Public Participation Powered by Design:

Developing a Measuring Instrument to Enhance Citizen Science Engagement

Master thesis by Paul Roelen

Master thesis

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Preface

This graduation thesis marks the completion of my master's degree Integrated Product Design at Delft University of Technology and the end of my journey as an industrial design student. This work has given me the opportunity to showcase the skills, knowledge and passion for design that I have developed throughout the years.

At the very start, I barely knew what citizen science was. I was familiar with bird counts, but an instrument that measures personal environments? That was not the sleek design challenge I was expecting when stepping into a design company. How was I supposed to design for this? As it turned out, I was wrong. What began with uncertainty gradually turned into a passion for the subject, and this project ultimately allowed me to incorporate so many aspects of design I truly enjoy, making the experience all the more rewarding.

I would like to express my sincere gratitude to all employees of Dott Achilles for their support during this time, with a special thanks to Ward Adriaenssen and Tim Ruytjens for investing their time and effort in supervising me. Being part of a design studio and witnessing firsthand how they operate was an eye-opening experience. Seeing how much broader and further a product can be developed made me realize how much there is still to learn.

This project has not only contributed to my professional development but has also been a personal journey, experiencing the differences between Belgium and the Netherlands—differences that continue to broaden my perspective.

A huge thank you to Laurens Kolks and Gert Pasman for their invaluable feedback and guidance throughout this process. Every time I became too immersed in the details again, they helped me to zoom out and regain a clear perspective.

And to you, the reader, I hope you enjoy this graduation report and see how design can affect event the most unexpected things.

Paul

Executive summary

Citizen science, an approach where the general public collaborates with academic researchers to contribute to scientific research, offers significant benefits for both science and society. Despite its potential, the field faces significant challenges that limit its impact, particularly in maintaining participant motivation. Additionally, citizen science projects often struggle with issues related to cost, especially when they incorporate physical measuring instruments. Limited budgets typically result in instruments that lack robustness, usability, and scalability, further diminishing participant engagement, and in turn, the overall effectiveness of citizen science initiatives. These challenges formed the foundation of the project's goal: design a measuring instrument for citizen science to enhance engagement.

Collaborating with design studio Dott Achilles, the project explored not only the technical and user-centred aspects of the design, but also the question whether commercialization could facilitate broader participation. The goal was to develop a product that could lower barriers to participation and increase incentives for both researchers and participants while adhering to the core principles of citizen science, such as transparency, ethical data use, and inclusivity.

To inform the design process, a comprehensive analysis of citizen science was conducted, combining a literature review with stakeholder interviews to identify key principles, challenges, and opportunities for improvement. This research led to the development of a vision for a modular, scalable and user-friendly product-service system that could engage a diverse range of participants across varying contexts, balancing the needs of citizen scientists, researchers, and local organizers.

Through an iterative process involving exploring, prototyping, testing, and refinement, a final product emerged centred around a physical measuring instrument. The instrument features customizable sensor modules and various mounting options, enabling deployment in numerous contexts, including outdoor residential and natural settings. Its plug-and-play design ensures accessibility for users, regardless of their technical expertise. The design adopts a stylized, friendly, and approachable aesthetic that aligns with citizen science principles and increases adaptability. Additionally, the design incorporates elements to inform non-participating, ambient users, stimulating trust and transparency. The robust, scalable, and repairable design allows the instrument to be reused across multiple projects, reducing environmental impact and enabling new financial models.

An integrated online platform complements the physical instrument. Features such as real-time data visualization, personalized feedback, and tools for data exploration and comparison were explored at a functional level, aiming to enhance participants' motivation by acknowledging the critical role of their contributions. Particular attention was given to the interactive installation help that utilizes the instrument's design cues to guide users during installation. This feature, alongside the instrument's general usability, was validated through a usability study and expert reviews.

This thesis demonstrates how design can address the challenges of citizen science, particularly in relation to physical measuring instruments. By creating an impactful product that empowers citizens, enhances engagement, and supports local organizers, the project contributes to maximizing the scientific and societal impact of citizen science.

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1 Introduction

This chapter outlines the domain of the project; introduces the graduation company; defines the assignment; and describes the project approach.

1.1 Domain: citizen science

Defining the domain of the project

This graduation project is set within the domain of citizen science, a collaborative approach to involve the general public—citizens, often without formal scientific education or training—in scientific research (Bonney et al., 2009b). In such projects, professional scientists engage so-called 'citizen scientists' to actively participate in various stages of the research process, ranging from data collection (called contributory citizen science or crowdsourcing), to analysing and co-creation (Bonney et al., 2009a; Haklay, 2013).

The application field spans a wide range of disciplines, with the largest focal point being in biology, conservation, and ecology (Kullenberg and Kasperowski, 2016). Examples include monitoring bird migrations (Greenwood, 2007); monitoring and predicting the spread of infectious plant diseases (Meentemeyer et al., 2015); classifying galaxies (Raddick et al., 2009); and tracking river water quality (Brooks et al., 2019). Projects vary in methodology: participants might record observations manually, such as counting birds, or use technological solutions, such as 'Telraam' (fig. 1) which allows for automatic traffic counting (Janež et al., 2022; Telraam, n.d.). In these projects, electronic measuring instruments are developed and used to allow participants to gather larger quantities of data and reduce fieldwork by facilitating remote data collection (Jalbert and Kinchy, 2016).

Citizen science has the ability to combine individuals' records to collect vast amounts of data across large, diverse areas (Bonney et al., 2009b; Hochachka et al., 2012; Loss et al., 2015), and numerous volunteers can execute work that would not be feasible otherwise, due to funding and logistical constraints (Greenwood, 2007). In addition, citizen science has many societal advantages. It educates the public about science (Jordan et al., 2012; Vohland et al., 2021), making research more accessible and raising people's understanding of science (Bonney et al., 2016; Ruiz-Mallén et al., 2016). Engaging citizens can help to democratize research (Strasser et al., 2018), and it can incorporate fresh perspectives (McKinley et al., 2017). By definition, citizen science balances the interests of two main stakeholders: scientists and citizens, as the name suggests.

fig. 1 *An installed Telraam device (Telraam, n.d.)*

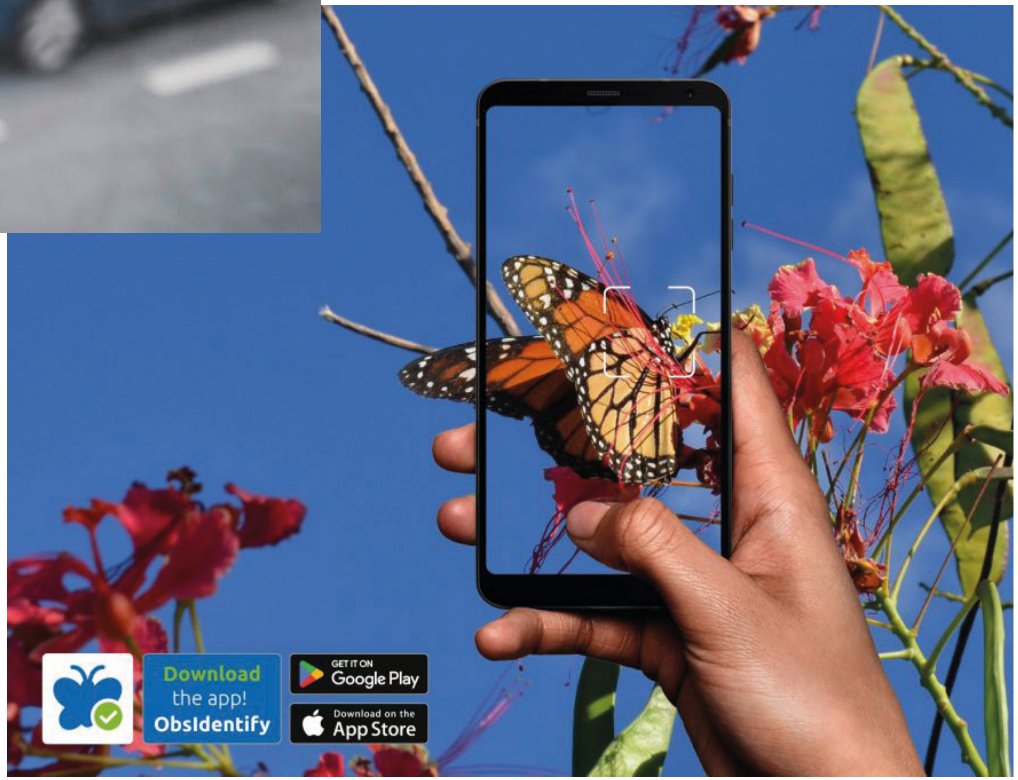


fig. 2 *ObsIdentify: a citizen science app that helps users identify plants and animals, and contribute to biodiversity research by collecting samples*

