# *Using tangibility to stimulate stakeholder alignment in asset management*

An Interaction Technology graduation project


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## Abstract

Asset managers of civil structures use a lot of data about historical, current, and predicted conditions of their asset in order to make meaningful decisions with a high certainty. The shift to more sustainable decision-making is difficult, because sustainable options lack a clear overview that provides certainty. This is caused by limited alignment between stakeholders, a lack of understanding in what sustainable options entail, and a general aversion to risk. This research explores how an interactive tool can play a role in stimulating alignment between stakeholders. Using an iterative and co-creative design approach, various design directions are explored that make use of graphical, tangible, and immersive interfaces. Two co-creation sessions were organised, three paper prototypes were discussed, and one Hi-Fi prototype focused on a tangible interaction is worked out. Through the use of external representations, the prototype helps stakeholders focus better on the discussion. The playfulness of the tool stimulates active participation and various tangible interactions give users the freedom to share their perspective in an accessible way. The concept of participatory sensemaking comes forward in the unique way the prototype is used during each session. Although the social impact of the prototype cannot be confirmed with certainty, the research sets the stage for follow-up research that can explore the validity of the observed potential impact.



**Keywords:** co-creation, tangible prototype, stakeholder alignment, interaction technology

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# Acknowledgments

This research project has seen many changes of focus, topic, and (design) directions. At some points, I barely could keep track of where we were and how broad my focus should be. Scoping… not my strongest feat. Luckily, my supervisors helped me define the right amount of focus and by asking critical questions and reassuring me that the scope was good enough. A special thanks go out to Max, for our productive weekly sessions with our coffee and chocolate milk, and Anis, for the never-ending positivity and supply of snacks during our meetings. Furthermore, I would like to thank Dennis for being a beacon of knowledge at the times it was needed, to help me dive into the details and stay closer to the academic side of this research. The last to join the team, Armağan, also deserves thanks, for providing clear feedback from an outsider perspective while also including happy faces and positive exclamations in her feedback notes. This helped me also see the strong points of my research!

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***"What determines success at the end of the day is the ability to develop systems that resonate with, rather than restrict, the social organization of action." – Paul Dourish*** [1]

[1] "Social Computing," in Where the Action Is, The MIT Press, 2001, p. 95. doi: 10.7551/mitpress/7221.003.0004.

# 1. Introduction

Civil structures, like tunnels and railways, are maintained by asset managers on a daily basis. Following the principles of asset management, they work together with various stakeholders to ensure the asset stays operational. In this research, the focus is put on asset management at Arcadis[2], a Dutch consultancy and engineering company. As part of a more sustainability-focused global corporate strategy, Arcadis requires the field of asset management to make a shift towards more sustainable decisions. However, this is difficult to implement due to insufficient overview on more sustainable strategies, the risk-averse nature of asset managers, and the fragmented communication between them and their stakeholders [1]. In this research, the aim is to explore how the use of an interactive tool can help bring these stakeholders together so they can better work together and discuss strategies. This is done by actively involving the stakeholder in an iterative design process that utilizes theory on stakeholder alignment and embodiment.

## 1.1 Background

Asset management is a way of working that revolves around *"information-based risk assessments that look at the short- and long-term effects of decisions"* [1, p. 24] for assets with a value. In the context of this research, these are civil structures and mechanics like tunnels. Asset managers are responsible for the day-to-day performance of an asset, which means they need a lot of information and consult a lot of people in order to execute well-informed decisions that reduce the risk and increase the result [1]. Arcadis, a consultancy and engineering company with a focus on sustainability, has constructed their own *"Way of Asset Management"* based on these principles [2]. They identified three stakeholders that each play their role in asset management: the asset manager, asset owner, and service provider. Each stakeholder has a different perspective that plays a role in asset management. Figure 1 and Figure 2 show how these stakeholders are related.

The asset manager reports to the asset owner, often a representative of a province or municipality, who is the legal owner of the asset. The asset owner defines the most important topics (e.g., safety, accessibility, and sustainability) in their value framework (see 'Context' in Figure 1). These shape the objectives of the asset manager (see the top part of Figure 1) when they define the policy of the asset. Additionally, they use information about the asset (e.g., past inspections, metadata about materials and components, measurement data from sensors) to conduct risk and performance analyses that help them define problems and plan maintenance sessions. Due to the focus on information-based risk management, they try to reduce the risks as much as possible. Maintenance work, inspections, and repairments are conducted by the service provider on an operational level. The asset manager constructs plans for this, which are forwarded to the service provider for execution (see bottom part of Figure 1). After finishing their work, the service provider reports back to the asset manager so they stay in the loop [1].

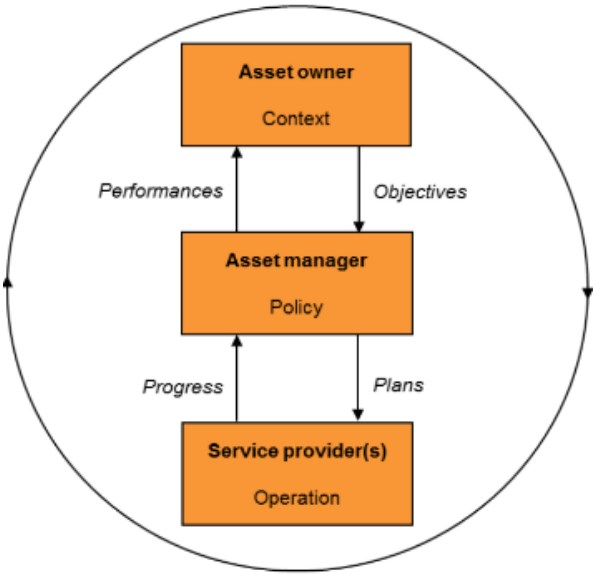



Figure 1. The three main asset management roles, from [2]

[2] https://www.arcadis.com/en/about-us

Besides the focus on asset management, Arcadis focuses on sustainability in their work. They have constructed a sustainability policy[3] in which several facets of sustainability are incorporated (e.g., energy consumption, circularity, societal impact). Ideally, this policy shapes the approach for all projects, but this can be difficult. In previous research [1], we have explored the opportunities and obstacles of sustainable asset management. Interviews were conducted with the stakeholders in asset management, after which it was concluded that three factors limit the adaptation of sustainability in asset management.

Firstly, sustainability is a very broad and convoluted topic which includes not only the impact of a product as its own, but also the production process, decomposition phase, and transport from and to the right location. This means that a lot of information is needed to make well-calculated sustainable decisions, which is not always presented in a clear overview. Additionally, asset managers focus on information-based risk management and are generally conservative. Missing information about a sustainable option makes it hard to assess its risk, so it is safer to stick to what is known. This hesitation to change due to uncertainties limits the possibilities for innovative decisions about sustainability. Lastly, we can look back at the *"Way of Asset Management"*. Although it provides a structured way of working through clearly defined roles and responsibilities, it also limits the collaboration between stakeholders. See Figure 2 for an overview. All stakeholders work relatively separately from each other, focusing on their responsibilities (left side of Figure 2) and work activities (middle part of Figure 2). Initially, their interests are aligned. Through their separate way of working this can change, but this is only found out when one of the stakeholders makes a decision and they come together (right side of Figure 2). This limited and fragmented communication reduces the amount of information known, making it difficult to make sustainable choices and slowing down the decision-making process in general.

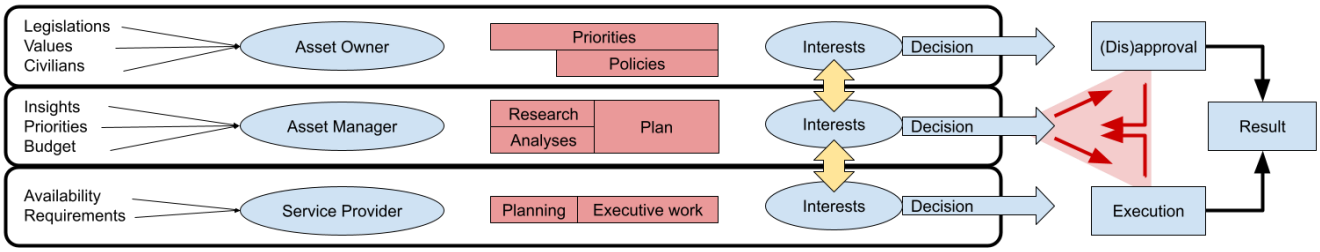



Figure 2. Diagram visualizing the current collaboration flow between stakeholders at Arcadis, based on [1, p. 24].

## 1.2 Research Goal

One part of the obstacle in incorporating sustainability in asset management lies in information provision, which could be solved by adapting a more data-driven approach. Arcadis is incorporating Digital Twin technology in their projects as a way to do this. Digital Twins are a relatively new technology, which can best be described as a specific digital version of a physical object/system with a connection between the two. Various data can be combined and analysed in the Digital Twin, which can help gain insights that would otherwise be difficult [1]. Looking at the context of asset management, this technology can help stimulate sustainable decision-making by using data to increase holistic and clear information provision about sustainable options. Next to this, it is important to consider the more social aspect of this obstacle – collaboration. It is important to look at how stakeholders can be stimulated to work together. From the perspective of Interaction Technology, this poses an interesting research challenge in using this data-driven approach in a socially stimulating way. In order to scope the research, we will zoom in on the latter.

Therefore, this research focuses on the lack of alignment between stakeholders and explore how such a technology can play a role in that. A tool is developed that might form the connection between the Digital Twin and the stakeholders of asset management, which could provide Arcadis with new insights on how to use Digital Twins for sustainable asset management. This is done by actively involving the

[3] Based on eight United Nations Sustainable Development Goals, via https://sdgs.un.org/goals and [1]

stakeholder in an iterative design process that utilizes theory on stakeholder alignment and embodiment. Hence, the research question is as follows: **To what extent can an interactive tool be designed that stimulates stakeholder alignment in asset management?** This question is addressed in the context of asset management at Arcadis, where the role of data-driven technologies like Digital Twins are explored to support a robust decision-making process with a sustainable outcome.

## 1.3 Research Approach & Outline

In order to answer the research question, literature research will help create an overview of factors contributing to shared understanding and alignment, which can be found in chapter 2. Theoretical Framework. A framework is developed to visualize how this can play a role in the asset management collaboration process, with clear pointers to what can be changed. In this phase, the sub-question is: **What elements contribute to stakeholder alignment that can be integrated into the design of the interactive tool?**

A research-through-design approach is used, which heavily involves stakeholders in the design process. The method is elaborated on in chapter 3. Methodology. Following the co-creative design approach, a site visit to the Waterwolftunnel is carried out and personas are created, which can be found in chapter 4. Research Context. Additionally, stakeholders participated in two co-creation sessions in which the problem statement as defined in previous research [1] is refined and their vision on possible solutions is shared. This can be found in chapter 5. Co-Creation Sessions. In this phase, the sub-question is: **How can the stakeholders' ideas about stimulating alignment be used in the design of the interactive tool?**

Following these results, initial requirements can be phrased that form the basis of the first three prototypes. These Lo-Fi prototypes are evaluated with stakeholders, ultimately leading to one Hi-Fi prototype. This prototype is first evaluated in terms of usability so more embodied interactions can be refined, after which its potential social impact is evaluated. The prototypes come forward in chapters 6. Lo-Fi Prototyping and 7. Hi-Fi Prototyping. In this phase, the sub-question is: **How does stakeholder feedback help in refining key elements that stimulate alignment in the interactive tool?**

Together, these research phases and evaluation sessions help answer the overarching research question. Where the first two sub-question have focused on 'gathering inspiration' about the possibilities of applying theory (first sub-question) in the domain of the stakeholders (second sub-question), the third sub-question revolves around the creation process. Using the third sub-question, key elements of the prototype are iteratively evaluated.

# 2. Theoretical Framework

Currently, the fragmented communication between stakeholders and the lack of confidence in and limited overview of sustainable options lead to limited stakeholder collaboration and alignment. This makes it difficult for stakeholders in the context of asset management to understand each other, find a common ground, and eventually move to more sustainable decision-making [1]. Three factors can be identified that can induce alignment, bringing stakeholders closer together from the start and stimulating them to work on a collective solution. These are visualized in Figure 3 as the ideal situation in which stakeholder alignment is realized before decisions are made. It can be used as theoretical reference for the design of the interactive tool.

The first level in Figure 3 is 'Engagement', where stakeholders are involved in the full process of the tool. In the design phase, co-creation sessions help with that [3]–[5]; in the use phase a positive experience with information that is easy to grasp are helpful [6]–[12]. A level deeper, we see 'Common Ground' emerge, which revolves around creating a shared experience that helps stakeholders understand and empathize with each other by better redirecting focus in discussions [4], [13]–[15]. Embodiment can play a big role in this, as it focuses on externalizing social signals that would otherwise stay hidden [11], [12]. Lastly, after establishing engagement and a common ground, stakeholders can use their shared understanding to make 'Compromises'. Visual elements can help create a holistic overview of options and preferences [1], [16], [17], while embodiment can help convey social information here as well [11], [18]–[20].

This chapter helps identify key elements that can be used in the design and development of the interactive tool, which can be combined with a co-creative approach to be adjusted to the subjectivity of the target group.

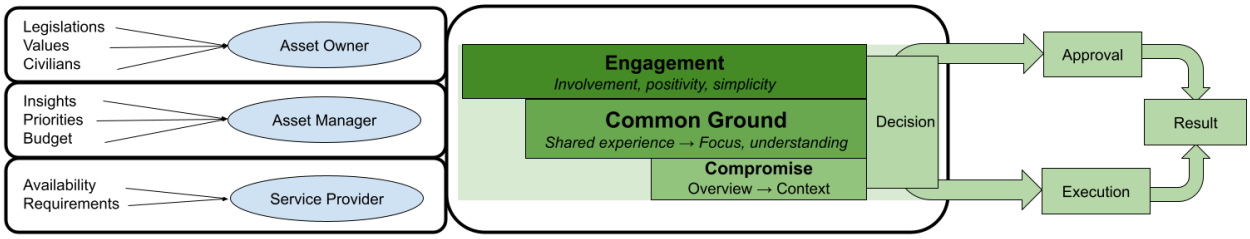



Figure 3. Diagram visualizing the ideal collaboration flow between stakeholders. The role division of stakeholders (left) stays the same, but now they are engaged with each other from the start, finding a common ground that helps them compromise (middle) so they can make a collective decision at the end that is quickly approved and executed (right).

## 2.1 Stimulating Engagement in a Discussion

The first step in aligning stakeholders is ensuring engagement with the discussion. Technology can be used to maintain attention and interest by focusing on factors such as affect, motivation, novelty, interactivity, and feedback [21]. It stimulates focus on the topic and paves the way for dialogue and common ground creation. Additionally, it helps maintain an overview of involved stakeholders and their interests [6], [21]. Therefore, it is important to look at how stakeholders can experience sustained engagement in the discussion. A tool can help attract stakeholder to the discussion by facilitating a positive experience. Relevant information can be conveyed in a simple way, so that it is easier to stay involved. Lastly, involving stakeholders not only in the use but also the design phase of a tool will help finetune its use to the user and already initiate stakeholder understanding and compromise.

### 2.1.1 Positive Participation

It is important to create a positive feeling that attracts users to participate. Gamification or playfulness can be valuable in this [21]. Research conducted by Bujic *et al.* [7] highlights how gamification with co-

players can stimulate immersion and flow, which help generate a positive experience. Zhang *et al.* [8] dive deeper into the concept of gamification, defining five 'gamification affordances' – rewards, competition, feedback, cooperation, and narrative. Game-like interactions with a tool make the experience fun. In line with Gibson's [22] definition of affordances, Zhang *et al.* describe it as the way the look and feel of a tool invites specific interactions or behaviours [8]. More subjective experiences are evoked, which are largely based on the user's background and experience level. This means that these five affordances not only create a generally entertaining experience but also ensure that it is different yet intuitive for every user, making it engaging for a broader user group. The study argues that integrating gamification elements in an application will motivate users and stimulate prolonged engagement – especially if more in-depth interactions are facilitated. This can be created by allowing for explicit comparisons between users (i.e., competition), but also steering towards solving a collective problem (i.e., cooperation) by enhancing relatedness between users. The use of narration provides additional context which stimulates immersion in the situation, enhancing the depth of the interaction even further.

Additionally, embodiment can be identified as a factor that enhances the positivity of playful participation. Embodiment theory focuses on the involvement of our bodies and actions in understanding and interacting with the world. Instead of only designing for cognitive understanding, embodiment includes the body as a whole – including the physical real in the playful experience. The aforementioned topic of affordance is related to embodiment, as it taps into a more subconscious relation between the tool, the context, and the user[4]. It is dependent on the environment and people that make use of it [22]. Through design, the affordance of a tool can be steered towards a playful experience. Furthermore, O'Brien and Toms [21], Van Dijk [11] and Jordà *et al.* [23] highlight that giving people autonomy and physical control of the tangible tool helps stimulate continuous engagement. Ideally, multiple people can interact simultaneously with multiple elements of the object, enhancing the equality between users [24], [25]. An open and equal discussion with intuitively playful elements stimulates collective sensemaking in a positive environment. By creating a strong link between physical actions and visual or tangible feedback, this positive participatory environment will be further enhanced [23]–[25].

### 2.1.2 Reduced Complexity

It is also important to keep engaging stakeholder in this discussion. This is done by facilitating the way information is conveyed in the discussion. Focusing on clear and accessible information provision, a feeling of confidence and comfort can be created that helps stakeholders stay a part of the discussion [9]. Zilouchian Moghaddam *et al.* [16] and Rundo *et al.* [9] describe using visualizations in a centralized tool to involve several stakeholders, which then helped them focus better on the topic and ease common ground creation. The use of visual elements helps convey complex information in a clearly perceptible way [1]. One of the most notable methods that can aid this, are the '10 Usability Heuristics' as defined by Nielsen [10]. A subset of these heuristics is specifically relevant for visualization. Firstly, using visualizations that clearly form a match between the system and the real world (Heuristic 2) will make it easier for users to interpret what it means. Building on that, it is easier for people to recognize what the visualizations focus on rather than having to recall all the information it represents (Heuristic 6). Secondly, it is important to use consistency and standards (Heuristic 4) for visualizations, so the user can anticipate what certain elements mean or do. Lastly, in order to further minimize an information overload, focusing on aesthetics and minimalist design (Heuristic 8) will ensure that only relevant information is presented to the user. The visualizations focus on the essentials and support the user's primary goal. By using these techniques to

[4] Imagine the role of scissors in the context of an Arts and Crafts room with fellow students, where it is used to cut materials. There, it serves as a tool for artistic expression. However, if the scissors appear in the context of the Hunger Games, where participants have to survive in a hostile environment, the scissors take on a different role. It can become a weapon when enemies are encountered, or be a survival tool to gather food and make tools.

decrease the cognitive load of processing information relevant to the discussion, it is easier to stay involved in the discussion.

In addition to using visual elements, some parts of embodiment theory can be useful in reducing the complexity of information to convey. The concept of external representation focuses on the use of physicality to convey information that would otherwise need to be memorized [11], [23]. Giving a physical form to otherwise digital or abstract elements, can make them easier to capture, memorize, and focus on [24], [26]. For this, it is important to find a balance between abstraction and accountability; simplifying complex information while still being able to observe and report what happens and making sense of it [27]. However, as Van Dijk states, the core of embodiment does not lie in data physicalisation but rather in the social role it plays (see 2.1.1 Positive Participation, 2.2.3 Common Ground in Practice, and 2.3.3 Providing Context). The use of external representations to provide context in a simplified way could, however, play a role in enhancing this social role [12].

### 2.1.3 Stakeholder Involvement in the Design Phase

Engagement is not only relevant in the discussion but also in the steps beforehand. Through inclusive design, a sense of collaboration and understanding can be generated that persists in the use phase of the tool. Font Barnet *et al.* actively involve stakeholders in their design process by organizing co-design sessions, arguing that the success of a product *"will depend on the ability to engage users as equal and integral partners in the whole process"* [3, p. 4]. Through their approach, stakeholders are able to share their perspectives and together reach an understanding. This leads to an end result that fits the users' needs, increasing its value. Similar research is conducted Fredericks *et al.* [4] who use participatory design methods to create installations that collect feedback and stimulate inclusive collaboration between various stakeholders in urban planning. Aguilar [5] had a similar approach, using an iterative design process with co-creation sessions to develop a tool that stimulates collaborative planning through stakeholder participation. In both cases, involving the stakeholders from the start of the design phase helped generate a sense of shared understanding which stimulated the stakeholders to collaborate and define a shared goal to work towards.

### 2.1.4 Engagement in Practice

The aforementioned concepts come together in a study conducted by Den Haan [28], utilizing the principles of gamification, tangibility, reduced complexity, and stakeholder involvement. The Virtual River Game (see Figure 4) consists of a minimalistic tangible user interface with projections that allow stakeholders to explore and discuss different ways of water management. All tiles on the table represent a piece of land or water and can be moved to different parts of the grid[5]. In a serious game-like fashion, stakeholders are stimulated to participate in this discussion by picking up pieces and seeing the impact of moving them around. The study sought a balance between abstraction and accountability when simplifying the reality of hydrodynamics with hexagonal tiles to make it easier to stay involved in the discussion. Using an iterative design approach, Den Haan ensured that stakeholders were also involved in the design process.

Figure 4. Virtual River Game, from [29]

[5] This is similar to simulation games like Sid Meier's Civilization V and the Catan board game.

## 2.2 Creating a Common Ground

After engaging stakeholders in the discussion, the second step in alignment focuses on creating a common ground that reduces fragmented communication. Fugelli *et al.* [30] describe a common ground as *"a shared social reality"* that is mutually accessible but intersubjective, in which people continuously adjust and coordinate their behaviour to each other. Four factors that comprise common ground can be identified: co-situatedness, co-perception, co-intent, and co-attend. By making internal knowledge visible in a shared experience (co-situatedness and co-perception) specific elements can be focused on together (co-attend) that help create a common ground with shared understanding, moving towards making a compromise (co-intent) [13].

### 2.2.1 Shared Experiences

Co-perception and co-situatedness contribute to common ground by generating empathy and awareness of the playfield through a shared experience. In co-situatedness, stakeholders are together in the same situation, such as being at the same grocery shop [13]. Examples from Fredericks *et al.* [4] and Lean IPD's Big Room [14] show how stimulating different stakeholders to physically or digitally meet in a neutral middle ground contribute to a shared knowledge, understanding, and an equal contribution to decision-making. When they are also experiencing the same things in the situation, like hearing the same conversations and seeing the same discounts in the grocery shop, they are *co-perceiving* the situation [13]. Examples from Zilouchian Moghaddam *et al.* [16] and Wang *et al.* [17] show how the use of a centralized, visual tool enhances the feeling of shared understanding, which makes it easier to create a common ground. Where the former developed a web application as a central platform to provide feedback, the latter used immersive technologies to facilitate participatory design and decision-making on-site. This brought the topic of discussion a lot closer compares to talking about it in an office and facilitated an open discussion. Additionally, an example from Ağça and Buur [15] highlights how making behavioural information about each other visible can increase understanding and affect intent. Considering these examples as a whole we can see that in a shared experience, stakeholders not only receive the same information abut also more easily share their perspective. This contributes to empathy and shared understanding, setting the stage for common ground creation and compromise [13].

### 2.2.2 Shared Focus

Co-intent and co-attend contribute to common ground by facilitating the recognition of a shared goal and redirecting attention towards a central point through shared focus. Following the example of the grocery shop, co-intent is created if stakeholders recognize that they have the same common goal of buying groceries for dinner. They might have a different opinion on what dinner should entail, but the dot on the horizon stays the same. This makes it easier to look for a decision that is desirable for both (see Section 2.3 Moving to a Compromise). When they actively direct their attention to the same aspect, like the vegetables section, co-attend is created [13]. Pustejovsky *et al.* [13] describes that a *"shared situated reference"* follows, which can be referred to and further externalized. Vocal and gestural explanations are put in perspective with the co-attend on the topic of conversation. In the example, pointing at the carrots while expressing disgust, will externalize otherwise internal feelings to the other stakeholders. Both factors are identified by Pustejovsky *et al.* [13] as strong factors that further stimulate collaborative communication, arguing that bringing stakeholders together in the same environment and demonstrating knowledge is essential to create a shared understanding. Including tangibility in this can further enhance the use of a shared situated reference due to its physical presence. Van Dijk [11], [12] describes the difference between objects being ready-at-hand – intuitively integrated with the background – and present-at-hand – becoming the focus of attention or interaction. When the object is the former, it can be seen as an extension of the body and can be intuitively used. As the latter, it becomes the centre of attention

and helps redirect focus. This dynamic can be used to further enhance the role of the shared situated reference.

### 2.2.3 Common Ground in Practice

There are some examples on how a shared experience and focus can be stimulated, with the use of tangible elements. One example is Axiom (see Figure 5) [31], a multi-user hologram table that allows users to observe hologram models in 3D on a table while presenting more detailed information on a connected flatscreen. A similar study is done by Belcher and Johnson [32], who create an AR-based table platform called MxR that allows the user to examine a 3D model and simulate how lighting (e.g. position, intensity) affects the model. The potential of these examples lies in using the setup of the table to generate a shared experience in which attention can be (re)directed to specific elements of the 3D model. This way, it physicalizes a common ground and acts as a supportive tool in a discussion about the physical model. The table becomes the shared situated reference. The digital augmentation can be used to visualize and analyse ideas that come up, stimulating shared understanding.

Figure 5. Axiom hologram table displaying a mountain and plane, from [31]

## 2.3 Moving to a Compromise

Once a common ground has been established, we can go a level deeper and start looking towards making a compromise. It is defined by Van Parijs [33, p. 2] as *"an agreement that involves mutual concessions"* in order to *"avoid an option which each [stakeholder] deems worse"*. A compromise is needed that makes all stakeholders feel represented, in order to maintain the common ground, avoid conflict, and battle indecisiveness [17], [33]. Zilouchian Moghaddam *et al.* [16] have explored what affects compromise and consensus building. In their research, a tool is designed that can track and compare design ideas more effectively. It provides a summary of the discussions taking place and the alternatives at hand, has an integrated voting system to support consensus building, and uses visual elements to make the tool easily perceptible. The study states that these four factors are key in making compromises.

### 2.3.1 Overview of Alternatives

It is important that stakeholders are aware of the possible options and their arguments in favour and against. Ideally, the (long-term) impact of options should also be included in this [17]. This helps create an overview of the breadth of the discussion, so the different possibilities do not *"get buried in the midst of a discussion"* [16, p. 8]. Additionally, it generates a feeling of control over and trust in the information presented [17]. The DECIDE framework [1] and the Choosing By Advantages (CBA) [34] method highlight the value

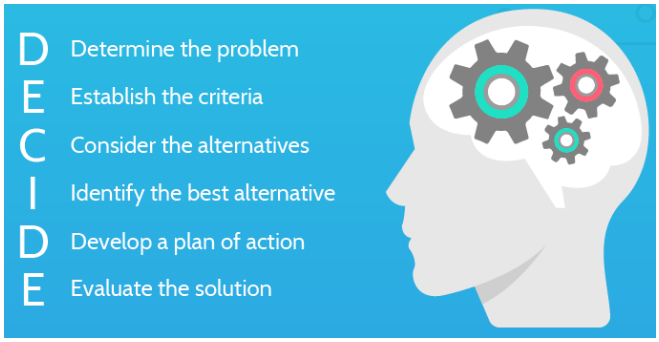



Figure 6. The DECIDE framework as defined by Guo [35]

of having an overview of alternatives as well. Both methods describe steps that help moving from indecisiveness to decision-making. DECIDE lists six steps (Figure 6) and CBA describes five phases, Stage-Setting, Innovation, Decision-Making, Reconsideration, and Implementation. After defining the situation, both methods focus on creating an overview of alternatives and weighing them. In the former, these steps are 'considering the alternatives' and 'identifying the best alternative' [1]. In the latter, these are 'Innovation' and 'Decision-Making' [34]. Presenting an overview of alternatives helps create a holistic structure in the discussion.

### 2.3.2 Indicating Preferences

Each stakeholder has their own perspective and interests, meaning that the alternatives available will have a different impact on each stakeholder. Zilouchian Moghaddam *et al.* [16] argue that visibly sharing the preferences of stakeholders will help in consensus building by continuously showing the level of alignment between stakeholders. The study uses mainly quantitative methods to indicate preferences, such as voting, ranking, but also mentions an affect analysis as a possible method. In CBA [34], this also comes forward in the fourth phase, Reconsideration. After identifying the most suitable alternative, stakeholders are asked to express their doubts and share how this decision will impact them. This is the final moment before the decision is implemented. By creating room to share and visualize preferences, stakeholders are invited to collaborate so that their collective goal (see 'co-intent' in Section 2.2.2 Shared Focus) is reached in the best possible way.

### 2.3.3 Providing Context

While the first two factors focus solely on the options at hand, the context is also important to include. This includes knowing when ideas were proposed or discarded, but also knowing who provided input. In the study done by Zilouchian Moghaddam *et al.* [16], there is a timeline containing all ideas that each have an integrated comment section for specific input. Other relevant contextual information comes forward in a study by Gururajan *et al.* [14], where visual information on project goals, trends, and team members is provided that can aid the discussion. Such information helps put arguments and (dis)advantages in perspective and help assess them more realistically.

The theory of embodiment also plays a role in providing context, namely in externalizing the way people interact with each other and their environment. These interactions can be seen as social signals that affect the way people communicate and understand matters [18]. De Jaegher has developed the theory of participatory sensemaking for this, which is defined as *"an interaction and coordination of two embodied agents"* in which meaning is provided through ongoing behaviour between people [19, p. 1]. Van Dijk and Hummels [20] use tangibility to support participatory sensemaking through embodied interactions. For example, the use of NOOTs and the creation of Floor-It which both focus on the use of traces in discussions. NOOTs are small tokens that can be physically grabbed to mark a moment in a discussion, representing the internal process of 'holding a thought'. The artefacts in Floor-It are photographs, which capture the results of a brainstorm session that took place beforehand. They can be interacted with by pointing to it or by using your feet to transform it in size and position. These artefacts leave traces when interacted with, conveying social signals and putting focus on the social context of the discussion. Van Dijk describes how picking up a NOOT-clip can be seen as a *"way of storing insights into the environment"* [11, p. 126]. Traces can also be left for future uses, as a physical history, to reduce the internal process of remembering information while *"enabling coordinated, goal-oriented behaviour"* [11, p. 133]. Then, they play an informative and socially coordinating role, which is defined as stigmergy [36].

### 2.3.4 Using Visualizations

The last factor contributing to consensus building and making compromises considers the presentation of information. This also plays a role in reducing the complexity of information as described in Section 2.1.2

Reduced Complexity, but is essential when moving on to compromise. As there is a greater amount of information involved, there is a risk for information overload. This reduces insights in available options and can make it harder to make a decision at all [1]. By using visual elements and a modular structure in the interface, this can be avoided. The use of the '10 Usability Heuristics' as defined by Nielsen [10] and as described in Section 2.1.2 Reduced Complexity are also relevant in this case.

Using visual elements (e.g., icons and colours) to represent otherwise convoluted data in a straightforward manner can be helpful. They allow users to better understand and trust key information while being able to focus on the most important elements [16], [17]. It can also be helpful to only present relevant information to the user, using a standard structure for the interface that is tailored to the type of user [37]. Such a modular structure can make use of separate spaces for specific uses (e.g. opinions, chatting, group posts) and filters to ensure the user only sees relevant information [16]. By using visualizations and modular interfaces, and putting a great focus on usability, the amount of information that is conveyed can be easier to interpret and make sense of [1], [16].

## 2.4 Research Opportunities

The past sections describe how engagement, common ground, and compromise each play a role in facilitating stakeholder alignment on a different level. Examples show how different technologies can play a role in this. This theoretical framework highlights the value of heavily involving stakeholders in the design process and identifies key elements that should be integrated in the design of the tool, such as gamification, embodiment, user autonomy, and information. Due to the context-dependent nature of these key elements, however, it is important to zoom in on the context of asset management. The diagram as visualized in Figure 3 can be used as the theoretical basis for a practical execution, with a focus on creating a common ground. This way, the set of key elements will become a complete tool that fits the wishes and properties of the stakeholder and their context. We need to find out how gamification and embodiment should appear in the tool, where stakeholders seek autonomy, what kind of information the stakeholders require, and which technology would fit best. A co-creative and iterative approach in which the personal experiences and expertise of stakeholders support the theoretical findings in defining requirements will help in that.

# 3. Methodology

This research focuses on the active involvement of stakeholders in an iterative design process. Following research through design principles, the context of the problem statement is continuously refined while design directions for a possible solution are explored through various research methods. The 5-stage process of design thinking (see bubbles in Figure 7) is combined with the 4-stage Creative Technology design process (see coloured areas in Figure 7) to iteratively guide the process towards one prototype that is worked out and evaluated as a conclusion to this research [38], [39]. Qualitative design methods are used to gather input on the wishes, experiences, and opinions of stakeholders. Where the first research sub-question has been answered in Chapter 2. Theoretical Framework, the other two come forward in the Ideation phase (context analysis and co-creation) and Specification-Realization-Evaluation phase (Lo-Fi and Hi-Fi phase) respectively.

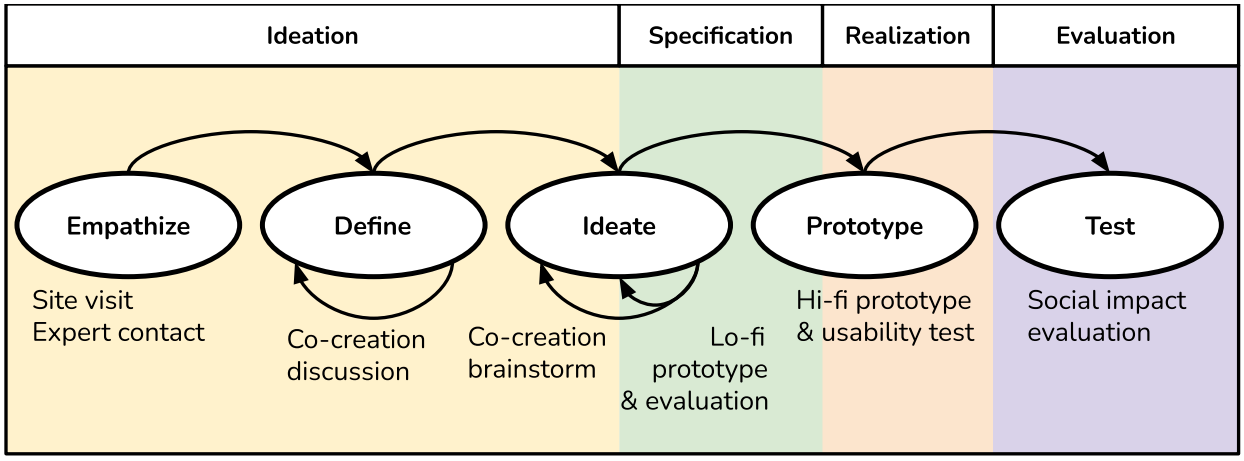



Figure 7. The iterative design process used in this research, with a big focus on ideation

Different levels of qualitative insights are obtained through different research techniques. In Figure 8, the relation between specific techniques and the obtained knowledge is visualized. During the site visit and the various evaluation sessions, interviews and observations are used to examine what people 'say & think' and 'do & use'. In the generative co-creation sessions, information about what people 'know, feel, and dream' about potential solutions is retrieved. This combination of research methods helps gain insights on the current situation and what stakeholders wish to see changed, which shapes the creation process that can then be reflected on during various evaluation sessions. This way, the vision of the stakeholder is continuously included in the design process.

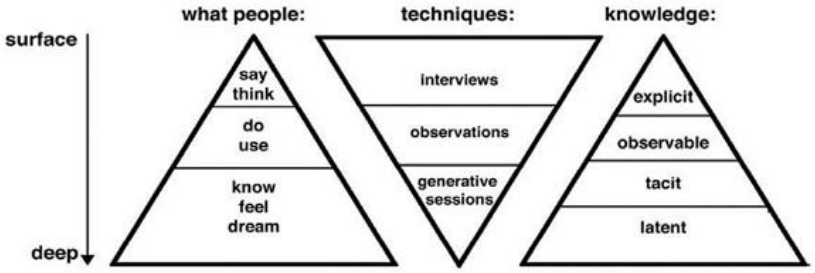



Figure 8. Different levels of knowledge are accessed by various methods, from [40]

## 3.1 Context Analysis of Asset Management

To help maintain a user-centred focus and increase empathy, the context of the Waterwolftunnel is further explored and each stakeholder is worked out in a persona (see Section 4. Research Context). A site visit is carried out, which is analysed using a PACT (People, Activities, Context, Technologies) analysis [41] after which the results are categorized using colours. The frequency of each category is counted, so the most important focus points can be identified [42]. This information is combined with stakeholder contact and the expert contact conducted in previous research by Van Meggelen [1] to create three personas.

### 3.1.1 Site Visit

One visit is planned via the asset manager of the Waterwolftunnel. Safety precautions (instructions and protective gear) were necessary to enter the tunnel. The researcher is granted a tour through the Waterwolftunnel and retrieves an explanation of the different components. Additionally, the researcher observes the way the asset manager communicates with other colleagues on-site and discusses these observations with the asset manager. Some focus points and questions were prepared beforehand, focusing on the current situation and identifying points for improvement. They can be found in Table 1 below.

Table 1. Overview of questions and focus points during the Waterwolftunnel visit.

| Topic | Question | Follow-up |
|---|---|---|
| **Question** | What kind of meetings are conducted here? | Which are most important? |
| **Question** | What kind of people work here? | With whom do you work here? |
| **Question** | How often do people work here? | How often do people work remotely? |
| **Focus point** | How do people work at the tunnel? | Where do people work most often? |
| | | How do people communicate? |
| | | What kind of situations are recurring? |
| | | Who work at this location? |
| **Focus point** | What are points for improvement in terms of collaboration? | What are frustrations? |
| | | What goes well? |
| | | What can be done better? |
| **Question** | Previously, you indicated that people do not always fill in everything. | Why is this? E.g., too much work, forgetting? |
| **Focus point** | What example is there in terms of collaboration and sustainability? | Which one is most important? |

The input gathered during the visit is analysed by conducting a PACT analysis, based on the outline presented by Nayanathara [41] and Reinius [43]. This analysis helps gain a complete overview of the context, by focusing not only on the individuals (People), but also their behaviours and goals (Activities), the environment in which they work (Context) and the tools they use (Technologies). This analysis is further analysed by defining recurring themes in the text and counting how often they appear, using colours to indicate them. Through this, the most important points are identified and an increased understanding about the relation between categories is created [42].

