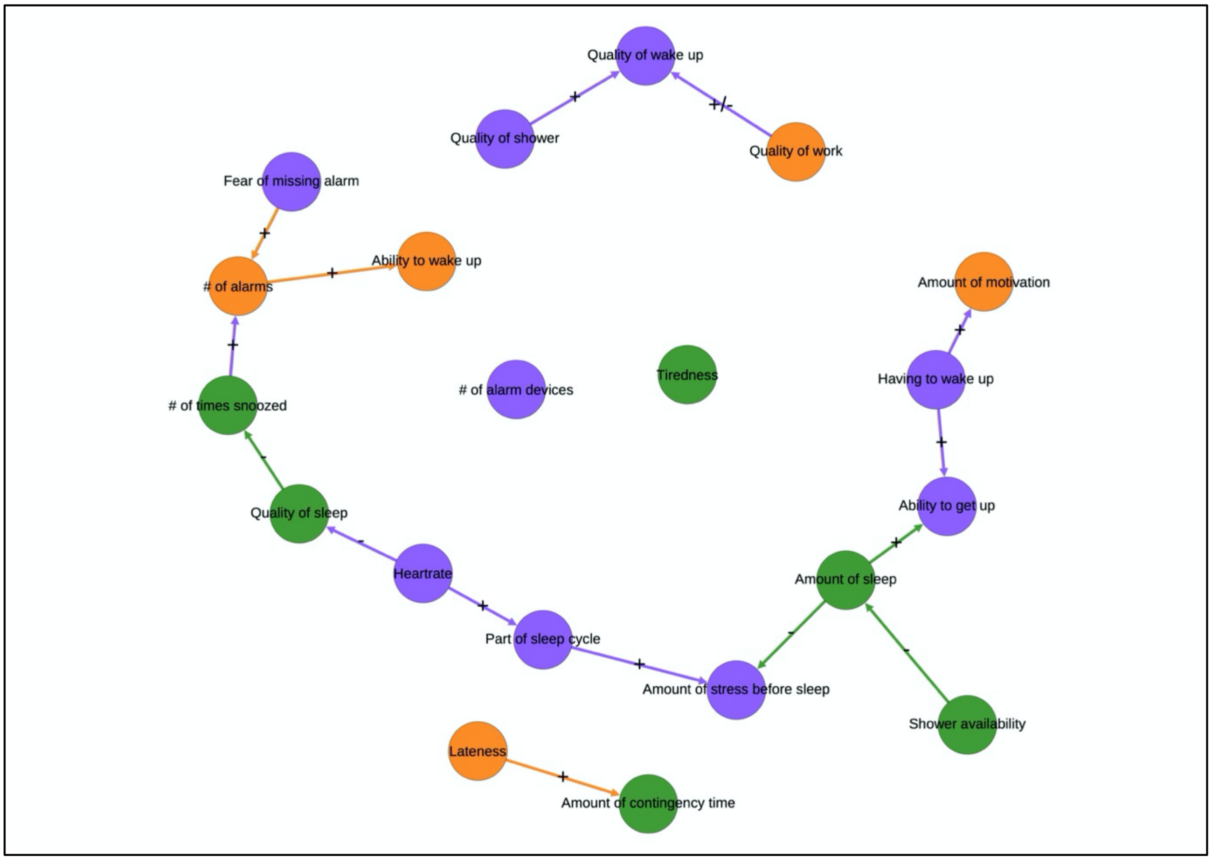
Amount of natural light
Season
+/-
+/-
Temperature differential
-
Quality of alarm clock sound
+
Ability to wake up
Amount of natural sounds
+
Amount of familiar voices
+
Ability to wake up naturally
Amount of cold
Ability to turn off alarm clock
Amount of darkness outside
Amount of darkness inside
Amount of darkness
-
+
-
# of necessary sleeping hours
+
Quality of waking-up experience
-
Coldness of bed
-
-
Amount of sound
-
-
Amount of stress
Ability to sleep
Early wake-up time
-
-
Sleeping earlier
+
# of next day requirements
+
# of external reminders