1.2 Graduation company: Dott Achilles

Introducing the graduation company

The project is executed in collaboration with Achilles Design, a Mechelen-based design studio that recently merged with Studio Dott in Antwerp, to form Dott Achilles (Dott Achilles, n.d.). Founded in 1994, it houses a multidisciplinary team of designers, engineers, experts, and developers operating across various design fields, including digital, branding, service, spatial, and product engineering. Collaborating with the product design and engineering department in particular allows the project to benefit from the team's expertise in mechanical, electronic, and product engineering.

fig. 3 *Samsonite Ibon suitcase, designed by Achilles (Achilles Design, n.d.)*

fig. 4 *Prototype of the Moose coffee milk frother, created in the R&D lab equipped with various machinery (Achilles Design, n.d.)*

fig. 5 *The Fairphone Fairbuds X; a modular headphone designed by Studio Dott (Studio Dott, n.d.)*

1.3 Project assignment

Introducing the project's goal

Currently, citizen science faces challenges that limit its impact, including sustaining participant motivation (Rotman et al., 2012; Spasiano et al., 2021); ineffective communication (De Vries et al., 2019; Dittmann et al., 2023; Golumbic et al., 2020); varying expertise among participants leading to data errors (Bonney et al., 2009b); and difficulty in establishing diversity among contributors (Paleco et al., 2021; Pateman et al., 2021; Wright et al., 2015). Additionally, citizen science often requires significant resources (Pocock et al., 2014), particularly when physical measuring instruments are involved. Limitations in available budget lead to design trade-offs that can result in tools that lack usability, standardization, robustness, and scalability (Skarlatidou et al., 2019). In turn, this can increase the threshold for participants to join and stay involved in citizen science projects, negatively affecting overall outcomes.

Through a client—a professor at the University of Antwerp involved in citizen science—Dott Achilles was asked whether commercializing such measuring instruments could increase participation, as it offers a different approach to address the limitations of current practices. Seeing an opportunity to improve the current process, the company initiated a project to design such an instrument.

The aim is to design a measuring instrument that supports citizen science by lowering barriers and increasing incentives for participants while enhancing data quality and quantity for researchers, balancing the interests of both. The ultimate goal is to broaden citizen science applications and maximize their scientific and societal impact. To prevent conflicts between societal goals and commercialization, the instrument must adhere to core citizen science principles—such as open-access data, benefits for both researchers and citizen scientists, and ethical considerations (Gold, 2022)—to preserve its values and advantages. Summarizing these objectives, the goal of this graduation project is:

Design a measuring instrument for citizen science to enhance engagement

1.4 Project approach

Defining the structure of this project

The approach for this project can best be described by a modified version of the double diamond model (fig. 6), structuring the design process into distinct phases of exploration and refinement. The process begins with an in-depth exploration of the context of citizen science through research and interviews. From there, the findings are synthesized to establish the foundation for the project, which includes defining the design scope, use case scenario, and stakeholders. This results in a vision that outlines the product's requirements and the issues it aims to address, marking the endpoint of the research phase and setting the boundaries for the design phase. Within these boundaries, the process moves to the conceptualization phase, where potential solutions are generated and iteratively refined towards a preliminary design. From there, the design is further embodied, resulting in a prototype that will be validated, ultimately resulting in the final project outcome.

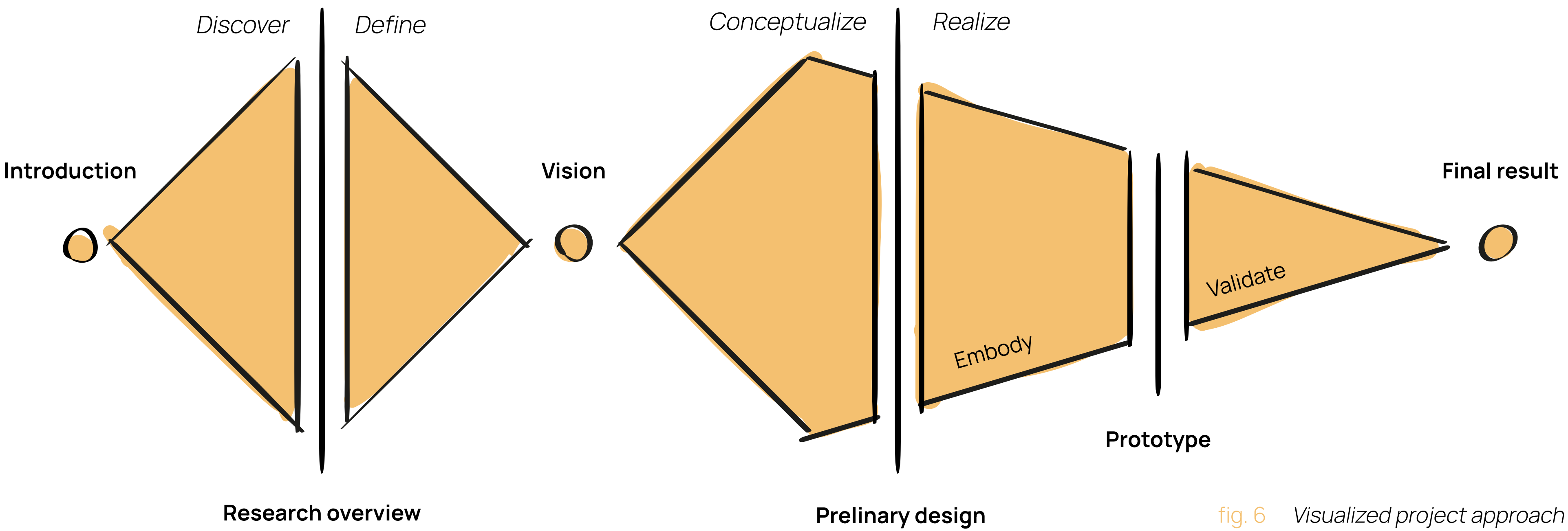


fig. 6 *Visualized project approach*

2
Discover

This chapter explores the context of citizen science, focusing particularly on measuring instruments. It outlines the essential preconditions that a product must meet, and identifies key opportunities for improvement to enhance existing practices.

2.1 Research objective

The aim of the discover phase

The project assignment required envisioning potential future improvements for measuring instruments. However, due to the assignment's broad nature, the product's purpose and target audience were unclear. Key questions arose: What specific data is the instrument actually going to measure, for whom, and in what context? Is the design meant for an educational environment, such as the classroom, or as a DIY kit for individuals? Who will be the primary customer—a university, a company, or another type of organization? Will it function within structured citizen science projects, or tailor to individual users?

In order to create a valuable product, these questions had to be answered. A thorough analysis of the broader context of citizen science was conducted to obtain a comprehensive understanding of its processes. This allowed for the identification of specific areas where design expertise could address issues or offer improvements effectively, ultimately determining where, how, and for whom an improved instrument could add the most value. The research objectives are as follows, serving as guidance rather than questions to be answered one-on-one:

i. **Defining citizen science principles:**
What defines citizen science, and what are the characteristics?

ii. **Understanding citizen science processes:**
How do citizen science projects currently function?

iii. **Exploring stakeholder motivations:**
What motivates stakeholders to participate in citizen science, and how can these motivations be influenced?

iv. **Identifying challenges and opportunities:**
What are current advantages and pitfalls of citizen science, both in general and specifically regarding measuring instruments?

v. **Assessing existing solutions:**
What are strengths and weaknesses of benchmark measuring products?

2.2 Research setup

The approach of the research

To investigate the outlined research objectives, this research combined a literature review with interviews of both experts in the field and citizen scientists who participated in a project. The purpose of these interviews was twofold: to validate findings from existing literature through practical experiences, and to generate new insights that could serve as a starting point for further literary exploration. The expert interviews provided insights into various aspects of the citizen science process, while the participant interviews focused on personal experiences and challenges. The expert interviews followed a semi-structured format, featuring a list of predetermined open questions to prompt discussion, while the interviews with participants were conducted in a more informal manner. For clarity in upcoming sections of the report, experts will be referred to as R (e.g. R1, R2, R3, R4), and participants will be referred to as P (e.g., P1, P2).

E1

An advisor on citizen science at Scivil, a Flemish knowledge center that promotes citizen science by producing guides and manuals and connecting stakeholders and tools. This expert provided a broad overview of dynamics, structures, and practices within citizen science.