### 3.1.2 Personas

Three personas are created, each representing one of the stakeholders. Similar to our previous research [1], they are made via UXPressia[6] and use pictures created via an online AI photo generator[7]. The persona of the asset manager is retrieved from [1] and is very elaborate as that is the main stakeholder of this research. The other two personas are more compact, but still convey the essence of the stakeholders. They utilize information gained through expert contact during (online) meetings, mail contact, and the site visit to the Waterwolftunnel.

## 3.2 Co-creation Sessions

After the context analysis is conducted, two co-creation sessions are organized in which stakeholders generate and discuss possible solutions to the problem (see Section 5. Co-Creation Sessions). To ensure the focus of the research remains representative and relevant, the problem statement is also discussed and refined. Each session results in a diverse set of ideas – created through discussions, post-its, brainstorm matrices, and paper prototypes. A set of requirements flowing from these sessions can then be used in the next phase of the research.

[6] https://uxpressia.com/personas-online-tool
[7] https://thispersondoesnotexist.com/

### 3.2.1 Participant Selection

To get a variety of input during the session without it being overwhelming, there will be 3-5 participants per session. This is preferably 1-2 asset managers and 2-3 other stakeholders, so that a diverse set of participants is present while a focus remains on the asset manager. Participants are either approached via email if they have already participated in a diary study or expert interview in our previous research [1], are suggested by the supervisor, or are a result of snowball sampling. They should work at or with Arcadis as an asset manager, asset owner, or service provider. Participants are excluded if they spend less than 50% of their work on asset management. After the session, participants were rewarded with a small present.

### 3.2.2 Study Outline

Both sessions are located physically in an Arcadis office and take 3-4 hours per session. Audio recordings and pictures are taken to support observation notes. The sessions follow the co-creation toolkit as defined by Man *et al.* [44] and use brainstorming techniques as proposed by Karahanoğlu[8]. See Table 2 for an outline of each session. After kicking off the session, the problem statement is first discussed with participants. This is done to ensure they are on the same page, but also provides room to refine the problem statement. After this, with a *"Pressure cooker approach"* as described by Karahanoğlu, the warming-up and ideation activities are carried out. They are relatively short and fast-paced, to stimulate brainstorming based on intuition instead of active thinking. The ideation activities ensure diverse data is collected. Vocal input through discussions, visual input through drawings and scribblings on post-its and brainstorm matrices, and tangible input through paper prototypes provide a broad spectrum of ideas and wishes. The paper prototypes are then evaluated in context-specific scenarios and discussed.

Table 2. Outline of the co-creation sessions

| Activity | Description | Timespan |
|---|---|---|
| **Welcome** | Introductions<br>Outline of the session | 2 minutes<br>3 minutes |
| **Alignment** | Discuss the problem statement and their current solutions | 15 minutes |
| **Warm-up** | Alternate uses<br>Pictionary | 2 minutes<br>3 minutes |
| **Ideation: Discussion** | Group Brainstorm<br>Reverse Thinking<br>Individual Brainstorm<br>Discussion | 5 minutes<br>5 minutes<br>10 minutes<br>15 minutes |
| **Ideation: Drawing** | Brainwriting/drawing<br>Discussion | 15 minutes<br>25 minutes |
| **Ideation: Prototyping** | Lo-Fi prototyping | 20 minutes |
| **Evaluation** | Role-playing<br>Discuss | 30 minutes<br>10 minutes |
| **Wrap up** | Conclusion, takeaways, feedback | 10 minutes |

Elaborate descriptions of each brainstorming and/or ideation technique that can be used can be found in Appendix B.1 Ideation Techniques. Several crafting materials are used to spark creativity and allow for the creation of (tangible) prototypes. Tinkering and brainstorming materials are present to facilitate the ideation process, as can be seen in Figure 9. These are writing materials (e.g., post-its, whiteboard, pen, markers, pencil) and several prototyping materials. Some crafting materials like carboard and paper, see-through sheets, scissors, glue, tape, and LEGO bricks are used. Scrap materials like game pieces, glowsticks, buttons, and wooden sticks allow participants to create more three-dimensional prototypes.

[8] A. Karahanoğlu, personal communication, May 3, 2023

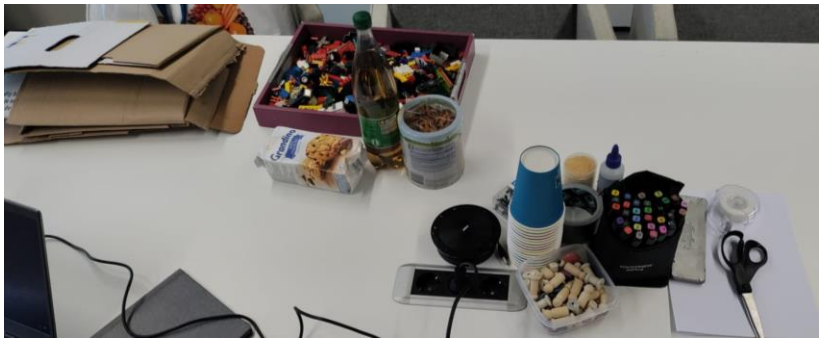


Figure 9. Materials (and snacks) used during the co-creation sessions.

### 3.2.3 Analysis

The audio recordings are transcribed using the Microsoft OneDrive transcribe function in Word, after which the transcript is finalized manually (e.g., fixing misinterpretations, anonymizing results). Participants are referred to using the first letter of their first name and irrelevant parts of the recording such as breaks are removed. The transcript is analysed by conducting a thematic analysis with a-priori codes (see Table 3) that are based on the findings of Van Meggelen [1] and the functional goal of the co-creation sessions. Each code is part of a subgroup, defining the function of the label and providing the basis for theme development as an outcome [45]. The trial version of Dovetail[9] is used to use coloured tags for each code. The tool allows users to filter segments of text based on the tag given, making it easy to see related elements in one overview. Ideas generated with post-its and the brainwriting exercise are grouped in an affinity diagram. This is a structured way to organize data by grouping the main findings of the sessions such that patterns and themes are identified [46]. From this input, requirements are formulated for the Lo-Fi phase. They are prioritized using the MoSCoW[10] method, labelling each requirement as a Must, Should, Could, or Won't have.

Table 3. Overview of codes used in the thematic analysis of the co-creation sessions

| Code | Subgroup | Meaning |
|---|---|---|
| Positive | Sentiment | Positive outcome or feeling |
| Negative | | Negative outcome or feeling |
| Quote | Functional | Useful to quote in the thesis |
| Outlier | | Off-topic or not in line with other participants |
| Example | | Descriptive paragraphs used to highlight statement |
| Requirement | Design Implication | Element identified as requirement in the design |
| Expectation | | Expected effect of a feature or function |
| Wish | | Suggestions and other non-essential wishes for design |
| Change Point | Problem Statement | Wish to adapt the existing problem statement |
| Refer to Point | | Point is made about the existing statement |
| New Point | | A new point is suggested |
| Remove Point | | An existing point is suggested to remove |
| Collaboration | Social Mediation | People actively working together |
| Information | | Stating which information is needed, acquired; questions that need to be answered |
| Alignment | | People aligning their views or information basis |
| Decision-making | | What is needed to make a decision, when or why a decision is made |
| Sustainability | | Sustainability factors that can be focused on, or matters that are important when considering sustainability |

[9] https://dovetail.com/

[10] https://www.interaction-design.org/literature/article/making-your-ux-life-easier-with-the-moscow

## 3.3 Prototyping

The set of requirements flowing from the co-creation sessions are used to create three Lo-Fi paper prototypes that each explores a different application of alignment theory and use of technology (see Section 6. Lo-Fi Prototyping). The most opportunity rich components of each paper prototype are integrated in a Hi-Fi prototype (Section 7. Hi-Fi Prototyping). Besides its practical functionalities, interactions that relate to embodiment theory are implemented to enrich the user experience.

### 3.3.1 Lo-Fi Prototype

The results of the co-creation sessions serve as input to conduct a brainstorm session. A brainstorm matrix is filled in to generate the first set of ideas that combine the different steps of alignment (defined in Section 2. Theoretical Framework) with the three types of interaction technologies (defined in our previous research [1]). These steps are redefined into 'engage & involve' (from Engagement), 'empathize' and 'discuss' (from Common Ground), and 'compromise' (from Compromise). The technologies cover 'graphical user interfaces', 'tangible user interfaces', and 'immersive technologies'. From this matrix, a minimum of 4 ideas are chosen per technology and worked out more elaborately in a sketch. The sketches are labelled based on the application domain they cover, to see which is the most opportunity-rich domain. For this domain, one idea per technology is worked out in a Lo-Fi paper prototype using the materials available during the co-creation sessions.

### 3.3.2 Hi-Fi Prototype

The results of the Lo-Fi evaluation sessions are used to conceptualize the Hi-Fi prototype. Additionally, follow-up research on embodied interaction allows for more natural interactions and interplay between the tangible and digital elements of the prototype. The concept of the Hi-Fi prototype is first worked out in sketches, after which another paper prototype is created using scrap materials and Microsoft PowerPoint. This paper prototype shapes the basis for the resulting Hi-Fi prototype, which is created using the tools AdobeXD, Arduino IDE, and Processing 4.3. The prototype, consisting of three tangible elements and a digital dashboard, is a combination of electronics, programming, and design.

## 3.4 Prototype Evaluation

The Lo-Fi prototype is evaluated with stakeholders to identify the most opportunity-rich prototype components to include in the Hi-Fi prototype (see Section 6. Lo-Fi Prototyping). This Hi-Fi prototype is then evaluated in twofold (see Section 7. Hi-Fi Prototyping). First, it is evaluated with peer students, to observe what usability issues are encountered and how the embodied interactions can be made more intuitive. After small touchups, the prototype is then evaluated in a simulated discussion setting where a group of stakeholders use the prototype in two scenarios under different conditions. After this, a group discussion and survey help paint a picture of the experiences and impressions of the participants. The resulting qualitative data is analysed using a narrow deductive-inductive thematic analysis. This means that the theoretical framework in chapter 2. Theoretical Framework is used to define the initial themes beforehand. Additional themes that are defined during the analysis are then explored in related theory [45]. This means that a strong relation between the theory of previous studies and practice of the current research is sought. The quantitative data is analysed per session by comparing the length or frequency of several predefined focus points between the two scenarios. Observable differences are discussed in a holistic view to see whether there is an observable trend. This will help conclude whether the chosen design direction did affect alignment and decision-making, and what can be adjusted in future research.

### 3.4.1 Lo-Fi Evaluation

For the Lo-Fi phase, a formative evaluation is conducted with stakeholders in which the paper prototypes that result from the co-creation sessions are explored and discussed. Strengths and weaknesses of the

three paper prototypes are discussed and the most opportunity-rich concept elements are identified that can be worked out more in detail in the Hi-Fi prototype.

### *Participant Recruitment*

Because the collected data is qualitative in nature, the goal is to have to 6 participants to ensure that consistent themes can be identified from the results. Participants are recruited from the participant pool of the co-creation sessions, so they are aware of the context of the prototypes. As stated before, all participants should be related to Arcadis and asset management.

### *Study Outline*

The evaluation sessions are one-on-one sessions that take place in an office at Arcadis and each take 45-60 minutes. They are audio and video recorded and notes are made by the researcher. The prototypes are presented to the participants in a different order each time, ruling out the possibility for bias among the results. See Table 4 for the activity outline. After some introductory questions, three pages are discussed that are the basis for all three prototypes. Then, the prototypes are discussed, showing one prototype at a time. Participants first share their first impression, after which they explore it while thinking out loud. After the concept behind the prototype is explained, participants can voice their thoughts before we move on to the next prototype. After all three prototypes have been discussed, participants are asked to rank the ideas (1 to 3) and technologies (1 to 3) based on several factors. After this, a general discussion is held in which prototypes are compared and their strong and weak points are collected.

Table 4. Outline of the Lo-Fi evaluation session.

| Activity | Description | Timespan |
|---|---|---|
| **Welcome** | Introductions<br>Outline of the session | 2 minutes<br>3 minutes |
| **General questions** | Ask participants their age, occupation, experience with asset management, and personal strategy in terms of making choices | 2 minutes |
| **Discuss standard pages** | Explain general functionality of the three standard pages (general overview, component-specific overview, filling in new option) | 5 minutes |
| **Interact with prototypes** | First impression<br>Explore and explain the prototype<br>*This is done three times, once for each prototype (in a different order)* | 2 minutes<br>5 minutes |
| **Ranking** | Rank ideas and technologies based on: general impression, aesthetics, ease of use, novelty, impact on compromise, impact on collaboration | 10-15 minutes |
| **Discuss ideas** | General impression, compare prototypes, strong and weak points | 10 minutes |
| **Wrap up** | Explain future steps and ask for remarks | 2 minutes |

### *Analysis*

A mix of data is collected during the evaluations:

- Age, years of experience, and the ranking of concepts and tech are quantitative as they are numerical values that can be analysed with statistical techniques;
- Occupation, decision-making strategy, explanation behind ranking, and all other comments are qualitative as they are descriptive, they can be analysed with a thematic analysis;

The quantitative results are analysed with basic statistics (average, minimum, maximum) to showcase the results. For the ranking, participants are asked to rank the ideas in a top-3, where 1 is best and 3 is worst. The qualitative results are analysed by summarizing the results per question/topic and highlighting recurring themes based on how often certain topics are addressed. Combining these results, a conclusion can be drawn as to which (parts of the) ideas and technologies seemed to be the most preferable.

### 3.4.2 Hi-Fi Usability Evaluation

In the first Hi-Fi evaluation, the usability of the prototype is discussed with peer students. This helps gain a general impression of the state of the prototype, to see how much still needs to be refined. Additionally, it helps get a grasp of which interactions with the ball are intuitive and how it might be expanded. It is the final evaluation phase before the prototype is finalized for this research.

#### *Participant Selection*

Since these evaluations are planned in a relatively short timespan, the target group will not be approached as they are less flexible. Instead, peer students will be asked to partake in the usability evaluation. The goal is to have 3-8 participants to ensure that consistent themes can be identified from the results. Participants are approached via the study association of Interaction Technology, either via word-of-mouth or via WhatsApp. They are included if they are a student that has not been involved in any previous research studies conducted in this thesis.

#### *Study Outline*

Each evaluation session will take place in the SmartXp room at the University of Twente and will take 15-30 minutes. No recordings will be made; only notes are taken. Participants are asked to share their impressions about the prototype, play around with it while thinking out loud, and then using the prototypes for four predefined interactions. Afterwards, their experiences and suggestions will be discussed. See Table 5 for a detailed activity outline.

Table 5. Outline of the first Hi-Fi evaluation session, focused on usability.

| Activity | Description | Timespan |
|---|---|---|
| **Welcome** | Explain outline of session, ask if they have some background knowledge about the prototype. | 2 minutes |
| **First impression** | What are the first thoughts and assumptions? | 2 minutes |
| **Exploration** | Let the participant explore the prototype while thinking out loud | 5 minutes |
| **Interactions** | Explain what the prototype is about.<br>Ask participants to use the prototype for specific tasks:<br>• Selecting an option<br>• Discussing an option<br>• Comparing options<br>• Indicating the preference | 2 minutes<br><br>1 minute<br>1 minute<br>1 minute<br>1 minute |
| **Discuss** | Discuss the experience and suggestions, see if anything was missing or should be changed | 5-10 minutes |

#### *Analysis*

As the data that is collected is purely qualitative, the results will first be summarized per activity. After this, a qualitative analysis is conducted that categorizes data based on recurring comments, from the perspective of human-centred design. This will help identify the most important themes that are relevant to the prototype. Quotes are used to highlight these themes. Points for improvement are divided between long- and short-term, so the short-term suggestions can still be taken into account when finalizing the prototype. Long-term points for improvement can be discussed for future work.

### 3.4.3 Hi-Fi Social Impact Evaluation

In the second Hi-Fi evaluation, the potential social impact of the prototype is evaluated. Up until this point, the functionality of the prototype has only been explored in theory. With this phase, the aim is to explore the impact of the prototype in practice to what extent this resonates with the expectations based on previous research. This will help us identify strong elements of the prototype in terms of stakeholder alignment that can be focused on in future work.

### *Participant Selection*

In this evaluation, group discussions will be organized. Since there are three stakeholders in this research, the aim is to have three participants per session – each representing a stakeholder. Participants will be recruited from the Asset Data Management and Asset Management Rail team of Arcadis, via word of mouth, Microsoft Teams messages, and e-mail. None of the members of this team have taken part in previous evaluations, so they are relatively unbiased while they are still familiar with the context of asset management. As an incentive to participate, lunch is arranged for them during the evaluation session.

### *Study Outline*

The evaluation session will take place physically at an office of Arcadis and will each take +-60 minutes. During each session, two scenarios will be acted out and a group discussion and survey are held. See Table 6 for the study outline. In one scenario, participants will utilize the full prototype (dashboard + tangible elements), in the other they only use the dashboard. After the scenarios, a group discussion is held and an individual survey is filled in. Participants are provided with a predefined role describing one of the three stakeholders, which they use to define their stances and arguments during the scenarios. Ideally, their role is related to their actual specialty, so it is easier for them to take part in the simulated discussion.

In total, at least four sessions are held where the order of the conditions and scenarios varies. This is done to rule out external factors like fatigue and learnability – normalizing the input. Some deception is present in this evaluation phase, as participants are informed of a very general goal (*"how people interact with data through the prototype"*) instead of the actual, more specific goal (*"observe how the prototype affects shared focus and stakeholder alignment"*). This is done to stimulate participants to behave more naturally and be open about their comments regarding the prototype's impact. Participants will be informed of that at the very end of the session, and they are asked to re-confirm their voluntary participation.

Table 6. Outline of the second Hi-Fi evaluation session, focused on social impact.

| Activity | Description | Timespan |
|---|---|---|
| **Welcome** | Check consent forms, explain outline of session.<br>Give a short demo of the prototype, so the main interactions are clear.<br>Brief participants of the general goal of this session. | 2 minutes<br>2 minutes<br>1 minute |
| **Warming up** | Give participants their roles and ask them to come up with a background story. | 5 minutes |
| **Read general scenario** | "Improve the sustainability and efficiency of the Noord-Zuid Verbindingstunnel" | 2 minutes |
| **Act out scenarios** | Scenario A: choose one of the options, LED (now), LED (6 months), or induction.<br>Scenario B: choose one of the options, daylight use, solar panels, optimize use. | Each 10-15 minutes |
| **Group discussion** | Ask participants about their impressions regarding role-playing, their experience with using the prototype, and interacting with the data. Compare the two conditions and discuss preferences and points for improvement. Ask participants to reflect on a real-life experience and how they would use the scenario. | 20 minutes |
| **Survey** | Let all participants fill in an individual survey about their general experience, preference, self-reported focus, and other comments. | 2 minutes |

### *Analysis*

Through this evaluation, a combination of qualitative and quantitative data can be processed. Most of the data is qualitative and will be analysed using a narrow deductive-inductive thematic analysis in which themes observed in related research are used as *"the lens through which we analyse and interpret data"* [45, p. 5]. Because each session has different participants, they are independent from each other and cannot be compared. However, within each session, two conditions are encountered (with and without tangible prototype). Differences between the two scenarios can be analysed.

The qualitative data retrieved from the scenarios (e.g., topics and depth of discussion), group discussion (e.g., experience, added value, difference between scenarios), and survey (e.g., explanation on preference, points for improvement, and self-reported behaviour) is summarized per session. Using the themes identified in other literature, the summary will be coded (deductive). In case other themes are defined that are not part of the literature, they will be coded separately (inductively). These can then be explored through additional literature research; increasing the validity of the data and leading to a more meaningful conclusion about the prototype's potential impact.

Quantitative data is retrieved from the audio and video recordings of the sessions. The recordings are transcribed including timestamps and speaker indicators. A limited amount of factors that can play a role in communication will be observed by quantifying their length or occurrence, focusing specifically on speech and gaze [47], [48]. The factors of speaker time division per scenario, the length of discussions, and the frequency of interruptions and off-track discussions are observed via the audio recordings. The factors of gazing at the screen and each other are counted by looking at the video recordings. The aim is to see whether there is an observable and consistent difference between the two conditions. These levels are averaged, and their minima and maxima will be noted. These results will be compared within the sessions, after which the resulting differences will be discussed in a holistic view to see whether there is an observable trend.

# 4. Research Context

While asset management has been described in a theoretical fashion, it is useful for the user-centred and practical nature of this research to consider a real-world context to apply this research to. For this, the Waterwolftunnel has been selected as Arcadis is the current asset manager and the tunnel has already been used in past research by Gankema [37]. From the site visit, it becomes clear that the main activities in the tunnel concern monitoring, optimization, and communication. The technologies and activities highlight how safety, certainty, and independence are the driving forces of the Waterwolftunnel. This input, together with our previous research [1] and a meeting with the asset owner of the Waterwolftunnel is used to create three personas that describe the interests and duties of the three stakeholders in this research.

## 4.1 Real-World Example

The input gathered during the site visit of the Waterwolftunnel was summarized and analysed using the PACT (People, Activities, Context, Technology) structure. Recurring categories were coloured and counted to identify the most important themes (see Appendix A.1 PACT Analysis for coded results). Table 7 shows how often each category occurred in the analysis. The themes of communication and safety came forward the most during the visit, resonating with the core factors of asset management. Communication revolved around the communication between stakeholders and communication between stakeholders and technologies (e.g., operating system). It became apparent that the former could be improved in terms of openness, especially between the asset manager and service provider. More face-to-face contact could help in that. Safety revolved around the wellbeing of motorists in the tunnel in case of normal use and emergencies, as well as the safety of employees (e.g., inspectors) when working on the tunnel. It became apparent that this helps maintain a conservative attitude, in which stakeholders prefer to stick to what is known – reducing the risk for surprises.

Table 7. Frequency of categories that came forward in the summarized PACT analysis.

| Category | Description | Freq. |
|---|---|---|
| **Communication** | Extent of and potential for contact between stakeholders and components | 30 |
| **Safety** | Focusing on the safety of users and visitors of the tunnel | 23 |
| **Information** | Matters entailing the disclosure and complexity of information present | 14 |
| **Availability** | Anything affecting the availability of the tunnel for its users | 14 |
| **Conserve** | Focused on preserving what is, versus looking for innovation | 11 |
| **Visual** | Visual elements and actions | 10 |
| **Automatic** | Considering an automated data collection and communication process | 6 |
| **Independent** | Anything affecting the independence of stakeholders working in the tunnel | 5 |

### 4.1.1 People

Three parties are identified that are involved with managing the Waterwolftunnel: one or two asset managers (always), one or two tunnel operators (often remotely), and two service providers (in case of maintenance). The asset manager is the mediator and point of contact for all parties to answer questions and solve issues, representing Arcadis. Tunnel operators monitor the tunnel installations and traffic in and around the asset with the use of their operating system. Service providers are present when needed, following a maintenance planning as defined by the asset manager. They are familiar with the asset and visit multiple assets a day. It can happen that during a maintenance session they get notified of a critical issue at a different asset, which they have to fix immediately. However, oftentimes, they can follow the planning as defined by the asset manager.

These stakeholders can be quite conservative, being reluctant in adopting big changes. This is because it is an investment that brings uncertainties about performance, reliability, and safety with it. For

example, the operating system was renewed but the interface that was already in use for 10 years was reconstructed in the new version. Next to this, the people working on the Waterwolftunnel each have a different background and attitude. Each person has different expertise related to the tunnel and not everyone is interested in being up to date with one another. This affects how well the stakeholders collaborate, currently often *"thinking easy"* and communicating minimally. This can lead to a lack of information, miscommunication, and frustration – further affecting the reluctance to change.

### 4.1.2 Activities

In the Waterwolftunnel, the main activities revolve around using the operation system to monitor the tunnel when needed and regularly planning meetings and maintenance sessions with stakeholders. Asset managers can use the data preserved in the operating system to stay informed, observe notifications and trends, conduct analyses, and optimize maintenance plannings that are presented to the service providers. They often work on tunnel-related matters (e.g., writing maintenance plans) while in the office and get regular calls with various questions. Operators monitor the status of installations and observe abnormalities in motorist behaviour. In case of an issue, they can respond through the operating system and notify the necessary people. They are often not present on-site, but in a nearby town. Service providers are only present when requested by the asset manager, following the maintenance planning that is defined by them. This is always done in duos, so there is assistance and a contact point in case of an emergency.

There are regular construction meetings and technical meetings in which topics like maintenance, issues, replacements, and sustainability are discussed. Furthermore, there are monthly inspection rounds and safety inspections where topics like defects, leakages, nuisance caused by mice, and fire safety and first aid kits are discussed. Everything is noted and registered; people entering and leaving, maintenance sessions, inspection rounds, and when the operating system is used. However, this is not always representative as sometimes service providers leave earlier than registered or work on tasks longer than registered. Materials that are used for critical components are stored in the warehouse and registered when they are used, so they are never out of stock. Small materials (e.g., screws) are not registered frequently, only once a year during a balance checkup. Therefore, written details by service providers to asset managers in the maintenance reports are needed to improve maintenance planning.

### 4.1.3 Context

The Waterwolftunnel is 10 years old, located in the province of Noord-Holland, and has a north and south office space attached to it. Most of the work is done in the north office. There are always at least two people present in the office, who are authorized access to specific rooms via a key(card). The asset managers work in the office room and sometimes move to the tunnel to find the source of issues. The operators work in on the operating system in the surveillance room which they should lock and log off if they leave, but this does not always happen. The service providers make use of the office connection that leads them to servers, power rooms, inventories, and to the tunnel itself. All components, areas, and actions in the tunnel are coded with abbreviations and ID numbers (e.g., Abbr-01-Room-02). Entering the rooms requires wearing a safety vest, helmet, and shoes. The middle part of the tunnel can be walked through for inspections and evacuations, being fire resistant for at least 90 minutes.

A lot of communication is online and sequential, via online or hybrid meetings, phone calls, and e-mails. When work needs to be done, a plan is first worked out by the asset manager, then sent to the asset owner to approve it, and then forwarded to the service provider to execute it. This way of working often leads to a slow communication flow with limited details. For example, when a maintenance session is finished, service providers fill in a report that asks for details and particularities regarding the session. The information that is returned to the asset manager often only confirms whether something is done or not. Frustrated, the asset manager often has to ask for more details or even requires the service providers

to conduct an additional session. In theory, the collaboration is top-down, but as observed during the visit each party has an effect on the other and all parties need to share their expertise to effectively work together. Ideally, this collaboration is done in more face-to-face so they can simultaneously focus on the same thing and better interpret each other, but this is difficult to implement.

### 4.1.4 Technology

The tunnel contains a lot of installations and users, which are monitored through a complex and versatile operating system. The system contains information about the behaviour of motorists, status of water tanks, fire extinguishers, electronics, air quality, lighting, heat, and more. It uses a systematic representation of the tunnel: a classic graphic user interface with various windows, icons, and menus. Components are visualized in 2D-maps and kept up to date with a continuous data flow. Each page has a tab title that contains letters representing the status of the installation (functioning, error, etc.) and the intensity of an error message to give the operator a quick overview. When data deviates from certain standards or installations stop working, the operator gets a notification that makes use of auditory (a bleep), visual (marking relevant information and showing relevant security cameras), and temporal (a timer) features. If the timer hits zero or the error is confirmed, a scenario is started (e.g., traffic light is set to red), otherwise it will be cancelled. There is also a multifunctional audio panel that enables independent communication with essential parties in case there is no reception. Internet and communication systems are all functioning independently; they are not affected by country-wide malfunctions or overloaded networks. As the tunnel is a critical installation, systems in the tunnel are based on obsolescence and certainty: there are duplicates of every server, component, and system in the tunnel so that in case one fails, the other can take over and guarantee a safe pass through the tunnel.

## 4.2 Personas

The stakeholder most involved in this research is the asset manager, as the executive manager of the asset and the point of contact between other stakeholders. As observed in the previous section, they contact the asset owner to discuss and approve of plans for change and plan maintenance and inspection sessions that are conducted by service providers. These stakeholders were presented in a persona created via UXPressia[11] so their roles can be easier to understand and empathize with [49]. They can be found in A.2 Personas. Operators in the real-world context work rather independently and are less involved with these stakeholders so they are left out.

In the personas, the priorities of the stakeholders come forward. For Anton, the asset manager, it is important that malfunctions are resolved so the asset is safely available to its users. Furthermore, he has to keep up to date with legislations and sustainability standards so he can plan maintenance and renovations that Peter, the asset owner, and Sam, the service provider, agree with. Peter, the asset owner, represents a local authority and has to make sure that legislations are followed, budgets are not exceeded, and the public remains content. His work leans more towards governance than the Anton's. Lastly, Sam, the service provider, has to execute the plans. In his interests lies the efficiency in which he and his team can conduct their work, as they work on different assets simultaneously. Speed and success are key factors in his work, as he is very busy.

## 4.3 Key Takeaways

Adding onto the theoretical knowledge acquired in previous research done by Van Meggelen [1] and Gankema [37], the visit to the Waterwolftunnel helped gain practical insights on asset management in the field which could be used to construct personas for the relevant stakeholders. Three 'People' are actively involved in the Waterwolftunnel: the asset manager, operators, and service providers. The asset owner is

[11] https://uxpressia.com/personas-online-tool

indirectly involved, identifying safety and availability as key values for the day-to-day operations of the tunnel. The main 'Activities' in the tunnel revolve around communication between each other (e.g., meetings and documents) and making use of information-based systems to monitor the status of the tunnel. Although the asset manager is described as a point of contact, 'Context' identifies the problem of fragmented communication in the field. Combined with a *"thinking easy"*-attitude and a focus on risk management, the relation with a reluctance to change is observed. The operation system is the key 'Technology' that is used in the tunnel, automatically collecting data about components in the tunnel and conveying this with visual elements and multimodal notifications. Asset managers use this system to monitor the performance of components and analyse problems when they arrive.

These insights show while there is a great focus on using information to get to the root of problems and improve, asset managers have limited insights about their stakeholders. This is due to a lack of alignment and communication, which halts innovation. This has been summarized in the personas, that can be used in the following steps of this research to quickly illustrate the main stakeholders, their values, and their relation with each other. This helps stay focused on the user that is being designed for and quickly informs participants in this research of the most relevant points for each stakeholder.

# 5. Co-Creation Sessions

Two co-creation sessions, each with 3 participants representing a stakeholder, were organized between 16 May and 19 June 2023. The goal of the sessions was to gauge the perspective of stakeholders on the problem statement of this research so it could be refined. Additionally, they were asked to come up with potential solutions, which were used to formulate requirements and move on to conceptualization in the Lo-Fi phase. A pilot session was conducted with three peer students to test the format of the co-creation sessions. Some scenarios were refined and tips for more effective guidance during the prototyping and evaluation phase were given, so it would be easier for participants to be more creative.

The problem statement was tweaked by nuancing the statement a little bit and by adding a third factor contributing to limited sustainable changes, namely a lack of overview. During the brainstorm for potential solutions, a couple of themes came forward: information provision and collaboration. These were also observed in the prototyping phase of the co-creation session, with ideas focusing on dashboarding, simulating, and visualizing what parameters are affected by different choices. Requirements were formulated that follow these themes as well, steering towards the creation of an engaging dashboard that shows users several options and what effect these options have.

## 5.1 Problem Statement

All participants agreed with the general sentiment of the statements. Some remarks were provided, which lead to the rephrase of the problem statement from "Sustainable choices are rarely made in asset management, due to limited collaboration between stakeholders and uncertainty about sustainable options" to: **"Only few sustainable changes are made in asset management because of limited collaboration, overview, and certainty."** Participants indicated that sustainable choices are currently being made in asset management (albeit not a lot), so that was nuanced. Additionally, instead of two, the new problem statement identifies three factors that contribute to this. While all three are important, the main focus for the remainder of this thesis will lie on the first factor due to its social focus.

Firstly, different stakeholders have different interests that are not aligned. Several participants describe a lack of communication between stakeholders, which is noticed when changes in e.g., policies are communicated too late or too vaguely. Often the reasoning behind a change is omitted from the communication. Such limited communication also often results in miscommunication.

*"I often see that they want something specific, but then they write it down in the wrong way, so they don't get what they want." – Participant 5*

One participant did argue that limited communication is needed in competitive environments, but this is only a small part. Two participants identified another factor that contributes to different interests, namely compliance to contracts. Through the structure of such contracts, some (mainly short-term financial) interests are stimulated while other (more long-term and sustainable) interests are not. This makes it more difficult to align stakeholders, as they only have little room for deviation from the contract.

*"A tender needs to be formally correct, otherwise you don't get it. There is a risk that someone will sue you, so you have to do it right. But then you see a lot of good intentions get lost in the process." – Participant 4*

Secondly, there is currently no uniform overview of sustainable options that is widely known. Participants explained they do not see a scoped description on sustainability and how to measure it,

although the network of Duurzaam GWW[12] provides a basis. However, most communication about this is not well-documented, leading to the reasoning behind certain choices missing or being misunderstood (like the phone game, or 'doorfluisteren' in Dutch). Especially in executive functions this is noticed.

*"Is it clear at the top what the original requirements and starting points are?" – "Oh no, almost never." – Participant 3 & 2*

The facet of compliancy also plays a role here; contract lengths are not linked to the life cycle length of an asset. This means contracts are often too short to stimulate people to do research on sustainable options. There is little priority in creating, maintaining, and communicating such an overview.

*"There is more information about sustainable options than you think, but nobody asks about it." – Participant 4*

Lastly, this lack of overview leads to uncertainty, which is undesired in this work field as it focuses heavily on risk management. All participants highlighted that the work field is very complex; you might never know beforehand what complete impact your choices have. Especially if there is no complete overview of the reasoning behind previous changes and choices. Therefore, stakeholders are hesitant to incorporate changes unless they are more certain.

*"People aren't scared to spend money, but they're scared to change. Also in fear that it might not work anymore, or at least not reliably." – "Or that if something happens, it's their fault." – Participant 3 & Participant 1*

*"If the client explains what needs to be done and you ask, 'Why do we have to do that?' they often respond, 'That's how it's always been done, for 20 years'." – Participant 6*

## 5.2 Brainstorm

After the problem statement was discussed, various techniques were used to generate multiple ideas. A group brainstorm and 'Reverse Thinking'-discussion started off the ideation session, followed by an individual brainstorm with post-its, and a brainwriting and -drawing exercise. During the first session, 27 ideas were generated with post-its and 36 ideas were derived from the brainwriting exercise. These exercises led to 20 and 24 ideas in the second session, respectively. The post-its of each session were grouped per theme, which were then used to label the brainwriting and -drawing exercise results (see Appendix B.3 Brainstorm Ideas (Digitized)). Combined with the results of the thematic analysis (see Appendix B.2 Codes & Themes), which was applied to the full transcript of each session, several overarching themes were identified. The most recurring themes revolve around information provision and collaboration, with key words like 'centralize', 'insights', 'decision-making', and 'share' adding to these points. Other themes are 'accessibility', 'regain', 'measuring', and 'electricity'. Furthermore, clear points for improvement regarding sustainability were identified.

### 5.2.1 Information Provision

In both sessions, various ideas described the use of one central dashboard in which information about component performances (e.g., energy consumption) and different strategies can be presented. Participants described having *"a single source of truth"*, that all stakeholders could access so you have the same information to base your stances on. This is in line with the risk-averse and information-based nature of asset management as described in Section 1.1 Background.

*"Work in one environment to, collectively, make the best decision." – Participant 2*

By combining several data sources (e.g., historical records, sensor data) and processing these efficiently, it might be possible to simulate the effect of choices and gain new insights. This might lead to

[12] https://www.duurzaamgww.nl/

more awareness and stimulate more sustainable behaviour, as long as stakeholders trust the data they see. As participants in session 2 argue, it is currently very difficult to see what 'real' impact your choice will have in the long-term. This is partly because many things can be affected by a single choice, which is very complex to visualize. Especially sustainable issues have this complexity, which leads to hesitancy among stakeholders to make sustainable choices.

*"How do I know that the choices I make now, lead to the optimal outcome?" – Participant 6*

*"We are not going to do this, because we don't understand this." – Participant 4*

### 5.2.2 Collaboration

Besides information provision, transparent communication and collaboration between stakeholders are also seen as important factors that can help stimulate more sustainable decision-making. By informing stakeholders about the short- and long-term gains and losses of each stakeholder, it can be possible to gain an understanding of everyone's position and see where interests overlap and where compensation might be appropriate.

*"What's in it for me?" – "What's in it for us?" – Participant 1 & 3*

One participant argues that specific technologies like virtual reality or tangible elements can help stimulate such understanding. However, several participants say that more is needed. They share that understanding and collaboration between stakeholders is hindered by strict and short-term contracts. They provide little room to look for collective solutions, demotivating stakeholders as they might not profit from the solution.

*"We have the same interests, but the rules we made up hinder collaboration." – Participant 5*

*"If it will change tomorrow, I am motivated to do something today. … If it takes 5 years to improve, I might not be the one to profit from it over 5 years." – Participant 3*

Therefore, a participant argues, it is important to focus on the common goal in the horizon. By looking ahead and shaping a long-term vision, it might be possible to get stakeholders to work together better.

### 5.2.3 Sustainable Changes

Besides more procedural changes that can help provide certainty and stimulate alignment between stakeholders, participants also came with practical suggestions that lead to more sustainable asset management. They focus on gaining insights (I), using resources locally (L), and using materials more efficiently I. See Table 8 for these suggestions. They can be useful when determining a more specific application context for a prototype later on in this research.

Table 8. Practical suggestions for more sustainable asset management.

| Theme | Suggestion |
|---|---|
| **I** | Gain insight in big consumers (components and companies) and identify opportunities for reduction |
| **I** | Retrieve accurate and up-to-date information on consumption and emission |
| **I** | See how an area is affected by emissions of an asset |
| **I, E** | Identify the ideal moment / tipping point for replacement or repair |
| **E** | Extending the life cycle of an asset or its components |
| **E** | Use components for multiple goals (e.g., camera for surveillance and fire detection instead separate) |
| **E** | Use white tiles and white asphalt in tunnels to reflect light and reduce the need for lamps |
| **E** | Use asphalt residue as foundation material to reduce new materials needed |
| **E** | Replace lightbulbs with more energy efficient LEDs |
| **E, L** | Transfer waste into a resource |
| **E, L** | Reduce the need for transport from / to the asset |
| **E, L** | Overview of where materials go, reusability on-site, and bigger / smaller stock need |
| **L** | Circular reuse of materials for nearby assets |
| **L** | Use locally acquired materials |

## 5.3 Prototyping

After ideas were generated, participants were asked to create prototypes that make their ideas more tangible, using scrap and tinkering materials, as can be seen in Figure 10 below.

Figure 10. Participants creating their prototype, made during the first co-creation session.