Group 3



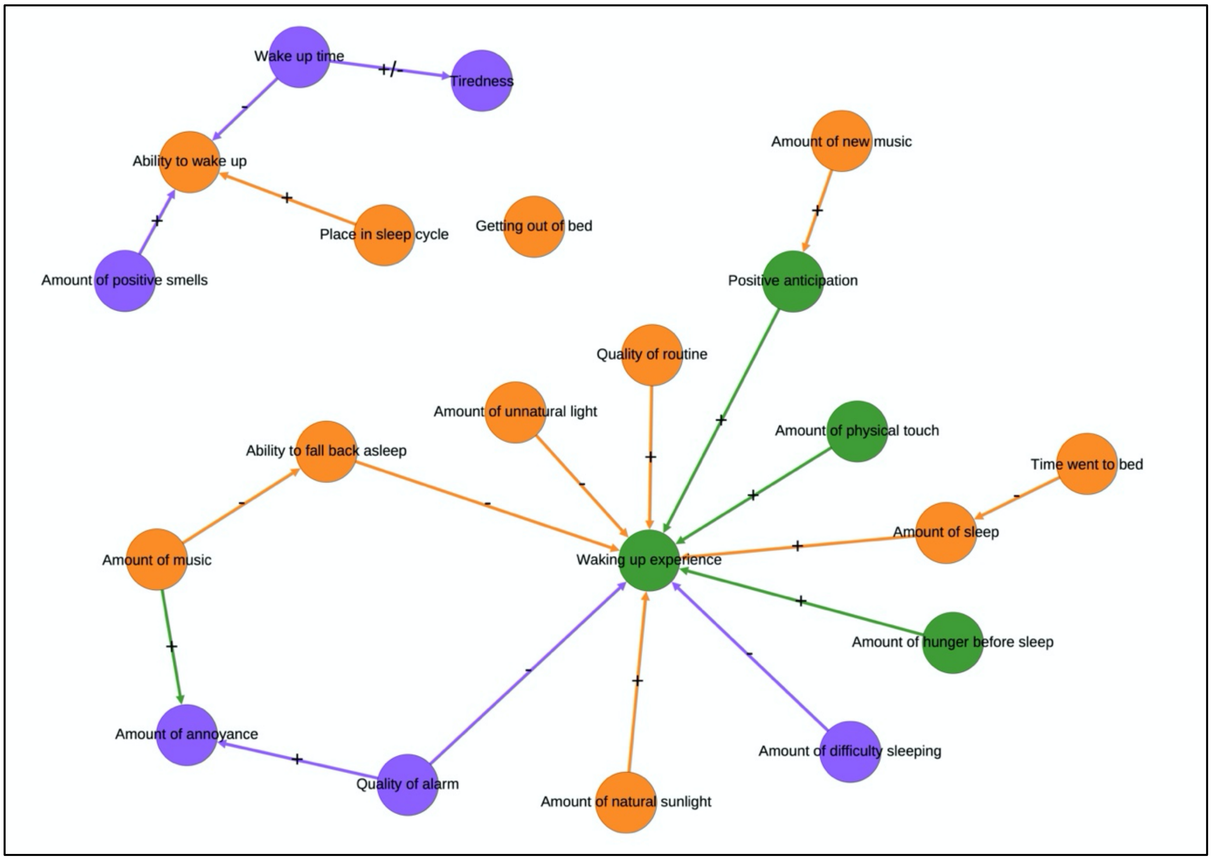
Amount of work
Stress
Ability to wake up
Sleeping
Ability to fall asleep
Amount of drugs consumed
Active state of mind
Amount of sense stimulation
Amount of natural light
Amount of reading
Desire to sleep
Amount of natural sound
Ability to get out of bed
Amount of activity before sleep
Amount of phone use
Temperature of the room
Quality of hygenic ritual
Amount of light
Quality of natural awakening
Quality of breakfast
Amount of warmth
Presence of smells
Amount of TV watched
Desire to get out of bed
Alarm sound
Ability to wake up naturally
Awareness of time left to sleep
Desire to wake up
Time went to bed
Waking up experience
Happiness
Sleepiness
Quality of sleep
Quality of activity
Hangover
Amount of shock when waking up
Efficiency of waking up
Amount of alcohol consumed