E2

A predoc at the University of Antwerp, specializing in real-time large-scale microclimate networks, which help to investigate climate change impacts on urban and rural ecosystems. Using the Flanders-based initiative 'CurieuzeNeuzen in de Tuin' as a case study—which involved over 4000 participants measuring temperature and soil moisture with specialized measuring instruments—this expert covers the technical aspects and challenges of measuring instruments.

E3

The client of this project, through Dott Achilles: A senior researcher at the University of Antwerp experienced in initiating citizen science projects, which could offer insights into the role of research institutions, project funding, and popular research topics.

E4

A communication and project manager with experience in various citizen science initiatives on a state level, who is closely connected with participants and offered insights into their perspectives and the challenges they face on a project level.

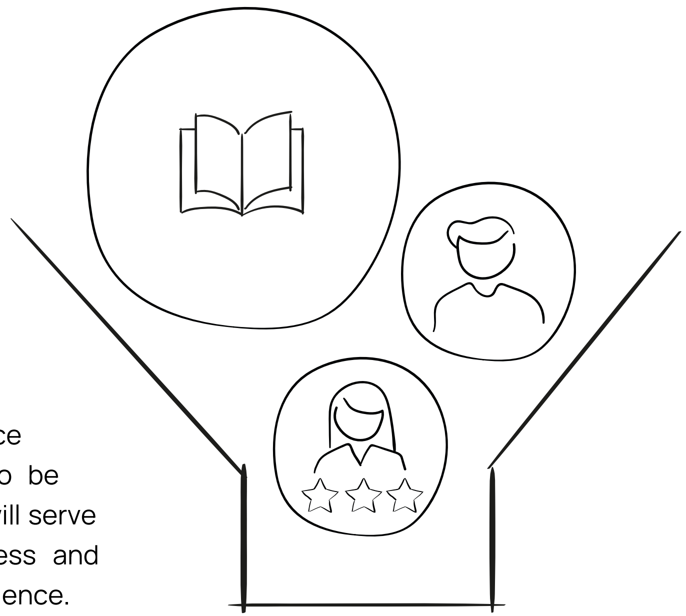
P1

Involved in the project of 'de Oorzaak' in Flanders.

P2

Participated in the 'Tuintesters' project in Mechelen.

Insights gathered from literature, experts, and users were synthesized into two main categories: preconditions and opportunities. From the opportunities, which apply to the entire citizen science process, a select number will be chosen to be addressed in this project. The preconditions will serve as a foundation to guide the design process and ensure it aligns with the principles of citizen science.



Preconditions

Integrates insights related to research objectives i, ii and iii to provide an understanding of the factors that influence citizen science participation, including motivations, barriers, and enablers. Normative in nature, it outlines essential considerations for citizen science projects, providing a foundation to inform the design of a measuring instrument that aligns with citizen science principles.

Opportunities

Integrates insights related to objectives iv and v to highlight current shortcomings in citizen science. Descriptive in nature, it focuses on areas where existing practices can be enhanced to better align with preconditions, thereby enhancing engagement and improving overall project outcomes.

Project scope

2.3 Preconditions

Defining factors that influence citizen science participation to guide the design of a measuring instrument that aligns with citizen science principles

Motivation is a cornerstone of citizen science and essential for the success of projects, as they depend on volunteers' contributions (Jaimes et al., 2015; Nov et al., 2014). Understanding how motivations, reasoning, and the underlying structure of emotions can affect participation helps to design for recruiting and retaining citizen scientists (Land-Zandstra et al., 2021).

2.3.1 Citizen science motivation dynamics

Before considering specific motivations, it is crucial to recognize that motivations in citizen science projects can dynamically evolve over time, and reasons for initial participation can be different from those that drive sustained participation (Asingizwe et al., 2020; Crowston and Fagnot, 2008; Lee et al., 2018; Palacin et al., 2020). To better understand and describe the complexities of participant motivations in citizen science initiatives, several studies have sought to classify and structure them. Rotman et al. (2012) proposed a model (fig. 7) that categorizes motivations based on whose interest they serve, drawing on a classification of social participation motives by Batson et al. (2002): egoism, altruism, collectivism and principlism. Respectively, they serve the welfare of oneself, others, the group that one belongs to, or uphold principles dear to one's heart. Compared to other studies as Land-Zandstra et al. (2021) – who divide motivations in 14 categories based on a framework by Jeanmougin et al. (2017) – the model loses some of the complexity of motivations, but does acknowledge the fluidity of them.

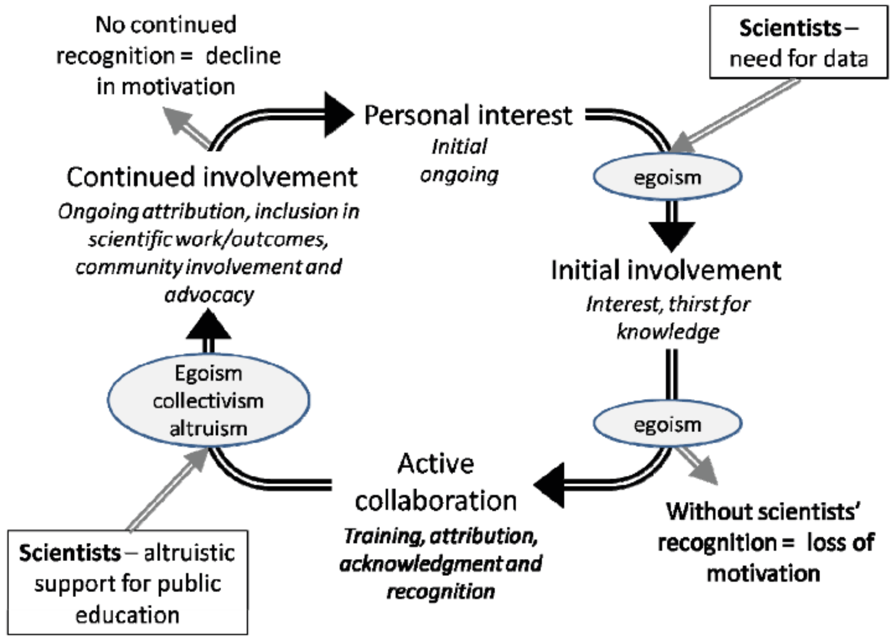


fig. 7 *Framework of volunteer and scientist involvement in citizen science by Rotman et al. (2012)*

2.3.2 Citizen scientists' motivations to join

Literature indicates numerous motivations (see fig. 8), emphasizing that they vary across individuals (Baruch et al., 2016; Rotman et al., 2012). As reflected in the model by Rotman et al. (2012), motivations categorized under "egoism", such as personal gain and curiosity, are leading drivers for initial engagement. Similarly, Hall et al. (2024) emphasize personal development, Baruch et al. (2016) mention fun, and Crowston and Fagnot (2008) highlight curiosity as initial motivators. E1 and E4 affirmed this, stating that curiosity and personal interest frequently drive initial engagement.

2.3.3 Citizen scientists' motivations for sustained participation

Motivations for sustained participation are different from initial participation and appear to be rather altruistic (Baruch et al., 2016; Hall et al., 2024). Long-term involvement is mentioned to be driven by extrinsic factors (Palacin et al., 2020), including social obligation, shared ideology, and a feeling of satisfaction (Crowston and Fagnot, 2008). Compared to new participants, motivations more profound in long-term participants were helping others (Rotman et al., 2012), environmental concerns, and learning (Ryan et al., 2001). Contributing to science is commonly cited as the most significant motivator for both sustained participation (Asingizwe et al., 2020; Raddick et al., 2009; Thompson et al., 2023), and initial participation (Lee et al., 2018). Self-directed motivation also plays a crucial role in sustaining enthusiasm and engagement (Palacin et al., 2020).