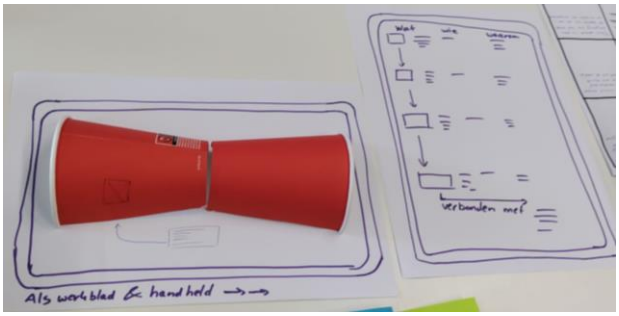


Figure 11. Prototype S1_1, with the 3D model in the office (left) and the app with info about the inspection (right).

In total, five prototypes were created – three in the first co-creation session, two in the second. All prototypes focused on visualizing and communication information, but each in their own way – see Appendix B.4 Prototype Descriptions for all details. Idea S1_1 (Figure 11) focused on sharing information about inspection tasks with inspectors 'in the field', using an app that also facilitates a direct communication link with people 'in the office'. With S1_2 (Figure 12) you can use extensive information about the whole life cycle of an asset, more specifically its materials, to simulate different solutions. Both ideas use a 3D model with a data link for informative visualization. S1_3 (Figure 13) uses AR technology to overlay live data on-site, so you can get to the core of the problem more quickly during an inspection.

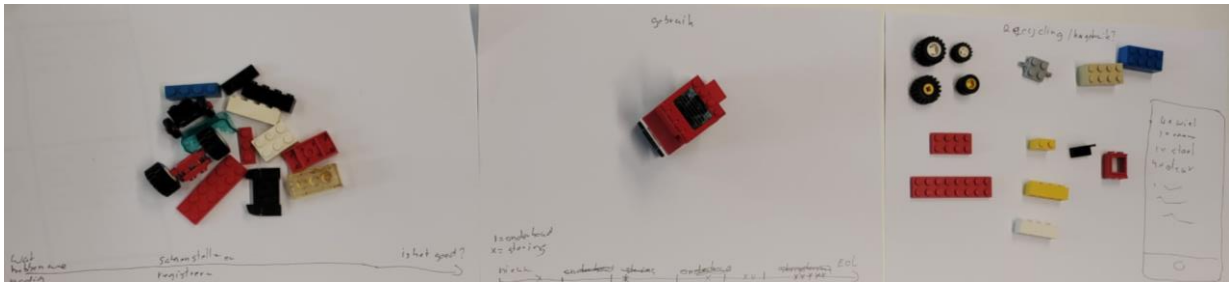


Figure 12. Prototype S1_2, showing a timeline of materials from the design phase (left) to maintenance phase (middle) to decomposition (right).


Figure 13. Prototype S1_3, the AR glasses overlay real-time information based on preferences (see yellow buttons on the right).

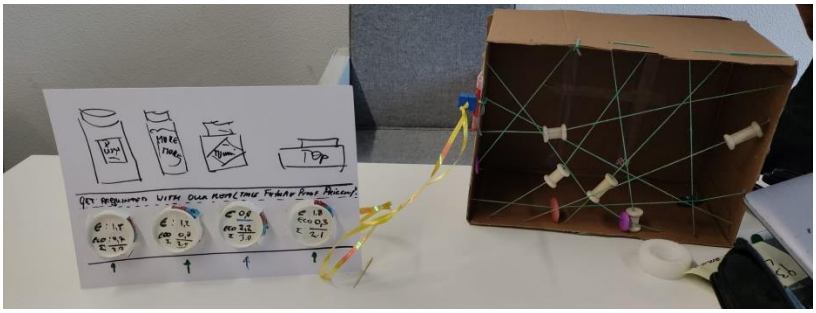


Figure 14. Prototypes S2_1 (right) and S2_2 (left), connected via the yellow strings.

S2_1 and S2_2 (Figure 14) both represented the complexity of choices. S2_1 resembles the 'network of dependencies' in the background, where pulling a string affects other strings and buttons in the network. S2_2 is the front-end of this complex network, providing an overview the 'real cost' of options that are

being considered. Not only financial costs, but also ecological and societal values are included. Connecting the two prototypes will allow for an interaction where you can show a subsection of options available in S2_2 by tweaking parameters in S2_1. The prototypes were evaluated in predefined scenarios (both context-specific and general). Although the idea was that the participants use the prototypes here, they did not do that in two of the five scenarios. In one of these cases, participants instead used the whiteboard in the room to illustrate options. Generally, participants used the prototypes as a discussion tool to identify what knowledge is needed in order to make a decision.

## 5.4 Requirements Lo-Fi Phase

Following the co-creation sessions, a set of requirements was defined that shape the first design concepts to be made in the Lo-Fi phase. Prioritizing the requirements using the MoSCoW method was done to help stay focused on the right elements, as can be seen in Table 9. The recurring themes of 'information' and 'collaboration' can be observed here as well in nearly all requirements. Only CO_2 does not have a clear link with either of these themes, instead focusing on creating a simple interaction that responds well to the needs of the user. This can be seen as a more generic requirement. The most important requirements are indicated with 'Must' and revolve around creating an engaging dashboard based on reliable data that show users what options can be considered.

Table 9. Requirements for the Lo-Fi prototypes, prioritizes using the MoSCoW method.

| Prio | Requirement | Description |
|---|---|---|
| **MU_1** | Use dashboarding to present data about the asset's performance | A dashboard is a common way to present complex data in an insightful manner. This can be data about the asset, its emissions and costs, maintenance rapports, etc. |
| **MU_2** | Use visualizations to engage and inform stakeholders | Visual cues are intuitive and reduce information overload, aiding in the user-friendliness of the product. Immersive or tangible technologies can further enhance this. |
| **MU_3** | Provide a centralized overview for all stakeholders to use | A "single source of truth" provides clarity, reduces miscommunication, which can help collective decision-making. |
| **MU_4** | Present an overview of different strategies that can be followed | By showing stakeholders what these strategies entail (description, goal, timespan, etc.) and their pros & cons, users can compare them more easily and make informed decisions. |
| **MU_5** | Stimulate trust and feelings of certainty when interpreting the information | By showing where information came from it becomes more trustworthy. This will reduce the uncertainty of sustainable options, potentially stimulating people towards more sustainable behaviour. |
| **SH_1** | Use dashboarding to present the perspectives of each stakeholder | Show (potential) overlap of stakeholders' priorities and interests, and their short- and long-term risks and gains. Helps create understanding and facilitate compromise. |
| **SH_2** | Document the context of strategies in discussion | Knowing the reasons why strategies emerged, why specific measures are relevant, and being aware of past strategies' results helps better assess the possibilities. |
| **SH_3** | Visualize the short-term impact of strategies in discussion | The overview in MU_4 can be enhanced by presenting an overview of parameters affected by the strategy, as well as a general description of the short-term impact on these parameters. This will help make better informed decisions. |
| **CO_1** | Present sustainability using measurable parameters | Sustainability is difficult to quantify. Formulating the true cost and gain of sustainable measures would be useful. This would be factors like the financial, ecological, and social costs / gains. |
| **CO_2** | Allow for easy, quick, and straightforward interaction | Stakeholders will value a solution that does not take a lot of time, quickly finding information is desired. |
| **WO_1** | Visualize the long-term impact of strategies in discussions | The overview in SH_3 can be enhanced by also presenting long-term effects that include the whole life cycle of an asset or provide more detailed prognoses on sustainability. |

Building onto the theoretical and practical insights gained in the previous chapters, the co-creation sessions have wrapped up the ideation phase of this research and paved the way for the specification phase. The sessions were the first step in actively involving stakeholders in this research, allowing us to focus on what is relevant to them in this research context. The problem statement was refined with a focus on the factors of collaboration, overview, and certainty. A combination of missing information and miscommunication leading to uncertainty is seen as the core contributor to a lack of alignment. The brainstorm activities brought a focus on information provision forward, through the use of dashboarding, data visualisations, and presenting options in an overview. Additionally, ideas focused on creating a central point of focus and collaboration, stimulating understanding about the impact of possibilities on the stakeholders, and providing a feeling of certainty. Together, this can help identify and work towards the common goal in the horizon. These insights largely resonate with findings from theory, highlighting the importance of overview, visual elements, and contextual information. Combining theory and practice, a first set of solid human-centred designed ideas can be constructed and worked out.

# 6. Lo-Fi Prototyping

Based on the requirements gathered from the co-creation sessions, a brainstorm matrix was filled in to generate the first 12 ideas. Using these ideas as inspiration, 14 more ideas were sketched. All 26 ideas revolved around visualizing the complexity of considering multiple options and/or stimulating collaboration through mutual understanding. From these ideas, three concepts were chosen to work out in more detail: a dashboard showing how much overlapping interests stakeholders have per idea, a virtual network resembling a timeline of discussion points, and a tangible interface representing different options as balls which are lifted up higher the more desirable they are. Paper prototypes were created and discussed with stakeholders to see what elements were desirable to pursue in the Hi-Fi phase. Generally, the tangible interface was seen as the best concept. Together with an informative dashboard that is not too overwhelming, and playful elements to increase engagement and focus, a new concept can be worked out in the next phase following updated requirements.

## 6.1 Ideation

A brainstorm matrix was used to generate the initial set of ideas. Each column represented an interaction technology and each row an application domain for the designed solution. For each cell in the matrix, an idea was sketched out (see Figure 15). To aid the ideation, key elements of each application domain (derived from the three levels in alignment in chapter 2. Theoretical Framework) were the basis for each concept. For 'engage & involve' this was the use of visual, immersive, and gamified elements to motivate participation. For 'empathize', the facets of co-situatedness and co-perception came into play. The domain of 'discuss' includes theory of co-intent and co-attend and focuses on presenting options in a clear way. 'Compromise' covers the steps of considering alternatives and indicating one's preference for an option. By combining these ideas and iterating on them, new ideas were generated. The aim was to have at least 4 ideas per interaction technology, so there would be sufficient variance between the ideas. In the end, 14 ideas were sketched (see Table 10 for the ideas, and Appendix C.1 Initial 14 Ideas for the sketches). The ideas were grouped based on application domain, to help scope the function of the resulting concept towards a more specific use (see Figure 16).

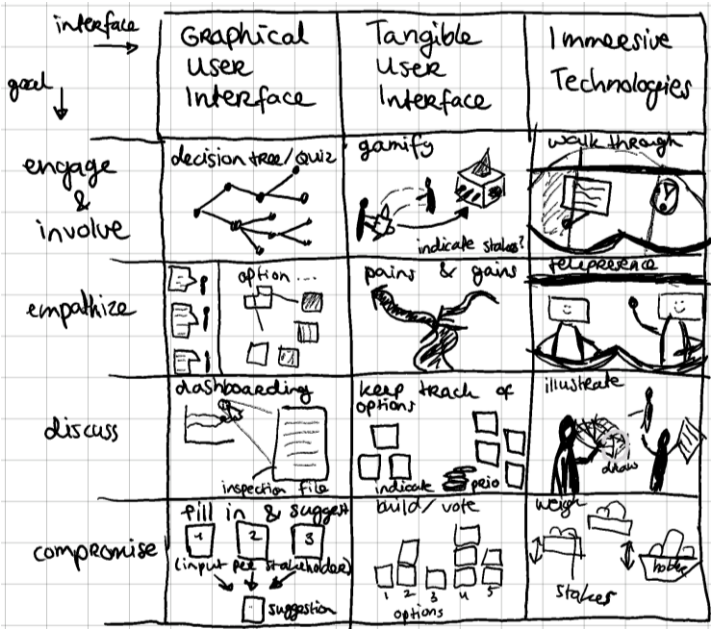



Figure 15. Brainstorm matrix with ideas per interaction technology and aspect of stakeholder alignment.

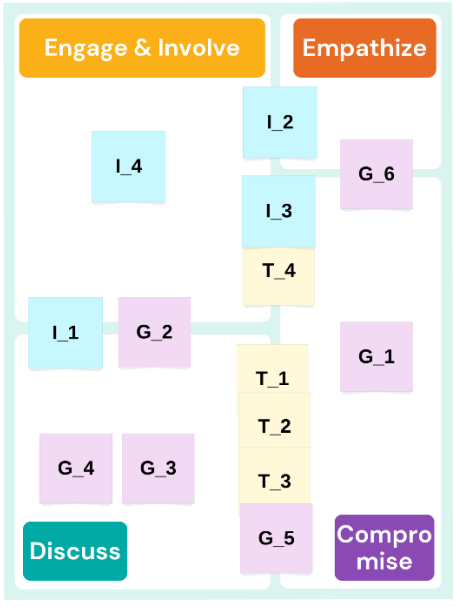



Figure 16. Overview of ideas, divided per application domain.

Table 10. List of ideas generated using the brainstorm matrix as inspiration, sorted per technology. G = Graphical User Interface, T = Tangible User Interface, I = Immersive Technology.

| ID | Description |
|---|---|
| **G_1** | Dashboard to compare energy consumption between similar assets in the area and components in the asset. Reports (e.g., maintenance) are connected and options for improvement can be ranked. |
| **G_2** | Assistive tool in making business plans, which can be presented to the project owner. |
| **G_3** | A live overview of energy consumption per component, sorted by impact. Look back & ahead as well. |
| **G_4** | No 3D model, only graphs to present energy consumption. You can write comments and acquire a TODO list for potential improvements. |
| **G_5** | A voting system: everyone votes individually, only options everyone voted on are retuned to the team. |
| **G_6** | A plot to see the positive impact and gain/loss of each possible solution, per stakeholder. Can help see the overlap in interests, differences, and difficulties. |
| **I_1** | 'Let's be alone together', a digital meeting with telepresence so it feels like you are physically present. Additionally, you can draw and move objects in the digital meeting space. |
| **I_2** | Bringing work close to the office by using AR to get a direct connection with people on-site. |
| **I_3** | Following prototype S2_2 in Section 5.3 Prototyping, visualize all related elements (costs, manpower, resources) of options in discussion in an AR/VR environment, let people adjust weights of each factor. |
| **I_4** | Visualise invisible processes that contribute to energy consumption (e.g., heat loss) on-site. |
| **T_1** | 'Poker'-like table with display in the middle. Topic is put in the middle; stakeholders can use cards to discuss options and coins to vote. |
| **T_2** | Table visualizing the pains and gains of stakeholders, see the in- and outflow of resources per person. |
| **T_3** | Cube representing the 'waterbedeffect', by moving the sides of the cube (representing a factor e.g., money, materials) out- or inward based on a choice made. They all need to be in balance to be optimal. |
| **T_4** | Bring a topic up (Dutch: 'Balletje opgooien') or down based on the preference of stakeholders. |

The application domain 'Compromise' was seen as the most suitable application domain to focus on, as many ideas (G_1, G_5, G_6, I_3, T_1 t/m T_4) revolved around it. Additionally, the theory of compromise identifies clear focus points, as can be seen in Section 2.3 Moving to a Compromise. This helps stay focused on including the right elements in the prototype. For each technology, an idea was chosen to work out more in detail. These were G_1 (and a little bit of G_3 and G_6) for the graphical UI, I_3 for the immersive technology, and T_4 (and a little bit of T_1) for the tangible UI.

## 6.2 Paper Prototypes

To further explore the possibilities of the concept ideas while narrowing down the number of options, three paper prototypes were created, each with a different interaction technology. The prototypes all revolve around the same goal: stimulating understanding and compromise amongst different stakeholders so that sustainable choices can eventually be made. Although the prototypes are different, they have the same standard elements to fall back on for information. These are dashboard pages that convey information about an asset in terms of energy consumption and performance. More elaborate explanations and interaction sketches can be found in Appendix C.2 Paper Prototype Sketches.

### 6.2.1 Standard Pages

On page A (Figure 17), the whole asset can be seen. Per component, the increase or decrease of energy consumption compared to other, similar assets is showcased. This way, one can see where big improvements can be made. Zooming in on said component (see Figure 18) provides more info, like the fluctuation in energy consumption over time, the status, and past maintenance reports. These pages aim to lead its user to the question *"I want to do something about it, what can I do?"*, to which the user can use the prototypes to consider different strategies. The strategies are all standardized in terms of information provided, which can be seen in Figure 19. A brief description explains what the strategy entails, stating its focus and ultimate goal. A projected result is provided, considering the monetary costs, energy reduction, and workload of implementing the solution. Furthermore, a list of TODOs is presented along with contact points so stakeholders can get started on it right away.


Figure 17. *Main page A, showing whole asset.*

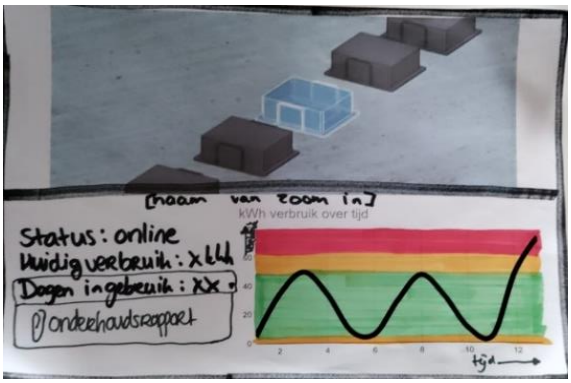



Figure 18. *Main page B, showing component.*

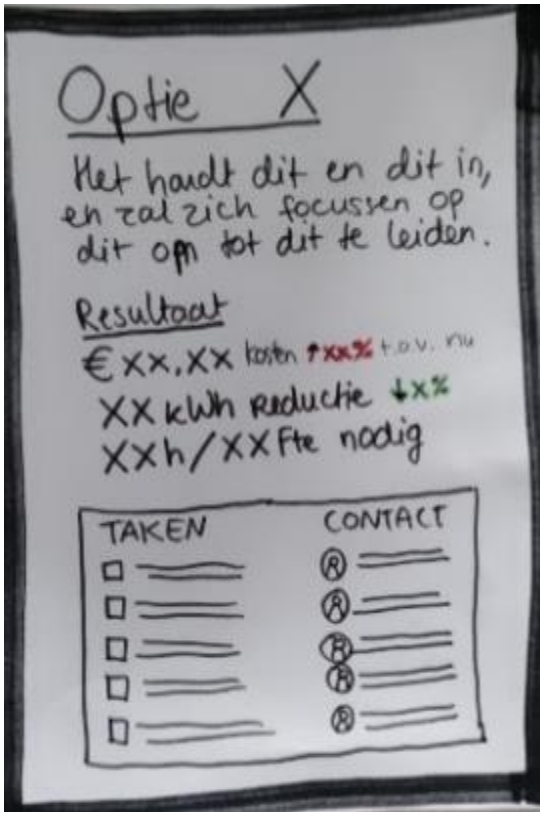



Figure 19. *Main page C, showing an option.*

### 6.2.2 Graphical User Interface

In the graphical user interface (G), users can consider different strategies by visualizing everyone's interests and a timeline of the discussion. The interface keeps track of suggestions in the timeline (bottom of Figure 20) through colour (who brought it up), starting point (when was it brought up), and possible end point (when was it discarded). This way, it is always clear which ideas are discarded and which are still in discussion. Additionally, stakeholders can plot their stances on the ideas in the graph (top left of Figure 20) based on sustainable impact (X-axis) and financial gains or losses (Y-axis) they need to make. Each coloured dot is a stakeholder, the area drawn around the dots is the collective interest (Dutch: 'draagvlak') of each idea. This way, the interests of all involved stakeholders are visualized, potentially making it easier to go for a strategy that has the best total outcome. Additionally, it can help spark understanding between stakeholders by making more tangible what everyone has to lose or win.

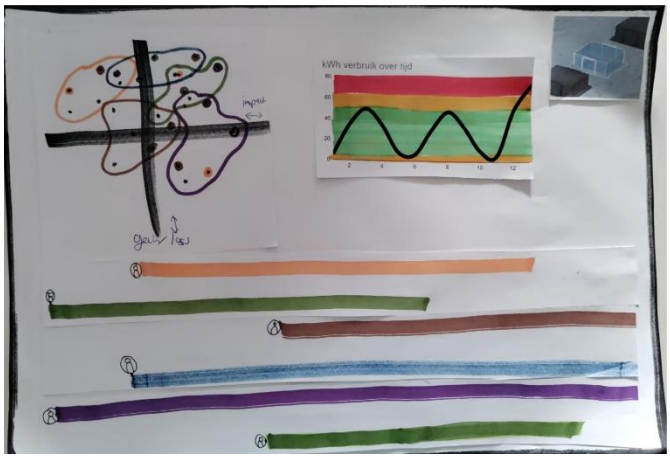



Figure 20. Paper prototype of the graphical user interface, with timeline (bottom) and interests visualized (top left).

### 6.2.3 Immersive Interface

In the immersive interface (I), users can build a network of discussion points and ideas throughout their meeting (see Figure 21). Each cube in the network represents a strategy or discussion topic and the colour of the lines between cubes represents the status (e.g., newly added is yellow, discarded is red). On the cube, all relevant information about the option or topic is represents; each side showing different information (Figure 22). This invites the user to actively grab a cube and rotate it while reading. New potential strategies can be added by making a 'bloom' gesture[13] and tapping on the green dot that appears. The new strategy can be created manually, or users can scan a QR code to upload a predefined strategy.

Figure 21. Network of cubes starting at the left, representing information about discussion or strategy.

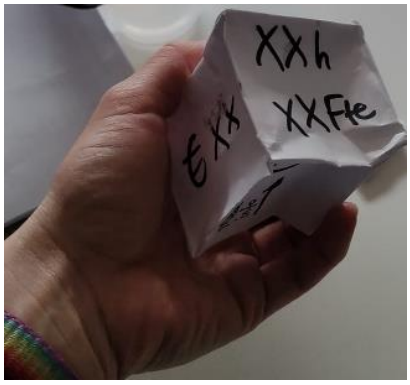



Figure 22. Each side of every cube has relevant information about the discussion or strategy.

### 6.2.4 Tangible User Interface

In the tangible user interface (T), each strategy in discussion is represented by a 'ball' (cylinder in Figure 25) and a small summary of each option (Main Page C) in front of it. Stakeholders can use the prototype during a meeting to get a complete overview of all strategies in discussion and their relevant information; as a central focus point. The colours of the ball indicate its status (e.g., discarded is red, new is blue) and the height its favourability. Users can indicate their preference for the ideas by pressing a speech bubble (Figure 25) to select an idea and then using the voting button (Figure 23) to indicate whether they are in favour (+) or against (-) implementing the idea. The ball will move up or down based on this input, providing a live bar chart of the preference for each strategy. The favourability of each idea is also visualized in an adapted version of Main Page B, by plotting each idea in terms of time (X-axis), impact (Y-axis), and costs (size), as can be seen in Figure 24.

Figure 23. One big voting button for all users to use.

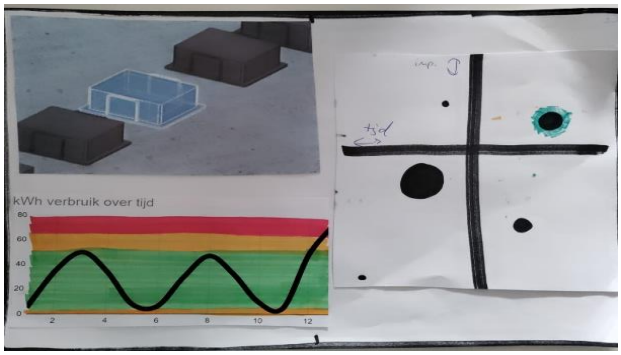



Figure 24. Adapted dashboard showing a plot of the favourability of each option, coloured dot is currently selected.

[13] Opening your hand from a closed fist, used in gesture-based devices e.g. https://learn.microsoft.com/en-us/windows/mixed-reality/design/system-gesture#bloom


Figure 25. Tangible interface showing each option as a ball with information, coloured per status and its height adapted to its favourability.

## 6.3 Lo-Fi Evaluation

The Lo-Fi evaluation phase took place between 7-13 July 2023. A pilot study was conducted on the 7th to test the format. Some small changes were made; five questions were removed due to redundance in answers and the order of questions was adjusted so that less important questions could be skipped if there was a lack of time. The prototypes were discussed with each participant, but each in a different order to rule out any bias. Six stakeholders participated in the Lo-Fi evaluation session, five of which had also participated in one of the co-creation sessions. They were between 33 and 64 years old (average: 48 years) and had between 6 and 28 years experience in the field of asset management (average: 17 years). Three participants were consultants, two were managers, and one participant was a project leader – all related to asset management in a strategic, tactical, or operational way. They were moderately experienced with technology, describing how they were *"able to understand new applications but not program them"*. When being asked how they currently make choices, most participants indicated using facts as a basis, by creating an overview and weighing options. All results can be found in Appendix C.3 Lo-Fi Evaluation Summary.

### 6.3.1 Qualitative Analysis

Several themes could be identified when discussing the standard pages and prototypes. See Table 11 for an overview of all themes, ordered by total frequency of appearance. When discussing the standard pages, most comments revolved around extra **information** that could be added to increase the level of insight gained. Additionally, participants were critical of the possibility in Main Page A to be able to **compare** the asset with other assets; this needs to be normalized well in order to be reliable. Lastly, participants noticed that each page served a different type of asset manager – strategic (A), tactical (B), and operational (C).

Table 11. Frequency of themes that came forward in the thematic analysis of the Lo-Fi evaluations.

| Code | Meaning | Frequency |
|---|---|---|
| **Information** | Data that should be included or used | 18 |
| **User** | Related to the user type or scenario | 10 |
| **Visualising** | Visual elements in the prototypes | 9 |
| **Complexity** | Extent to which information, design, or use case is complex | 8 |
| **Clarity** | Extent to which information or design is clear | 6 |
| **Interests** | Talking about priorities, values, and interests of stakeholders | 6 |
| **Comparing** | Comparing options, assets, elements, etc. | 3 |
| **Objectivity** | Extent to which information or behaviour is rational rather than emotional | 3 |
| **Gamification** | Focused on the playfulness of an interaction or prototype | 3 |

When discussing the prototypes, the themes of **clarity**, **complexity**, and **interests** came forward often. Prototype G, although familiar in technology, was seen as very overwhelming and complex. The interest graph received criticism, as it would be very difficult to keep objective and might not be very useful at all. The timeline was better received, seeing it as a way to gain insight in the timespan of strategies. However, one participant questioned whether it would be used as well. Participants ranked it from 1 (best) to 3 (worst) as 2.25 (idea) and 2.03 (tech), with the best rankings in the categories ease of use (1.48 and 1.33 out of 3) and collaboration (1.60 and 1.63 out of 3) and the worst rankings in the categories novelty (2.75 and 3.00 out of 3) and compromise (2.70 and 2.33 out of 3).

Prototype I was seen as a cool and futuristic idea. The visualization of ideas through a network was seen as useful, quick, and easy, but could also get complex quite quickly. Participants liked the gamified elements (i.e., slapping the cube to vote) and simple shapes. They missed documentation on the reasoning behind choices. Participants ranked it from 1 (best) to 3 (worst) as 1.88 (idea) and 2.23 (tech), with the best rankings in the categories aesthetics (1.76 and 2.00 out of 3) and novelty (1.38 and 1.33 out of 3) and the worst rankings in the categories ease of use (2.20 and 3.00 out of 3) and compromise (2.50 and 2.67 out of 3).

Prototype T was seen as a good tool to weight and discuss options using clear and straightforward interactions. Participants liked the playful feeling of the prototype and suggested elaborating it further by allowing users to pick up the balls and move them around. There was some criticism on the voting button, as it might be intimidating to vote centrally instead of anonymously. Additionally, participants missed a possibility to access more detailed information and expressed their wish to preserve information about arguments and choices, so that it could be used in follow-up meetings as well. Participants ranked it from 1 (best) to 3 (worst) as 1.67 (idea) and 1.74 (tech), with the best rankings in the categories aesthetics (1.80 and 2.00 out of 3) and compromise (1.00 and 1.00 out of 3) and the worst rankings in the categories ease of use (2.12 and 1.67 out of 3) and collaboration (2.60 and 2.13 out of 3).

### 6.3.2 Opportunities

The evaluations were conducted with the goal of identifying opportunity-rich elements of the concept ideas. Prototype T scored the best overall, mainly due to its tangibility and simplicity in representing the different options in discussion. It is more intuitive for non-technological people than an immersive interface but bears the same feeling of novelty. Using more playful elements and simple shapes (consider Prototype I as well), can help increase this feeling. It also leads to more user engagement and autonomy, which was currently missing. This could help stimulate more collaboration among stakeholders as well, by staying focused on the same thing. Although Prototype G received a lot of criticism, the way a dashboard with graphs can convey information was deemed as important as well. It should not be overwhelming, using more straightforward graphs and a greater focus on objective data would be better. Lastly, a more anonymous way of indicating preferences that is still tangible is highly preferred.

## 6.4 Requirements Hi-Fi Phase

From the Lo-Fi evaluations, the set of requirements as defined in Table 9 can be evaluated and refined. In all Lo-Fi designs, the requirements MU_1, MU_2, MU_3, MU_4, and SH_3 were met. MU_5 is a subjective feeling that could not be evaluated in this phase of the research. SH_1 and SH_2 were met in Prototype G. CO_2 was explored through the different prototypes and came best forward in Prototype T. The other two requirements did not come forward in this phase. In Table 12, an updated version of the previous set of requirements (Table 9) can be found. All bold elements have been changed. Requirement MU_5 added 'objectivity' as a focus point, due various participants stressing the value of presenting objective data. SH_1 and CO_2 changed places, because participant feedback indicated that literally seeing the perspectives of stakeholders is not a great focus, while having easy and straightforward interactions are. Lastly, MU_6, MU_7, SH_4, and CO_3 are newly added. The new requirements focus on more concrete functionalities, like anonymous voting, adding options to be discussed, and comparing strategies.

Table 12. Requirements for the Hi-Fi prototype prioritized using the MoSCoW approach. CC = Co-Creation, LO = Lo-Fi

| Phase | Prio | Requirement | Description |
|---|---|---|---|
| **CC** | **MU_1** | Use dashboarding to present data about the asset's performance | A dashboard is a common way to present complex data in an insightful manner. This can be data about the asset, its emissions and costs, maintenance rapports, etc. |
| **CC** | **MU_2** | Use visualizations to engage and inform stakeholders | Visual cues are intuitive and reduce information overload, aiding in the user-friendliness of the product. Immersive or tangible technologies can further enhance this. |
| **CC** | **MU_3** | Provide a centralized overview for all stakeholders to use | A "single source of truth" provides clarity, reduces miscommunication, which can help collective decision-making. |
| **CC** | **MU_4** | Present an overview of different strategies that can be followed | By showing stakeholders what these strategies entail (description, goal, timespan, etc.) and their pros & cons, users can compare them more easily and make informed decisions. |
| **CC, LO** | **MU_5** | **Create a feeling of certainty and trust by presenting objective information** | **Knowing what the information presented is based on will create a feeling of trust and reduce their uncertainty. Since most sustainable options are uncertain, this could help steer people towards more sustainable behaviour.** |
| **LO** | **MU_6** | **Be a modular tool with simple interactions.** | **The amount of data presented in the prototype is quite complicated, this can be counteracted with easy and accessible interactions.** |
| **LO** | **MU_7** | **Let users be able to compare strategies in an overview when discussing them** | **Because options are weighed against each other during a discussion, this should be facilitated through the functionalities of the prototype as well.** |
| **CC** | **SH_1** | **Allow for easy, quick, and straightforward interaction** | **Stakeholders will value a solution that does not take a lot of time, quickly finding information is desired.** |
| **CC** | **SH_2** | Document the context of strategies in discussion | Knowing the reasons why strategies emerged, why specific measures are relevant, and being aware of past strategies' results helps better assess the possibilities. |
| **CC** | **SH_3** | Visualize the short-term impact of strategies in discussion | The overview in MU_4 can be enhanced by presenting an overview of parameters affected by the strategy, as well as a general description of the short-term impact on these parameters. This will help make better informed decisions. |
| **LO** | **SH_4** | **Allow users to add new strategies to discuss** | **It is important to stakeholders to feel autonomous when using the prototype, giving them power to add to the prototype will help with that.** |

| | | | |
|---|---|---|---|
| **CC** | **CO_1** | Present sustainability using measurable parameters | Sustainability is difficult to quantify. Formulating the true cost and gain of sustainable measures would be useful. This would be factors like the financial, ecological, and social costs / gains. |
| **CC** | **CO_2** | **Use dashboarding to present the perspectives of each stakeholder** | **Show (potential) overlap of stakeholders' priorities and interests, and their short- and long-term risks and gains. Helps create understanding and facilitate compromise.** |
| **LO** | **CO_3** | **Allow for users to express their preferences anonymously** | **Participants indicated that public voting could be intimidated and voting power could be abused, anonymous voting can mitigate that.** |
| **CC** | **WO_1** | Visualize the long-term impact of strategies in discussions | The overview in SH_3 can be enhanced by also presenting long-term effects that include the whole life cycle of an asset or provide more detailed prognoses on sustainability. |

In this phase, three concrete ideas have been worked out in paper prototypes. Each prototype includes the key elements that were derived from theory, worked out in a different interface type. This way, a wide variety of functionalities and interfaces could be evaluated. They were discussed with stakeholders so their feedback could further be incorporated in the design of the interactive tool. The most opportunity-rich parts of the ideas were identified, and the existing requirements were refined to support this. These parts revolve around using a dashboard to convey more detailed information and using tangibility to playfully interact with the different options to discuss and compare them on the dashboard. Additional attention should be put on including capturing context and preference in the prototype, as that was currently limited in some prototypes. Next steps can focus on working this out in a functional and usable prototype that can be evaluated in the research context, to observe the impact it has on a group discussion.

# 7. Hi-Fi Prototyping

Building on the results of the Lo-Fi prototyping phase, the requirements and key points were worked out in a working prototype in which strategies can be compared and discussed. A snapshot of the Hi-Fi prototype can be found in Figure 26. The prototype consists of a tangible interaction device and a responsive informative dashboard. Each strategy is represented with a coloured ball, which can be picked up and moved around to affect the dashboard screen. Using theory of stakeholder alignment, the Hi-Fi prototype allows users to compare alternatives, indicate preferences, and preserve the context of the discussion. The prototype uses clear visualizations to facilitate quick and intuitive information retrieval. Additionally, theory of embodiment is used due to the tangibility of the prototype, so its intuitiveness can be enhanced, and stakeholder alignment can be facilitated.

Figure 26. The Hi-Fi prototype, with tangible and digital elements.

Two evaluation tests phases have been carried out in order to assess the impact of the prototype. Firstly, a usability test was carried out to assess the level of intuitiveness in the interactions and identify improvement points that could be implemented for the second test phase. As a result, the 'highlight' interaction has been worked out a bit more. The second test focus on observing the potential social impact of the prototype by simulating a discussion with three participants, each representing one of the stakeholders in this research. The themes of active participation, communication, focus, structure, and visualizations played a role in the use of the tangible elements of the prototype.

## 7.1 Sketches & Mock-ups

Following the results of the previous chapter, and using the tangible prototype as inspiration, the Hi-Fi prototype idea was worked out in more detail. The starting points were:

1.) Using balls to represent strategies and being able to compare them by holding multiple balls,
2.) Having a dashboard connected to the balls providing all relevant information, and
3.) Finding an anonymous yet tangible way to facilitate preference indication.

First, sketches were made to try out variations of these points. See Appendix D.1 Hi-Fi Sketches for these sketches. Besides exploring the shape and layout, sketching helped define natural interactions and technological necessities.

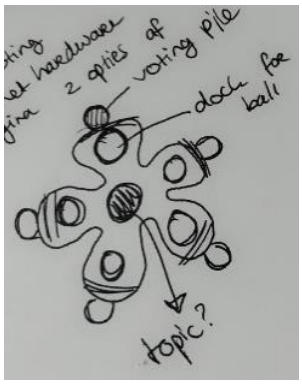


Figure 27. *Sketch of the base shape.*


Figure 28. Paper prototype with coloured balls next to the base.

From this, the decision was made to use round shapes for the 'base' of the balls (see Figure 27) and use a bar chart-like representation for the voting. With the use of tinkering materials, a paper prototype was created that represented the ball base (see Figure 28). In PowerPoint, a mock-up for the dashboard was made (see Figure 29 and Figure 30). As these mock-ups were tangible, they could be interacted with, and small adjustments could be made to shape the design of the full Hi-Fi prototype. After exploring and adjusting these mock-ups, a final design was determined. Instead of one big base, each ball had its own base in the shape of a teardrop. This way, the number of balls could be adjusted to the number of strategies to be discussed. The 'voting skewers' became actual, more sturdy and visible bars that people could 'build' by putting voting blocks on the designated spot. The dashboard design used more windows to create structure and reduce overwhelm.

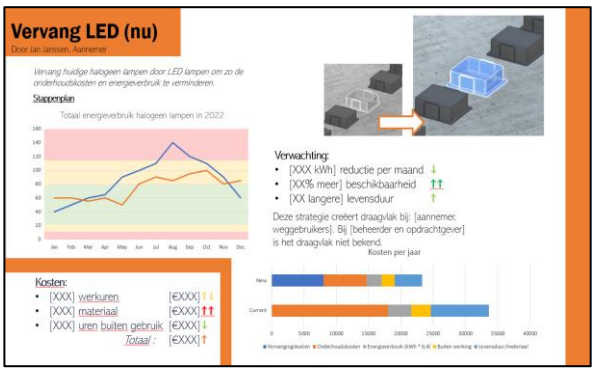



Figure 29. Dashboard mock-up page showing a possible strategy.

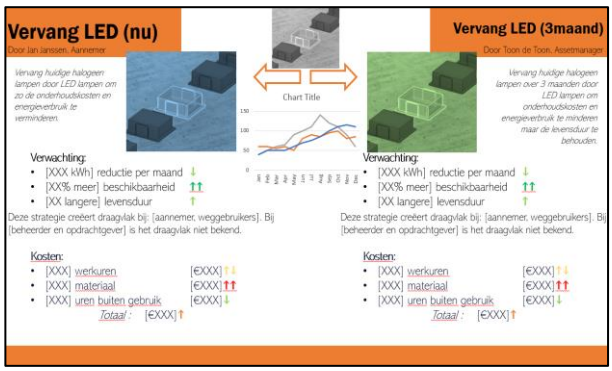



Figure 30. Dashboard mock-up page comparing two strategies.

## 7.2 Interactions

Four key interactions are worked out, each playing their role in stimulating alignment among stakeholders. The tangible elements in the prototype allow users to navigate through the dashboard, compare and focus on alternatives, indicate preferences, and capture the context of the discussion. Closely related with theory for compromise (Section 2.3 Moving to a Compromise), common ground (Section 2.2 Creating a Common Ground), and embodied interactions (Chapter 2. Theoretical Framework in general), these interactions stimulate a shared experience with active participation by its users. Because users can provide input through the discussion, through voting, and by recording voice notes, it can become easier to partake in the discussion and share their perspective. The affordance of the ball is to pick it up and move it around, which can be done by all users at the same time. In addition to the continuous interplay between the physical object and the digital dashboard, active participation is stimulated.