Group 4

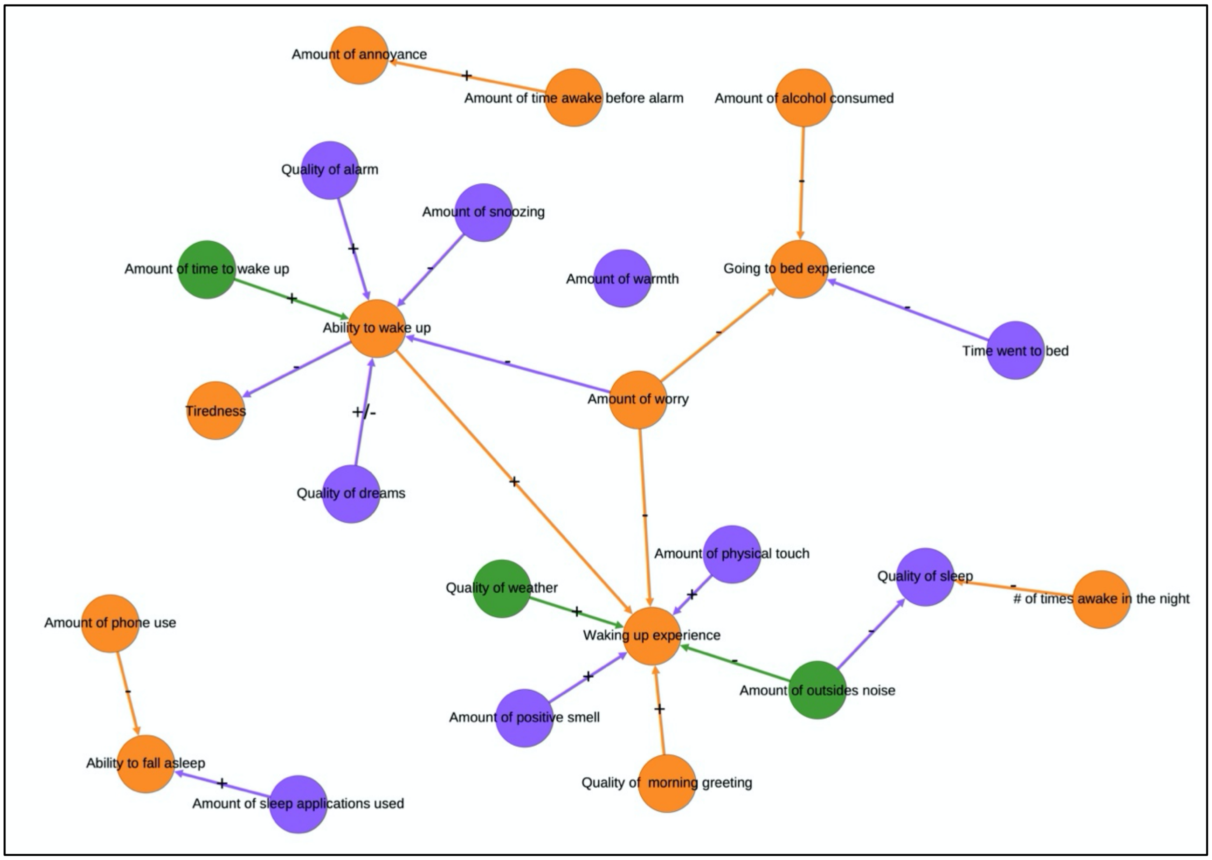


Quality of wake up
+
+/-
Quality of shower
Quality of work
Fear of missing alarm
+
Ability to wake up
+
# of alarms
Amount of motivation
+
+
# of alarm devices
Tiredness
Having to wake up
# of times snoozed
-
+
Quality of sleep
Ability to get up
-
+
Heartrate
Amount of sleep
+
Part of sleep cycle
-
+
-
Amount of stress before sleep
Shower availability
Lateness
+
Amount of contingency time