Motivation	Found by
Fun	Baruch et al., 2016; Curtis, 2015; Land-Zandstra et al., 2021; Raddick et al., 2009
Learning new things	Asingizwe et al., 2020; Lee et al., 2018
Contribute to science	Asingizwe et al., 2020; Curtis, 2015; Land-Zandstra et al., 2021; Lee et al., 2018; Raddick et al., 2009
Helping	Asingizwe et al., 2020; Lee et al., 2018; Raddick et al., 2009
Contribute to specific project goals	Asingizwe et al., 2020; Land-Zandstra et al., 2021
Curiosity or intrinsic interest in the project topic	Asingizwe et al., 2020; Curtis, 2015; Land-Zandstra et al., 2021; Raddick et al., 2009
Seeking to become part of a community	Land-Zandstra et al., 2021; Lee et al., 2018; Raddick et al., 2009
Teaching or advocacy (i.e. teaching others about the topic)	Raddick et al., 2009

fig. 8 *Participant motivations to join citizen science*

2.3.4 Citizen scientists' barriers to participate

Barriers that cause participants to be hesitant to join include perceived power imbalances between scientists and volunteers, which can result in distrust and apprehension (Rotman et al., 2012). Participants' willingness to engage in citizen science can also be affected by how well a project matches their motivation and to what extent they experience that they can contribute to a project (Land-Zandstra et al., 2021). Additionally, participants mention the inability of scientists to address or recognize their needs and motivations (Burgess et al., 2017; Land-Zandstra et al., 2021; Rotman et al., 2012). Furthermore, volunteers feel the need for attribution and recognition for their work, accompanied by a desire to get feedback on how the collected data is used and whether it is valuable (Asingizwe et al., 2020; Land-Zandstra et al., 2021; Palacin et al., 2020; Rotman et al., 2012).

2.3.5 Researchers' motivations and barriers

Rotman et al. (2012) suggest that scientists demonstrate a narrower motivational range compared to volunteers, primarily viewing citizens as a means for large-scale data collection, which was also highlighted by E3. However, others nuance this by arguing the existence of other strands of citizen science that focus on public participation (Adler et al., 2020; Kullenberg and Kasperowski, 2016). Davis et al. (2023) further state that most citizen science projects fail to produce peer-reviewed publications, making their "science" element largely irrelevant. Projects focused on public participation are driven by more altruistic motivations, such as educating the public about science, its methods (Land-Zandstra et al., 2021), and its influence on policy decision-making (Rotman et al., 2012), while researchers also benefit from new perspectives on their research topics (Rotman et al., 2012).

Next to a lack of institutional support (L'Astorina et al., 2023), a frequently cited barrier for researchers is that citizen science often does not generate sufficiently high-quality data or use sufficiently rigorous methods (Burgess et al., 2017; Elliott and Rosenberg, 2019; Flanagin and Metzger, 2008; Fritz et al., 2022; Wesseling et al., 2016).

2.3.6 Transparency

A particularly important enabler in citizen science is transparency, being one of the 10 core principles of citizen science (Gold, 2022). It is a participant's right, and organizers should ensure clear information about a project and its outcomes (Land-Zandstra et al., 2021). Transparency is also valued in project platforms, as noted by Baruch et al. (2016). Gold (2022) emphasizes the importance of open access to results and publicly available meta and project data while also addressing security and privacy concerns, issues further emphasized by Jaimes et al. (2015). The findings are echoed by E4, who recommends to clearly identify the parties responsible for organizing the project and those with access to the data.

2.3.7 Communication

Another key enabler is effective communication, particularly to address potential participants' motivations (Land-Zandstra et al., 2021). E1 and E4 agree with this, stating that recruitment strategies are often project-specific and typically occur through smaller, community-based networks, such as neighbourhoods. This is in line with Pateman et al. (2021), noting that participants are effectively reached through third parties already embedded within communities.

Communication of outputs and results is crucial to sustaining engagement during the project (Baruch et al., 2016; Land-Zandstra et al., 2021), and for effectively concluding it (De Vries et al., 2019). E4 agrees, mentioning that communication helps participants anticipate results and highlighting the importance of a conclusion about outcomes in the end to give the project societal continuation.

E4 also mentions that obvious commerciality can cause aversion for the project. This might be particularly relevant, considering that contributing to science is a key motivator for participants. To address these motivations, incorporating friendly and approachable communication into the design of measuring tools might be beneficial.

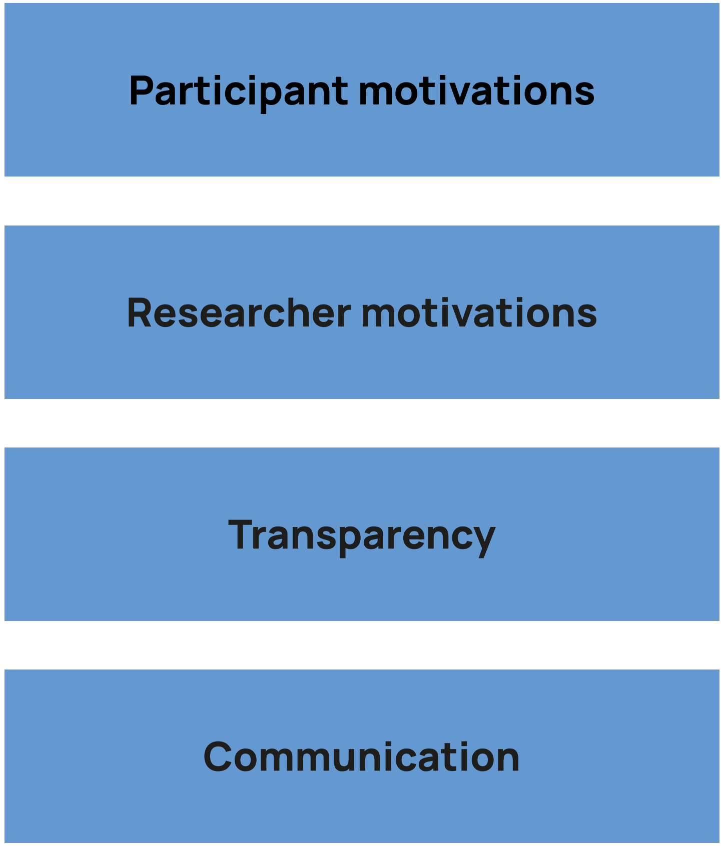


fig. 9 *Overview of identified key factors that identify citizen science participation*

Key insights: preconditions

Citizen scientist motivations for participation are numerous they vary across individuals, are dynamic over time, and are egoistic and intrinsic for initial participation and altruistic and extrinsic for sustained participation. Contributing to science is a key motivation, and self-steered motivation works most effectively.

Citizen scientist barriers are researchers being unable to address participant needs and motivations, a perceived power imbalance between participants and researchers, and unmet needs for attribution and recognition.

Researchers' main motivations are collecting data or public engagement, depending on different citizen science strands. Barriers are low quality data; a lack of scientifically rigorous methods; and a lack of institutional support.

Transparency about the project, its involved parties, and its outcomes is a key requirement.

Communication is project-specific, diverse, and can occur through third parties. Communicating results is a key aspect, and project appearance should be friendly and approachable.

2.4 Opportunities

Current pitfalls of citizen science and opportunities for improvement

Opportunities to improve citizen science are divided into four aspects: product, product-service, service, and business. The product category focuses on the physical measuring instrument itself, while service covers systems or processes that support or complement the product but still function rather independently.

The hybrid product-service category addresses services that root in, or are influenced by the physical product, combining elements of both. The business category involves broader, more abstract opportunities that focus on strategic and systemic improvements.

Product	Product-Service	Service	Business
Scalability	Installation help	Improved content quality	Viable model
Robustness	Troubleshooting	Standardized dashboard	Diversity
Modularity	Standardized data protocol	Mobile app	
Reuse	Plug-and-play		
	Ambient user communication		

fig. 10 *Overview of identified opportunities*

2.4.1 Product: Scalability

Regardless of whether an initiative's goal is to gather data or public engagement (Kullenberg and Kasperowski, 2016), its scalability can significantly impact its reach and effectiveness. Recent advancements in air pollution monitoring practices, including the shift from costly stationary equipment to more affordable, portable sensors that provide near real-time data (fig. 11), present opportunities to enhance existing monitoring capabilities and explore new applications (Snyder et al., 2013). This aligns with E3's projection that IoT-based measuring instruments will see increased use due to their remote accessibility. However, while digital and web-based technologies offer scaling potential (Spasiano et al., 2021), it is harder to quickly scale physical measuring instruments. For example, the "CurieuzeNeuzen in de Tuin" project received over 50,000 applications but could only include 4,400 participants because of a fixed number of instruments (CurieuzeNeuzen, n.d.-a). More scalable instruments like "Telraam" (fig. 1) can increase the number of devices more easily (Janež et al., 2022), but are designed for a specific research focus, traffic monitoring in this case, restricting their applicability across diverse citizen science projects.