### 7.2.1 Navigate

By picking up a ball, information of the option it represents is showcased. If another ball is picked up, information about both options can be compared. The same occurs when all three balls are picked up. See Figure 40, Figure 41, and Figure 42 for a demonstration of these interactions. These **'navigation'** interactions are made to be simple, straightforward, and intuitive so that little overhead is needed to find a way through the dashboard. It helps strengthen the link between the tangible object and the information presented on the screen.

Figure 31. Pick up one ball to see all information about that strategy.

Figure 32. Pick up a second ball to compare these two strategies.

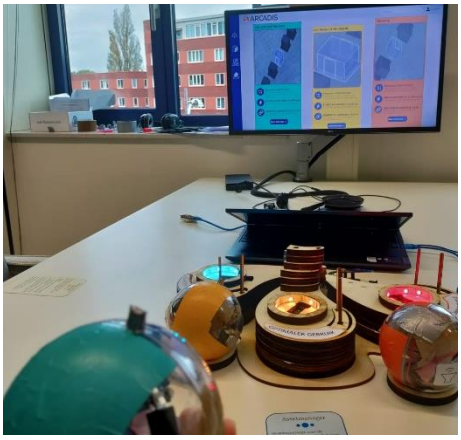


Figure 33. All three options can be compared in one screen.

The theory of **considering alternatives** (Section 2.3.1 Overview of Alternatives) and **external representation** (Section 2.1.2 Reduced Complexity) comes forward in this interaction, by representing each strategy both digitally on the screen and physically with the ball. Users can compare the information on the screen using the balls, sharing the control of the prototype – and with it, the information on the screen. The **affordance** of the ball is to grab it, move it around, and perhaps even throw it. Together, these elements stimulate engagement and more **active participation** in the discussion. The balls are **ready-at-hand** in this interaction, integrating into the environment intuitively as a way to navigate through the dashboard. To make it easier to interpret and memorize the amount of information conveyed to the user, the dashboard and tangible elements make use of **clear visualizations** (Sections 2.1.2 Reduced Complexity and 2.3.4 Using Visualizations) and **abstraction** (Section 2.1.2 Reduced Complexity). Icons, graphs, and coloured elements are used in the dashboard and the balls are purely visual and tangible. This simplifies the interaction of navigating through the dashboard and acquiring information from the dashboard, while giving users the autonomy to dive into details if they want.

### 7.2.2 Highlight

When users hold the ball during a discussion, they can use it as a focus point. Moving the ball or shaking it will vibrantly colour the information block summarizing the strategy on the dashboard. Additionally, it will move upwards a bit – mimicking the physical act of drawing attention to something by holding it up. Figure 34 and Figure 35 showcase this. The balls have not been moved for a while, becoming idle and fading out. Moving the orange ball will bring it back to the foreground of the discussion, literally **'highlighting'** it for everyone to see.

Figure 34. Yellow and orange balls are picked up but idle, fading out on the screen.

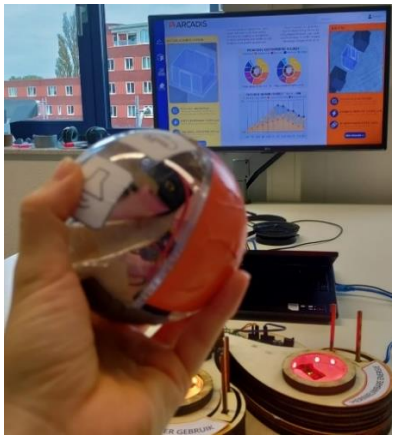


Figure 35. The orange ball is moved around, vibrantly coloured and moved upwards on the screen.

This interaction relates to the theory of **co-attend** (Section 2.2.2 Shared Focus) and **providing context** (Section 2.3.3 Providing Context) by allowing users to actively draw the attention to a strategy, both in the dashboard and with the ball – making it easier to **consider alternatives**. The balls become **present-at-hand** (Section 2.2.2 Shared Focus), evoking a feeling of literally holding the strategy in your hand. This is further increased by fading out the information on the screen if the ball is idle, stimulating **active engagement** with the object. The relationship between the physical and digital elements is strengthened due to this feedback loop. Ideally, different movements and movement intensities can be distinguished so that different actions can be taken with the ball, increasing the immersion of the tangible objects in the decision-making process.

### 7.2.3 Weigh Options

During or after the discussion, users can indicate their preference or support for a strategy by placing voting blocks on the designated spot near each ball (see Figure 36). These can be stacked, making a bar chart to quickly see which strategy has the most support. Additionally, each bar chart is weighed using the load cell and displayed on the screen, using a combination of visual and numerical elements to help quantify the level of support (see Figure 37). With this functionality, users can **'weigh their options'** in a tangible and visual manner.

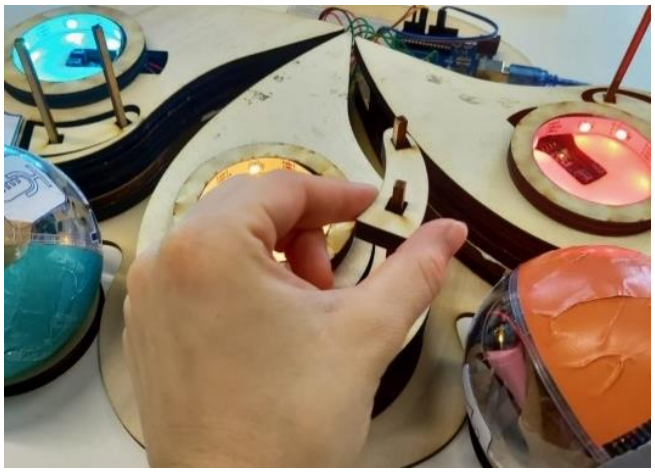


Figure 36. Stack wooden blocks to indicate your preference.

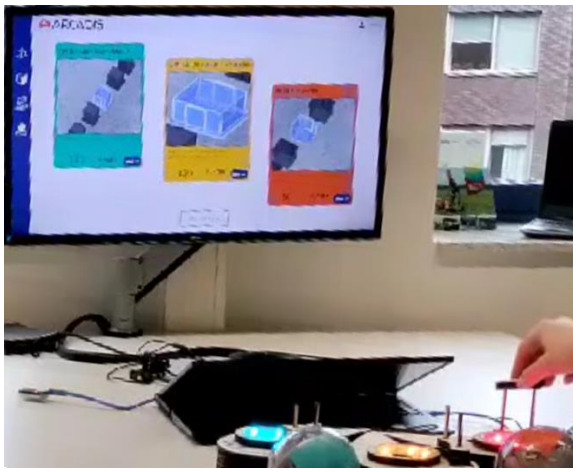


Figure 37. The screen displays the live score for each strategy.

The theory of **indicating preferences** (Section 2.3.2 Indicating Preferences) clearly comes forward in this interaction. Together with theory revolved around **traces, active participation,** and **accountability** (Sections 2.1.1 Positive Participation, 2.1.2 Reduced Complexity, and 2.3.3 Providing Context), this interaction actively engages users to signal their preference or support in a transparent and clearly interpretable way that makes room for open conversation. The level of alignment between stakeholders can be visualized, providing insights into big differences and similarities – especially if used continuously. Moving blocks from one strategy to another has social implications (*"this is where I am right now"* and *"your comment made me change my mind"*) similar to Floor-It and NOOTs in Van Dijk's research [11]. Furthermore, the status of the voting blocks can be used as starting points for follow-up meetings as well, by simply leaving them where they were. They can be used to resume the meeting or present the discussion status to other stakeholders.

### 7.2.4 Record

The last interaction focuses on preserving the context of a discussion by recording voice notes with the ball. This interaction is not worked out using technology due to the scope of this research, but instead uses stickers with icons to visualize the interaction (see Figure 38). By moving the slider, users can indicate which type of voice note they wish to record or play (argument in favour, argument against, comment, or question). The 'record' button (microphone) can be pressed to create the voice note. By pressing the 'play' button (speaker), the voice notes of the selected type will be played. This functionality aims to support the discussion by preserving the thought processes behind the decision made at the end by allowing users to capture their thoughts and worries **'for the record'**.

Figure 38. Fake buttons for recording and playing arguments, comments, and questions.

This interaction heavily relates to the theory of **providing context** (Section 2.3.3 Providing Context) by painting a picture of arguments given, questions asked, and information and sidenotes provided. Because an audio recording is made, the voice and emotional state of the person providing the voice note could be recognized, providing more contextual information. The perspectives of all stakeholders can be captured this way, stimulating more **active participation** (Section 2.1.1 Positive Participation). This functionality does not only help users in the current discussion, but also leaves **traces** for next sessions to follow (Section 2.3.3 Providing Context). Ideally, the recordings are sorted in a timeline and can be linked to the object they talk about[14] so the history of the discussion can really be replicated. This further enhances the added value of creating voice notes compared to taking notes.

## 7.3 Technical specifications

The dashboard was initially made in Adobe XD, using various existing dashboard templates[15] as inspiration. A colour scheme was chosen that contained the 'Arcadis-orange' whilst also inhibiting other colours that could allow for a clear visual distinction between options. Graphs and other visual data visualizations were used to convey the multitude of information in a more accessible manner. The base and ball each contain several sensors and actuators that are programmed using Arduino IDE. Via Processing 4.3, the dashboard screens (exported from Adobe XD as PNGs) could be imported and programmed to respond to sensor input. The electrical components were brought together in a plastic ball and lasercutted base, as can be seen in Figure 39 below. Colourful tape was used to match the ball to the right base.

[14] Much like the "pin" option when reviewing an Adobe XD application, where you can pin a comment to a specific object on the screen.

[15] Via https://www.xdguru.com/adobe-xd-dashboard-templates/, the templates 'XD Home Monitoring Dashboard', 'Dashboard attendance XD template', 'Yalla Compare', and 'One More UI - Insta Free' were used for inspiration.

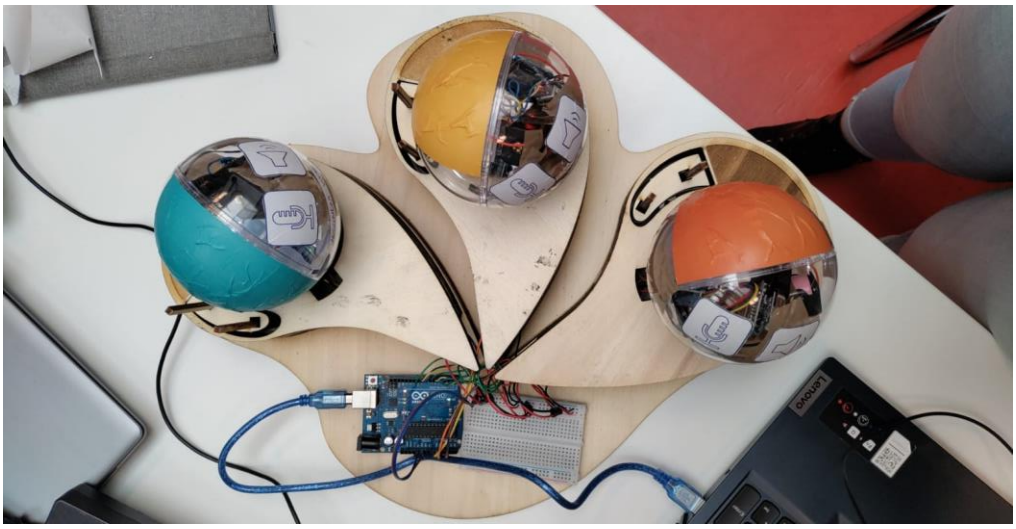


Figure 39. Top view of the tangible elements of the prototype.

### 7.3.1 Design

The balls have minimal design features; they are round, see-through plastic balls each with their own colour and (fake) buttons. Each coloured part has a slightly different shape to help tell the balls apart in case of colour blindness. The buttons are big, so they are easily pressed, using general icons to communicate their function. A slider is used to indicate the type of recording. The dashboards follow a relatively standard build-up, with a navigation bar on the left and the use of graphs and icons to simplify data representation in line with Alber *et al.* [50]. Each strategy has its own colour (the same colour as the ball) and is summarized in a coloured block on the side of the page. When two ideas are compared, the coloured blocks are positioned on both sides, with information in the middle (Figure 40). When two ideas are compared, you only see the coloured blocks (Figure 41). Interactions between pages are created in AdobeXD using the 'Prototype' menu. Since programming is not possible in Adobe XD, all components on the pages are exported as PNGs and imported in Processing 4.3 so they can respond to the retrieved sensor input from the tangible elements. The full prototype (tangible elements and dashboard) is therefore accessed via Arduino IDE and Processing 4.3, leaving AdobeXD for the dashboard-only display.

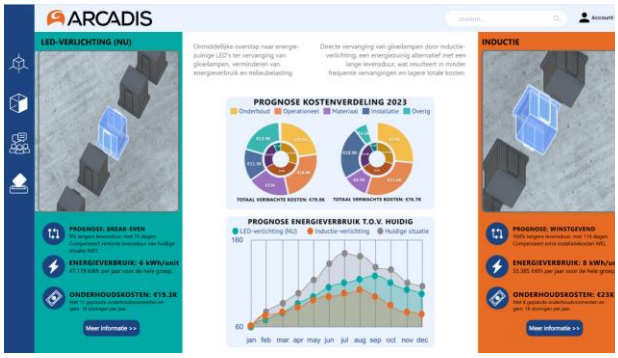



Figure 40. Dashboard page comparing two options.

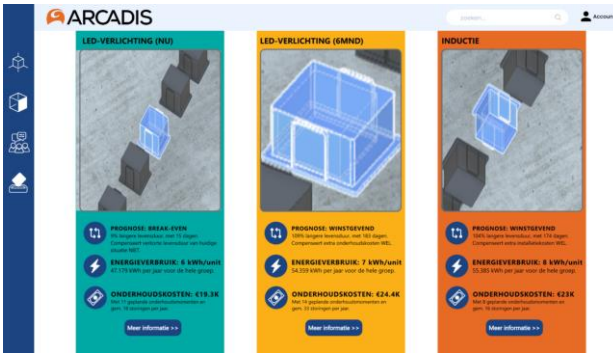



Figure 41. Dashboard page comparing three options.

The data presented in the dashboard is fake, created mainly with the help of ChatGPT 3.5[16], some internal documents of the Waterwolftunnel, and experience gained throughout the research. ChatGPT was used for several goals. It was used to define the six strategies (three per scenario) as discussion points, to write summaries for each strategy, and to compose the general situation and stakeholder roles for the scenarios. Lastly, it served the basis for all numerical values in the dashboard, by defining semi-realistic

[16] https://chat.openai.com/

performance descriptions. All ChatGPT output was textual; numerical values used in the prototype were made up based on these descriptions. This was done by defining values for the current situation and deviating one or more categories per strategy, such that all options had a relatively even number of pros and cons. All output was re-written to make it more coherent. See Appendix D.2 Fake Dashboard Data for an overview of ChatGPT prompts and outputs, and for all fake data that was generated.

### 7.3.2 Electronics

Several electronical components were integrated in the prototype. Each base contains a load cell to weigh the voting blocks, infrared sensor to indicate whether a ball is picked up, and LED strip to show which ball belongs where. They are all connected via wires to the Arduino UNO. In each ball, an accelerometer is connected to an ESP8266 which is powered with a Li-ion battery through the USB DC-DC converter. It communicates with the ESP32 via Wi-Fi. A Fritzing sketch is made to visualize all wiring (see Figure 42) and the components are specified in Table 13. The circuit in the ball is completely soldered. The wiring to the components in the base is soldered as well, and all wires come together in one breadboard which is connected to the Arduino UNO. Using plastic balls and lasercutted wooden shapes, the components are 'hidden' in the prototype. While the wooden elements are glued together, the plastic balls use tape to stay closed, as they need to be opened regularly to connect the battery.

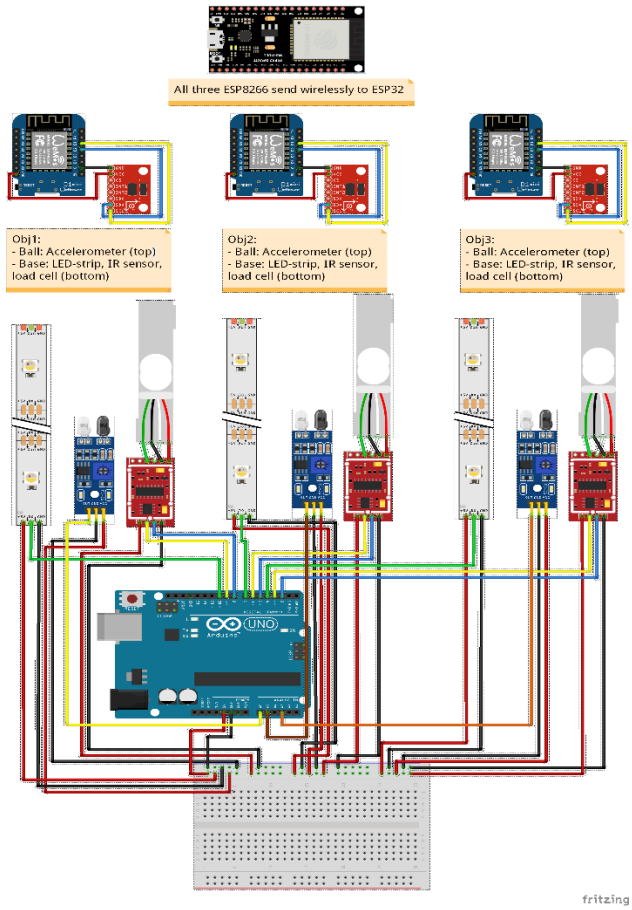



Figure 42. Overview of components in and wiring of the prototype.

Table 13. Specification of all electrical components in the prototype.

| # | Component | Goal |
|---|---|---|
| 3 | 5KG Load Cell + HX711 Transformer | Measure the weight of voting blocks |
| 3 | InfraRed (IR) Sensor | Notify program when a ball is picked up |
| 1 | Digital 5050 SK6812 RGBW LED strip | Indicate which ball is picked up |
| 1 | Arduino UNO | Process data received from / sent to the components above |
| 3 | Digital 3-Axis ADXL345 Accelero-meter Module V2 | Measure the ball's movement |
| 1 | ESP32 DOIT DEVKIT V1 | Wirelessly receive data from the balls |
| 3 | ESP8266 LOLIN WEMOS D1 mini clone | Wirelessly send accelerometer data to ESP32 |
| 3 | USB DC-DC converter 1000mA Li-ion C&P | Safely charge the ESP8266 |

### 7.3.3 Programming

In the Arduino IDE, data is retrieved from sensors and processors and forwarded to one of the two Processing files. The Arduino UNO contains code for the IR sensor, Load cell, and LED strips. The LED strips are controlled in the Arduino file, based on the IR sensor data. The processed IR sensor data (converted from integers to strings) and load cell values are forwarded to Processing. Due to time and

technical limitations, the load cell values are sent to a separate Processing file that only focuses on the interaction of voting. The Adafruit_NeoPixel library is used to communicate with the LED strip, and the HX711 library helps configure the load cells. The ESP8266 contains code to receive the accelerometer values, convert them to X, Y, Z G-force values, and communicate them to the ESP32 using its MAC address. The ESP32 receives this data by recognizing the ESP8266 ID value and forwards the accelerometer data with the corresponding ID to the Processing sketch. The ESP_NOW & WiFi libraries are used to communicate wirelessly between the ESP32 and ESP8266. The ADXL345_WE & Wire libraries are used to process the accelerometer data.

## 7.4 Usability evaluation

Between 2-4 October 2023, the usability evaluation was carried out with five peer students. They were approached and asked to express their opinion and thoughts on the prototype while exploring it. Additionally, a brief discussion was held afterwards, in which the potential of the embodied interactions was reflected on. Two participants were already aware of the goal and functionalities of the prototype, three were not. Overall, participants were very positive and found the prototype intuitive and clear to use. The physical elements were seen as stimulating to more structured yet playful discussions that improve focus. Based on the usability evaluation, small changes have been made to the prototype. Some data visualizations have been improved. In addition to responsive movement, the options on the screen now also fade in colour when the ball is idle. Moving a ball will recolour the option again.

### 7.4.1 Qualitative Analysis

A summary was created based on the input of participants (e.g., opinions, expressions) and observational notes (e.g., interactions with the prototype, facial expressions). It was divided into three parts: a general impression of the prototype, the user experience per interaction, and points for improvement. Similar comments were grouped until most data had been categorized, colour coding them based on the general sentiment of the group (see Table 14). The frequency of appearance per category was collected, to see which categories played a bigger role. Generally, participants responded positively to the prototype. After being informed of the generic functionalities of the prototype, all of them found its use very **intuitive**. The **physical** elements of the prototype were *"nicely heavy"* and comfortable to hold.

*"If there is one person who knows how to use it, everyone learns it very quickly from them." – Participant 2*

Table 14. Frequency of themes that came forward in the analysis of the Hi-Fi Usability evaluations.

| Code | Meaning | Freq |
|---|---|---|
| **Intuitiveness** | The way the prototype is understood and used naturally | 10 |
| **Physicality** | The tangible elements of the prototype as well as physical interactions | 9 |
| **Structure** | Order during discussions and other session | 9 |
| **Clarity/overwhelm** | Feelings of overview and overwhelm when using the prototype | 8 |
| **Visualizations** | Consistent use of colours and icons in the digital and tangible elements | 5 |
| **Added value** | The envisaged value of the prototype | 4 |
| **Focus** | Level of attention during discussions and other sessions | 3 |
| **Playfulness** | Level of engagement, playful and game-like experiences | 2 |

Participants liked using the balls to navigate through the prototype, but the information was a bit **overwhelming** at first. However, after reading the information it was deemed sufficiently detailed, with clear **visualizations** to help convey this information.

*"The screen feels like an encyclopaedia for what you want to discuss, the background information that supports your discussion." – Participant 5*

Participants liked the way the movements of the ball were represented in the screen, expressing that it might lead to more **playful** meetings. One participant highlighted that it is easy to pick up a ball and start interacting; playing around. At the same time, most participants saw the **added value** of this interaction

in terms of staying **focused** on the topic and adding more **structure** to the discussion. Especially in combination with the recording option, participants expected it to lead to shorter, more efficient discussions. Additionally, they saw the recordings as a way to let the prototype play a role outside of meetings (e.g., help prepare for a follow-up meeting).

*"It works well in big meetings, to have a central point and ensure everyone feels heard." – Participant 4*

There was some discussion about the implications of the voting interactions, due to its transparency and freedom in how it should be used. Participants pointed out that it would be nice to include more context about the votes, like when the block was placed and by whom. Two participants remarked this would go at the cost of the voter's anonymity and that this might limit the openness of users in expressing their opinions. Additionally, two participants did not see the added value of the physical elements. One stated that a show of hands would be sufficient. The other suggested using a closed box to vote anonymously and then displaying the results on the screen after everyone had voted.

*"Voting is clear, but what is the added value of the physical parts? The screen works just fine." – Participant 3*

Some participants suggested using the voting blocks during the discussion, as a way to indicate which options are *"doing well"*, whether people are on the same page, and where points of discussions lie. This could help move toward a conclusion more quickly. Combining this with a functionality in which voice notes are collected in a timeline, it could be used to observe which arguments and questions had the biggest impact on the discussion. This would be interesting for future situations like follow-up meetings.

*"Maybe vote during the discussion, so you can keep track of the status of each option and avoid long discussions where everyone unknowingly agrees with each other." – Participant 1*

### 7.4.2 Opportunities

Various suggestions were proposed by the participants, both for this prototype as well as the concept in general. Practical suggestions included finalizing details for the dashboard (e.g., consistent colouring, additional voting page information) and ways to elaborate the 'highlight' interaction. Several participants suggested fading out idle strategy blocks and limiting the movements to preserve readability. Other suggestions were made to pulsate the block and smoothen the movements, but these were not implemented due to technical limitations of Processing.

Besides practical, short-term suggestions, participants also came up with more theoretical suggestions to enhance the user experience and improve stakeholder alignment. For the dashboard, participants suggested displaying customizable features (e.g., costs, energy consumption) so only relevant information is compared. Furthermore, the screen could allow for more direct interactions (e.g., drawable) and display voice notes near the element it focused on. For the base of the ball, participants suggested improving the voting interaction by moving each strategy's bar chart next to the other (to increase overview), use closed boxes instead (to preserve anonymity), and to allow users to attach voice notes (to preserve context). Other suggestions for the base were adding a button to press when you want to talk so it can be *"a multi-player discussion"*, adding a small basket to collect notes and sketches (to preserve context), and creating an overview of the history of arguments and related voting scores. For the ball itself, participants opted to use more sturdy material like rubber so it would not feel so fragile (and invite interactions like throwing). When interacting with the screen, participants suggested adding a focus button that could be pressed to highlight one specific strategy. When comparing two strategies, it might be nice to move the strategy blocks next to each other (like when comparing three options) for better readability. Participants suggested limiting the length of voice notes and creating a summary at the end to avoid messy voice notes. Lastly, participants saw the potential in expanding the movements of the ball – adding specific gestures like throwing, squeezing, and rotating to enrich the embodied experience without getting distracting.

## 7.5 Social Impact Evaluation

Between 11-19 October 2023, four simulated discussions were organised with each three participants. Three of these sessions were carried with Arcadis employees at the office, one session took place with peer students at the University of Twente. The results per session can be found in Appendix D.4 Social Impact Evaluation Results. Although the sessions are independent from each other, overall patterns (and a lack thereof) can be observed. From related research, five main themes were defined that were used to conduct the thematic analysis of the summarized results. See Table 15 for an overview of the themes. All discussions took between 5-20 minutes, with an average of 11 minutes per discussion (12 minutes without, 10 minutes with the tangible elements). A clear choice for an option was made in 3 out of 4 scenarios with the tangible elements, compared to 1 out of 4 scenarios without. Where the dashboard screen provided a solid basis of clear information provision, the tangible element stimulated participants to conduct more in-depth discussion. It led to a feeling of more grip and structure during the discussion, which was observed through longer silences and shorter utterances in general.

Table 15. Overview of themes used in the thematic analysis of the session summaries.

| Theme | Description | Retrieved from | Freq. |
|---|---|---|---|
| **Active engagement** | The extent to which people are (equally) involved.<br>**Subthemes**: gamefulness, intuitiveness, exploration | 2.1.1 Positive Participation and 2.2.1 Shared Experiences | 50 |
| **Communication** | Sharing one's perspective and finding a compromise.<br>**Subtheme:** empathy | 2.2.1 Shared Experiences, 2.3.2 Indicating Preferences, and 2.3.3 Providing Context | 38 |
| **Focus** | Level of attention on a specific topic or element.<br>**Subthemes:** memory, context | 2.1.2 Reduced Complexity, 2.2.2 Shared Focus, and 2.3.4 Using Visualizations | 33 |
| **Structure** | The extent to which the whole discussion is affected by the tool, creating order or chaos.<br>**Subtheme:** participatory sensemaking | 2.3.3 Providing Context | 28 |
| **Visualizations** | Using images, icons, sketches, and other visual elements to convey and interpret information. | 2.1.2 Reduced Complexity, 2.3.1 Overview of Alternatives, 2.3.3 Providing Context, and 2.3.4 Using Visualizations | 14 |

### 7.5.1 Active Engagement

In Table 15, the theme of active engagement comes forward the most as a strong point in terms of intuitiveness, playfulness, and equal participation. In the thematic analysis, participants self-report that they are more involved in the discussion, because *"everybody is able to do something, stimulating you to take part in the discussion"*. In several sessions, participants highlight that as everyone can grab the balls, an equal playing field is created – giving control of what is being discussed to all people. Especially more introverted people are attracted, as the various interactions also provide different ways of sharing their opinion. Furthermore, the playfulness of grabbing the balls and moving them around keeps the discussion light-hearted, making it more fun and accessible to partake.

In the survey, the differences in energy, active participation, and tiredness are observed (see Figure 43). In 3 out of 4 sessions, participants indicate that their energy increases with 0.3, 0.7, and 1.0 point (comparing two survey answers on a scale from 1-5). In the same sessions, participants also self-report a higher participation rate (increased with 0.7, 0.7, and 0.3 respectively). Their tiredness, however, does not show the same pattern – increasing for two sessions, staying neutral for one, and decreasing greatly for the latter session.

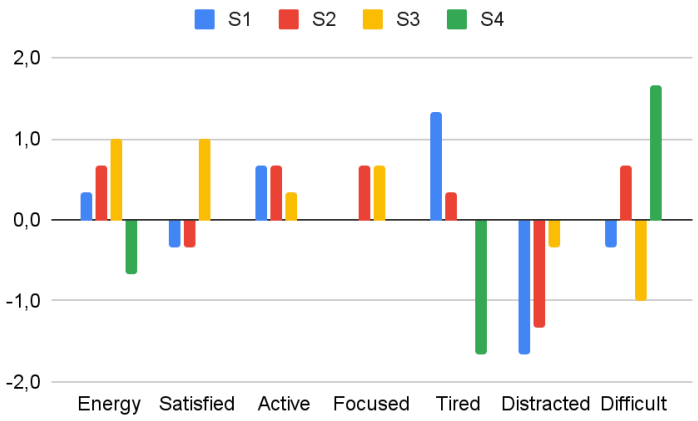



Figure 43. Average difference in self-report of the participants per statement per session, where participants were asked whether they disagreed (1) or agreed (5) with the statements.

When comparing these insights with divisions of speaker contributions per discussion, we can see no clear pattern. In 2 out of 4 sessions, the frequency of speaking becomes more equally distributed (from 41-39-20% to 39-29-32% and from 43-26-30% to 39-29-32%) but in the other two sessions not much changes. As for the division of total time spoken by participants, even less can be seen; only one session shows a more equal distribution (from 50-32-18% to 38-35-27%). The average utterance lengths per speaker get closer to one another in 2 out of 4 sessions as well (from 8.8-3.9-3.6s to 4.3-2.4-2.0s and from 6.2-4.5-3.8s to 5.1-3.2-3.5s). Overall, little consistency is seen that can confidently support the qualitatively gained insights.

### 7.5.2 Communication

Communication was also a key theme, often appearing together with active engagement, focus, and structure. In several sessions, participants indicated that they felt like the discussion went more in-depth when using the tangible elements. As the tangible elements *"provide a different way of looking at information"*, the discussions feel more in control and help users *"see what is important"*. This was partly observed a well, where two sessions put more focus on understanding each other's perspectives when they used the tangible element. However, in one session this occurred when participants did not use the tangible element, so it is not consistent.

A different pattern that was observed was the way people communicated with each other via the prototype. In all cases where the tangible element was used, participants had a collective conversation (see also 7.5.1 Active Engagement) where they actively responded to each other's comments and questions. This was only the case for half of the discussions without a tangible element. There, they were also often talking past each other, as if they were having discussions with themselves. This can also be observed in the number of interruptions in both conditions. In 3 out of 4 sessions, there are more interruptions when people do not use the tangible elements. They also look at the screen more and have less eye contact with their fellow participants.

Lastly, there was no observable difference in the length of the discussions and the topics discussed in both conditions. In all cases, participants first discuss the information present on the screen, then start comparing options, after which they make a choice. In two sessions, the discussion with the tangible prototype took longer – the opposite was the case for the other two sessions. However, most participants indicated that they felt like the discussion with the tangible elements went smoother and provided a better overview of the discussion.

### 7.5.3 Focus

Strongly related with structure, active participation, and communication, the theme of focus highlighted how the tool could be used to get and maintain grip on the topics that are discussed. For this, the balls were very useful, as their intuitive interactions and affordance to hold it gave a literal feeling of *"holding the option in your hand"*. Additionally, it was seen as *"a central point for everyone to focus on"*. The interaction of comparing strategies was also helpful, because it put the focus on the most information of the two or three strategies that are discussed. The main topics of focus were costs and energy consumption, which is understandable given the stakeholders and the context of application. The interaction of highlighting strategies to put more focus on them (e.g., moving, removing the fade) was used in half of the sessions, with participants indicating that more smooth movements and the ability to 'squeeze' a strategy to keep it in focus would be very valuable.

Overall, the addition of the ball was seen as a nice way to keep the overview, redirect attention, and not *"drown in all the details, in all the text on the screen to read"*. The number of observed distractions does not bring this forward. In 3 out of 4 sessions, the number of distractions increases (with a small number, staying under 1 per minute in all cases). However, screen time reduces and eye contact increases, which might indicate an improved focus on the discussion; but this is difficult to say. However, the survey results show that the focus of participants increase with 0.7 point (comparing two survey answers on a scale from 1-5) for half of the sessions. In the other half, it stays the same. Considering the level of distractedness, participants indicate in 3 out of 4 sessions that they are less distracted when using the tangible prototype (decreased with 1.7, 1.3, and 0.3). In the last session, it stays the same.

### 7.5.4 Structure

Closely related to communication, the theme of structure focuses on the impact of the tool on the discussion as a whole. Where the first three themes relate more to individual processes stimulated by the tangible tool, the theme of structure is an effect that comes forward in a group setting. In the first and last session the tangible element is used as a central point in the discussion, but otherwise has little impact on the structure of the discussion. This is because the balls were only used by one person, or they were put down after grabbing them. In the second session, the balls were actively used as discussion tools – giving the *"power of speaking"* to the person holding the ball they want to talk about. In the third session, the balls were divided among participant as if they were theirs, putting more focus on the participants instead of the screen. When observing the frequency of screen and eye contact per session, a small pattern is observed that relates to this structure. In all cases, the frequency of eye contact increases with the tangible prototype – from 2.86 to 3.02, 2.37 to 4.33, 3.71 to 4.71, and 4.43 to 4.98 moments per minute. This could suggest that the balls help redirect more attention to the other participants instead of the screen, as a central discussion point.

All sessions followed the same structure: discussing the ideas 1-by-1, comparing two or more options, and then trying to choose one by discarding options. Observations indicate that there was more structure and patience during the discussions with the tangible elements. Comparing this with the quantified results, a limited pattern can be observed that supports these findings. A choice was made in 3 out of 4 scenarios with the tangible elements, but only in 1 out of 4 scenarios without. The average utterance length per speaker decreases in most (10 out of 12) cases when the tangible prototype is used (see Table 16) – meaning their utterances are shorter each time they speak. Comparing these insights with the frequency of talking and length of talking (Figure 44 and Figure 45), this pattern is not as strong (6 out of 12 cases for both), meaning that they do not necessarily talk less often or less long in total. However, when considering Figure 44 and Figure 45 for the silence elements solely, we can see that the length and frequency of silences consistently increases when the tangible prototype is used, as does the average length of silences in 3 out of 4 sessions (see Table 16). Adding to this the insight that the number

of interruptions per minute also decreases in 3 out of 4 sessions, it could indeed indicate that there is more structure, less chaos, and more control when participants use the tangible prototype.

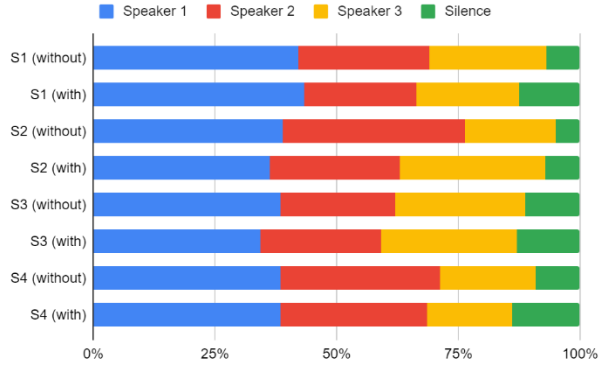


Figure 44. Frequency of talking per speaker, in percentage of the total discussion.

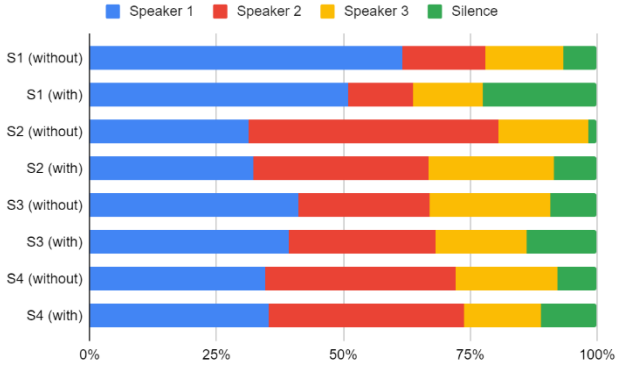


Figure 45. Length of talking per speaker, in percentage of the total discussion.

Table 16. Average length of utterances per speaker, condition, and session in seconds (excerpt from Appendix D.5)

| | Session 1 | | Session 2 | | Session 3 | | Session 4 | |
|---|---|---|---|---|---|---|---|---|
| | Without | With | Without | With | Without | With | Without | With |
| **Speaker 1** | 8.8 | 4.3 | 3.8 | 3.5 | 4.1 | 4.3 | 5.3 | 4.5 |
| **Speaker 2** | 3.6 | 2 | 6.2 | 5.1 | 4.3 | 4.4 | 6.7 | 6.3 |
| **Speaker 3** | 3.9 | 2.4 | 4.5 | 3.2 | 3.5 | 2.4 | 6.0 | 4.3 |
| **Silence** | 5.6 | 6.5 | 1.7 | 4.6 | 3.2 | 4.0 | 4.9 | 3.8 |
| **Avg length of utterance p/m** | 6.0 | 3.6 | 4.7 | 3.9 | 3.9 | 3.8 | 5.8 | 4.9 |

In the survey, all participants indicated that they preferred the prototype with tangible elements over the prototype with only the dashboard. This was mainly due to its tangibility, making it *"clear and easy to see who is talking and what kind of point they want to make"*. Participants did emphasise that this prototype would work best in smaller groups with a small number of strategies to discuss (maximum 5) as the distracting elements would otherwise probably get the upper hand. Their self-reported satisfaction with the result is high for all cases with the tangible prototype (4.7, 4.3, 4.0, and 4.3 out of 5). In the latter case, this is an increase of 1.0 point (on a scale of 1-5) compared to the discussion without the tangible prototype. In two sessions, the satisfaction decreases a little bit (0.3 point). Their self-reported difficulty ratings are not that conclusive. In two sessions, participants report that it was more difficult to make a choice with the tangible tool (increasing with 0.7 to 2.7 points and 1.7 to 3.3 points out of 5). The other two show a decrease in difficulty (decreasing with 0.3 to 2.7 points and 1.0 to 3.0 points out of 5).