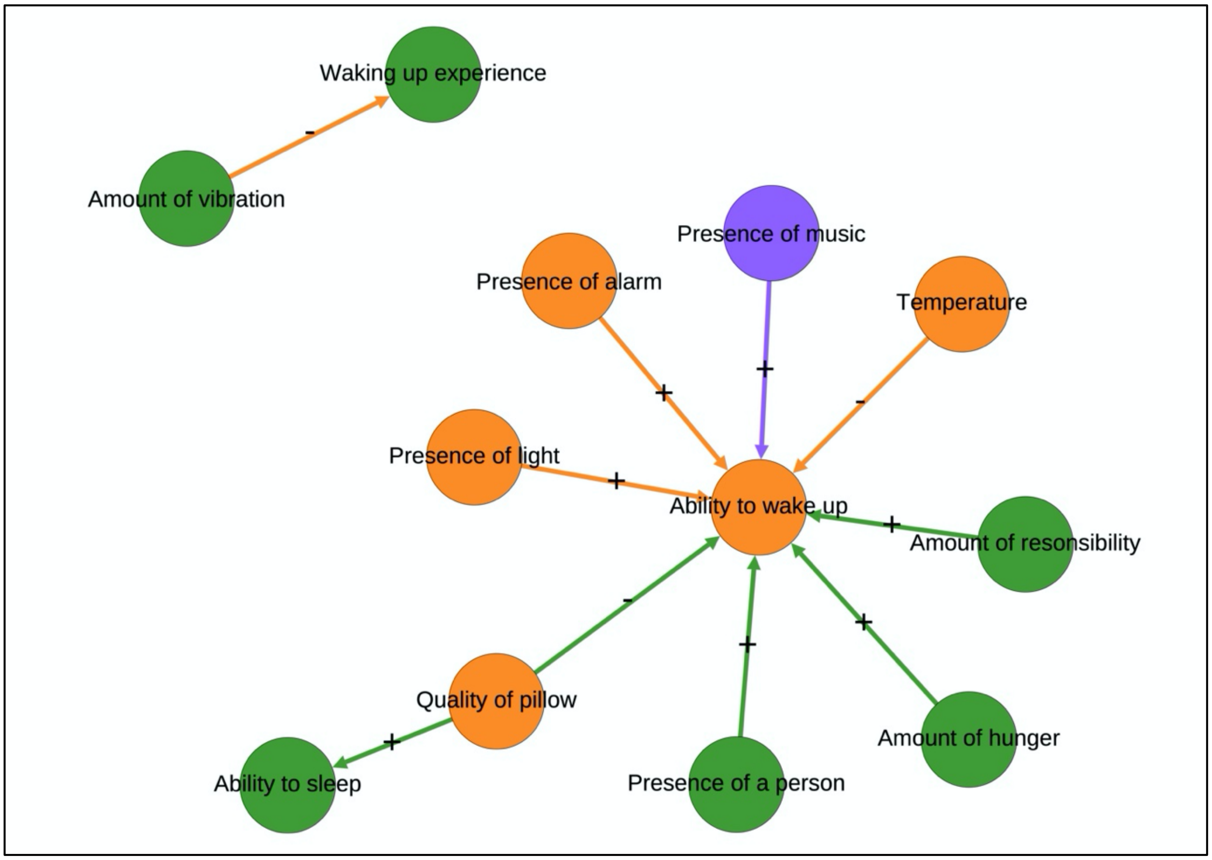
Group 5


Wake up time
+/-
Tiredness
-
Ability to wake up
+
Place in sleep cycle
Getting out of bed
+
Amount of positive smells
Amount of new music
+
Positive anticipation
Quality of routine
Amount of unnatural light
Ability to fall back asleep
+
Amount of physical touch
Time went to bed
-
+
-
-
+
Amount of sleep
-
Amount of music
Waking up experience
+
+
Amount of hunger before sleep
-
-
+
+
Amount of annoyance
+
Amount of difficulty sleeping
Quality of alarm
Amount of natural sunlight