In discussions on scalability with interviewees, E2, E3, and E4 identified a significant barrier for the researcher: the need to execute tasks manually, such as responding to volunteer emails. E3 further emphasized that these challenges are caused by fixed or limited project funding. This observation aligns with findings by L'Astorina et al. (2023), who note that insufficient institutional support—coming from a lack of interest or inadequate funding for citizen science—hinders the establishment of long-term relationships and restricts the lifespan of projects.

fig. 11 *An example of an affordable, portable measuring instrument, used in the "CurieuzeNeuzen in de Tuin" project (De Standaard, 2021)*

2.4.2 Product: Robustness

As limited institutional support and funding constrain long-term planning (L'Astorina et al., 2023), measuring instruments do not have to be designed to last for years either, especially when they are tailored to specific project goals. E2 echoes this, highlighting that instruments often need to be developed or adapted to fit the context of individual projects. For instance, European-funded projects like CityTRAQ (European Commission, n.d.-a), VAQUUMS (European Commission, n.d.-b), and COMPAIR (COMPAIR, n.d.), have project durations of 3 to 4 years, and most projects rarely exceed this time frame. E3 notes that these constraints lead to trade-offs between costs and functionality during instrument design, often resulting in lower-quality devices that are prone to malfunction and failure.

Although the issue of low robustness has received little attention in literature, studies on instrument usability accentuate the challenges caused by it. Collier-Oxandale et al. (2022) argue that air quality sensors, for example, should be more user-friendly, noting that unreliable Wi-Fi connections are a barrier to using them. Similarly, Robinson et al. (2018) found that technical malfunctions during everyday use reduced volunteers' motivation to use measuring devices. Interviews with experts and users confirmed these findings. E2 and E3 reported frequent connectivity issues with instruments used in the "CurieuzeNeuzen in de Tuin" project, with E3 adding that a lack of robustness required additional tools for installation (fig. 12). E1 mentioned that sensor case failures sometimes lead to sensor and instrument malfunctions, while both P1 and P2 reported that instrument malfunctions caused interruptions in data collection.

This suggests that improving instrument robustness could enhance their durability, user experience, and participant motivation, which in turn might lead to better data quality.

fig. 12 *Additional tools (hammer, blade and wood) required to install the instrument in the "CurieuzeNeuzen in de Tuin" project (CurieuzeNeuzen, 2022)*

2.4.3 Product: Modularity

Instruments like "Telraam" (Telraam, n.d.) and those used in the "CurieuzeNeuzen in de Tuin" project (CurieuzeNeuzen, n.d.-a) feature highly specialized sensors and unique approaches, making them difficult to adapt across diverse projects. E2 agrees, noting that the instruments were stored after the project ended and remained largely unused due to their highly specific application. A product that aims to tackle this is the "Smart Citizen System" (fig. 13), a modular kit designed to support various sensors, allowing for its use in multiple projects (Camprodon et al., 2019; Smart Citizen, n.d.-a). However, the usability of such systems is limited, as their installation and operation demands significant effort and technical expertise. Compared to manual field monitoring, which does not require particular skills (Schmeller et al., 2017), they are less accessible to the general public.

E2 and E3 observed that people tend to adapt existing instruments creatively. For example, E2 noted that municipalities desired to use instruments from the "CurieuzeNeuzen in de Tuin" project solely for monitoring freezing temperatures, in order to determine when to deploy gritters. Similarly, E4 shared that she used several "Telraam" instruments in a study on air quality to compare traffic data insights with the data from air quality instruments.

These findings suggest that systems designed with flexibility and openness to interpretation can attract a broader range of potential users and applications. By allowing for the extension or modification of sensors while maintaining usability, a modular measuring instrument could offer significant advantages. Such instruments would need to be adaptable to various contexts, appealing to diverse contexts and users.

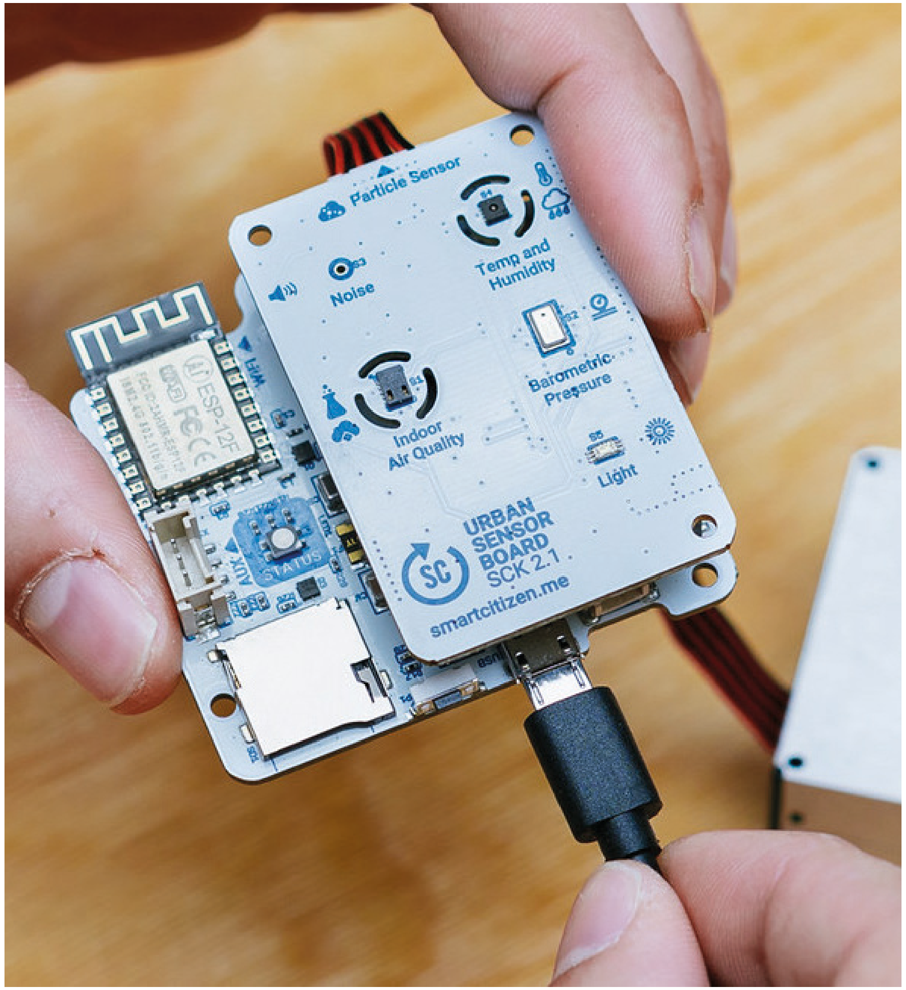


fig. 13 *Modular Smart Citizen Kit* (Smart Citizen, n.d.-b)

2.4.4 Product: Reuse

When instruments will improve in robustness and versatility, their lifespan can be extended and they become reusable across multiple projects. This does not only offer environmental benefits by reducing waste and resource consumption but also enhances cost efficiency. As noted by E2 and E3, reusability can influence design trade-offs and allow production costs to be spread across several uses.

Key insights: product opportunities

Opportunity: Scalable instruments
Scalability is limited for physical measuring instruments as they are designed for very specific research focuses; require a lot of manual tasks for organizers; and have limited product funding restricting projects' lifespan.

Opportunity: Robust instruments
Instruments are not designed to last for years, leading to trade-offs between costs and functionality during development, leading to lower quality, leading to lower usability.

Opportunity: Modular system
Very specific instruments limit applicability across projects, but modular kits and DIY solutions lack usability. Users are creative with applying instruments.

Opportunity: Design for reuse
Reusing instruments offers environmental benefits, different trade-offs and cost efficiency.

2.4.5 Product-service: Installation help

Several studies highlight the insufficient consideration of volunteers' needs and frequent usability issues in citizen science measuring instruments (Collier-Oxandale et al., 2022; Robinson et al., 2018; Skarlatidou et al., 2019). According to Robinson et al. (2018), this is not surprising, as devices are primarily tested on technical capabilities and designed with researchers in mind, rather than focusing on the needs of the public and end users. For example, a study focusing on mosquito traps found that participants identified inefficiency, lack of feedback, and difficulties in collecting observations as barriers to remain involved (Asingizwe et al., 2020). Providing support materials, such as manuals or guides, can support participants' understanding of project processes and ensure task completion (Bonney et al., 2009b; Budde et al., 2016). Collier-Oxandale et al. (2022) specifically emphasize the importance of assisting volunteers with the initial installation of devices. These findings align with E2's observation that users often struggle with instrument installation. Submitting a photograph of the installed sensor for assessment, for example, could assist participants in correct installation (Collier-Oxandale et al., 2022). E2 and E3 confirmed that this strategy was applied in the "CurieuzeNeuzen in de Tuin" project, but added that manually reviewing these images was time-consuming and did not provide users with immediate feedback.