### 7.5.5 Visualizations

The last theme covers the use of visual elements in order to convey information better. This mainly revolves around the dashboard due to its active use of icons and colours. Participants liked the dashboard screen, it felt relatively complete and made good use of visualizations to help convey the information more clearly. Its consistent use of coloured blocks and icons helped participants navigate through the dashboard very easily. Additionally, it helped them redirect their focus to the core elements of the discussion both by looking at these elements and by using the visual cues to point them out to other participants (*"I want to talk about the yellow option"*). In the survey, several participants fortified this by stating that the overview of information provided by the dashboard was clear and that the use of colours and icons was helpful.

## 7.6 Takeaways

In this phase, the results of the Lo-Fi phase have taken shape in the Hi-Fi prototype. The interactions combine insights gained via the research context with theoretical findings. During the usability evaluation, small adjustments could be identified that could be implemented before the social impact evaluations. These mainly revolved around further integrating concepts of embodiment in the prototype, by adjusting

the movements on the screen as a result of 'highlighting' strategies. During the social impact evaluation, the themes of structure, visualizations, and focus consistently came forward. The themes of active participation and communication showed less consistent results but nevertheless could be identified throughout the sessions. Concluding the practical steps of this research, we can now move on to interpreting these results and seeing what it means for the initial research question.

# 8. Discussion

This research has made use of various methods in the domain of Interaction Technology that involved stakeholders in the iterative design of the prototype. After several designs, mock-ups, and evaluations, the Hi-Fi prototype presents the final results of this research. It uses tangibility and embodiment as core elements that could stimulate shared attention and stakeholder alignment. The social impact evaluation allows us to see how it affects shared attention and alignment. The strength of tangibility lies in the playfulness and engagement it stimulates, in relation to other people but also for oneself. It physicalizes otherwise internal processes, making them easier to grasp, redirect, and memorize. In the evaluation results, these phenomena are observed to a limited extent. Due to the subjectivity and small scale of this evaluation, it is difficult to confidently identify a pattern. However, the themes of active engagement, enhanced focus, and a different conversational structure certainly come forward.

## 8.1 Background of the Researcher

Throughout this research, a lot of ideas and results have been constructed from the perspective of Interaction Technology. This means that focus is put on the use of technology in a human-centred context using human-computer interaction principles. The goal was to design user-friendly human-technology interactions that enrich the human experience in a valuable way. This research was by no means a sociological research nor a technical assessment. Rather, it straddled the line between these two domains, taking inspiration from both. First, technological skills were used to conceptualize a tool based on social principles. Then, the tool was evaluated with stakeholders in a social context, using the insights to define technological improvements. Therefore, the main focus of the research was put on using brainstorming and prototyping to collect experiences, interpretations, and thought processes of the target user. These were interpreted and grouped in themes, translated to design requirements, and conceptualized in various mock-ups and a functional prototype – all by looking at how it affects the user in a valuable way.

## 8.2 Stakeholder Involvement

As became apparent over the course of this research, the stakeholders related to this research context have played an active role in shaping the outcome of this research. This was done by planning sessions where they shared their experiences, brainstormed on potential solutions, and discussed the findings from their point of view. This helped shape the context in more detail and stay close to the stakeholders' wishes in the design process, leading to a tool that not only finds a connection to academic research but also relates strongly to the field of asset management. There were several traits and properties that affected the design and use of the Hi-Fi prototype.

Firstly, the focus on information-based decision-making in order to minimize risks played a great role. Stakeholders repeatedly expressed their need for both certainty and trust by asking a lot of follow-up questions, looking for details in the prototypes, and trying to see the complete picture. This led to two insights. On one hand, the tool should contain information in order for stakeholders to engage with it – a dashboard was seen as the most fitting solution. On the other hand, the information should not be too detailed at first sight as that can distract stakeholders by drowning them with information.

Secondly, they affirmed that the domain was conservative and that compliancy with contracts is important. From this, we learnt that the tool should not be too futuristic or disruptive in its use and content as that would discourage stakeholders from using it. This led to some conflicting feelings when implementing embodiment theory as it focuses on natural interactions but can also evoke awkward feelings at first, which can be discouraging. A balance between this was constantly sought.

Lastly, stakeholders indicated feeling a lack of autonomy because of their relation with other stakeholders during meetings. For some, this meant that the asset owner holds most of the decision-

making power, whereas others shared how the lack of in-depth communication between all stakeholders makes it difficult to smoothly formulate a common plan. From this, the focus on using meetings as the application context of the tool was defined.

## 8.3 Social Impact

Five themes were derived as factors contributing to stakeholder alignment and were used in the analysis of Section 7.5 Social Impact Evaluation. This was done with the use of theory on stakeholder alignment and embodiment. Even though there were different participants each session, some recurring themes could be observed in (nearly) every session. There was a clear indication that the tool had a social impact in providing a unique structure and helping redirect focus during meetings. The structure of the meetings differed per session, which is in line with theory from participatory sensemaking stating that the 'activity' (i.e. discussion structure) is dependent on the people and context of use [20], [51]. It also helped using the tool as a central point of focus, being 'present-at-hand' for participants to gesture to and keep returning to [11], [12]. Generally, the results resonate with a related study conducted by Jaasma *et al.* [52], who explore the role of external representation for participatory sensemaking in a multi-stakeholder environment. The study describes how physical elements invited participants to express their thoughts and feelings, which aligns with how – during the social impact evaluations – the type of discussion changed when using tangible elements. It became much more of a conversation, rather than independent monologues.

Although a link to theory can be found, it remained difficult to connect these insights to quantitative data. The reduced frequency of interruptions, increased frequency of eye contact, and generally shorter utterances did point in a similar direction but not all data was consistent. The level of improved communication and active participation, for example, had more limited results. Participants indicated that the tangible elements distributed the power of the meeting more equally, because everyone can grab a ball and move it around – opposed to one person managing the cursor in a graphical interface. It is interesting to see this brought up so specifically during the evaluations, since limited information on this was found in related work. Participants also shared that the use of tangibility stimulated more active participation by everyone, including introverted people. In the quantitative data, this was somewhat observed in a decrease of interruptions and lower average speaking time. However, the speech time or frequency was not consistently equally distributed. Facets of playfulness and novelty could have contributed to the improved perceived participation, something which is also pointed out by Jaasma *et al.* [52]. Following O'Brien and Toms [21] stance on novelty, it can be combined with positive affect, feedback, and flow to maintain this engagement. From this, we might see a link between positive participation and equal power distribution as well. We see how the playful use of physical balls as representations helps induce a positive ambience and make room for a more open discussion, as long as playfulness does not become distracting.

Additionally, some interactions were seen as less valuable than initially expected. The way movements with the ball translated to movements on the screen did not really stand out. In some sessions, this was because the balls were not moved a lot, but generally the movements were also too stiff to feel natural. The voting interaction again sparked debate, as seen in previous instances of the prototype, but now with a focus on its added value. In line with some comments in the usability evaluation, participants did not really see the added value of physical voting. The presentation of votes on the screen seemed to be sufficient, if voting other than a show of hands was used at all. This is in contrast with findings by Zilouchian Moghaddam *et al.* [16] who see it as one of the core factors in building consensus. This might be because it was a separate application, so it was difficult to use as 'subtly' as other interactions. Additionally, it had no extra purpose other than visualizing votes. For example, Jaasma *et al.* [52] used representations to visualize conflicting interests, which sparked discussions again. It might have been good

to incorporate something similar in the voting blocks as well. In the current context of a discussion with three stakeholders, there does not seem to be added value in voting physically.

## 8.4 Contributions

With the use of concepts of stakeholder alignment and embodiment, a tool could be designed specifically for the context of asset management. In contrast with previous research, we have not developed an interactive table, but a modular prototype that can be transported between locations to fit the right context. Balancing between stakeholder needs and theoretical practices, a combination of information representation and embodiment is used to stimulate an open discussion where stakeholders collectively focus on the available content. Even though the social impact of this prototype cannot clearly be confirmed, the research as a whole has explored and combined various topics that have led to new insights and provide an added value to the academic world and Arcadis as a client.

### 8.4.1 Scientific Contribution

This research has used theory on stakeholder alignment to construct a framework visualizing the ideal communication flow of stakeholders and has made a first step in translating this into practice. The framework has been constructed as an answer to the current communication flow of stakeholders in the research context of asset management. Based on recurring themes in theory, with a main focus on Pustejovsky *et al.* [13], Zilouchian Moghaddam *et al.* [16], and Van Dijk [11], the concepts of common ground, compromise, and embodiment have taken shape in the resulting Hi-Fi prototype. This research shows how generic insights from theory can be used in a very specific context, by using an iterative and co-creative approach to assess which insights have the best potential in said context.

Additionally, it builds on the concepts of embodiment – mainly participatory sensemaking and representation – and explores the friction between embodiment and data representation. Because stakeholders were heavily involved in the research and expressed their need for information provision, a big part of the prototype focuses on information provision. This is in contrast with some of the embodiment theory used, as that tends to focus more on social happenings 'below the content' [12] and keeps the meaning of tangible elements more open [52]. The balance between data representation and embodiment is sought in this research, tiptoeing between the balls acting as representations of the information visible on the screen and using the balls to stimulate a more active discussion with a central focus point. Arguably, a combination of the two can be seen as enriching for the user experience, by putting tangible elements in the background but allowing users to look for detailed information if needed. The social role of embodiment helps the stakeholders focus on the conversation and open themselves up to each other by externalizing social cues. The representation of information with the balls facilitates this on a content-wise level, adhering to the need of the stakeholders for information provision and making it easier to have that discussion. This links to findings by Jaasma *et al.* [52], who state that representations can a add a scaffolding layer to the discussion that helps open up the discussion and stimulate shared understanding. Where their representations provided information of conflicting interests, our research represented information about different strategies.

### 8.4.2 Societal Contribution

The research contributes to society in two manners, by showcasing a new way in which tangibility can be used to stimulate stakeholder alignment and by providing Arcadis specifically with some pointers that can be integrated in their way of working. The prototype has provided the basis for a tangible prototype that stimulates active participation and focus during a discussion, which allows stakeholders to have more open communication and work together. The key lies in making a prototype with playful elements and interesting features that also provides enough structure to stay focused on the goal behind the prototype. The physicality of the prototype helps evoke such playful feelings, while the use of representation theory

helps make abstract concepts easier to grasp. By involving the user's body in the use of the object, it becomes easier to redirect attention to the discussion and express otherwise internal (thought) processes. The use of these concepts also expands the potential for the tool beyond using it for discussions, by using it after discussions or applying it in different contexts. Although the tool has been designed specifically for stakeholders in asset management (see also 8.2 Stakeholder Involvement), the theory used in the development of the tool is relevant to a broader social spectrum. It could mean that the tangible elements are suitable for more generic uses, whereas the information and the dashboard are more target group dependent. Defining the flexibility of the tool in its application is a valuable contribution and enhances its added value in future work.

For Arcadis, the main value of this research lies in both its approach and its result. The iterative and co-creative way of working can be adapted to bring the company closer to its end user, getting a better image of their problems, ideas, and wishes. Input and brainstorm sessions much like the co-creation sessions can be organized, using mock-ups to acquire quick feedback during projects and speed up the creation of more valuable end products, which is currently not a point of focus. This could help Arcadis facilitate a more open work process in which input and feedback from stakeholders is taken along, working on their mission of *"putting people first"*. Besides acquiring design feedback, some points for improvement in terms of sustainability (e.g., circularity and waste minimization) were also identified that can be useful in upcoming projects. Furthermore, the prototype has the potential to be expanded for other cases and meetings at Arcadis as well, such as brainstorm sessions, maintenance plannings, constructing tenders, work demonstrations, contract negotiations, and more. This also has the potential to provide a link with Digital Twin applications that Arcadis is exploring, such as condition-based monitoring and maintenance.

## 8.5 Limitations

An aspect of an intensive user-centred focus throughout the research is the use of mainly qualitative methods such as interviews and design sessions to identify relevant themes and points for improvement. These themes and focus points were based mainly on stakeholder input, with retrospective links to theory which can be subject to confirmation bias. Only for the co-creation sessions and the social impact evaluation were themes defined beforehand. It would have been better to define themes beforehand in all research steps (e.g., site visit, usability evaluations). Although that might lead to the inclusion of less relevant themes, it helps paint a more objective picture of this research in relation to other theory. This would help induce a stronger link with theory, which currently is not always clearly present, and show where it contributes something new or different to the research domain. The qualitative nature of this research also means that no significant conclusions can be made. Due to the explorative and iterative nature of this research, the sample size of each research method was small, and several translation steps were continuously taken that influence the results (from observation to notes to summary to themes). In research with a similar approach, however, Van Dijk [11] and Den Haan [28] imply that qualitative data – although subjective in nature – can still be used to determine draw conclusions about the impact of the prototype. By comparing the results with other research, some themes are defined that are starting points for future research with a greater focus on consistency and significancy.

Additionally, the setting of the research has its limitations. Generally, it has focused on the context of asset management in the Waterwolftunnel. Although many stakeholders have been involved in the process and a visit to the tunnel was planned, the input retrieved this way mainly represents asset managers only. Only one meeting was held with the asset owner, as they were unavailable for the start of the research. After this meeting, they expressed no interest in participating in other parts of the research. The service providers indicated they were too busy and did not participate as well. This means that the image created of these two stakeholders is largely based on second-hand information via asset managers, in combination with literature research.

By specifically focusing on the social impact evaluation, we can also see the limitations of the setting of this research. Users were asked to take on a role and take part in two simulated discussions, one with and one without the tangible elements, all while being observed. Because both the role and the scenarios were simplified and fictional, it was easier for participants to participate but more difficult to apply the results to a real-world scenario. It was also the first time they saw the prototype, including the information on the screen. This can affect results because they are not used to the prototype and its information so they might behave differently. Because the stakeholders tend to focus on the information at hand, it might have also affected the social dynamic between stakeholders in the evaluation, further reducing its applicability to a real-world scenario. Furthermore, participants were aware they were being observed, potentially leading to more socially desirable answers and missing out on realistic behaviour. This was partly mitigated by using deception and sharing the actual goal of the research afterwards. Although the setup of the evaluation makes it difficult to apply the results to a real-world scenario, it is a good basis for more in-depth follow-up evaluations that can look for a stronger link with reality.

## 8.6 Future Work

In this research, we have explored the potential of using a tangible tool to stimulate alignment and understanding in a multi-stakeholder environment. We have seen how it contributed to more active and equal participation and helped participants stay focused on the discussion. The main limitations and concerns lie in the qualitative nature of the research and the fact that the tool was evaluated in a simulated setting. In future work, the next step could be to consider a long-term social impact evaluation of the tool in a natural setting, focusing on the trade-off between playfulness and distraction or the increase in active and equal participation. This way, focus can be put on drawing consistent results from the prototype evaluations. It would be beneficial to expand the research team such that multiple observers can take notes and process the data, reducing the level of subjectivity in the results. The impact of variables in the evaluation can be explored by varying them (e.g., location, group size, complexity of discussion, number of options and interactions). A pre-test can be conducted in which the scenario information is provided without a prototype, so that a baseline can be defined and familiarity with the content can already be induced. A different study outline would be using various yet subtle ‘depths’ of the prototype (e.g., one with and one without the ‘highlight’ feature). This way, the risk for socially desirable answers is reduced and the impact of such variations can be observed.

Once the social impact of the tool has been identified properly, there lies potential in diverging again – exploring the look and feel of the prototype and expanding its application domain. The former can be done by expanding the number of possible interactions with the dashboard and balls – e.g., giving users the freedom to add strategies themselves, filter ideas, or use specific movements to perform specific actions. This could lead to a more refined and more effective prototype. For the latter, it would first be interesting to observe the effect of the prototype beyond a discussion. The voting blocks and audio recordings preserve information about the discussion in the tangible prototype. Ideally, the recordings and history of votes can be connected such that the provenance of choices and arguments can provide context about the course of the discussion. Information could then be transferred between meetings in a rich and arguably more transparent way. Additionally, the tangible elements could also be explored in individual use, to (re)structure one’s thought process and memorize information better. The focus would shift from alignment between stakeholders to remembering complex information better. Lastly, we can zoom out in the context of asset management at Arcadis and look at how we can include Digital Twin technology in this tool. It could play a role in the information provision, by using various data (e.g., sensor input, maintenance documents) to provide insights and predictions on performance and costs. Additionally, it could help create insights that convey (conflicting) interests of stakeholders better.

# 9. Conclusion

Throughout this research, the obstacle of fragmented communication and collaboration between stakeholders in asset management has been explored in theory, in context, and in design. The question **"To what extent can an interactive tool be designed that stimulates stakeholder alignment in asset management?"** was explored by combining these three domains in one prototype. It resulted in a functional tangible tool that uses balls to represent different options on a dashboard, which can be interacted with to navigate through the dashboard and remain focused and involved with the discussion. By answering the three sub-questions, we can formulate an answer to the main research question of this research and look ahead at what follow-up research can mean for this field.

### Sub Q1: What elements contribute to stakeholder alignment that can be integrated into the design of the interactive tool?

An interactive tool was constructed that focuses on theory of engagement, common ground, and compromise to stimulate alignment. For engagement, this meant involving stakeholders early on in the design process through co-creation sessions and evaluations while using the concept of embodiment to evoke playfulness while keeping the use of the tool simple. Common ground could be stimulated with a central tool that creates a shared experience, allowing for shared attention redirection. Facets of compromise that came forward in the prototype were the use of visual elements to create an overview of alternatives, while also giving users the autonomy to indicate their preference and capture and share context about the discussion.

### Sub Q2: How can the stakeholders' ideas about stimulating alignment be used in the design of the interactive tool? & Sub Q3: How does stakeholder feedback help in refining key elements that stimulate alignment in the interactive tool?

Stakeholders shared their vision on our problem statement and ideas throughout the research by participating in co-creation sessions, interviews, and evaluations. They were given the possibility to share their own ideas during co-creation sessions (Q2) but were also asked to interact with mock-ups or prototypes and give feedback on them (Q3). Stakeholder ideas identified design directions and stakeholder feedback helped choose the most suitable direction. Both of these methods helped include the context of asset management in the design of the tool through formulating requirements, so that it not only had a theoretical but also a practical basis. From this, a heavier focus was put on information provision, certainty, and overview. Various ideas were iteratively conceptualized in three mock-ups, after which one of them was worked out in the Hi-Fi prototype.

From the social impact evaluation, we can answer the main research question by concluding that the functional tool has the potential to align stakeholders by using the principles of participatory sensemaking and representation to create a unique meeting structure in which the tangible elements can be used to redirect focus and equally participate in the discussion. Follow-up research is needed to see whether this pattern is continued consistently, so the impact of the prototype can be refined, and its use can be expanded beyond stimulating stakeholder alignment through discussions. This can be done by exploring which elements can be generalized and which are stakeholder-defined, and by involving the use of Digital Twins in the tool. All in all, this research has defined a starting point for using tangibility to stimulate alignment in a multi-stakeholder environment. Through follow-up research, the prototype can be refined so it can help bring different stakeholders together, understand each other, and work together on a sustainable future.

## References


[1] D. van Meggelen, "Digital Twins for sustainable asset management: identifying opportunities for design," 2023.

[2] D. Burggraaf, *Private communication*, Nov. 2023.

[3] A. Font Barnet *et al.*, "Climate services for tourism: An applied methodology for user engagement and co-creation in European destinations," *Climate Services*, vol. 23, p. 100249, Aug. 2021, doi: 10.1016/j.cliser.2021.100249.

[4] J. Fredericks, G. A. Caldwell, and M. Tomitsch, "Middle-out design: collaborative community engagement in urban HCI," in *Proceedings of the 28th Australian Conference on Computer-Human Interaction*, in OzCHI '16. New York, NY, USA: Association for Computing Machinery, Nov. 2016, pp. 200–204. doi: 10.1145/3010915.3010997.

[5] R. Aguilar, "Co-designing planning support tools for stakeholder engagement in collaborative spatial planning processes," PhD, University of Twente, Enschede, The Netherlands, 2022. doi: 10.3990/1.9789036554206.

[6] P. Ardiana, "Conceptualising stakeholder engagement in sustainability reporting: A review of literature and research agenda using neo-institutional theory," *Jurnal Ilmiah Akuntansi dan Bisnis*, vol. 17, pp. 1–21, Jan. 2022, doi: 10.24843/JIAB.2022.v17.i01.p01.

[7] M. Bujić, A.-L. Macey, S. Järvelä, and J. Hamari, "Playing With Embodied Social Interaction: A Thematic Review of Experiments on Social Aspects in Gameful Virtual Reality," *Interacting with Computers*, vol. 33, no. 6, pp. 583–595, Jul. 2021, doi: 10.1093/iwc/iwac012.

[8] L. Zhang, Z. Shao, J. Benitez, and R. Zhang, "How to improve user engagement and retention in mobile payment: A gamification affordance perspective," *Decision Support Systems*, vol. 168, p. 113941, May 2023, doi: 10.1016/j.dss.2023.113941.

[9] L. Rundo, R. Pirrone, S. Vitabile, E. Sala, and O. Gambino, "Recent advances of HCI in decision-making tasks for optimized clinical workflows and precision medicine," *Journal of Biomedical Informatics*, vol. 108, p. 103479, Aug. 2020, doi: 10.1016/j.jbi.2020.103479.

[10] J. Nielsen, "10 Usability Heuristics for User Interface Design," Nielsen Norman Group. Accessed: Jul. 12, 2023. [Online]. Available: https://www.nngroup.com/articles/ten-usability-heuristics/

[11] J. van Dijk, "Creating traces, sharing insight: explorations in embodied cognition design," Eindhoven University of Technology Library, Netherlands, 2013. [Online]. Available: 978-94-6191-699-0

[12] J. Van Dijk, "Designing for Embodied Being-in-the-World: A Critical Analysis of the Concept of Embodiment in the Design of Hybrids," *Multimodal Technologies and Interaction*, vol. 2, no. 1, Art. no. 1, Mar. 2018, doi: 10.3390/mti2010007.

[13] J. Pustejovsky, N. Krishnaswamy, B. Draper, and P. Narayana, "Creating Common Ground through Multimodal Simulations," 2017, [Online]. Available: https://aclanthology.org/W17-7103.pdf

[14] A. Gururajan, R. Snelling, and A. G. and R. Snelling, "Big Room | Collaboration | Lean IPD | Construction," Lean IPD. Accessed: Jul. 12, 2023. [Online]. Available: https://leanipd.com/blog/going-big-in-the-big-room/

[15] A. Ö. Ağça and J. Buur, "Data Drawing and Data Tinkering," in *KSIG 2023 Proceedings From Abstractness to Concreteness – experiential knowledge and the role of prototypes in design research: International Conference 2023 of the Design Research Society Special Interest Group on Experiential Knowledge (EKSIG)*, S. Ferraris, V. Rognoli, and N. Nimkulrat, Eds., 2023, pp. 15–29.

[16] R. Zilouchian Moghaddam, B. P. Bailey, and C. Poon, "IdeaTracker: An Interactive Visualization Supporting Collaboration and Consensus Building in Online Interface Design Discussions," in *Human-Computer Interaction – INTERACT 2011*, P. Campos, N. Graham, J. Jorge, N. Nunes, P. Palanque, and M. Winckler, Eds., in Lecture Notes in Computer Science. Berlin, Heidelberg: Springer, 2011, pp. 259–276. doi: 10.1007/978-3-642-23774-4_23.

[17] R. Wang *et al.*, "Transparency in persuasive technology, immersive technology, and online marketing: Facilitating users' informed decision making and practical implications," *Computers in Human Behavior*, vol. 139, p. 107545, Feb. 2023, doi: 10.1016/j.chb.2022.107545.

[18] De Jaegher, "participatory sense-making | the enactive approach to intersubjectivity." Accessed: Jul. 12, 2023. [Online]. Available: https://hannedejaegher.net/
[19] T. Fuchs and H. De Jaegher, "Enactive intersubjectivity: Participatory sense-making and mutual incorporation," *Phenom Cogn Sci*, vol. 8, no. 4, pp. 465–486, Dec. 2009, doi: 10.1007/s11097-009-9136-4.
[20] J. Van Dijk and C. Hummels, "Designing for Participatory Sensemaking," in *11th EAD Conference Proceedings: The Value Of Design Research*, Sheffield Hallam University, Jul. 2016. doi: 10.7190/ead/2015/97.
[21] H. L. O'Brien and E. G. Toms, "What is user engagement? A conceptual framework for defining user engagement with technology," *Journal of the American Society for Information Science and Technology*, vol. 59, no. 6, pp. 938–955, 2008, doi: 10.1002/asi.20801.
[22] J. J. Gibson, "The Theory of Affordances," in *The Ecological Approach to Visual Perception*, 1st ed., New York: Psychology Press, 2014, p. 346. [Online]. Available: https://cs.brown.edu/courses/cs137/2017/readings/Gibson-AFF.pdf
[23] S. Jordà, G. Geiger, M. Alonso, and M. Kaltenbrunner, "The reacTable: exploring the synergy between live music performance and tabletop tangible interfaces," in *Proceedings of the 1st international conference on Tangible and embedded interaction*, Baton Rouge Louisiana: ACM, Feb. 2007, pp. 139–146. doi: 10.1145/1226969.1226998.
[24] H. Ishii, "Tangible bits: beyond pixels," in *Proceedings of the 2nd international conference on Tangible and embedded interaction*, Bonn Germany: ACM, Feb. 2008. doi: 10.1145/1347390.1347392.
[25] T. Djajadiningrat, B. Matthews, and M. Stienstra, "Easy doesn't do it: skill and expression in tangible aesthetics," *Pers Ubiquit Comput*, vol. 11, no. 8, pp. 657–676, Dec. 2007, doi: 10.1007/s00779-006-0137-9.
[26] J. Hollan, E. Hutchins, and D. Kirsh, "Distributed cognition: toward a new foundation for human-computer interaction research," in *ACM Transactions on Computer-Human Interaction*, vol. 7, 2000, pp. 174–196. Accessed: Nov. 01, 2023. [Online]. Available: https://dl.acm.org/doi/10.1145/353485.353487
[27] P. Dourish, "Social Computing," in *Where the Action Is*, The MIT Press, 2001. doi: 10.7551/mitpress/7221.003.0004.
[28] R.-J. den Haan, "Games to Collaboratively Explore Environmental Complexity: Designing the Virtual River Game," Oct. 2020, doi: 10.3990/1.9789036549653.
[29] *University of Twente | Robert-Jan den Haan Virtual river game | Explainer on Vimeo*, (Jan. 2023). Accessed: Jul. 12, 2023. [Online Video]. Available: https://vimeo.com/775065367/775058407
[30] P. Fugelli, L. Lahn, and A. Mørch, "Shared prolepsis and intersubjectivity in open source development: Expansive grounding in distributed work," presented at the Proceedings of the ACM Conference on Computer Supported Cooperative Work, CSCW, Feb. 2013, pp. 129–144. doi: 10.1145/2441776.2441793.
[31] "Hologram Tables," Axiom Holographics. Accessed: Jul. 12, 2023. [Online]. Available: https://axiomholographics.com/hologram-tables/
[32] D. Belcher and B. R. Johnson, "MxR: A Physical Model-Based Mixed Reality Interface for Design Collaboration, Simulation, Visualization and Form Generation," presented at the ACADIA 2008: Silicon + Skin, Minneapolis (Minnesota), USA, 2008, pp. 464–471. doi: 10.52842/conf.acadia.2008.464.
[33] P. Van Parijs, "What Makes a Good Compromise?1," *Government and Opposition*, vol. 47, no. 3, pp. 466–480, 2012, doi: 10.1111/j.1477-7053.2012.01371.x.
[34] "Choosing By Advantages," Lean Construction Institute. Accessed: Jul. 12, 2023. [Online]. Available: https://leanconstruction.org/lean-topics/choosing-by-advantages/
[35] K. Guo, "DECIDE: A Decision-Making Model for More Effective Decision Making by Health Care Managers," *The health care manager*, vol. 27, pp. 118–27, Apr. 2008, doi: 10.1097/01.HCM.0000285046.27290.90.
[36] C. Hummels and J. Van Dijk, "Seven Principles to Design for Embodied Sensemaking," in *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*, Stanford California USA: ACM, Jan. 2015, pp. 21–28. doi: 10.1145/2677199.2680577.

[37] Y. Gankema, "Bringing the human factor back in Digital Twins," Essay (Master), University of Twente, Enschede, 2021. [Online]. Available: http://essay.utwente.nl/89113/1/Thesis_Yvon_Gankema%28Nov9%29.pdf
[38] "An Introduction to Human Centered Digital Transformation." Accessed: Jul. 13, 2023. [Online]. Available: https://www.idealstate.co/blog/human-centered-digital-transformation
[39] A. H. Mader and W. Eggink, "A Design Process for Creative Technology," in *Proceedings of the 16th International conference on Engineering and Product Design, E&PDE 2014*, E. Bohemia, A. Eger, W. Eggink, A. Kavacevic, B. Parkinson, and W. Wits, Eds., The Design Society, Sep. 2014, pp. 568–573. Accessed: Apr. 04, 2023. [Online]. Available: https://research.utwente.nl/en/publications/a-design-process-for-creative-technology
[40] R. Van Westen and D. Van Dijk, "D4.2 Good practices and methods for co-creation." RICHES, 2019. [Online]. Available: https://resources.riches-project.eu/wp-content/uploads/2015/12/RICHES-D4-2-Good-practices-and-methods-for-co-creation_public.pdf
[41] R. Nayanathara, "PACT Analysis," Medium. [Online]. Available: https://bootcamp.uxdesign.cc/pact-analysis-3ac5fbe8817
[42] K. Baxter, C. Courage, and K. Caine, "Chapter 9 - Interviews," in *Understanding your Users (Second Edition)*, K. Baxter, C. Courage, and K. Caine, Eds., in Interactive Technologies. , Boston: Morgan Kaufmann, 2015, pp. 218–262. doi: 10.1016/B978-0-12-800232-2.00009-2.
[43] J. Reinius, "The PACT Analysis Framework. A case study of 1177.se," Master Thesis, Blekinge Institute of Technology, Karlskrona, Sweden, 2011. [Online]. Available: https://www.diva-portal.org/smash/get/diva2:830667/FULLTEXT01.pdf
[44] M. Man, T. Abrams, and R. McLeod, "Implementing and evaluating co-design: a step-by-step toolkit." NPC. Accessed: Apr. 21, 2023. [Online]. Available: https://www.bl.uk/collection-items/implementing-and-evaluating-co-design
[45] V. Braun and V. Clarke, "One size fits all? What counts as quality practice in (reflexive) thematic analysis?," *Qualitative Research in Psychology*, vol. 18, no. 3, pp. 328–352, Jul. 2021, doi: 10.1080/14780887.2020.1769238.
[46] K. Baxter, C. Courage, and K. Caine, "Chapter 12 - Focus Groups," in *Understanding your Users (Second Edition)*, K. Baxter, C. Courage, and K. Caine, Eds., in Interactive Technologies. , Boston: Morgan Kaufmann, 2015, pp. 338–376. doi: 10.1016/B978-0-12-800232-2.00012-2.
[47] K. Sharma, I. Leftheriotis, and M. Giannakos, "Utilizing Interactive Surfaces to Enhance Learning, Collaboration and Engagement: Insights from Learners' Gaze and Speech," *Sensors*, vol. 20, no. 7, Art. no. 7, Jan. 2020, doi: 10.3390/s20071964.
[48] S. Price and C. Jewitt, "A multimodal approach to examining 'embodiment' in tangible learning environments," in *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*, Barcelona Spain: ACM, Feb. 2013, pp. 43–50. doi: 10.1145/2460625.2460632.
[49] A. Harley, "Personas Make Users Memorable for Product Team Members," Nielsen Norman Group. [Online]. Available: https://www.nngroup.com/articles/persona/
[50] N. Alber, M. Alonso, G. Geiger, and S. Jordà, "The Reactable: A Collaborative Musical Instrument for Playing and Understanding Music," *Heritage & Museography*, vol. 11, no. 2, pp. 36–43, 2010.
[51] H. De Jaegher and E. Di Paolo, "Participatory sense-making: An enactive approach to social cognition," *Phenom Cogn Sci*, vol. 6, no. 4, pp. 485–507, Dec. 2007, doi: 10.1007/s11097-007-9076-9.
[52] P. Jaasma, J. V. Dijk, J. Frens, and C. Hummels, "On the Role of External Representations in Designing for Participatory Sensemaking," in *Proceedings of the Conference on Design and Semantics of Form and Movement - Sense and Sensitivity, DeSForM 2017*, M. B. Alonso and E. Ozcan, Eds., InTech, 2017. doi: 10.5772/intechopen.71207.

# Appendix A – Research Context

## A.1 PACT Analysis

### 1. People

The target user group consists of several stakeholders involved in the management of an asset, with its main focus lying on the asset manager. During the site visit, the role of the asset manager came forward as the mediator and point of contact. There are always 1-2 asset managers present to answer questions and solve issues ("brandjesblussers"). They are all Dutch males between the age of 30-60 years old, working at Arcadis. One of these managers is left-handed.

Other parties that are often on-site are 1-2 tunnel operators that monitor the tunnel installations and traffic in and around the asset. They make use of an operating system in which they can see all kinds of information about these factors. The head of these operators is always present at a different location nearby. In case of maintenance, there are also two people from a service provider present. These are always the same people, so they are familiar with the asset. They follow a maintenance planning that is defined by the asset manager and conduct maintenance on multiple assets a day. It can happen that during a maintenance session they get notified of a critical issue at a different asset, which they have to go and fix immediately. However, oftentimes, they can follow the planning as defined by the asset manager.

These stakeholders can be quite conservative, being reluctant in adapting big changes. For example, the operating system was renewed but the interface that was already in use for 10 years was reconstructed in the new version. The status quo is leading, incorporating change is an investment and brings uncertainties about performance, reliability, and safety with it. Furthermore, a lot of the collaboration between people working in/on the tunnel is defined by the differences between people. It differ per person how much expertise there is about the tunnel and how much interest is shown in being up-to-date with one another. Some people have some technical experience and/or knowledge, others stay on the management side. Some people want to be informed about what everyone is doing; which helps them gain an overview who works (less) hard or delivers (lesser) quality work. One person on-site indicates that a lot of people "think easy" when working. This is also observed in the communication between asset managers and service providers, and further affects the reluctancy for change.

### 2. Activities

In the Waterwolftunnel, the main activities are monitoring and optimization. Operators monitor the status of installations and observe abnormalities in motorist behavior. In case of an issue, they can respond through the operating system and notify the necessary people. This is mainly done in the main location of the operating system, which is in a town nearby, but can be done at the north office of the Waterwolftunnel. Asset managers can use the data preserved in the operating system to stay informed, observe notifications and trends, conduct analyses, and optimize maintenance plannings that are presented to the service providers. They often work on tunnel-related matters (e.g. writing maintenance plans) while in the office and get regular calls with various questions. Service providers are only present when requested by the asset manager, following the maintenance planning that is defined by them. This is always done in duos, so there is assistance and a contact point in case of an emergency. In general, a lot of abbreviations are used to refer to components, areas, and actions.

There are also regular meetings scheduled with various stakeholders. There are regular construction meetings and technical meetings in which topics like maintenance, issues, replacements, and sustainability are discussed. Furthermore, there are monthly inspection rounds and safety inspections where topics like defects, leakages, nuisance caused by mice, and fire safety and first aid kits are discussed. Everything is noted and registered; people entering and leaving, maintenance sessions, inspection rounds, and when the operating system is used. The functioning of the tunnel is critical, meaning that the safety of

its users should always be guaranteed. That is why there are regular inspections, all components and servers have backups (e.g. pumps, electronics, servers, lighting, ventilation), and the communication system is independent.

Maintenance sessions take time and resources. In a registration system and on a receipt, the entry and exit times of service providers are registered. However, they are not always representative as sometimes service providers leave earlier than registered or work on tasks longer than registered. Materials that are used for critical components are stored in the warehouse and registered when they are used, so they are never out of stock. Small materials (e.g. screws) are not registered frequently, only once a year during a balance checkup. Therefore, written details by service providers to asset managers in the maintenance reports are needed to improve maintenance planning.

### 3. Context

The tunnel is 10 years old, located in the province of Noord-Holland, and has a north and south office space attached to it. Most of the work is done in the north office. There are always 2-4 people present in the office, who can access the area through a key(card). The operators work in the surveillance room, which is secured with a lock, and need to log out of the system every time they leave the room (but this does not always happen). The asset managers that work at Arcadis prefer to work in the office of the Waterwolftunnel and sometimes move to the tunnel to find the source of issues. From the office, there is a connection to the tunnel via server and power rooms, down a staircase, to the middle part of the tunnel. All components in the tunnel are coded with abbreviations and ID numbers (e.g. Abbr-01-Room-02). Entering the rooms requires wearing a safety vest, helmet, and shoes. Keys and keycards are needed to access the specific rooms, so no unauthorized access can be granted. Walking through the middle part of the tunnel, you can see a lot of cables and concrete walls. The cables and concrete are fire resistant for at least 90 minutes, so it can be used as an evacuation route in case of fire. On the walls, old notes are left behind that indicate which components should be placed where, but these are not used anymore.

In managing the tunnel, a lot of communication is online. Many meetings are via completely or partly via Microsoft Teams and people are often contacted through their phone. When work needs to be done, a request is sent to be approved and then forwarded to the right party to execute it. The asset manager indicated they prefer to have physical contact for such matters, as people currently easily get distracted by other tasks and are more difficult to "read". They try to organize more physical meetings and let people work in the office, but it seems to be a residue of the COVID-19 pandemic. However, this can more easily lead to miscommunications or a lack of communication in general. For example, when a maintenance session is finished, service providers fill in a report that asks for details and particularities regarding the session (e.g. what was done, what is replaced, what is the status of components). However, the information that is returned to the asset manager is limited; often only whether something is done or not. As the asset manager indicated, "getting little detail is sadly the standard here", which leads to frustration they cannot improve their work with this information. To quote: "Yeah nice, but we can't do anything with this." In reaction, they ask for more details or require the service providers to conduct an additional session. In theory, the collaboration is top-down, but as observed in practice it is more equal and all parties need to share their expertise to effectively work together.