Group 6

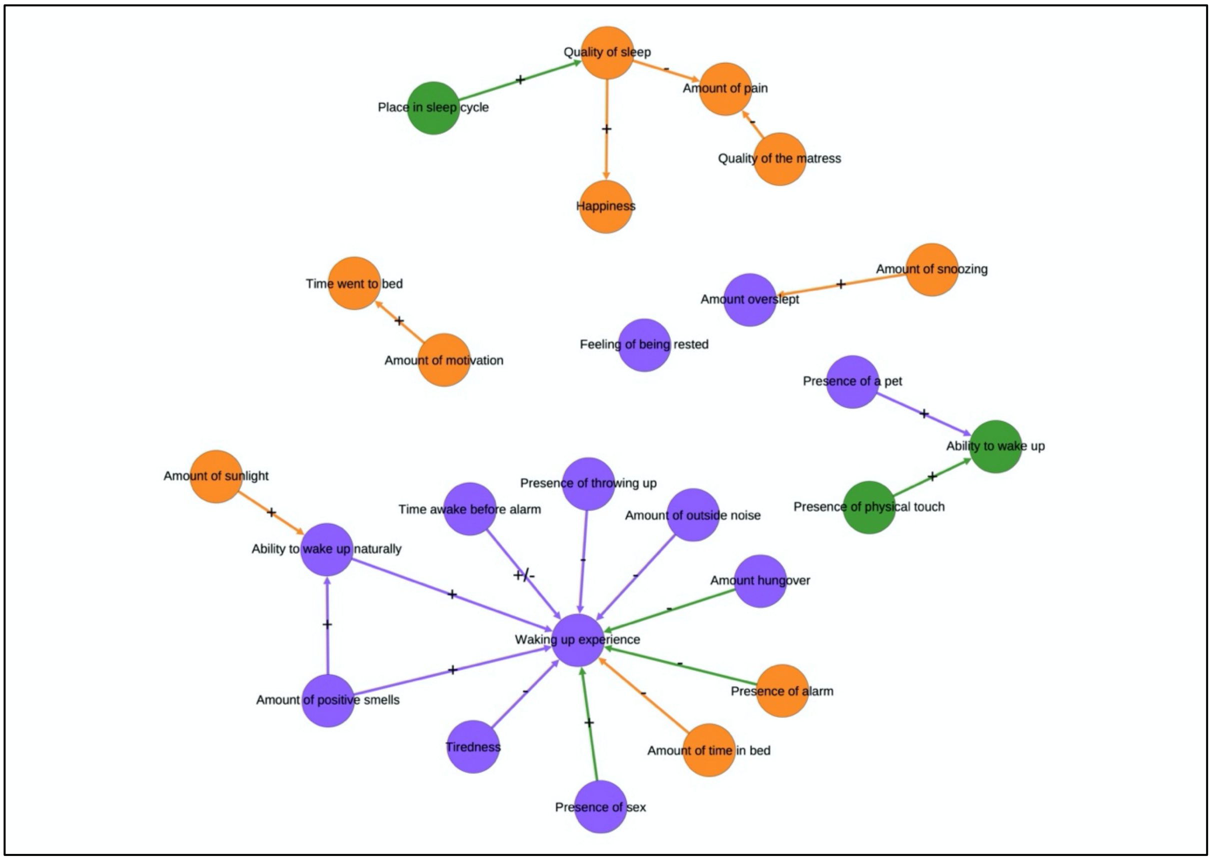

Amount of annoyance
+
Amount of time awake before alarm
Amount of alcohol consumed
Quality of alarm
Amount of snoozing
-
+
-
Amount of time to wake up
+
Amount of warmth
Going to bed experience
-
-
Ability to wake up
Time went to bed
-
-
Amount of worry
Tiredness
+/-
+
Quality of dreams
-
Amount of physical touch
Quality of sleep
-
# of times awake in the night
Quality of weather
+
+
Amount of phone use
Waking up experience