Further, participants may feel pressured to produce 'good' measurements (Asingizwe et al., 2020). This aligns with findings by Rotman et al. (2012), who identified a perceived power imbalance between volunteers and researchers. Support mechanisms, such as installation manuals, could help to steer or reassure users about their handling. Manuals could also provide additional training for skill-intensive projects (Catlin-Groves, 2012), which are projects in which participants have to do more than field counts.

While volunteers would prefer self-explanatory devices, they desire any necessary manuals to be clear, simple, concise and accurate (Robinson et al., 2018). E3 mentioned that while the "CurieuzeNeuzen in de Tuin" project provided manuals, these often proved to be complex. Providing task-specific, short-form information, such as an in-app tutorial, can be an effective approach (Budde et al., 2016), and breaking tasks into smaller ones can further enhance usability (Rotman et al., 2012). This suggests that an interactive manual with step-by-step guidance could offer a solution.

2.4.6 Product-service: Troubleshooting

Robinson et al. (2018) observed that volunteers were often unsure whether their devices were actively collecting data. This lack of feedback when instruments stopped collecting without participants realizing it led to frustration and data loss. Providing the user feedback could therefore be helpful (Budde et al., 2016). User interviews showed similar problems: for instance, P2's instrument seemed inactive, though it was still storing data locally without submitting it to the online database, while P1 experienced data loss due to an unnotified update.

Asking the experts about their experiences, E2 and E3 noted that misplaced or malfunctioning instruments in the "CurieuzeNeuzen in de Tuin" project, could often be detected remotely from their implausible data patterns (e.g., ongoing -30°C temperature or 0% soil moisture). However, fixing these instruments proactively, for example, by contacting participants, would have been time-consuming, and therefore they were only flagged. However, E2 and E4 indicate that not immediately addressing these issues resulted in participants emailing about errors, with E3 and E4 adding that these emails were often repetitive and could have been addressed with standardized responses.

To enhance engagement and data recovery, notification systems can be implemented to alert users when a sensor goes offline (Collier-Oxandale et al., 2022). Providing feedback enables the user to correct errors, enhancing both data quality and user trust in the data (Skarlatidou et al., 2019). Incorporating troubleshooting mechanisms, such as support for resolving connectivity issues (Collier-Oxandale et al., 2022), could further enhance user experience. E3 agrees with these findings, suggesting automated flagging of malfunctioning instruments as a potential solution. E4 emphasized that empowering users with feedback to prevent or solve issues could enhance scalability by shifting workload from organizers to participants. However, careful design is necessary, as Robinson et al. (2018) found that LEDs indicating different ongoing processes may also bother volunteers.

2.4.7 Product-service: Standardized data protocol

As seen in chapter 2.3, academic doubt towards citizen science is often caused by a lack of rigorous methods and reliable data quality validation mechanisms (Burgess et al., 2017; Catlin-Groves, 2012; Elliott and Rosenberg, 2019; Flanagin and Metzger, 2008; Fritz et al., 2022; Wesseling et al., 2016). This concern is partially due to challenges related to participants, who are often untrained (Bonney et al., 2014), and have varying skill levels (Pateman et al., 2021). Post hoc evaluation metrics, as error detection, can help address researchers' concerns by assessing the reliability of data (Burgess et al., 2017). E2 and E3 note that in the "CurieuzeNeuzen in de Tuin" project, data is indeed evaluated after collection. However, appropriate ad hoc measures and protocols can help participants to collect data of comparable quality to that collected by experts (Bonney et al., 2014). Nonetheless, while training participants could help them to perform tasks correctly, it may be challenging to create understanding for more complex materials (Budde et al., 2016).

Therefore, standardized and universal collection protocols can help to increase scientific rigor. For example, protocols describing sampling processes can promote consistency (Bird et al., 2014; Burgess et al., 2017). Without such protocols, methodologies often become inconsistent (Burgess et al., 2017), limiting interoperability across projects (Spasiano et al., 2021). In practice, organizations tend to develop their own non-standardized structures (Schmeller et al., 2015), despite many different projects collecting similar data in similar locations (Bonney et al., 2014). This lack of harmonization limits large-scale meta-analyses, which require rigorously collected and uniform data (Adler et al., 2020; Egloff et al., 2016; Loss et al., 2015; Rotman et al., 2012; Spasiano et al., 2021; Vohland et al., 2021). E3 agrees, mentioning that the findings from various similar Belgian air quality projects are not combined.

Although standardized protocols can enhance participant-level accuracy, scientific rigor and interoperability, their impact on data quality remains limited by other factors like sensor performance constraints (Budde et al., 2016; Robinson et al., 2018; Wesseling et al., 2016). It is also important to recognize that rigorous data collection is not always the primary objective of citizen science projects; some prioritize public engagement over data quality (Adler et al., 2020; Davis et al., 2023; Kullenberg and Kasperowski, 2016).

2.4.8 Product-service: Plug-and-play

In a meta study by Vasiliades et al. (2021), the majority of citizen science initiatives were reported to be locally oriented (48%), compared to nationally (39%). E4 agrees, adding that the "CurieuzeNeuzen in de Tuin" project is already quite large-scale. Additionally, the study found that 63% of initiatives were coordinated by academic institutions, 37% by NGOs, and 15% by governmental organizations (Vasiliades et al., 2021). E1, E2, E3, and E4 similarly noted that there are limited opportunities for individuals to engage in citizen science.

Despite this, E1 and E3 observed local governments and smaller civic organizations expressing interest in citizen science. Literature mentions that public input and engagement are essential for governmental bodies to formulate and achieve goals for conservation (McKinley et al., 2017). Participants can also help to share results with local municipalities and collaborate with them (Land-Zandstra et al., 2021). Many citizens participate in projects driven by concerns about local environmental issues, and the outcomes of these initiatives can empower them to address and influence policy decisions (Janež et al., 2022; Land-Zandstra et al., 2021). Many initiatives also encourage participants to engage in such efforts (Kullenberg and Kasperowski, 2016; Vasiliades et al., 2021). E1 echoes these findings, mentioning that for such types of projects, this is indeed a reason to join. P1 also noted that local environmental concerns were the main reason to join. A pitfall of public engagement is the underrepresentation of low socio-economic groups, who are less likely to participate in citizen science (Pateman et al., 2021). This limits their influence on decision-making, despite these groups being the most vulnerable to environmental injustice and most in need of local environmental information (Purcell et al., 2012).

Resource constraints may be one reason why fewer projects are organized by governmental and civic organizations. Compared to academic institutions, they have limited access to established funding structures, partnerships and expertise. To ensure sustainability, initiatives typically require multiple funding sources, particularly from universities and NGOs (Vasiliades et al., 2021). E1 and E4 shared similar views, mentioning that local initiatives typically have tight budgets and limited employees. E1 added that this decreases their ability to purchase or develop measuring instruments, further constraining their capacity to produce scientifically rigorous data. The hesitancy towards citizen science from policymakers, driven by concerns about unprofessional and weak methodologies (Vohland et al., 2021), exacerbates the vulnerable position of civic organizations in governmental decision-making, according to E1. Furthermore, citizen science projects often involve sensitive personal data, requiring careful attention to privacy and ethics (Anhalt-Depies et al., 2019; Bowser et al., 2017; Janež et al., 2022). E3 mentioned there is a variety of measures that can be taken, such as anonymization or rounding of coordinates. Academic institutions have established committees for such oversight, but smaller organizations lack comparable support.

A potential solution is in the development of plug-and-play measuring instruments with automated protocols. These could help to democratize citizen science by providing accessible, standardized instruments while also addressing ethical, privacy, and scientific concerns. Ultimately, this approach would facilitate broader participation and enable small, resource-constrained organizations to engage more effectively in citizen science.

2.4.9 Product-service: Ambient user communication

Privacy concerns in citizen science (Anhalt-Depies et al., 2019; Bowser et al., 2017), extend beyond participants and organizers to non-users—members of the public who may be indirectly affected by data collection, particularly when measuring instruments are involved. Augustin et al. (2020) argue that the concept of "non-user" is not absolute but exists on a spectrum (fig. 15). Two key groups of non-users are particularly relevant in this context: laggards, who have not yet engaged but may be convinced to do so with information, and resisters, who refused to participate and may only be reassured through informative efforts. P1 provided an example of the latter, reporting that neighbors expressed fear of being eavesdropped on by audio-recording devices in the project of "de Oorzaak" (fig. 14). Similarly, E2 described incidents during the "CurieuzeNeuzen in de Tuin" project where instruments were moved or temporarily removed, likely out of curiosity or suspicion. Regardless of whether this skepticism or distrust is justified, it highlights the need for clear instrument communication to inform this group of "ambient users".