### 4. Technology

Keys and keycards are needed to access the tunnel and its offices. Everyone has a different authorization; only for relevant spaces. The tunnel contains a lot of installations and users, which are monitored through a complex and versatile operating system. The system contains information about the behavior of motorists, status of water tanks, fire extinguishers, electronics, air quality, lighting, heat, and more. It uses a systematic representation of the tunnel: a classic Graphic User Interface with various windows, icons, and menus (reconstructed half a year ago from the original design in 2012). Components are visualized in 2D-maps and kept up-to-date with a continuous data flow. Each page has a tab title that contains letters

representing the status of the installation (functioning, error, etc.) and the intensity of an error message to give the operator a quick overview. When data deviates from certain standards or installations stop working, the operator gets a notification:

- Audio: a bleeping sound is played;
- Visual: some letters in the tab title are marked, the component in the designated tab is colored, and the corresponding security camera images are presented;
- Temporal: a timer is started, if it hits zero (or the operator confirmed the error), a scenario is started (e.g. traffic light is set to red). If the operator indicates it is not an error, it will be canceled;

Besides the operating system, there is also a multifunctional audio panel (MAP) that enables an independent communication with essential parties in case there is no reception. Internet and communication systems are all functioning independently; they are not affected by country-wide malfunctions or overloaded networks. All systems in the tunnel are based on obsolescence and certainty: there are duplicates of every server, component, and system in the tunnel so that in case one fails, the other can take over and guarantee a safe pass through the tunnel.

## A.2 Personas

NAME

Anton de Maas

TYPE

**Rational**

### Background

Anton has never been able to sit still for a long time. Two years ago, he was appointed as asset manager of a tunnel in The Netherlands. He has to make sure the tunnel is open and safe to use, by making informed decisions with high certainty. He likes the variety of his job and the amount of contact he has with other people. It is not a full-time job, but in practice, it's on his mind all week. Small tasks that come in between or urgent things that arise during meetings and inspection sessions cannot be postponed.

Due to a recent change in legislation, Anton has to replace the draining system in the tunnel with pipes made of more sustainable materials. Sustainability is a hot topic nowadays, but no one has sufficient knowledge about it; sustainable options are often left aside. It is difficult for Anton to think of an appropriate solution for the draining system.

### Quote

*"We should think of ways to make the world a little better, but I don't have the information to make my work more sustainable."*

### Goals

- Make the tunnel accessible to drive through
- Ensure the tunnel is safe and in a good shape
- Meet the requirements set by standards and laws
- Increase the sustainability of his work

### Demographics

- 40-year-old male
- Married
- Studied Civil Engineering & Management
- Asset Manager of a tunnel in The Netherlands

### Tasks & Responsibilities

- Plan maintenance and inspection sessions
- Discuss plans and options with stakeholders
- Follow the goals and values set by the asset owner
- Write up documents on inspections, plans, permits, research
- Align the vision of the asset owner with the possibilities of the service providers

### Methods & Tools

- Meeting tools for physical and virtual communication
- Asset management software to keep track of plans and do risk analyses
- File editing software to write up and review documents and sheets
- Modeling software to highlight specific plans

### Motivations

- A tunnel is important for many people, Anton is really making an impact
- It is refreshing to work on various things, with the same goal in mind
- Being in contact with so many people is energizing.
- It's a really practical, real-world job.
- Working efficiently is a nice challenge.

### Frustrations

- Anton does not always get all information from his stakeholders, making him lag behind
- He often feels like it is hard to make decisions as an asset manager
- Without long-term information, it is difficult to propose changes
- Stakeholders do not actively collaborate, they work past each other and decreases efficiency

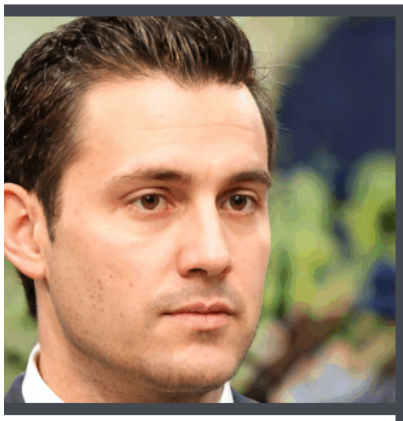
Figure A1. Persona representing the asset manager, from [1]

NAME

Peter van den Bergt

TYPE

**Idealist**



## Goals

Ensure province policies and strategic goals are included in the asset manager's policy.

Ensure civilians don't complain about the state of the tunnel.

## Quote

*Building a seamless connection between policy and public satisfaction is the cornerstone of effective asset management.*

## Demographic

Male 36 years

Amsterdam

Divorced

Asset owner of a tunnel in the Netherlands

## Background

Peter van den Bergt is a dedicated asset owner employed by the province of Noord Holland. With a solid background in civil engineering and extensive experience in infrastructure management, Peter is committed to upholding the province's policies and strategic goals within the realm of tunnel assets. He understands the importance of maintaining the tunnels in optimal condition to ensure the safety and convenience of the public. Peter's expertise and proactive approach enable him to address any potential issues promptly and effectively, striving to minimize complaints from civilians and enhance their overall tunnel experience.

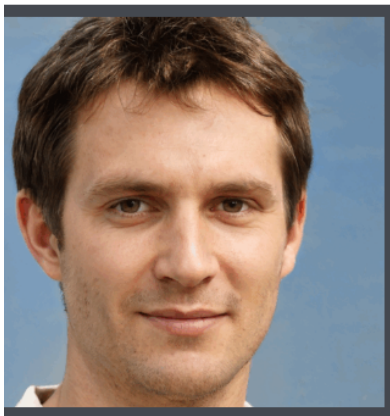
Figure A2. Persona representing the asset owners, from UXPressia

NAME

Sam Pelsen

TYPE

**Specialist**



## Goals

Efficiently complete tasks without getting lost in unnecessary details or delays, for a nice flow of progress.

Put in the necessary effort during work hours, but also prioritize enjoying personal time outside of work, embracing a healthy work-life balance.

## Quote

*Roll up the sleeves, cut to the chase, and make it happen. Getting things done with efficiency allows for a satisfying workday.*

## Demographic

Male 35 years

Beverwijk

Married

Service Provider at a maintenance company

## Background

Sam Pelsen is a skilled maintenance worker specializing in the upkeep of construction assets. With years of experience in the industry, Mark possesses a deep understanding of the importance of efficiency and progress. Known for his ability to streamline tasks and avoid unnecessary delays, he ensures that projects move forward smoothly. While he is dedicated and hardworking during work hours, Mark also values his personal time and believes in maintaining a healthy work-life balance. This perspective allows him to approach his responsibilities with renewed energy and enthusiasm, ultimately benefiting both his professional and personal life.

Figure A3. Persona representing the service provider, from UXPressia

# Appendix B – Co-Creation Session

## B.1 Ideation Techniques

Several ideation techniques were utilized during the co-creation sessions, depending on the activity:

- **Warming up:** Two activities took place, each taking +-3 minutes.
    - Alternate uses: Participants are asked in turns to name a different use for a common object (e.g. pen). After naming a use, they give the object to the person next to them, who then has to name another use.
    - Pictionary: In turns, participants get one minute in which they can draw as many objects as possible that are provided on an instruction card. Other participants have to guess what these objects are before they can start drawing another one.
- **Ideation:** To stimulate participants to look at the topic from different angles, two ideation techniques were used in addition to vocal brainstorming and using post-it notes.
    - Reverse thinking: Instead of thinking about what can be done to solve the problem, participants are asked to name what they can do to make it worse or achieve the opposite. Reversing these ideas can help identify new solutions.
    - Brainwriting- and drawing: In an adaptation of the 6-3-5 method in which six participants write down three ideas on a worksheet in five minutes, the 3-5 participants are asked to draw or write down four ideas on a worksheet in four minutes. After these four minutes, the sheet is given to the person on their right, who uses the next four minutes to add four more ideas to the sheet. By using the previous ideas as inspiration, they can come up with new ideas or build unto the existing ones.
- **Evaluation:** Role-playing in a scenario is used to observe the impact of the ideas. The prototypes are tried out in scenarios that are based on the context of the problem statement. To provide extra guidance, each participant is given a specific role they can follow. The role-playing provides quick insights in intuitive use and usability of the prototypes.

In case participants had a hard time coming up with ideas, creating a prototype, or other obstacles occurred, there were backup ideation techniques to use.

- **Bodystorming:** Similar to role-playing, the problem context is used to enact a scenario. In bodystorming, participants are asked to define three possible scenarios that can take place and think of issues that can occur before enacting the scenarios. One participant serves as observer and can freeze the situation and create "what-if" scenarios to follow inspiration.
- **Bad ideas:** Similar to reverse thinking, instead of looking for a solution the aim is to make it worse. What can be done to increase the problem, create new problems, etc.
- **Inspiration cards:** From a pile of 20 cards with random images, a participant can draw one and use that card as inspiration for a new idea. They can focus on what stands out the most and combine that with the problem statement.
- **What-if:** Sometimes it can help to look at different perspectives; when imagining varying conditions using the "What-if" prompt, this can be done.
- **Yes, and…:** This is a useful technique in case one participant is being rather negative. Instead of breaking down an idea, they have to add to it by following one's idea with "yes, and…" and their thought.

## B.2 Codes & Themes

Table B1. Overview of codes used in the thematic analysis of the co-creation sessions

| Code | Subgroup | Meaning | Freq. in session… | |
|---|---|---|---|---|
| | | | #1 | #2 |
| **Positive** | Sentiment | Positive outcome or feeling | 22 | 6 |
| **Negative** | | Negative outcome or feeling | 39 | 17 |
| **Quote** | Functional | Useful to quote in the thesis | 11 | 36 |
| **Outlier** | | Off-topic or not in line with other participants | 13 | 5 |
| **Example** | | Descriptive paragraphs used to highlight statement | 41 | 29 |
| **Change Point** | Problem Statement | Wish to adapt the existing problem statement | 4 | 1 |
| **Refer to Point** | | Point is made about the existing statement | 7 | 9 |
| **New Point** | | A new point is suggested | 8 | 6 |
| **Remove Point** | | An existing point is suggested to remove | 0 | 0 |
| **Requirement** | Design Implication | Element identified as requirement in the design | 31 | 26 |
| **Expectation** | | Expected effect of a feature or function | 29 | 28 |
| **Wish** | | Suggestions and other non-essential wishes for design | 65 | 40 |
| **Collaboration** | Social Mediation | People actively working together | 58 | 26 |
| **Information** | | Stating which information is needed, acquired; questions that need to be answered | 128 | 89 |
| **Alignment** | | People aligning their views or information basis | 51 | 26 |
| **Decision-making** | | What is needed to make a decision, when or why a decision is made | 49 | 56 |
| **Sustainability** | | Sustainability factors that can be focused on, or matters that are important when considering sustainability | 43 | 53 |

## B.3 Brainstorm Ideas (Digitized)

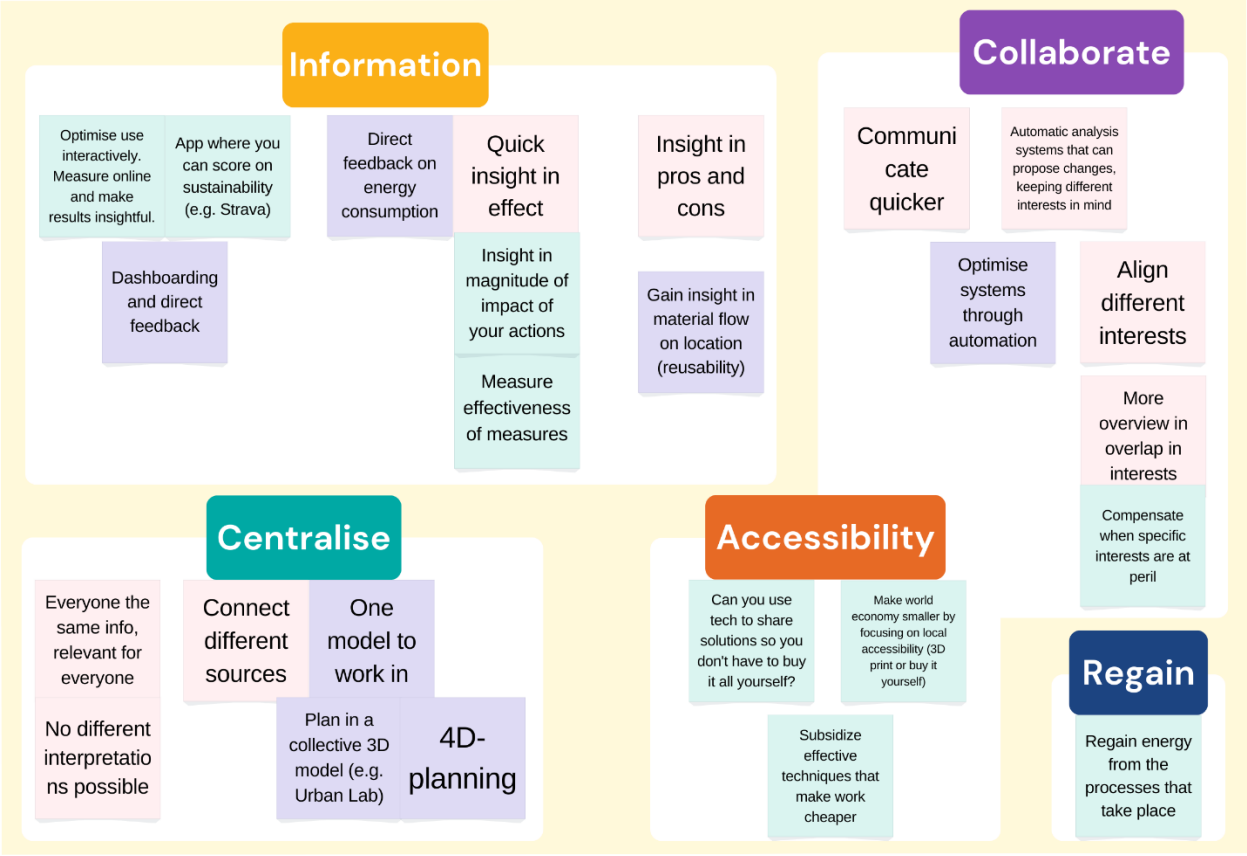



Figure B1. Digitized version of post-it exercise of session 1 (translated from Dutch)

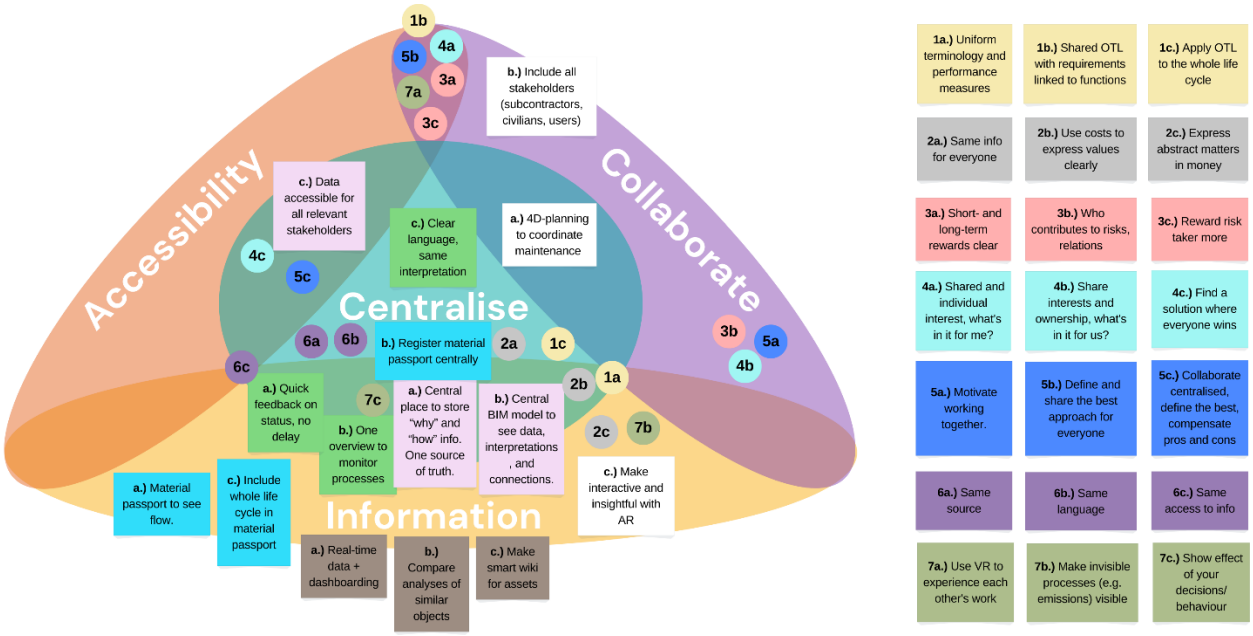



Figure B2. Digitized version of the brainstorming exercise of session 1 (translated from Dutch)

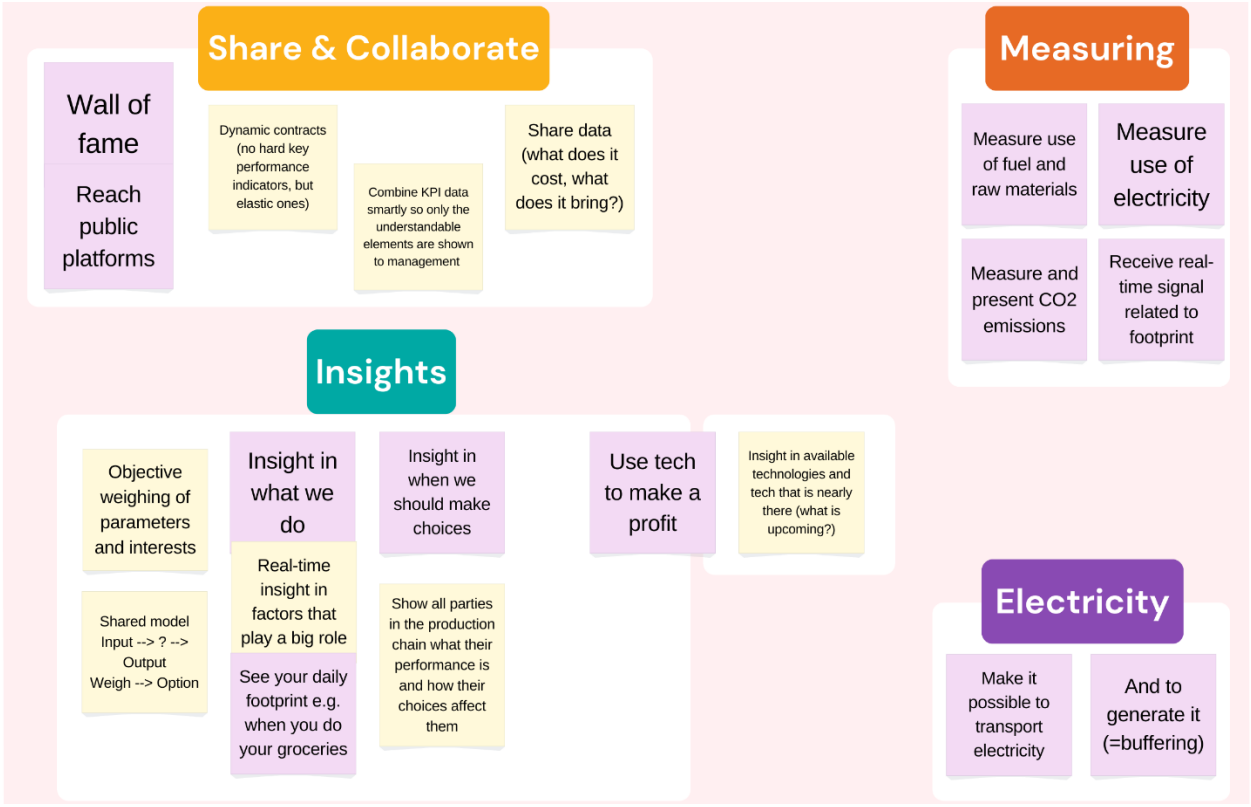



Figure B3. Digitized version of post-it exercise of session 2 (translated from Dutch)

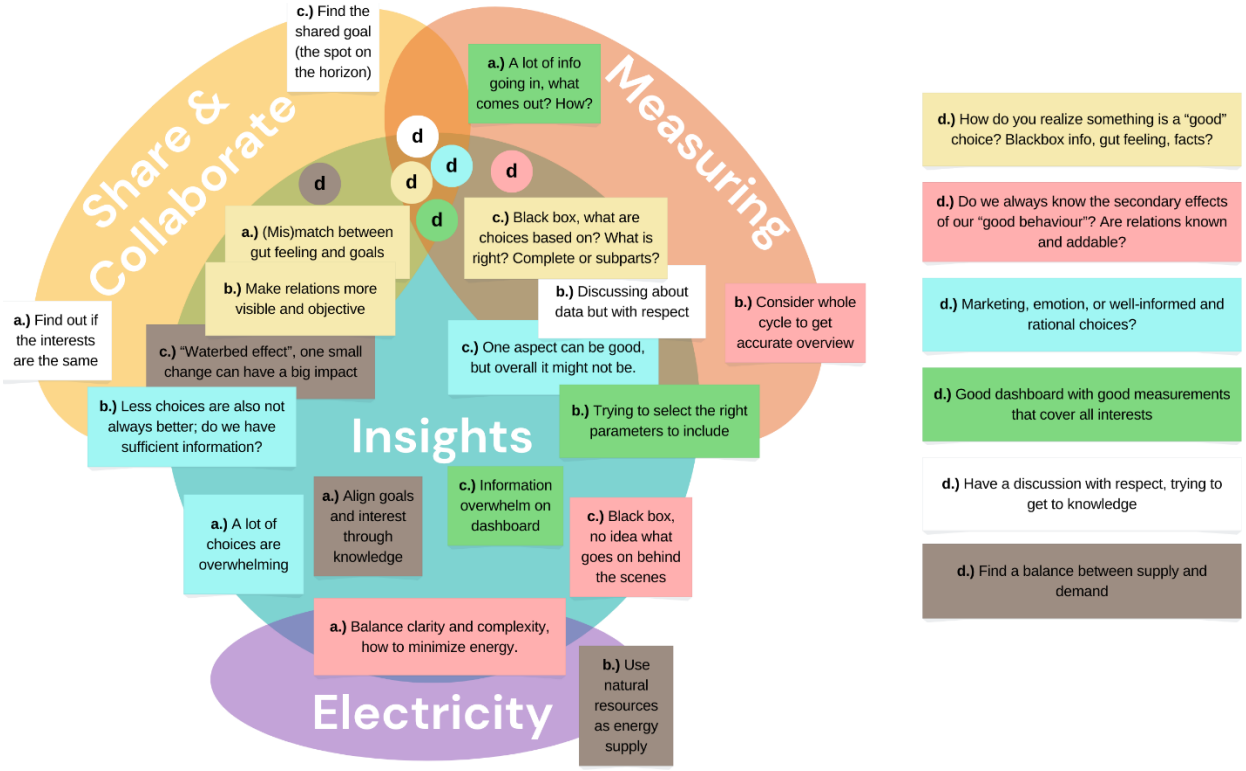



Figure B4. Digitized version of the brainstorming exercise of session 1 (translated from Dutch)

## B.4 Prototype Descriptions

Table B2. Description of prototypes made during co-creation sessions.

| ID | Idea Description | Observations / comments |
|---|---|---|
| **S1_1** | Handheld device to use during inspection, connected to 3D model in the office. Used by inspectors to get relevant information on-site but staying connected with "the office".<br>**Information**: Historical (materials, purpose of component, previous inspection) and real-time (condition, other sensor data) | • Swiping and scrolling to interact with handheld<br>• Use gestures to explain observations<br>• Expected information about inspection (goal, location, action, context)<br>• Face-to-face communication preferred over talking via devices |
| **S1_2** | 4D-application covering the whole life cycle of an asset in a timeline; from planning and maintenance to disposal. It can be used to simulate design and solutions.<br>**Information:** Historical (initial materials, materials replaced, reusable materials) and real-time (condition of materials) | • Felt similar to S1_1 but with focus on materials<br>• 3D model only useful if there is extra info or a cross-section view<br>• Expected confusion about status of material at start vs. end of life cycle |
| **S1_3** | AR glasses with buttons to filter and see specific info about specific components on-site. Gain insight in current status, find out cause of errors, communicate with office.<br>**Information:** Real-time (condition & emission of components, temperature, life cycle status) | • Purely real-time is hard to trust, data might be ignored by experts<br>• Showing were data comes from helps<br>• Use it for more efficient inspections<br>• Make it easy to update, little steps needed (with sensors and scanners) |
| **S2_1** | A visualization of the complexity of decision-making. When you change one thing, it will affect many other things you are probably not aware of ("waterbedeffect").<br>**Information:** Real-time (condition, consumption, emissions) | • A lot of face-to-face communication<br>• Little use of prototype during evaluation, using decision matrix to work on scenario<br>• Gesture towards matrix to illustrate options and suggest a solution |
| **S2_2** | Showing the true price of products; not only financial value but also ecological impact, societal value, etc. Allow people to compare products according to these prices.<br>**Combine with S2_1:** Use S2_1 to indicate your priorities and values, so only products that suit your interests are shown.<br>**Information:** Historical & real-time (different costs made for materials, maintenance, transport, compensation; emissions, insight on work conditions, life cycle, etc.) | • Complex concept, priority is evoking trust<br>• Use of app to fill in options and preferences, get suggestions based on these factors – use button to tweak<br>• Use location tracking to give real-time suggestions<br>• A lot of focus on getting all the details |

# Appendix C – Lo-Fi Phase

## C.1 Initial 14 Ideas

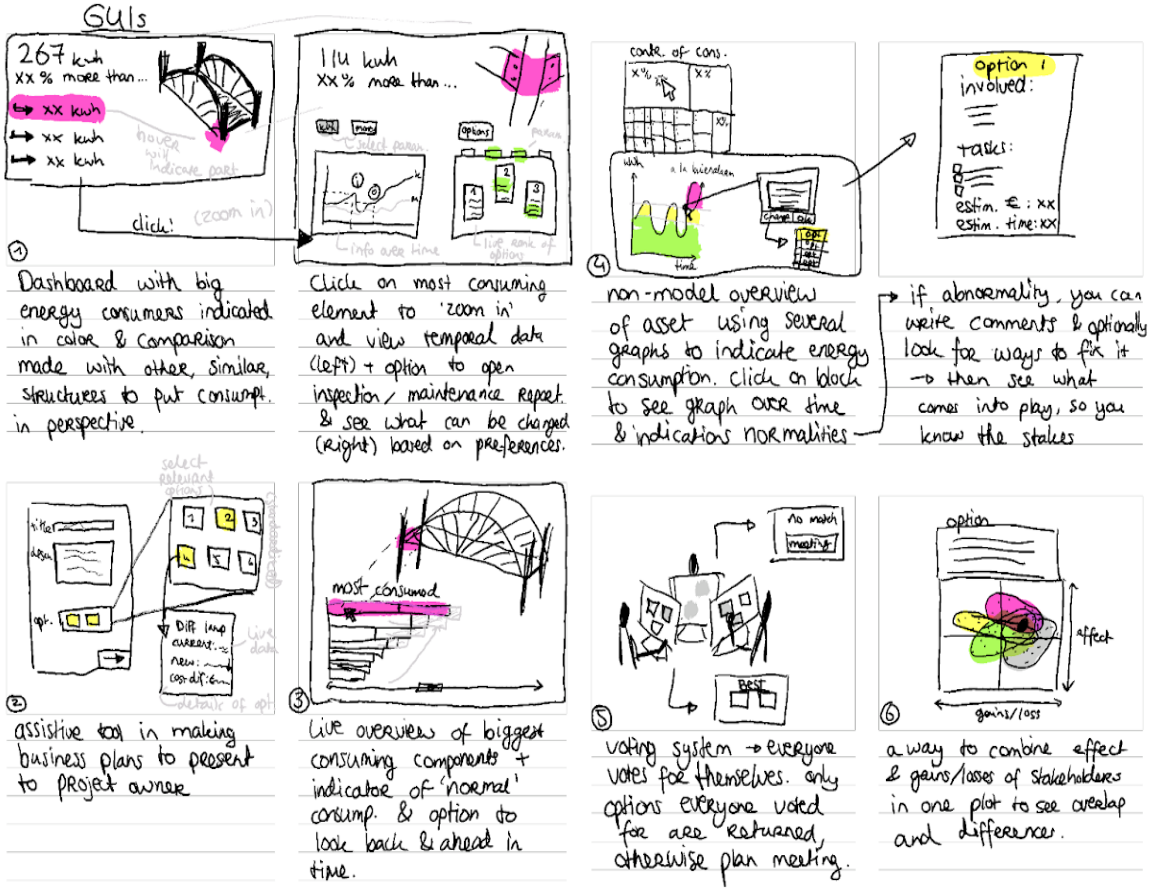



Figure C1. Sketches of the six ideas focused on a graphical user interface, made with the Remarkable 2

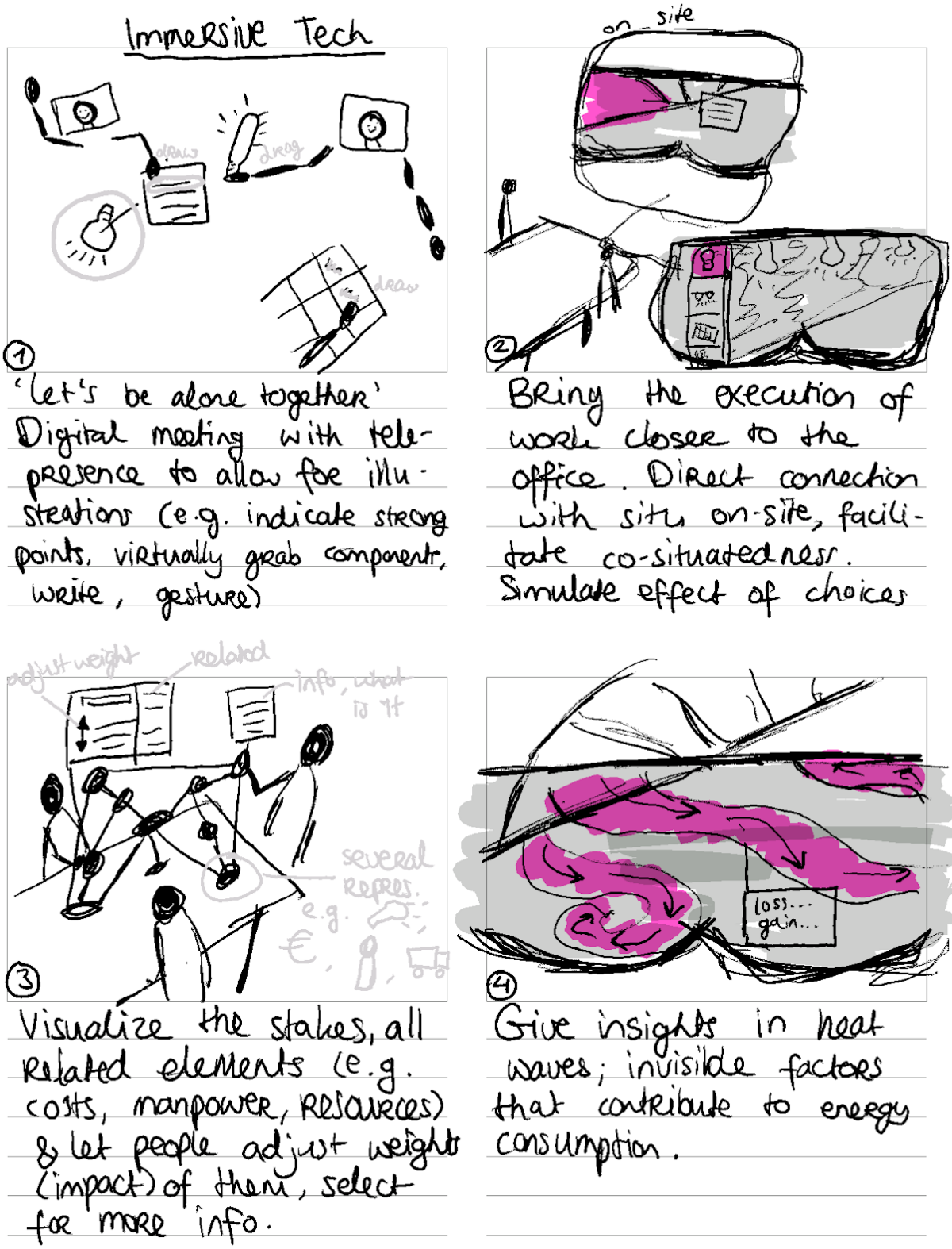



Figure C2. Sketches of the four ideas focused on a immersive technologies, made with the Remarkable 2

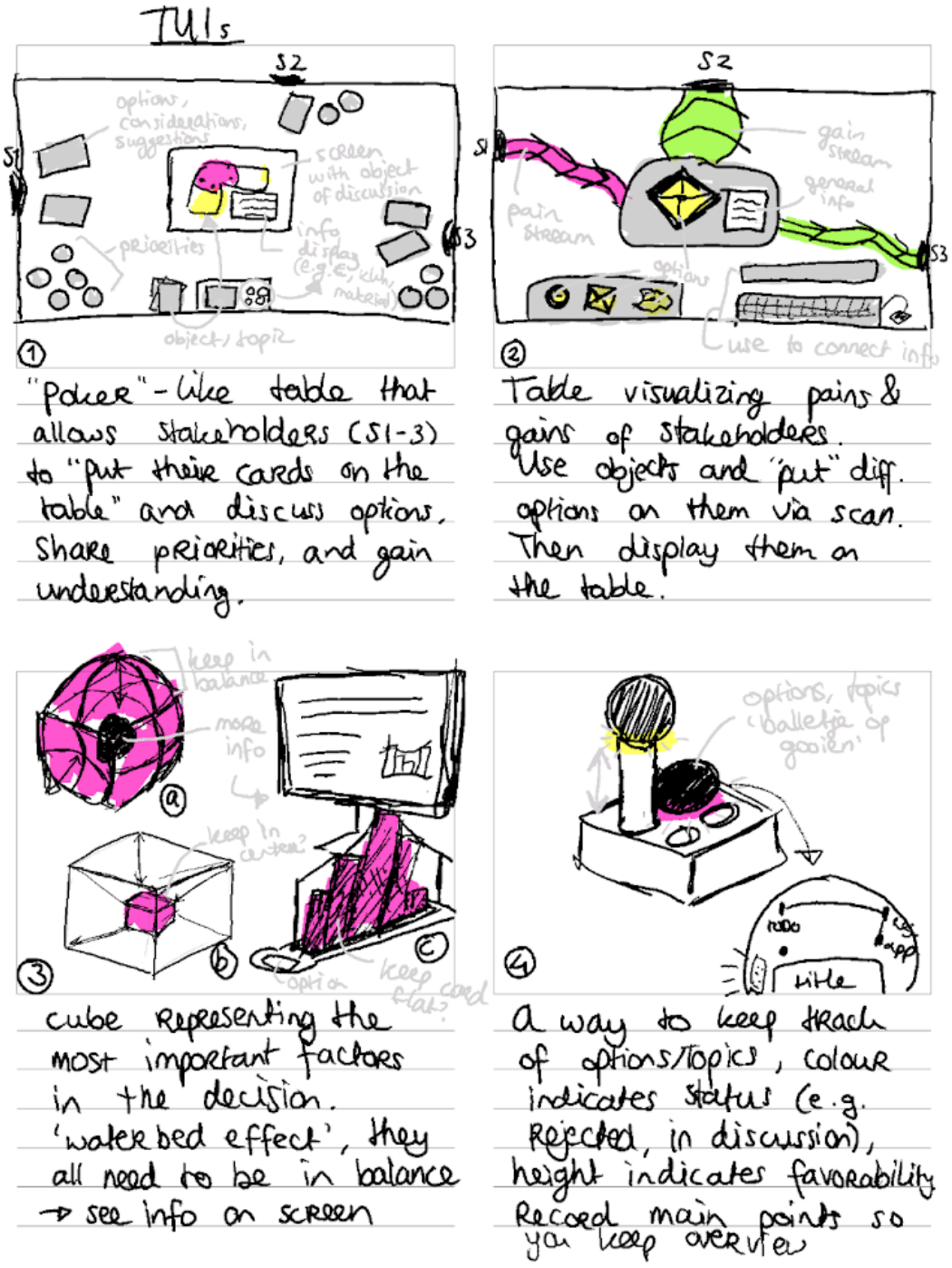



Figure C3. Sketches of the six ideas focused on a tangible user interface, made with the Remarkable 2

## C.2 Paper Prototype Sketches

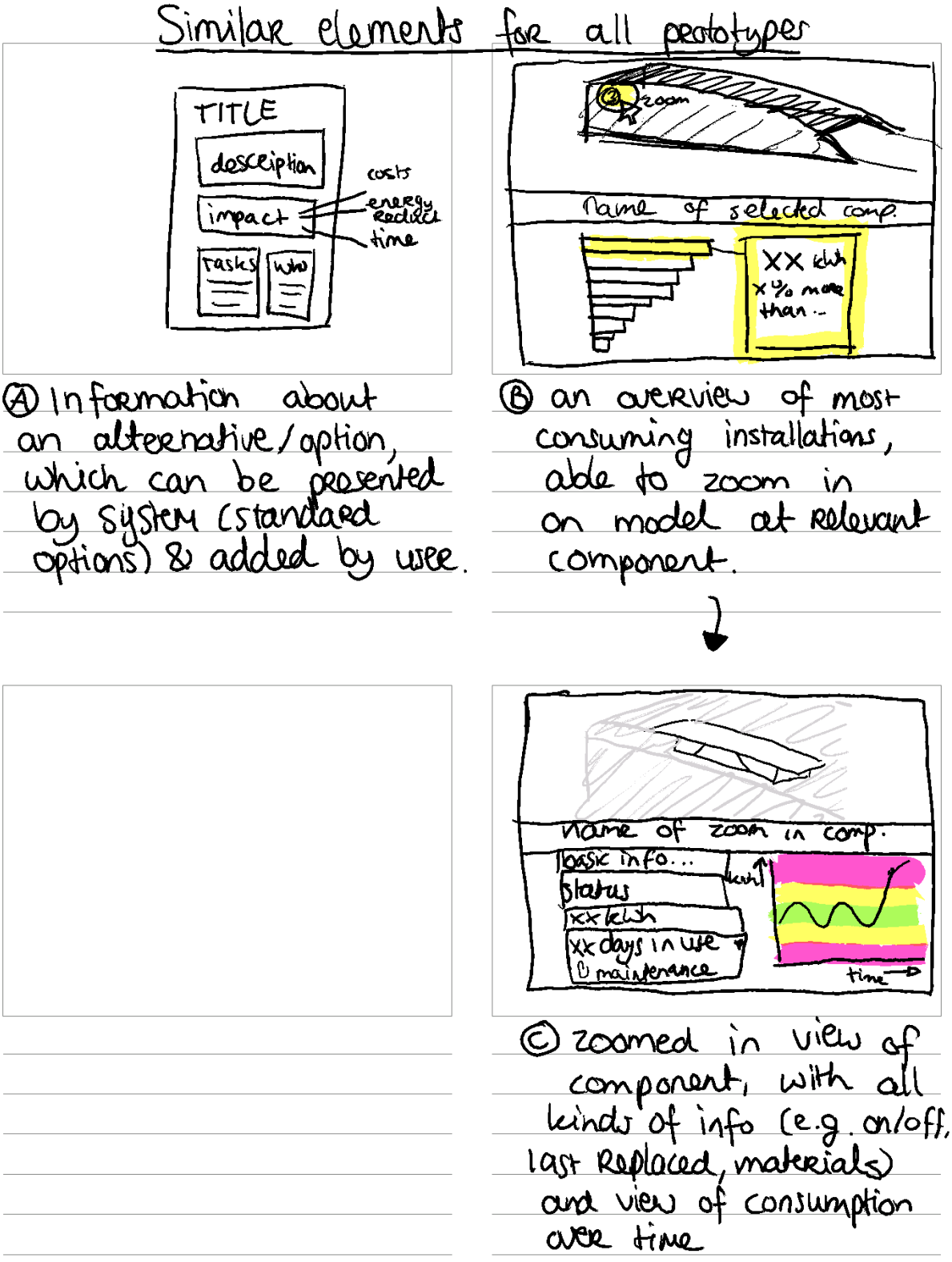



Figure C4. Sketches of the standard pages used in the paper prototype, made with the Remarkable 2