-
-
+
-
Amount of outsides noise
Amount of positive smell
+
Ability to fall asleep
+
Quality of morning greeting
Amount of sleep applications used

Group 7

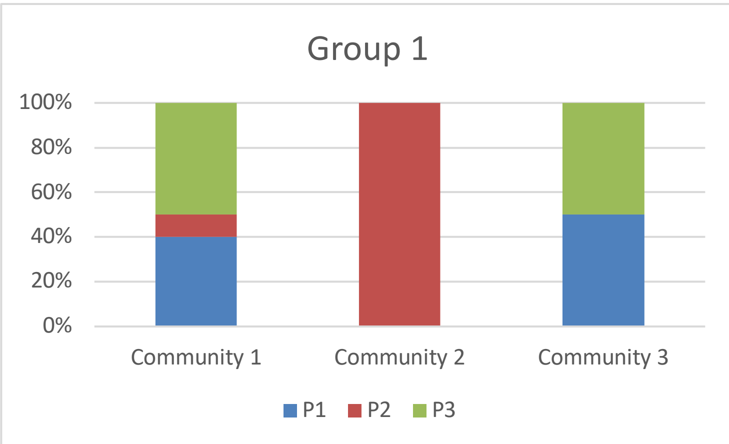


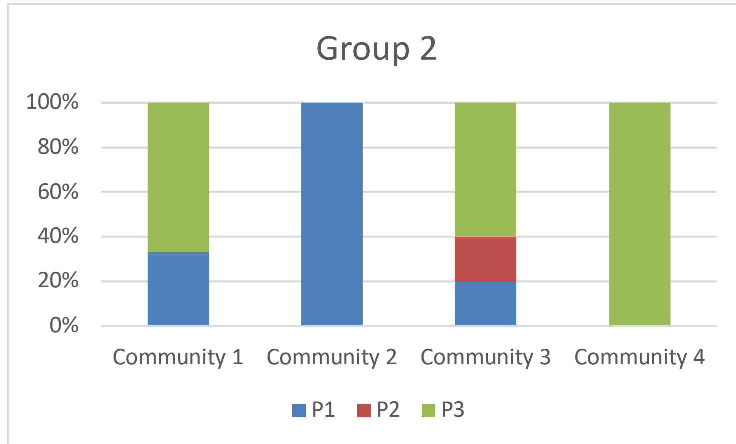
Waking up experience
Amount of vibration
Presence of music
Presence of alarm
Temperature
Presence of light
Ability to wake up
Amount of resonsibility
Quality of pillow
Ability to sleep
Presence of a person
Amount of hunger