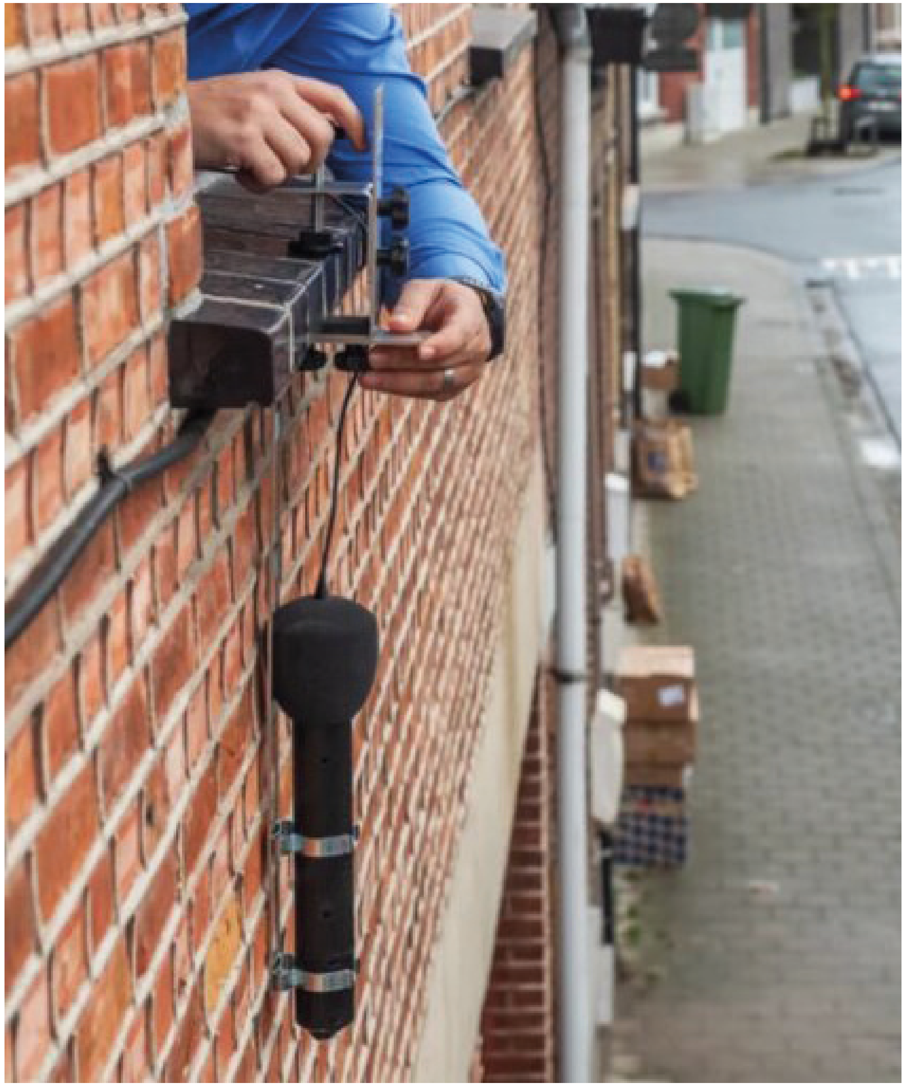


fig. 14 *The measuring instrument of the "de Oorzaak" project (Universiteit Antwerpen, n.d.)*

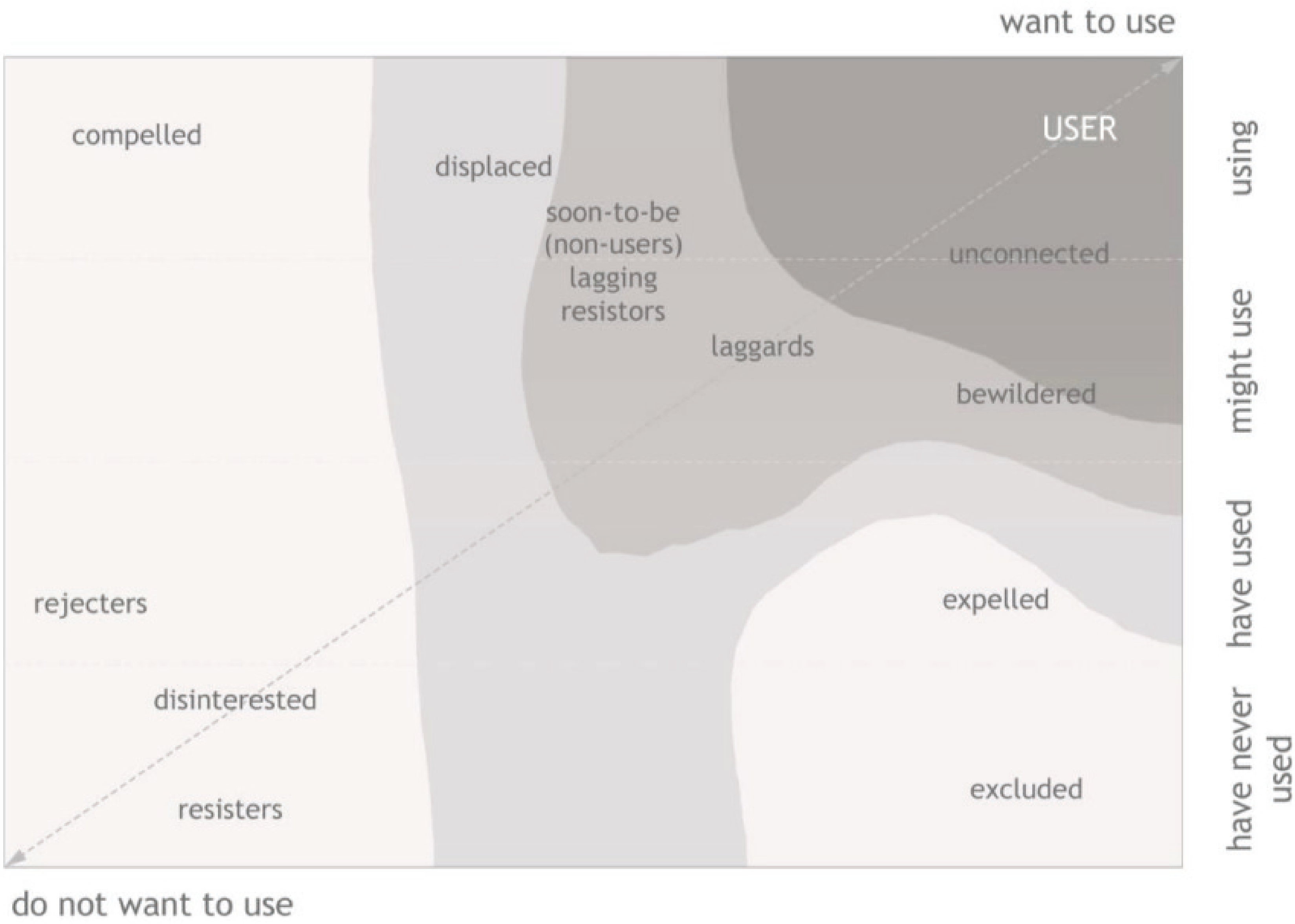


fig. 15 *Spectrum of non-users (A*ugustin et al., 2020)

Key insights: product-service opportunities

Opportunity: Interactive installation manual
Current solutions lack usability, especially when installing. Aiding materials can help to steer or reassure participants.

Opportunity: Troubleshooting
Users struggle with understanding (malfunctioning) devices, causing dissatisfaction. Automated flagging and feedback can help the user to identify and address issues, reducing labor-intensive manual intervention by organizers.

Opportunity: Standardized collection protocols
A lack of rigorous methods and reliable data quality validation mechanisms can be solved by ad hoc measures such as standardized data collection protocols that promote consistency, interoperability, and participant-level accuracy.

Opportunity: Plug-and-play solution
(Civic) organizers do not have funding structures, partnerships and expertise in privacy, ethics and scientific rigor. Automated plug-and-play instruments can deal with these issues.

Opportunity: Communication to ambient users
Instruments affect a group of ambient users indirectly. Clear information can reassure resisters and persuade laggards, increasing support.

2.4.10 Service: Improved content quality

Next to concerns about local environments and the need for data to validate these concerns (Janež et al., 2022; Land-Zandstra et al., 2021), the opportunity to gain insight into data (Robinson et al., 2018) and experiment with emerging technology is a motivator to participate in citizen science initiatives. E1 similarly mentioned he observed two major groups of participants in projects involving instruments: those motivated by local environmental concerns and "geeks" intrigued by the technology. He adds that providing data can offer these groups something unique.