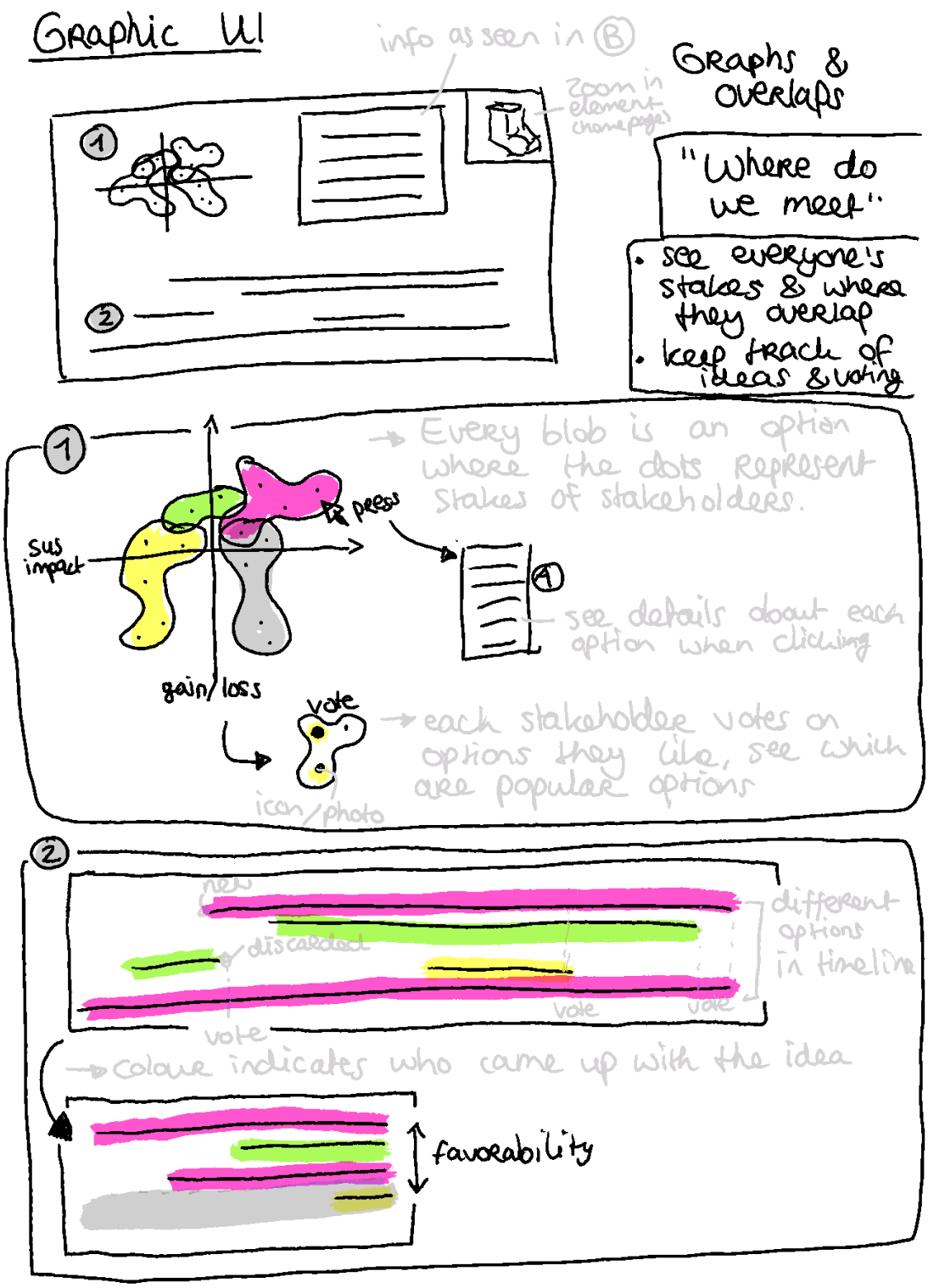



Figure C5. Sketches of the graphical user interface paper prototype, made with the Remarkable 2

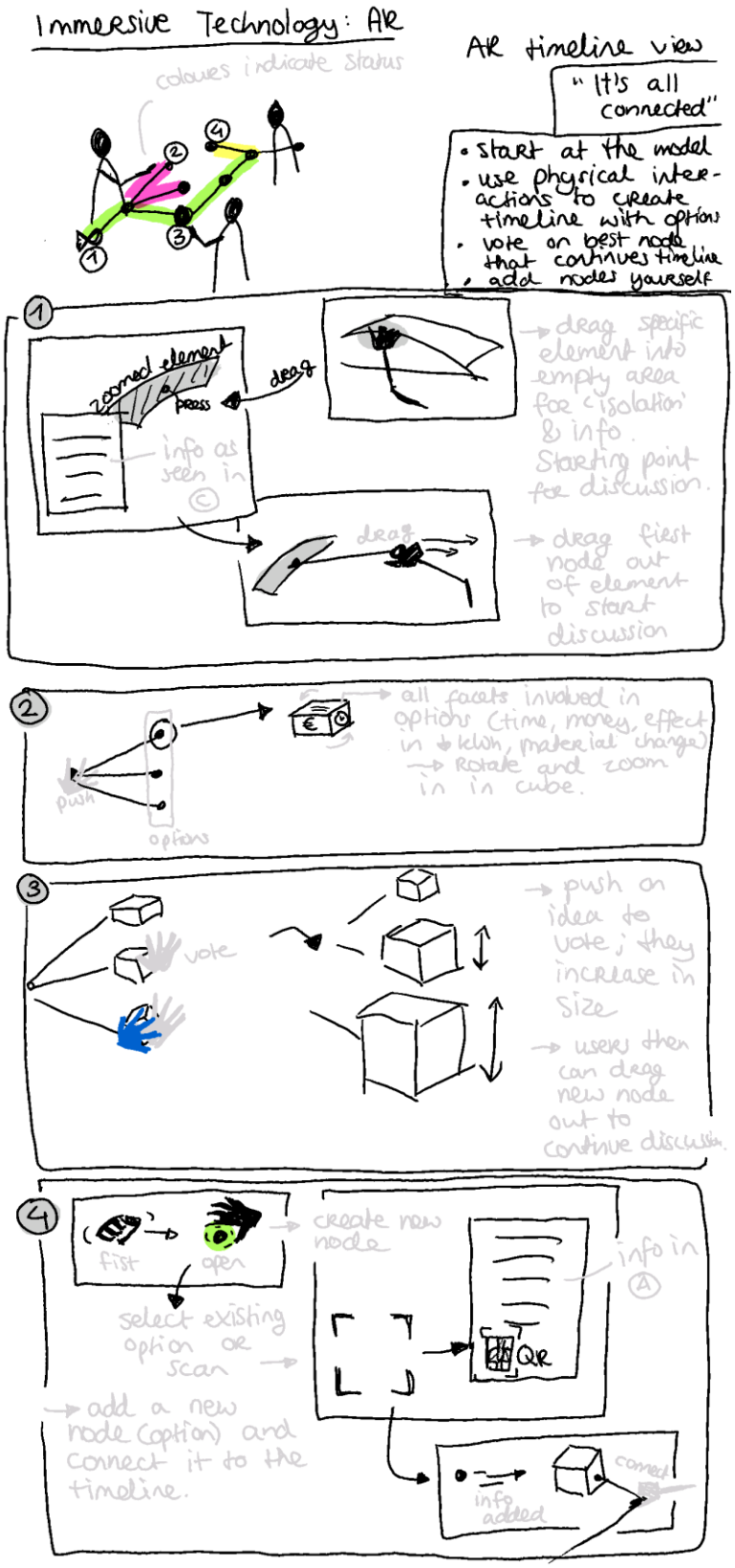



Figure C6. Sketches of the immersive technologies paper prototype, made with the Remarkable 2

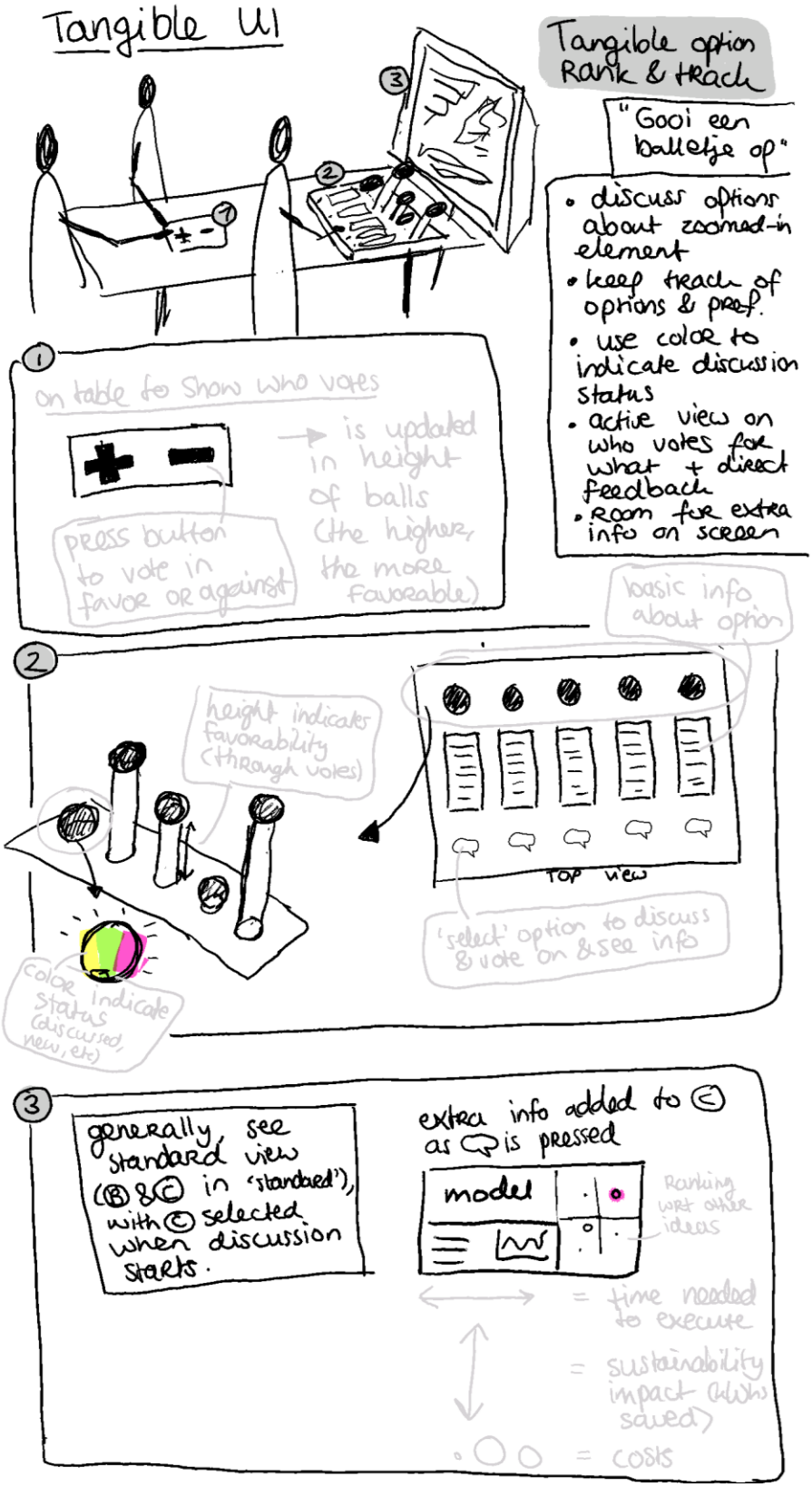



Figure C7. Sketches of the tangible user interface paper prototype, made with the Remarkable 2

## C.3 Lo-Fi Evaluation Summary

Table C1. Summary of the Lo-Fi evaluation sessions, grouped per topic and coloured per theme

| | | |
|---|---|---|
| **General Questions** | | |
| **Age** | 33-64 years, average 48 years | |
| **Occupation** | Consultant (3x), manager (2x), project leader (1x) | |
| **Years Experience** | 6-28 years, average 17 years | |
| **Experience Tech** | Average | • The interest is there, but it's not as easy anymore<br>• Experienced 'for an older guy'<br>• No early adaptor<br>• Knows in theory what it is about |
| | Above average | • Can program a little bit<br>• Can model a little bit |
| **Decision-Making Strategy** | Facts-Based | • Create an overview, weigh options and trade-offs (3x)<br>• Discuss facts with people in the field (1x) |
| | Feelings-Based | • Think about the added value (2x) |
| **Standard Pages** | | |
| **Main Page A** | | |
| Two participated highlighted that this page is good for **strategic** asset management (or for an asset owner), you can include KPIs (key performance indicators) and risk analyses to make it more precise. Although the page is not new in the industry, it is new in the infrastructure sector that lags behind in technological innovations. One participant suggested expanding the use case of energy consumption to circularity as well, since that is also upcoming.<br><br>Participants were critical of the comparison with other assets, stressing that "you should know what you are comparing". Focus on normal use (excluding calamities or exercise) and consider comparing with previous years, other assets, or nationwide averages. It is necessary to normalize energy consumption per km tunnel while taking into account the shape and angle of the tunnel as well. Therefore, it is wise to include a margin of uncertainty. Furthermore, it could be good to look at examples of energy consumption dashboards (e.g. Eneco, Pure Energie) to see how they compare. | | |
| **Main Page B** | | |
| A participant highlighted that this page is good for **tactical** asset management as it can help explain why specific choices are made. The page was received well; participants pointed out that the historical trend curve with coloured areas is clear. One participant stressed that you should really focus on one component; so not a group (i.e. a single light, not a light group). | | |
| **Main Page C** | | |
| A participant highlighted that this page is good for **operational** asset management as it clearly shows what must be done - for the "why" you can go to Page B. Participants had some suggestions, like including 'availability' and 'reliability' as factors and plotting the expected results of proposed options over each other to see differences clearly. One participant suggested reasoning the other way around: from X budget and FTEs, what are the options that are left? One participant indicated that the point of contact beside tasks did not feel useful. Lastly, a participant stressed that it is necessary for users to be able to add options themselves to allow for flexibility and a feeling of autonomy. | | |
| **Prototype Discussions** | | |
| **Graphical User Interface** | | |
| Although G is the most conventional technology, all participants found the prototype a bit overwhelming. It was crowded with a lot of information and elements, and the information was complicated. Therefore, participants saw it as a tool for more complex situations. Two participants suggested using the prototype when complex interests arise and gut feelings should not interfere, one suggested using it for long-term decisions. One participant stated that, after taking it all in, it was quite clear. They saw a strong link with Main Page B, where G is the people-focused side and B is the information-based side. | | |

The timeline stood out most for half of the participants, seeing it as a way to make the playing field of each strategy more insightful. For two participants, it should help visualize when strategies can be implemented and how long they take. One participant would use it to see how valuable the input of all stakeholders is, by looking at whose ideas are still in the running, and who has suggested most ideas. Some participants, however, did not see this use. One was unclear about its functionality, and one other participant stated that "it is a nice element but it will not be used".

The interest graph sparked more discussion. Some participant expressed that it is a nice idea, but very difficult to keep objective, as the information source is either very limited or very biased - "How do you measure gains or losses?". One participant identified the risk of it being too transparent, sharing interests that should not be shared with everyone. One participant also questioned whether it was useful at all, as "it is not a democracy, who thinks what does not matter". However, they did state that "you do have different interests" in there. They suggested that adjusting the parameters to see which parameters affect stakeholders the most might be a nice alternative function. Additionally, it can be useful to see what is most important for stakeholders when making a decision. However, a stakeholder analysis can also help with some of that.

**Immersive Technology**

Generally, participants liked the prototype and found it "cool" and "futuristic", seeing themselves using it with an AR or VR headset. However, this was also the downside of the prototype. Three participants questioned whether people would be able to use it well, asking "are people ready for this?". Most participants saw a risk in the network getting too complex and overwhelming if people can add new cubes continuously, leading to never ending discussions. It would become "too clear and detailed". However, they did think it would work well in quicker and simpler discussions, as adding new points and including small comments is rather easy. As one participant stated: "If it saves me work, then it is awesome!"

Most participants appreciated the gamified nature of the prototype (especially slapping the cubes) and said that the use of simple, more abstract shapes help simplify discussions. Three participants indicated that creating your own network helps create more depth in the discussion, as it "opens the room for the 'why', much like opening the hood of a car to inspect it". However, participants missed the documentation of the 'why' once the discussion has been wrapped up.

Some suggestions were made to help structure the discussion a little bit. Providing an overview of which parameters can be found where can help show what kind of information is available. Letting the network adjust itself to priorities could de-complexify the prototype a little bit, by only showing what is prioritized. Lastly, a participant suggested collecting data about the stakeholders' preferences and thoughts, so you can retrieve that data when you have a different meeting with different stakeholders.

**Tangible User Interface**

Participants were quite positive about this prototype, appreciating the clear overview and straightforward interactions. All elements can be seen at once, are easy to interpret, and the voting button is easy to use. One participant did indicate that it might become a bit too much if you have more options, especially because the info screen is small, but they did affirm that it is clear what everything means. Participants liked the playful feeling of the prototype, suggesting to elaborate it further, especially because the interactions are currently limited. For example, hitting the balls to vote (similar to hitting a cube in I) or being able to pick up a ball to discuss.

Participants saw the prototype as a good tool to weigh and discuss options, seeing how much each parameter contributes to the solution, and helping with a rational solution. It is less helpful for actually making a choice, as there is no endpoint. One participant saw it differently, stating that the discussion might be limited because the height of the balls already indicates which strategy to choose. Furthermore, a participant pointed out that voting with one central button might be intimidating if you have an "unpopular" preference. Individual voting buttons might be better.

There were some suggestions to provide and preserve more information while using the tool. Instead of providing an overview of strategies, one could present an overview of arguments to also include the "wisdom of the minority". The reasoning behind choices made (e.g. context, ratio, arguments) should be collected. Ideally, this can also be retrieved so that follow-up meetings can access this information as well. Adding labels on the data points of the graph that quantify the favorability of an option would help communicate data more objectively.

Furthermore, it would be nice to adjust the axes of the graph to the priorities of the asset owner, so you always consider their perspective. This helps present a suitable strategy to the asset owner. Lastly, it would be nice to adjust the colour codes of the balls, so you can sort or filter based on topic, status, arguments, etc.

**Ranking**

| Criterium | G (Idea) | G (Tech) | I (Idea) | I (Tech) | T (Idea) | T (Tech) |
|---|---|---|---|---|---|---|
| Generally | 2.50 | 1.88 | **1.67** | 2.13 | 1.83 | 2.00 |
| Aesthetics | 2.44 | 2.00 | **1.76** | 2.00 | 1.80 | 2.00 |
| Ease of use | 1.48 | **1.33** | 2.20 | 3.00 | 2.12 | 1.67 |
| Novelty | 2.75 | 3.00 | 1.38 | **1.33** | 1.88 | 1.67 |
| Compromise | 2.70 | 2.33 | 2.50 | 2.67 | **1.00** | **1.00** |
| Collaboration | **1.60** | 1.63 | 1.80 | 2.25 | 2.60 | 2.13 |
| Total average | 2.25 | 2.03 | 1.88 | 2.23 | **1.67** | 1.74 |

**Strengths & Weaknesses**

**Graphical User interface**

| | |
|---|---|
| **Strong** | • Already common, so people know what to expect and what to do;<br>• Easy and quick to implement;<br>• Good for complex situations, you see what stakeholders want and collect historical information over time that helps in the debate; |
| **Weak** | • Complex visualizations;<br>• Difficult to collect stakeholder input as rational data, it is too transparent;<br>• Criteria are missing on what parameters are priorities;<br>• It does not feel useful to focus on stakeholder interests solely;<br>• A very flat and uninspired interface type;<br>• The added value of this prototype is uncertain; |

**Immersive Technology**

| | |
|---|---|
| **Strong** | • A playful, immersive, and futuristic prototype, that invites interaction;<br>• Attractive technology with good potential for visualizations;<br>• The properties of options are clearly visible;<br>• The network is clearly visible at once, it is easy to see information and preferences; |
| **Weak** | • The reasoning behind choices is not stored;<br>• Can become too complex, making the discussion go on forever and losing overview;<br>• Risk of power (someone hitting cube multiple times, everyone seeing what you vote);<br>• The added value of this prototype is uncertain;<br>• Size of cube is difficult to interpret objectively;<br>• Too futuristic, can be difficult to learn how to use; |

**Tangible User Interface**

| | |
|---|---|
| **Strong** | • Very clear overview of all options in one view, very recognizable and interpretable;<br>• The physical appearance evokes curiosity and playfulness;<br>• Safer to indicate preference here than in I, you can see how people respond; |
| **Weak** | • The reasoning behind choices is not stored;<br>• Risk of power (keeping the voting button to yourself);<br>• Autonomy of user feels limited;<br>• There is a low focus on information, and some of the info is not quantitative; |

# Appendix D – Hi-Fi Phase

## D.1 Hi-Fi Sketches

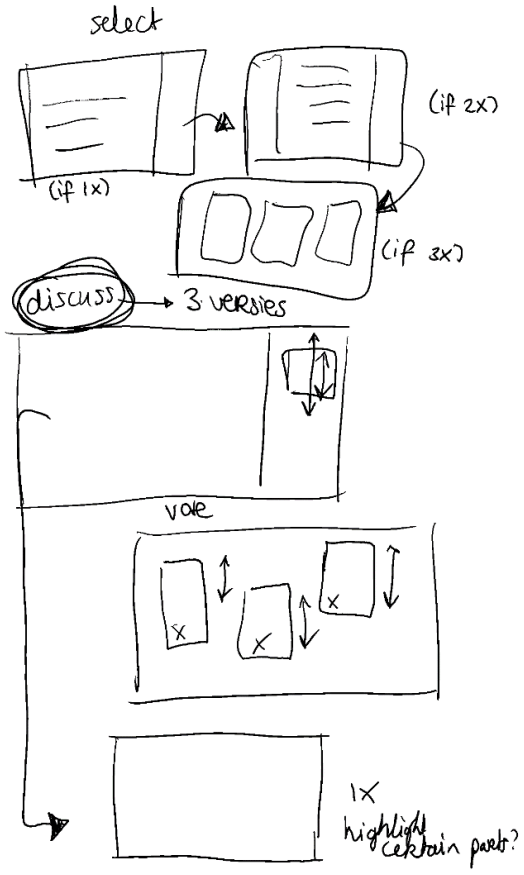



Figure D1. Sketches for the dashboard screens.

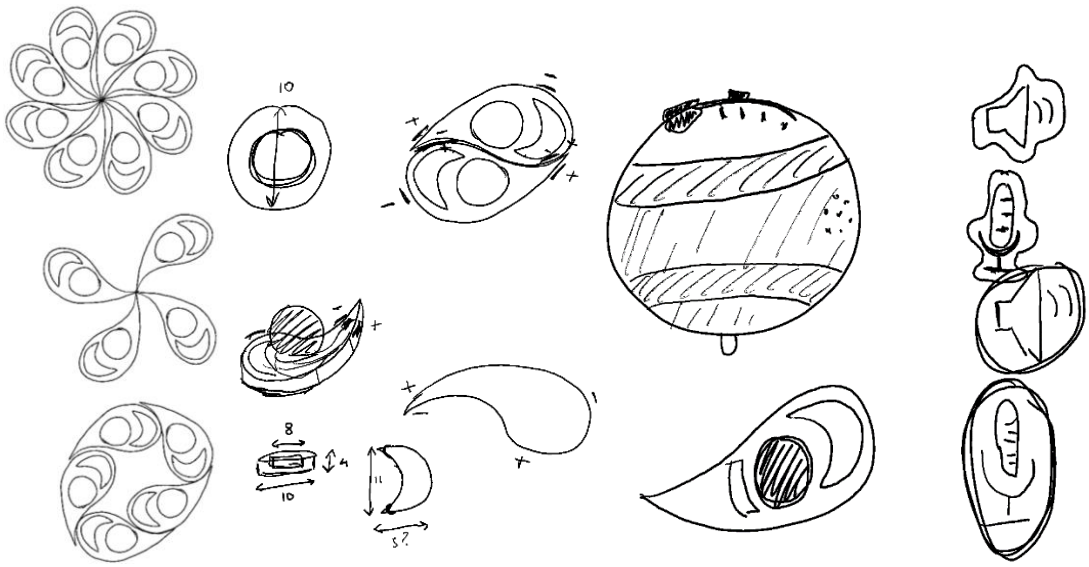



Figure D2. Exploring the possibilities of the teardrop-like shape of the balls and the interactions on the balls.

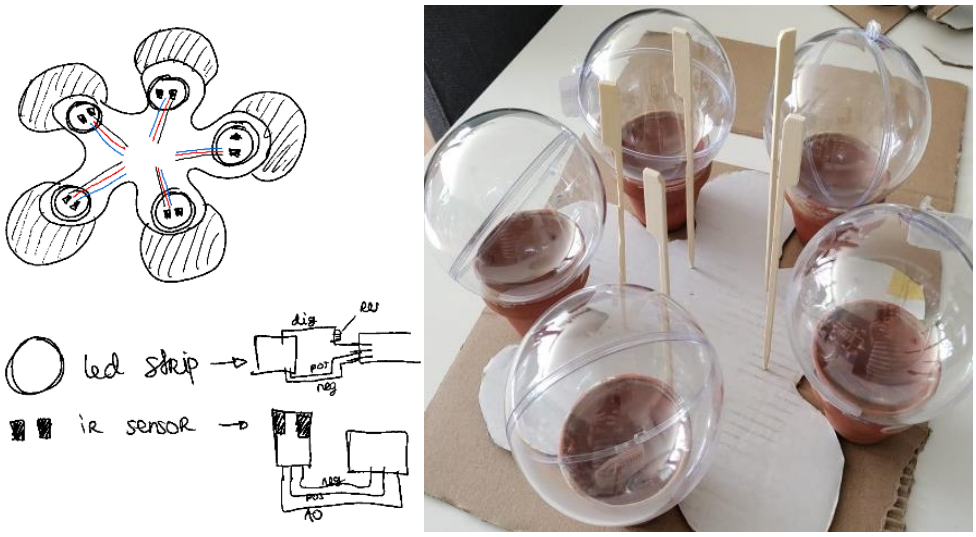



Figure D3. Sketch and resulting paper prototype of the new Hi-Fi ideas.

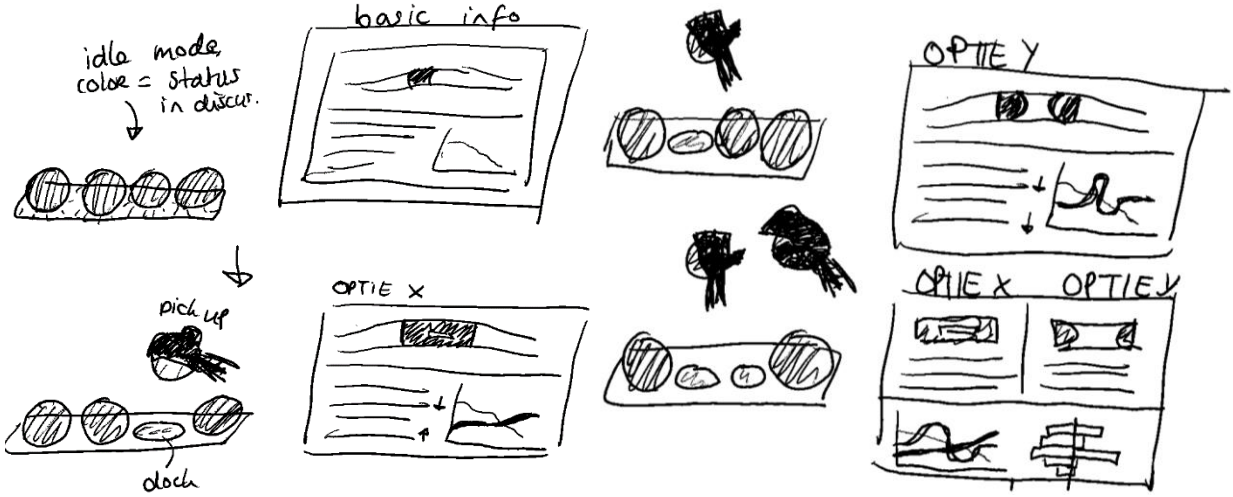



Figure D4. Sketches trying out the link between the interactions and the screen.

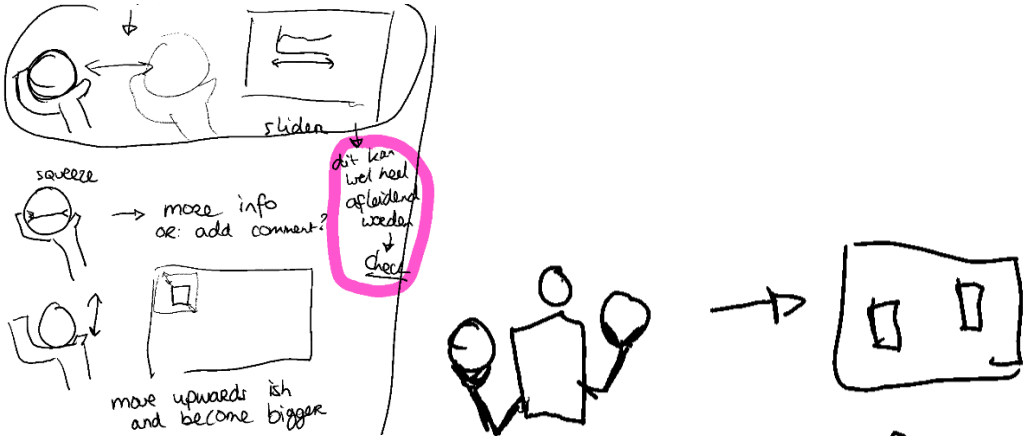



Figure D5. Exploring ways to expand the embodied interactions with the balls.

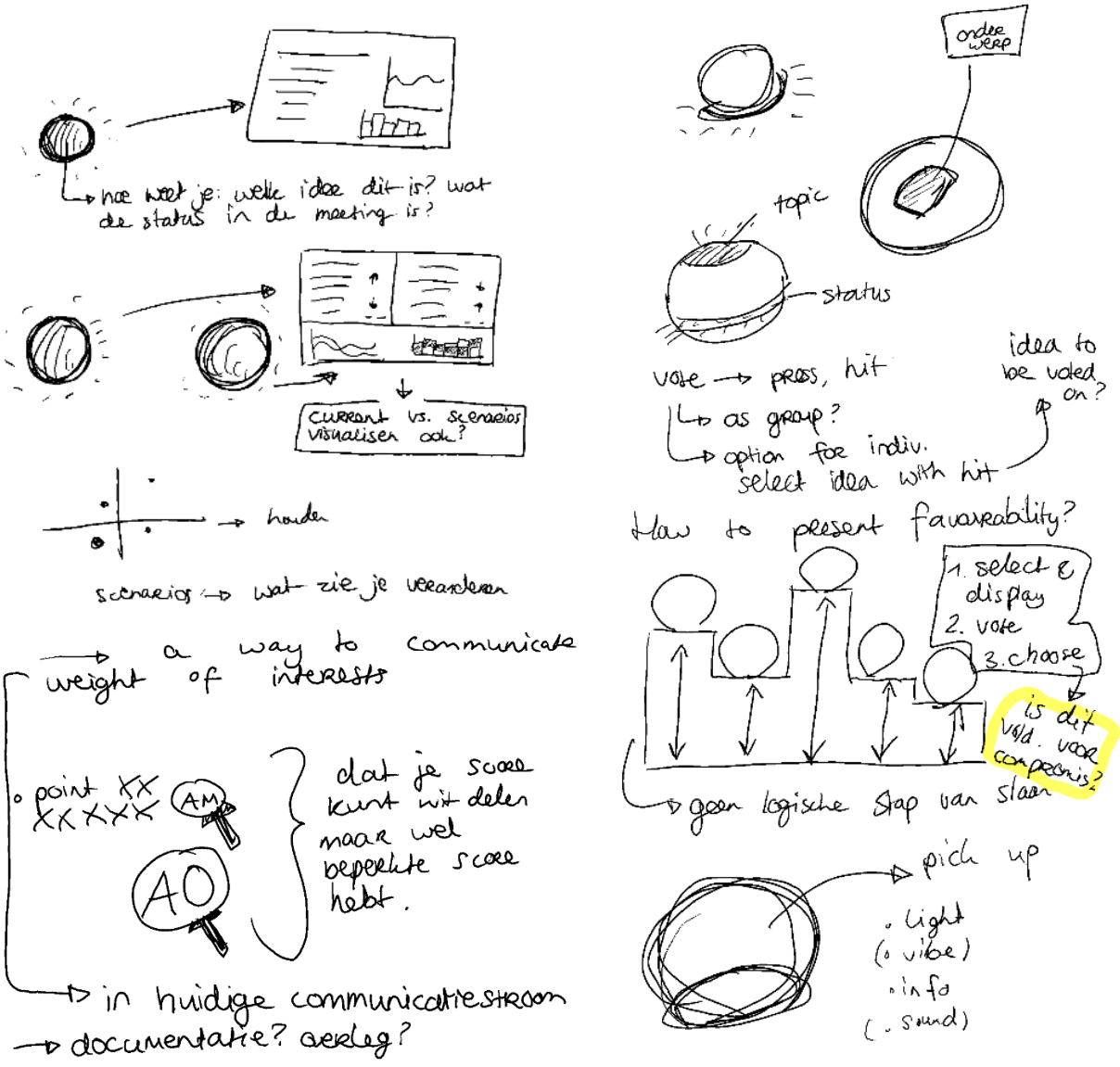



Figure D6. Exploring the ways to visualise context and stakeholder preferences.