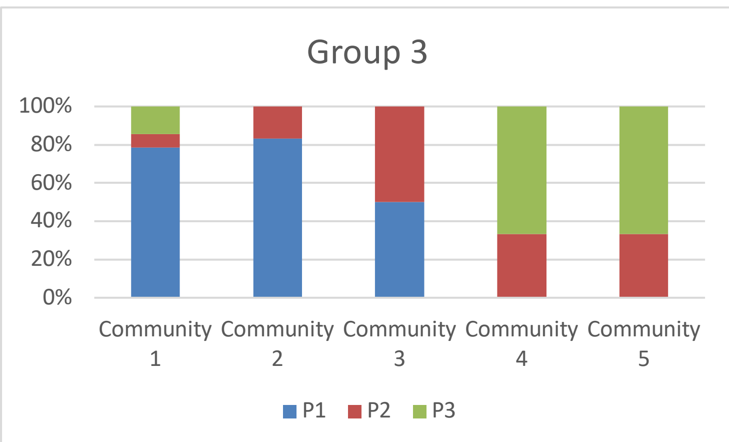
Group 8

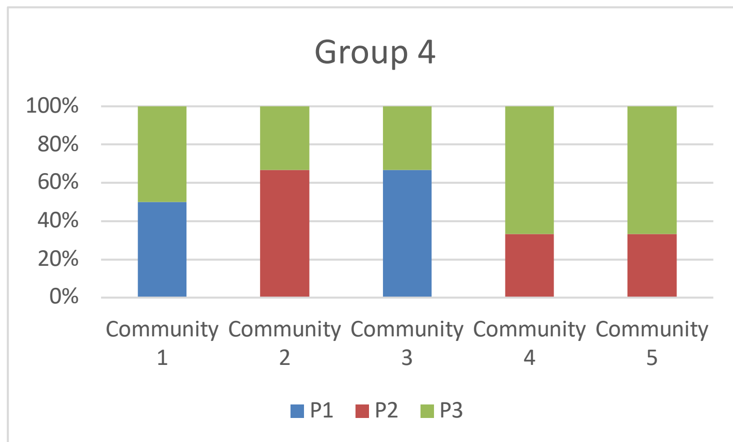


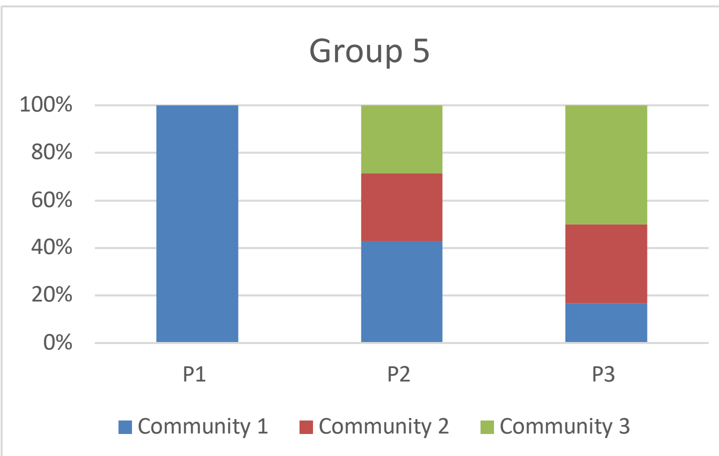
Quality of sleep
Place in sleep cycle
Amount of pain
Quality of the matress
Happiness
Time went to bed
Amount of motivation
Feeling of being rested
Amount overslept
Amount of snoozing
Presence of a pet
Ability to wake up
Presence of physical touch
Amount of sunlight
Ability to wake up naturally
Time awake before alarm
Presence of throwing up
Amount of outside noise
Amount hungover
Waking up experience
Presence of alarm
Amount of positive smells
Tiredness
Amount of time in bed
Presence of sex

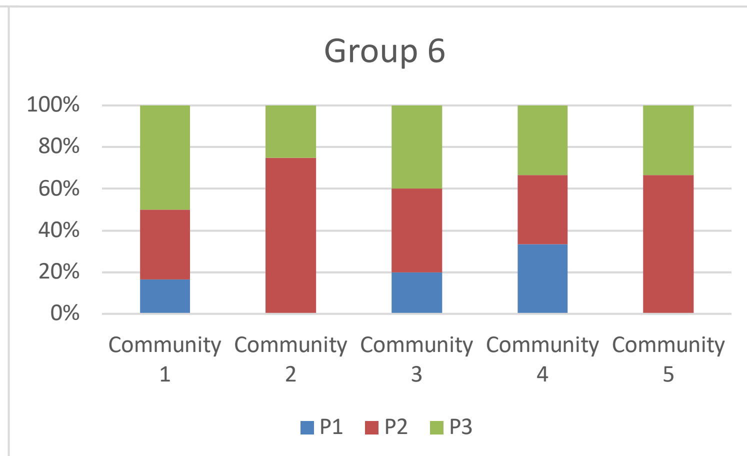

Group 1
100%
80%
60%
40%
20%
0%
Community 1
Community 2
Community 3
P1
P2
P3

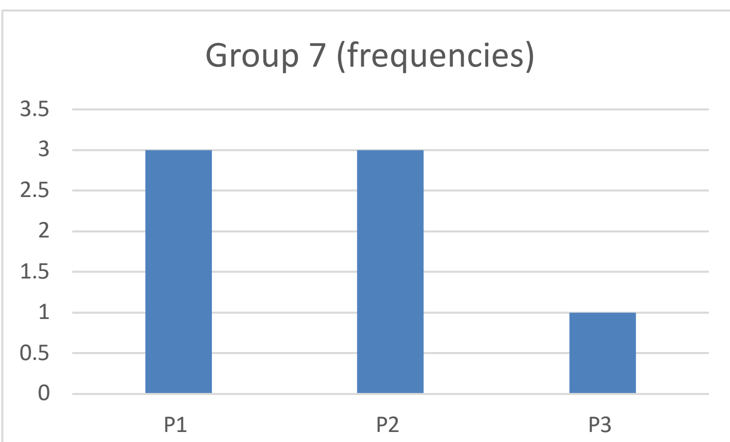

Group 2
100%
80%
60%
40%
20%
0%
Community 1
Community 2
Community 3
Community 4
P1
P2
P3

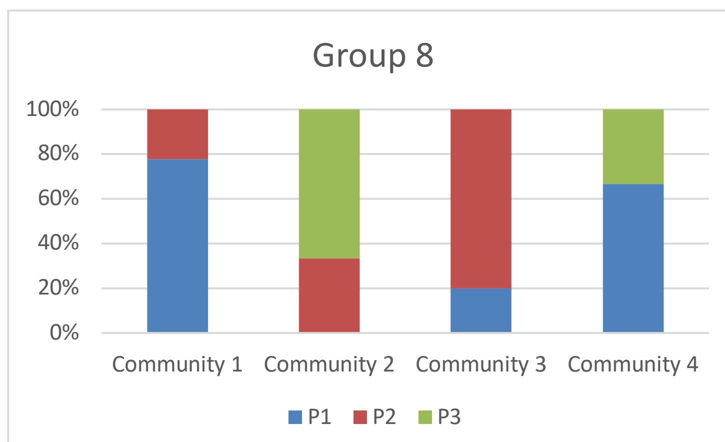

Group 3
100%
80%
60%
40%
20%
0%
Community 1
Community 2
Community 3
Community 4
Community 5
P1
P2
P3


Group 4
100%
80%
60%
40%
20%
0%
Community 1
Community 2
Community 3
Community 4
Community 5
P1
P2
P3


Group 5
100%
80%
60%
40%
20%
0%
P1
P2
P3
Community 1
Community 2
Community 3


Group 6
100%
80%
60%
40%
20%
0%
Community 1
Community 2
Community 3
Community 4
Community 5
P1
P2
P3


Group 7 (frequencies)
3.5
3
2.5
2
1.5
1
0.5
0
P1
P2
P3


Group 8
100%
80%
60%
40%
20%
0%
Community 1
Community 2
Community 3
Community 4
P1
P2
P3