## D.2 Fake Dashboard Data

Table D1. Overview of ChatGPT prompts and outputs used for the creation of fake data, all in one conversation.

| Goal | Prompt | Output |
|---|---|---|
| **Strategy** | Imagine I manage a tunnel with lighting, and I want to make it more sustainable.<br>**1.)** What other kind of lighting could be an option beside LEDs?<br>**2.)** Do you have another option that fits this context?<br>**3.)** Besides renewable energy, optimal use of lighting, and different lighting, what are other ways of reducing energy consumption in a tunnel? | A list of options with brief descriptions of 2-3 sentences.<br>**1.)** 5 options, "induction" was added.<br>**2.)** 8 options, "Renewable energy" and "Optimal use" were added.<br>**3.)** 8 options, "Daylight use" was added. |
| **Summary** | **Provide description of research goal, stakeholders, and expectations of each option**<br>**1.)** Could you write a description about each option in 2-3 sentences?<br>**2.)** And in 50-100 words? Add information about the costs and gains and write it in an informing way, so they can be put on a dashboard and support a discussion. | **1.)** A list of six strategies with title, short description, and one sentence explaining what needs to be done.<br>**2.)** Six descriptions that describe the strategy and its pros and cons in terms of financial, sustainable, and long-term investments. |
| **Scenario & Roles** | **Provide a very elaborate description of research progress: research goal, problem statement, stakeholders, compromise theory, prototypes, goal of evaluation. Also provide a description of the fake tunnel, scenario, viewpoints of the stakeholders, and prototype interactions.** I have the factors of energy consumption, asset availability, lifecycle changes, maintenance frequency, and energy, maintenance, material, and installation costs.<br>**1.)** Could you help me write a realistic scenario that spread these factors realistically & relatively evenly over the stakeholders as a priority? | **1.)** A scenario title, background, and overview which describe what has happened and why the "meeting" has been planned. A role description for each stakeholder, listing their tasks, desires, and struggles. A list of 5 discussion points and 4 objectives that guide both the researcher and the participants. |
| **Performance values** | **1.)** How much maintenance do solar panels, LEDs, light bulbs, induction lighting, and daylight use require compared to each other?<br>**2.)** How do these compare in terms of energy use, maintenance costs and frequency, life cycle and malfunctions, installation costs, effort, and costs of the materials? | **1.)** Five descriptions, listing maintenance frequency and tasks in 1-2 sentences.<br>**2.)** The situation for each strategy is described in 1 sentence per criterion ("energy use", "maintenance costs and frequency", "lifecycle and malfunctions", and "installation costs, effort, and material costs"). |

Table D2. All fake data used in the dashboard.

| **Descriptions of each strategy (all in Dutch)** | | |
|---|---|---|
| **Strategy** | **Description (long)** | **Description (short)** |
| **Current: light bulb (Dutch: gloeilamp)** | Het verlichtingssysteem van de "Noord-Zuid VerbindingsTunnel" (NZVT) is strategisch geplaatst langs de gehele lengte van de tunnel, inclusief de in- en uitgangen, de hoofdrijbaan en eventuele nevenpassages. Het systeem maakt gebruik van gloeilampen voor een kostenbesparing en toegankelijke verlichting. Binnen de tunnel is het verlichtingssysteem opgedeeld in verschillende lichtgroepen, elk met specifieke regelingen voor intensiteit | - |

| | | |
|---|---|---|
| | en kleurtemperatuur om aan verschillende verkeersomstandigheden te voldoen, zoals daglicht of avondspits. Momenteel bevindt het verlichtingssysteem zich in een operationele status, zonder gemelde problemen. | |
| **1A: LED (now)** | Deze optie omvat een onmiddellijke vervanging van bestaande gloeilampen door energiezuinige LED-armaturen. Hoewel dit kan leiden tot afval van gloeilampen die nog niet het einde van hun levensduur hebben bereikt, resulteert het in aanzienlijke energiebesparingen en een lagere milieu-impact op de lange termijn. De implementatie houdt in dat gloeilampen direct worden vervangen door LED-armaturen, wat initieel hogere kosten met zich meebrengt maar op de lange termijn gunstig is voor zowel het milieu als de kostenbesparingen. | Onmiddellijke overstap naar energiezuinige LED's ter vervanging van gloeilampen, verminderen van energieverbruik en milieubelasting.<br><br>Uitvoering: Gloeilampen vervangen door LED-armaturen. |
| **2A: LED (6 months)** | Deze strategie omvat een stapsgewijze overgang naar LED-verlichting waarbij de huidige gloeilampen behouden blijven tot ze het einde van hun levensduur bereiken. Hoewel er minder verspilling van gloeilampen optreedt, kunnen hogere energie- en onderhoudskosten tijdens de overgangsfase worden verwacht. Uitvoering omvat het wachten op het einde van de levensduur van gloeilampen en geleidelijk vervangen door LED's, met de nadruk op kostenbeheersing en geleidelijke duurzaamheidsverbeteringen. | In een geleidelijke overgang worden gloeilampen behouden tot het einde van hun levensduur om verspilling te minimaliseren, terwijl de voorbereiding en installatie van LED-armaturen wordt gepland en uitgevoerd.<br><br>Uitvoering: Wachten tot einde levensduur van gloeilampen en vervangen door LED's. |
| **3A: Induction (Dutch: inductie)** | Deze optie omvat de directe vervanging van bestaande gloeilampen door inductieverlichting, een energiezuinig alternatief met een lange levensduur. Hoewel het vergelijkbaar is met LED in levensduur, kan inductieverlichting initiële installatiekosten met zich meebrengen, maar biedt het lagere onderhoudskosten en minder frequente vervangingen. De implementatie omvat het vervangen van gloeilampen door inductie-armaturen, met de nadruk op kostenefficiëntie en langdurige prestaties. | Directe vervanging van gloeilampen door inductieverlichting, een energiezuinig alternatief met een lange levensduur, wat resulteert in minder frequente vervangingen en lagere totale kosten.<br><br>Uitvoering: Gloeilampen vervangen door inductie-armaturen. |
| **1B: Daylight use (Dutch: daglichtbenutting)** | Deze optie houdt in dat daglichtsystemen zoals lichtkokers, lichtstraten of lichttunnels worden geïnstalleerd om de natuurlijke lichtinval in de tunnel te maximaliseren. Hierdoor wordt er minder gebruik gemaakt van verlichting, wat leidt tot energiebesparingen en een lagere milieubelasting op de lange termijn. Hoewel de initiële installatiekosten aanzienlijk kunnen zijn en de effectiviteit ervan weersafhankelijk kan zijn, vereist dit systeem weinig onderhoud en heeft het een lange levensduur. | Verbeter de daglichttoetreding in de tunnel door middel van lichtkokers, lichtstraten of lichttunnels. Dit maximaliseert het gebruik van natuurlijk licht en vermindert de behoefte aan kunstmatige verlichting overdag.<br><br>Uitvoering: Installatie van daglichtsystemen en lichtsturingen voor efficiënt gebruik van natuurlijk licht. |
| **2B: Optimal light use (Dutch: optimalisatie licht)** | Deze strategie richt zich op het minimaliseren van energieverbruik door gloeilampen minder vaak in te schakelen en de lichtintensiteit te verminderen zonder fysieke vervanging. Hoewel het geen ingrijpende | Verminder energieverbruik door lichten minder vaak aan te zetten en dimniveaus te verlagen, zonder fysieke vervanging. |

| | | |
|---|---|---|
| | verandering oplevert, kan het de operationele efficiëntie verbeteren en de levensduur van de verlichting verlengen. Uitvoering omvat aanpassing van schakeltijden en lichtintensiteit, met de nadruk op directe kostenbeheersing en geleidelijke duurzaamheidsverbeteringen. | Uitvoering: Aanpassing van schakeltijden en lichtintensiteit. |
| **3B: Renewable energy (Dutch: zonnepanelen)** | Deze optie betreft de installatie van zonnepanelen om duurzame energie te leveren voor tunnelverlichting. Hoewel de initiële investering hoog is, leidt dit op de lange termijn tot aanzienlijke energiebesparingen en een vermindering van de ecologische voetafdruk. Het kan de totale eigendomskosten verlagen, maar vereist enige weersafhankelijkheid en een hogere initiële investering. Implementatie omvat de integratie van hernieuwbare energiebronnen voor de voeding van de verlichting, met de nadruk op langdurige kostenbesparingen en milieuvoordelen. | Installeer zonnepanelen om de verlichting van de van duurzame energie te voorzien. Dit vermindert de ecologische voetafdruk en energiekosten op de lange termijn.<br><br>Uitvoering: Implementatie van hernieuwbare energiebronnen voor de voeding van de verlichting. |

**Costs for the graphs, in 1000 euros**

| Strategy | Maintenance costs | Operational costs | Material costs | Installation costs | Other costs | Tota l | Diff. with current |
|---|---|---|---|---|---|---|---|
| **Current year - 1** | 27.4 | 22.1 | 20.8 | 0.0 | 5.6 | 75.9 | -4.1 |
| **Current: light bulb (Dutch: gloeilamp)** | 29.6 | 24.0 | 20.8 | 0.0 | 5.6 | 80.0 | - |
| **1A: LED (now)** | 19.3 | 18.4 | 15.0 | 11.3 | 15.9 | 79.9 | -0.1 |
| **2A: LED (6 months)** | 24.4 | 21.2 | 15.0 | 11.3 | 2.0 | 73.9 | -6.1 |
| **3A: Induction (Dutch: inductie)** | 23.0 | 21.6 | 8.9 | 18.9 | 4.3 | 76.7 | -3.3 |
| **1B: Daylight use (Dutch: daglichtbenutting)** | 7.0 | 18.6 | 15.0 | 28.3 | 6.4 | 75.3 | -4.7 |
| **2B: Optimal light use (Dutch: optimalisatie licht)** | 21.2 | 20.2 | 17.6 | 0.0 | 5.6 | 64.6 | -15.4 |
| **3B: Renewable energy (Dutch: zonnepanelen)** | 15.1 | 8.0 | 20.2 | 28.3 | 8.4 | 80.0 | 0.0 |

**Information for the colored blocks**

| Strategy | Prognosis | Lifecycle | | Energy consumptions | | Maintenance costs | | |
|---|---|---|---|---|---|---|---|---|
| | | *Days in use* | *Days left* | *Total kWh (oper. costs*1000)/0.39* | *Per unit per day (total kWh/365/20)* | *#mainte-nance* | *#unavailable* | *#mal-function* |
| **Current: light bulb (Dutch: gloeilamp)** | Good | 34 | 134 | 61.538 | 8 | 19 | 10 | 45 |
| **1A: LED (now)** | Profitable | 0 | 183 | 47.179 | 6 | 11 | 5 | 18 |
| **2A: LED (6 months)** | Profitable | 34 | 317 | 54.359 | 7 | 14 | 8 | 33 |
| **3A: Induction** | Profitable | 0 | 342 | 55.385 | 8 | 8 | 4 | 16 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **(Dutch: inductie)** | | | | | | | | |
| **1B: Daylight use (Dutch: daglichtbenutting)** | Profitable | 34 | 399 | 47.692 | 7 | 2 | 6 | 3 |
| **2B: Optimal light use (Dutch: optimalisatie licht)** | Profitable | 34 | 176 | 51.795 | 7 | 5 | 8 | 36 |
| **3B: Renewable energy (Dutch: zonnepanelen)** | Break-even | 34 | 408 | 20.513 | 3 | 5 | 10 | 4 |

| **Icon percentages**, calculated using "(new-old)/old*100" formula to compare strategy vs. current | | | | |
|---|---|---|---|---|
| **Strategy** | Energy reduction | Cost reduction | Lifecycle increase | Availability increase |
| **Current: light bulb (Dutch: gloeilamp)** | 8.6% | 5.4% | - | - |
| **1A: LED (now)** | -23.3% | -0.1% | +9% | +43.0% |
| **2A: LED (6 months)** | -11.7% | -7.6% | +109% | +18.0% |
| **3A: Induction (Dutch: inductie)** | -10.0% | -4.1% | +104% | +49.3% |
| **1B: Daylight use (Dutch: daglichtbenutting)** | -22.5% | -5.9% | +158% | +48.0% |
| **2B: Optimal light use (Dutch: optimalisatie licht)** | -15.8% | -19.3% | +25% | +16.0% |
| **3B: Renewable energy (Dutch: zonnepanelen)** | -66.7% | 0.0% | +163% | +27.3% |

## D.3 Usability Evaluation Summary

### General Demographics

All 5 participants were peer students, studying or having studies Creative Technology or Interaction Technology. From these, 3 participants were aware of the goal and functionalities of the prototype, 2 were not.

### Experience

#### General

People generally liked the prototype; all participants indicated that it looked "happy and clear" and that it was "consistent and visually appealing". The colours between the digital and physical elements match well and make the connections intuitive. The icons are also helpful. The dashboard screen was a bit overwhelming for 3 participants, as there is a lot of info and a lot of bright colours. They indicate that once you know the information on the screen it is OK and that the right information stands out. The base for the tangible elements are a nice, calm, contrast according to a participant. A participant added that the tangible ball helps focus on your discussion, reducing the feeling of overwhelm.

Participants that were unaware of the goal had some trouble finding out what the functionalities of the prototype were. After some exploration, however, they quickly knew what to do. All participants found the prototype intuitive in use after some exploration. The potential added value of the prototype was noticed by most participants (3 out of 5), especially in terms of staying focused and retrieving your attention. One participant saw an opportunity in brainstorm sessions as well, whereas another speculated that "it will probably work well in big meetings where you want to keep the discussion focused and ensure everyone feels heard." One participant did indicate that the buttons on the dashboard interface do not really match the kind of interactions the ball stimulates. The screen has the indication of buttons that can be clicked with a cursor, whereas the idea is that the ball is used to interact with the dashboard. This can be improved.

Participants liked holding the prototype, as it was "nicely heavy" and comfortable in size. The interactions with the ball were clear and well-appreciated. Especially the possibility of comparing multiple options was well-liked, although some participants were not immediately aware that this was possible. However, after this was found, it was described as "way less effort than switching back and forth" between options.

#### Navigate

While the dashboard was experienced as a bit overwhelming at a glance, it was seen as informative and sufficiently detailed without becoming too much. The "tweakers"-style way of comparing options using coloured blocks was well-appreciated. One participant indicated that the dashboard felt a bit separate from the tangible elements, but that it was a good way to prepare for the meeting in an easy way. One other participant highlighted that they saw the true function of the prototype as being compatible with any dashboard-like pages like this one.

***"The screen feels like an encyclopaedia for what you want to discuss, the background information that supports your discussion."***

#### Highlight

One participant remarked that the use of a ball might lead to more "playful meetings". A different participant highlighted that "playing around is easy" with the tool, as "you can always start with something". Using the ball to appoint people to talk were seen as a way to stay focused on the topic and remain clear about who can provide input.

Participants really liked the simplicity of holding a ball. One called it "literally something to hold on to (Dutch: houvast), to have under control (Dutch: in de hand hebben)".

The movements that were possible with the ball were somewhat in line with what participants expected. The most intuitive movements that were tried out were:

- Moving the ball upwards (expecting movement on the screen upwards);
- Rotating it (to scroll through the page);
- Throwing the ball (to appoint someone to talk);
- Using it as a pointer on the screen (especially when only one option is discussed), and
- Shaking it (to put one option in focus or hear a sound);

One participant expected sound to be played when the ball is picked up. In the prototype, only the movements of shaking and moving the ball upwards had corresponding animations on the screen. This did feel intuitive, albeit a little bit rough still. The coloured blocks of the option that is represented by the ball moved upwards the more movement there was.

**Weigh Options**

Participants generally liked the interactions and animations that came with the voting system, they found them intuitive. However, they had some concerns about the implications of voting. The different voting blocks can have a different weight so, if exploited, some opinions might literally weigh more heavily. This is a socially undesirable effect that should be watched out for, but is also partly a group responsibility to stay wary of.

An alternative way of using the voting blocks, might be to vote throughout the discussion instead of at the end; so you can already see during the discussion whether there are any big differences. Then it might be a good indicative tool for a follow-up discussion ("I see big differences between these two") or conclusion ("We are discussing, but it seems we want the same thing").

**Record**

Most participants expected to be able to record (parts of) their meetings, like arguments. A participant indicated that the current design stimulates people to have short recordings as well. However, some participants expected extra/other interactions to be possible, like speaking with other participants (or other ideas) through the balls. Several participants also expected that the text and sliders on the ball indicate an 'agenda' of the meeting, and one participant compared the functionality with the "finger system" used during meetings to indicate whether a person wants to add something to the discussion, start a new topic, etc.

Participants really liked the recording function, in case you were not present at the meeting, wish to listen to it again, or have to prepare a follow-up meeting. There were some remarks and concerns about the possibility to record arguments and comments. Participants indicated that the recordings might get messy, incomplete, or they might not be used during heated discussions. One participant remarked that there needs to be some consistency in how much is recorded. It might be that one dedicated person needs to be present for the recordings.

**Suggestions for change**

**Practical**

| | |
|---|---|
| Dashboard | • Ensure that the titles are consistent across all pages.<br>• Make the icons all white instead of using the "option colours".<br>• Neutralize the colour scheme used for graphs a little bit, so there is no confusion between the colours used for graphs and colours to represent the strategies.<br>• Adding the core elements also to the vote page. |
| Base | • One participant indicated that it might be nice to have a "pausing place" for the balls/strategies that are still viable but not being discussed right now. They also realised that this can be the base, but it might be interesting to see what participants do naturally.<br>• Add a title on the base so you know which ball is which idea without having to check the screen. |
| Ball | Instead of/in addition to moving elements on the dashboard upwards, it might be possible to:<br>• Fade out the colours of an option that is idle;<br>• Pulsate the coloured area (so not the text) a little bit when picked up;<br>• Smoothen and quicken the changes on the screen;<br>• Not move the elements too much, as that hinders its readability; |

**Theoretical**

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| Dashboard | A future feature might be to make the screen drawable, so more direct interactions can be added to the screen. However, this might distract users from the balls, so this needs to be evaluated. Another suggestion was made to find a way to display the recorded notes by pinning them to the right element on the screen. It might also be nice to be able to select features that participants are interested in (e.g. energy consumption, maintenance costs, life cycle extension) so the coloured block represents only relevant information. |
| Base | Consider putting the physicalizations of the votes next to each other so it is easier to compare. An alternative would be using a closed-box voting system with a direct output on the screen (similar |

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| | to current situation). This will help preserve anonymity, and one participant indicated that ánd physical element ánd weight ánd position on the screen are a bit too much (one or two of these are fine according to 2 participants). Voting can be expanded by allowing participants to attach an audio recording to a voting block, so you can include more context about the reasoning behind the vote. Include a button or another tangible object to allow participants in a discussion to indicate they want to talk. "The current prototype is a bit single-player, but it is a multi-player discussion." Two participants indicated that small baskets per strategy in which notes and sketches can be stored might also be a nice way of preserving the context of the discussion over time. It might be good to visualize the history of arguments and relate this with the voting scores at that time, so you can see which arguments made a difference. One participant argued that this would result in early arguments getting lost in the conversation, advising against it. |
| Ball | Ensure that only limited snippets of voice recordings can be made, to limit the messiness of recordings. Additionally, a way to structure the recordings and/or create a summary out of it can be helpful as well. Consider making the balls out of more sturdy materials like rubber, so it is more inviting to throw and squish the ball. Now, it feels a bit fragile (also because you can see all the tech). A nice interaction when comparing two ideas might be to put the information in the coloured block next to each other if the balls are touching physically as well. A suggestion is made to make the animations on the screen more smooth, and adjust them based on specific movements (like gestures). However, participants acknowledged that this is a technical limitation of the current stage of the research. Adding a "Focus" button on the ball that can be pressed to keep an option up in the screen might also be nice. |

## D.4 Social Impact Evaluation Results

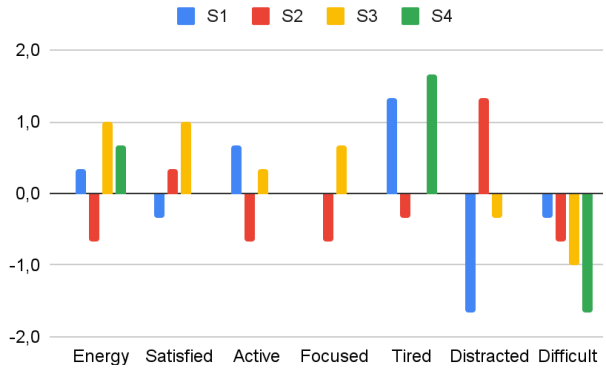


Figure D7. Average difference (first and second discussion) in self-report of the participants per statement per session.

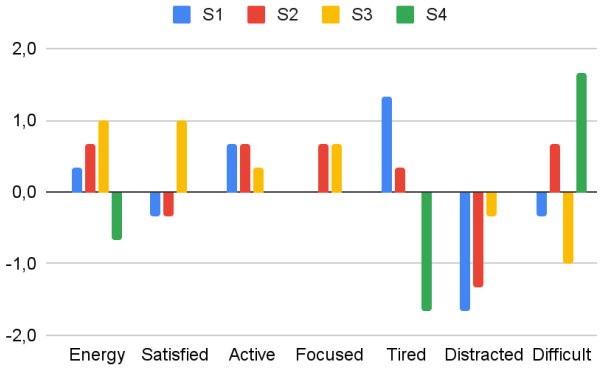


Figure D8. Average difference (with and without tangible elements) in self-report of the participants per statement per session.

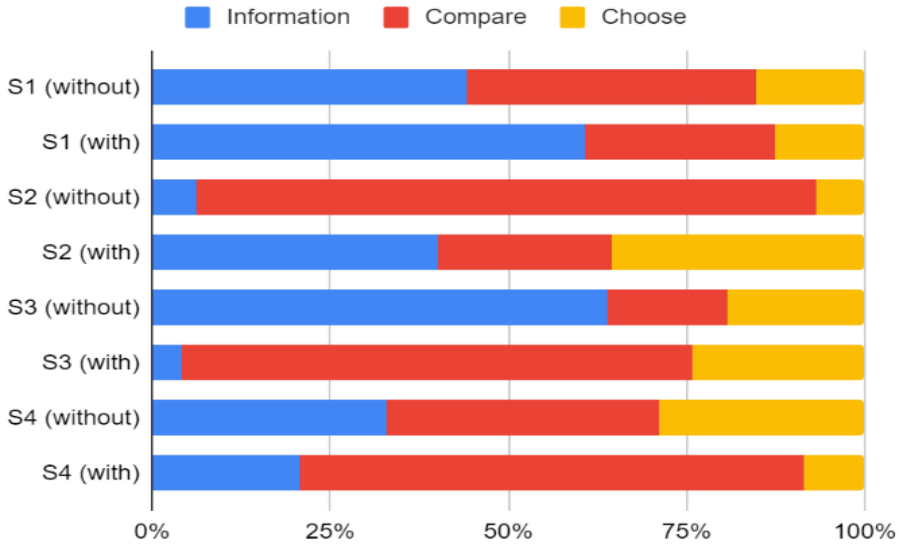


Figure D9. Division of topics over the discussion, in percentage of the total discussion.

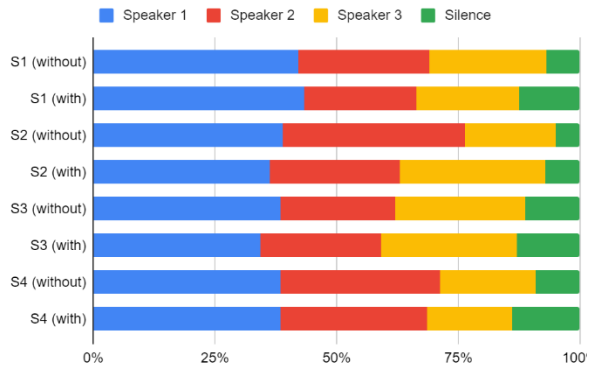


Figure D10. Frequency of talking per speaker, in percentage of the total discussion.

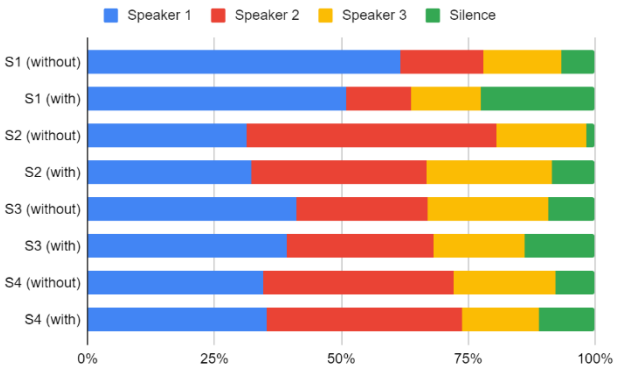


Figure D11. Length of talking per speaker, in percentage of the total discussion.

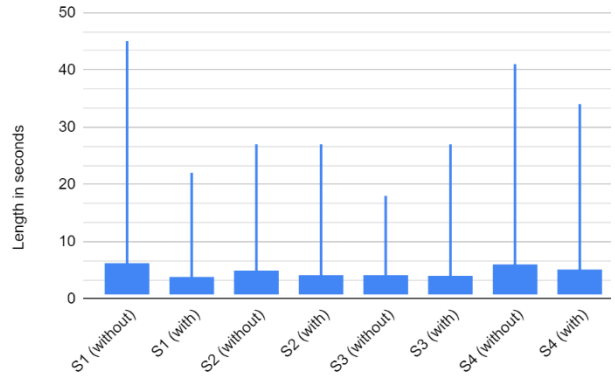


Figure D12. Average total range of utterances per discussion, with maxima.

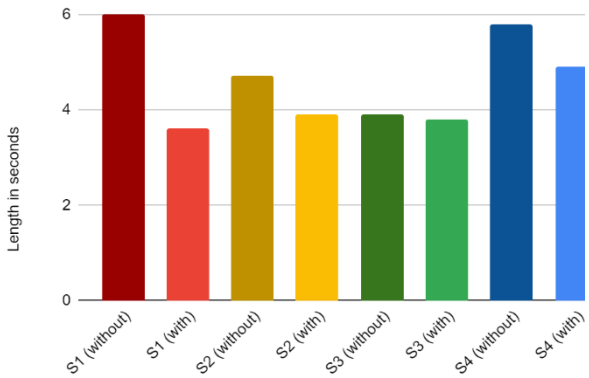


Figure D13. Average length of utterances per discussion, coloured per session.

Table D1. Frequency of socially disruptive behaviours and eye and screen contact moments per minute.

| | Session 1 | | Session 2 | | Session 3 | | Session 4 | |
|---|---|---|---|---|---|---|---|---|
| **Interruptions** | 2.22 | 2.39 | 2.80 | 1.48 | 3.28 | 2.26 | 2.01 | 1.11 |
| **Distractions** | 0.47 | 0.95 | 0.43 | 0.49 | 0.52 | 0.19 | 0.07 | 0.13 |
| **Eye contact** | 2.86 | 3.02 | 2.37 | 4.33 | 3.71 | 4.71 | 4.43 | 4.98 |
| **Screen contact** | 5.14 | 5.89 | 4.09 | 3.46 | 6.30 | 5.65 | 4.90 | 4.39 |

Table D2. Average length of utterances per session in seconds (sp = speaker, sil = silence)

| | Session 1 | | | | | | Session 2 | | | | | | Session 3 | | | | | | Session 4 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Avg | | Min | | Max | | Avg | | Min | | Max | | Avg | | Min | | Max | | Avg | | Min | | Max | |
| **Sp. 1** | 8.8 | 4.3 | 1 | 1 | 45 | 22 | 3.8 | 3.5 | 1 | 1 | 12 | 27 | 4.1 | 4.3 | 1 | 1 | 14 | 27 | 5.3 | 4.5 | 1 | 1 | 29 | 34 |
| **Sp. 2** | 3.6 | 2.0 | 1 | 1 | 28 | 5 | 6.2 | 5.1 | 1 | 1 | 27 | 24 | 4.3 | 4.4 | 1 | 1 | 18 | 16 | 6.7 | 6.3 | 1 | 1 | 28 | 31 |
| **Sp. 3** | 3.9 | 2.4 | 1 | 1 | 20 | 6 | 4.5 | 3.2 | 1 | 1 | 24 | 20 | 3.5 | 2.4 | 1 | 1 | 12 | 7 | 6.0 | 4.3 | 1 | 1 | 41 | 18 |
| **Sil.** | 5.6 | 6.5 | 1 | 3 | 11 | 13 | 1.7 | 4.6 | 1 | 3 | 2 | 7 | 3.2 | 4.0 | 2 | 2 | 7 | 8 | 4.9 | 3.8 | 2 | 2 | 15 | 7 |
| **Avg p/m** | 6.0 | 3.6 | 1 | 1 | 45 | 22 | 4.7 | 3.9 | 1 | 1 | 27 | 27 | 3.9 | 3.8 | 1 | 1 | 18 | 27 | 5.8 | 4.9 | 1 | 1 | 41 | 34 |

Table D3. Self-reported ratings per statement per session. WO = without, W = with, Δ = difference, - = min., + = max.

| During the session, I… | Session 1 | | | | | Session 2 | | | | | Session 3 | | | | | Session 4 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | WO | W | Δ | - | + | WO | W | Δ | - | + | WO | W | Δ | - | + | WO | W | Δ | - | + |
| *…had a lot of energy during the session* | 4.3 | 4.7 | 0.3 | 4 | 5 | 3.0 | 3.7 | 0.7 | 2 | 4 | 3.3 | 4.3 | 1.0 | 3 | 5 | 4.7 | 4.0 | -0.7 | 3 | 5 |
| *…was satisfied with the outcome* | 4.3 | 4.0 | -0.3 | 2 | 5 | 5.0 | 4.7 | -0.3 | 4 | 5 | 3.3 | 4.3 | 1.0 | 3 | 5 | 4.3 | 4.3 | 0.0 | 4 | 5 |
| *…actively participated* | 4.3 | 5.0 | 0.7 | 4 | 5 | 4.0 | 4.7 | 0.7 | 3 | 5 | 4.3 | 4.7 | 0.3 | 3 | 5 | 4.7 | 4.7 | 0.0 | 4 | 5 |
| *…could focus well on the topic* | 4.3 | 4.3 | 0.0 | 4 | 5 | 4.0 | 4.7 | 0.7 | 3 | 5 | 3.7 | 4.3 | 0.7 | 3 | 5 | 4.7 | 4.7 | 0.0 | 4 | 5 |
| *…was very tired* | 1.3 | 2.7 | 1.3 | 1 | 4 | 2.0 | 2.3 | 0.3 | 1 | 4 | 2.3 | 2.3 | 0.0 | 1 | 4 | 3.0 | 1.3 | -1.7 | 1 | 4 |
| *…was distracted a lot* | 3.0 | 1.3 | -1.7 | 1 | 4 | 2.3 | 1.0 | -1.3 | 1 | 4 | 3.0 | 2.7 | -0.3 | 1 | 5 | 1.7 | 1.7 | 0.0 | 1 | 3 |
| *…found it hard to make a choice* | 3.0 | 2.7 | -0.3 | 1 | 5 | 2.0 | 2.7 | 0.7 | 1 | 4 | 4.0 | 3.0 | -1.0 | 2 | 5 | 1.7 | 3.3 | 1.7 | 1 | 4 |

Table D4. Thematic analysis of the sessions and survey results.

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| **Session 1** | |
| **Without tangible elements** | Participants are quite passive, they stay seated and only one person is clicking. One person is talking and interrupting a lot, one does not say much and mumbles a lot. They are talking to the screen, not really communicating with each other. They are focused, with a little bit of eye contact. First they discuss their goals, then they discuss the options 1-by-1, mainly focusing on energy consumption and costs. The atmosphere is positive, with room for jokes. **No choice is made.** |
| **With tangible elements** | Participants are again quite passive, one person is using the balls. There was a moment of awe when the movements were seen on the screen. Fade and move is used a little bit, the voting element is used playfully. The disbalance remains, but now the interruptions are more simultaneous than 1-on-1. The interruptions feel more "eureka"-like than "corrective"-like. The structure of the meeting is the same, but they move quicker to comparing options. It is quicker overall. They focus more on long-term implications and want to see if they can combine elements of options. **A choice is made.** |
| **Discussion** | Generally, the prototype was very recognizable and quick to use. It is easy to grasp what you should be doing. A participant imagined that "it makes it easy to show the costs and gains of an option". They were positive about the tangible elements but had some critical remarks.<br><br>On the dashboard, most information is there. Comparing options on the screen is clear, it provides a clear overview. It would be nice to add more options or combine existing ones. Some detailed information about long-term effects, lifecycle costs, and safety implications is missing. Participants indicated that information would always be missing, so that would be difficult.<br><br>With the balls, you get more actively involved in the discussion, it is easier to grab a ball and join the conversation. It is a central point for everyone to focus on and you can quickly navigate through the options, providing a direct overview of the discussion status. It feels playful and helps with getting an image of the discussion, but can also distract you - especially the movements on the screen. Because of this, the groups should not be too big. Compared to the discussion without the tangible elements, participants indicated that the balls helped keep the overview and not "drown in all the details, all the text on the screen to read".<br><br>Suggestions are made to include the KPIs in the dashboard, perhaps representing these with the balls, or integrate an internal optimisation application with the prototype. Furthermore, participants suggest explicitly including the assessment framework the asset manager and asset owner use to customize the features represented in the dashboard. This way, only relevant information is shown. Additionally, a participant suggested using this for maintenance planning, as the stakeholders are more equal in this situation and you need to balance various features as well. Then, you can use the voting blocks as a way to represent the tasks to be divided. Lastly, they suggested using the tool for brainstorming, as you can take people along in the decision-making process in a very tangible way. |
| **Session 2** | |
| **Without tangible elements** | Participants are passive, they stay seated and one person is clicking. Two people are in discussion, one person is distracted and passive. However, it seems they talk more equally. They look at the screen a lot. First they read the general information, then they go past each option 1-by-1, then they compare and choose. They have a brief discussion and get to a conclusion quickly. **A choice is made.** |
| **With tangible elements** | Participants are actively using the balls and have more eye contact. They use the balls to structure their conversation, talking via the ball with each other and using it to indicate who is talking. The ball is either handed to someone else or put down, it is not held for long. They interrupt each other when all of them start talking at the same time. The conversation is positive, with some jokes. They first explore what they can do with the balls, then "open the meeting", discuss the strategies, and then after comparing use the voting to quantify their arguments (for each argument in favour, they put down a block - for arguments against, they remove one). **A choice is made.** |

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| **Discussion** | Generally, participants liked using the prototype and were happy using it. They highlighted the quick use when wanting to navigate through the dashboard. It was also easy to learn how to use it. The dashboard was clear to the participants, even though they were not familiar with the domain at all. A participant stated that "if you work in this field, I think it is very clear what you can do".<br><br>The balls were a pleasant speaking tool. It helped keep a structure during the meeting, ensured everyone had an equal amount of control, and made the discussion feel deeper and pleasant. They were uncertain what to do with the voting blocks at first, but found their way around it. They liked the recording function a lot, it is practical and helps you be mindful about what you want to say. The way the balls represent the strategies was also liked. One participant shared that "you may not have all the information, but you do know what the balls mean" and that it adds a feeling of playfulness to the discussion. The group also argued that a facilitator would be happy using this tool to include more "difficult" people (e.g. introverts, quickly distracted people) as it stimulates engagement and directs attention to the balls.<br><br>Participants suggested using less visually disruptive elements to visualize the relation between the balls and the screen, as it might hinder readability. Additionally, they debated the role of a note taker in combination with the recording interaction; stating that it might help them structure their notes, or replace their job. They stated that a maximum of five balls and a maximum of five participants would be ideal in keeping the structure of the discussion. |
| **Session 3** | |
| **Without tangible elements** | Participants talk past each other via the screen, gazing at the screen a lot. There is little eye contact. One participant indicated they are not able to read what is on the screen, they are also more in the background. One participant is clicking, they talk and interrupt a lot as well. Interruption are done to correct people. First they compare the three options at the same time, then they discuss goals, go past the options 1-by-1, compare duos of ideas, and try to move to a conclusion. They focus on costs, energy consumption, maintenance, and errors. **No choice is made.** |
| **With tangible elements** | More active participation, but still rather passive - looking at the screen a lot. They respond to each other more, it feels more like a conversation. More eye contact between all three at the same time. They each hold a ball, as if that is their option (also how they are called - "Can you move your option for me?") but point to the screen to draw attention to elements. They also use the colour of the idea to refer to it. There is a large focus on the graphs, less on the textual information. The participation of the participants feels more equal. Instead of "corrective" interruptions, they seem to be more about "thinking out loud" for two participants. However, in the final discussion to choose an option, the interruptions are "corrective" again. The structure is comparable, with a focus on costs, energy consumptions and errors. Comparing the ideas goes a lot quicker compared to the dashboard. **A choice is made.** |
| **Discussion** | Generally, participants like the prototype. The colouring is seen as consistent and clear, with a nice use of graphs to convey information. The theme of the prototype fits the discussion (e.g. using LEDs to indicate information about the lighting system of a tunnel) and would fit a more modern "discussion" room with smart elements. Participants were happy with the experience in both scenarios, but highlighted that using the balls engaged them more actively. They said that "everybody is able to do something, stimulating you to take part in the discussion", highlighting more equal control of the discussion. One participant shared that in the discussion without the prototype he "would sit there in the background, and maybe ask 'can we do the green one?' but that's it. Now you can just say, 'I want to talk about the yellow option' and grab it." It is more proactive and includes introverted people. The novelty and playfulness help with this, and because the prototype can easily be picked up you are more inclined to explore.<br><br>One participant highlighted that it gave some more structure to the discussion, because you literally hold the option in your hand. They saw it as a "scepter to decide where the discussion would go". The movements were experienced as neutral, with participants stating that "it should serve the conversation, the discussion is the most important". One participant liked the movements as it helped them regain focus and stay involved, while another did not even notice that things moved on the screen. Participants debated the risks of of "power abuse" by grabbing all |

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| | balls and refusing to give them back, or by having more childish people in the discussion. Additionally, a participant thought it might get more chaotic - but noticed that removing detailed information when moving from a 2-way to a 3-way comparison helped reduce the chaos. They stated that groups should not be too big.<br><br>Participants did miss some additional information, but they acknowledged that it is difficult to create a fully realistic scenario for this test session. They were able to take on the perspective of their roles, but noticed that this was sometimes forgotten. However, one participant argued that this would also happen in real life, they did not see an issue in it. Suggestions were made to enhance the movements with the ball, e.g. by squeezing it when putting focus on a strategy. Additionally, a discussion arose on the possible role of AI (e.g. Microsoft Copilot) in this tool, to better capture the context of the discussion. It can be used to take notes, make records, and provide a clear timeline of the history of the discussion. That would be very valuable. Combined with a facilitator, they envisioned a new way of meeting that would be more social, structured, and more in-depth. |
| **Session 4** | |
| **Without tangible elements** | The group is passive, reading and processing the information on the screen a lot. There are a lot of long pauses and there is some eye contact. Two participants are talking a lot, both using the mouse to navigate through the dashboard (although one person is the "main" user). One of them is sometimes distractedly clicking around the dashboard, also interrupting a lot. There are a lot of interruptions but also a lot of eye contact when comparing options. A focus is put on the coloured blocks, looking at financial aspects of each strategy. They first read the information on the screen out loud, then compare options by looking at the graphs and coloured blocks. Then, options are considered 1-by-1 to try and make a choice. **No choice is made.** |
| **With tangible elements** | Participants are passive as well, reading a lot from the screen and putting the balls down immediately after picking them. They seem to have more eye contact, everybody takes part in the discussion, and they seem to actively work together. They all talk slowly. Instead of naming the colour of the option, they refer to the strategy through its position on the screen. One participant asks a lot of questions and interrupts people a lot. They approach the discussion information-specific, with one participant looking at the text and two focusing on graphs. However, they also focus on understanding each other's position, really looking at the possibilities for collaboration. "What do you find more important? Sustainability, energy consumptions, or costs?" When they compare the options, they look less at the dashboard - having more eye contact. There is some debate on the use of voting blocks; it might not be needed, but it is fun and new to try out. The structure is the same as the other sessions: discuss options 1-by-1, compare them, and move to a choice. **No choice is made.** |
| **Discussion** | Generally, participants liked the prototype and were happy with how well it worked. They immediately saw added value in "helping you see what is important" and highlighted how it could be used for "anything in which you have to make a decision, as long as you have variables and variants". The dashboard information and the way strategies were presented is clear, consistent, and interpretable. Although the whole casus was missing, participants expressed they had enough information to work with. Comparing options works well and the coloured block makes it easy for the user to know what to focus on. There is a clear overview.<br><br>Participants indicated that using the balls was easy and pleasant. One shared that it is "nice to do something separate from your laptop for once" and that "you can get a whole group in a conversation". Comparing options is easy and more fun than only using the dashboard for this. Additionally, it feels like the control is more equal when using the balls, making it more accessible to intervene when needed.<br><br>Currently, the balls look fragile because of their transparency and the materials used. This discouraged them from holding the balls and moving them around. However, participants did say that the balls helped them talk more freely during the discussion but that "you need to have something to talk about, so the screen is still needed". The voting element of the prototype was debated; participants indicated that it's relevancy |

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| | depends on the group and context. It could be used at the end, to check out the status of alignment, agreement, and interest overlap (perhaps as a "referendum").<br><br>Suggestions were made to represent the interests of the participants more explicitly in an overview. This can be information about the pros and cons of each strategy for each stakeholder, showing "what it means for everyone" to opt for this choice. Considering the business values matrix could help in this. Furthermore, a reference was made to the Catchbox[17], a microphone in the shape of a foam cube. The affordance of the object stimulates more rough interactions like throwing it to people, something which this prototype could benefit from. |
| **Survey Results** | |
| All participants preferred the tangible prototype over the prototype with only the dashboard. This was mostly the case due to its easy, simple, and intuitive interactions and the physicality of the balls. Five participants highlighted how the prototype invited everyone in the group to partake in the discussion, even more introverted people. Three participants indicated they liked the overview of information provided by the dashboard and the interaction of comparing strategies. One participant added that the use of colours and icon was very helpful in keeping the overview. Three other participants focused on the social impact of the prototype, stating that it "provides a different way of looking at information". To them, the conversation went deeper and became more lively, while providing a feeling of responsibility to contribute to the conclusion. One participant indicated it makes it "clear and easy to see who is talking and what kind of point they want to make". However, two participants worried that the prototype might be distracting, especially if used in a bigger group. | |

[17] https://www.ct-av.nl/catchbox-microfoon/