Providing access to data can serve as a mechanism to deliver the desired feedback (see chapter 2.3) on how collected data is used and whether it is valuable, thereby offering participants attribution and recognition. Doing so acknowledges participants and treats them as collaborators, not only as means to an end (De Vries et al., 2019), and highlights the uniqueness of contributions, further increasing motivation (Rotman et al., 2012).

Data visualization dashboards (see fig. 16, fig. 17 and fig. 18) are essential tools to provide access to data and deliver feedback on volunteer's contributions and their necessary role in achieving research objectives (Spasiano et al., 2021). These dashboards manage large datasets and process them into meaningful information (Collier-Oxandale et al., 2022). As a result, many projects, such as "CurieuzeNeuzen in de Tuin" (CurieuzeNeuzen, 2021) and "Samen Meten" (RIVM, n.d.-b), aim to integrate them. However, dashboards alone are not enough to establish a sense of attribution and recognition. For example, P2 noted feeling undervalued when their device broke, stating that it seemed more intended to benefit researchers than participants. Robinson et al. (2018) also mentioned devices designed for researchers rather than for the public.

Experts (E2, E3, E4) and users (P1, P2) highlighted the potential to improve user engagement by expanding the functionalities and options for accessing and interacting with collected data or, in other words, giving them more tools to explore and derive value from data. Accessibility to collected data was found to be critical (De Vries et al., 2019), particularly for historic (Collier-Oxandale et al., 2022) and real-time data (Golumbic et al., 2019), as difficulties in accessing can lead to declining interest over time. Both E2 and P2 suggested using personalized tips and "hooks" to increase value and trigger motivation. Passive hooks, such as notable weather events, were observed by E2 to drive increased platform activity in the "CurieuzeNeuzen in de Tuin" project. Active hooks, like self-set conditional alarms triggered by specific data patterns, were suggested by P2. Literature highlights similar user preferences, with participants suggesting functions to alert them about high pollution levels (Robinson et al., 2018), or significant air quality events (Collier-Oxandale et al., 2022).

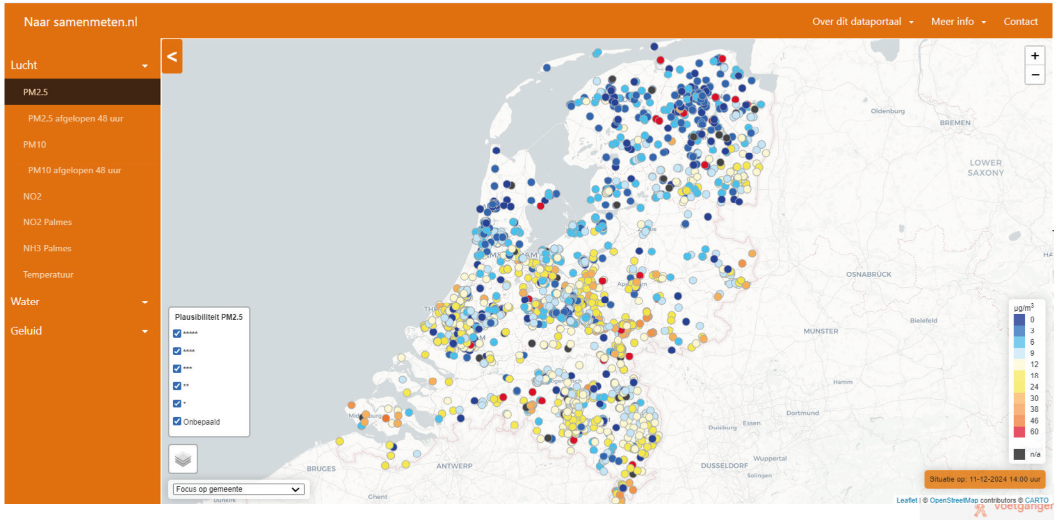


fig. 16 *"Samen Meten" dashboard* (RIVM, n.d.-b)

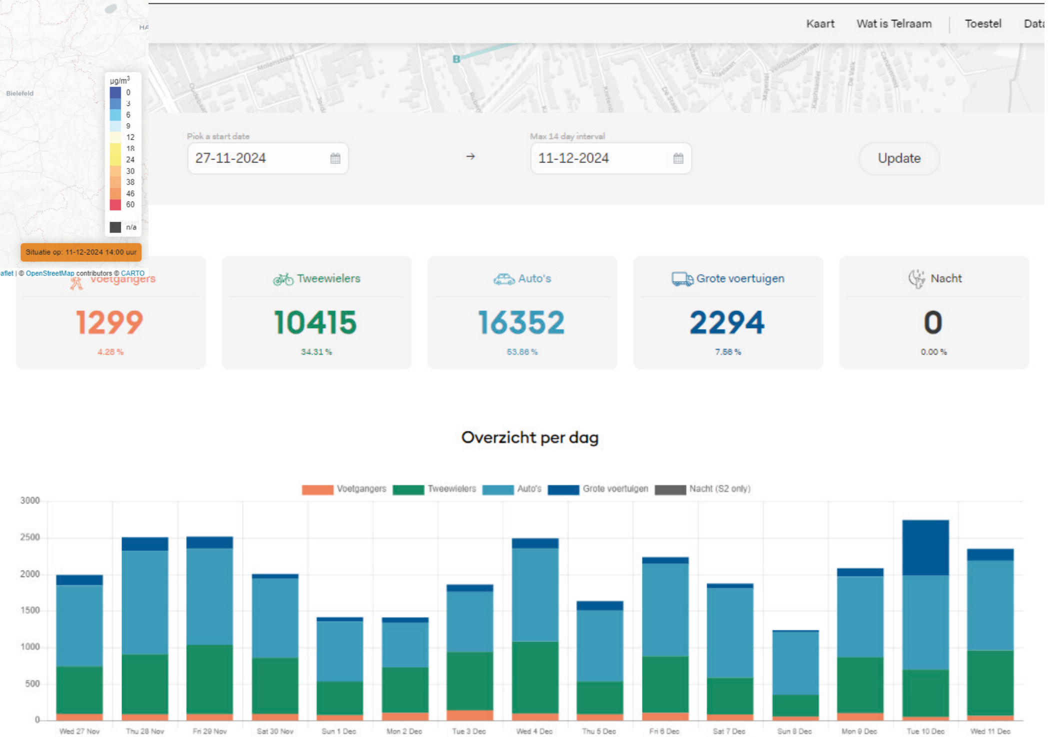


fig. 17 *"Telraam" dashboard* (Telraam, n.d.)

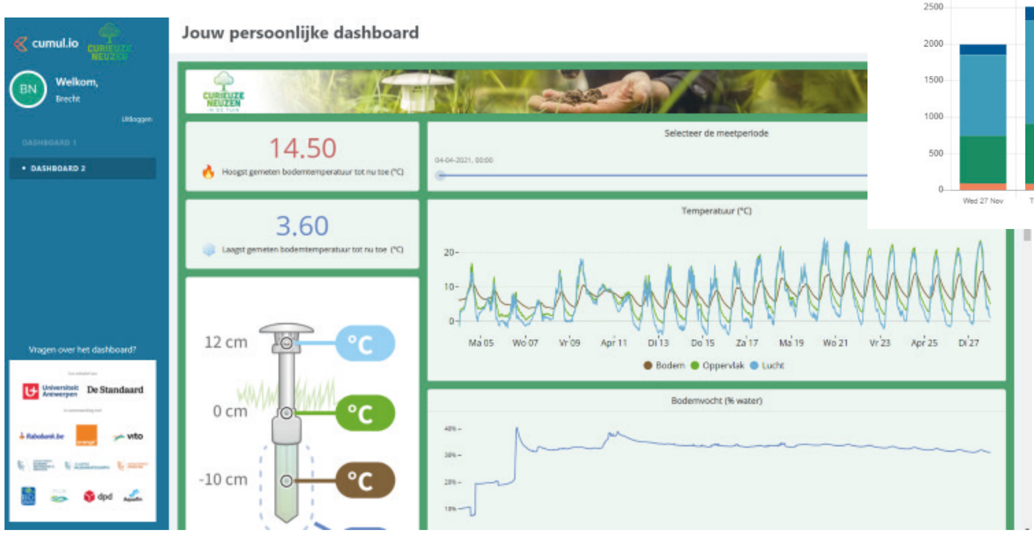


fig. 18 *"CurieuzeNeuzen in de Tuin" dashboard* (CurieuzeNeuzen, 2021)

2.4.11 Service: Standardized dashboards

Despite widespread adoption of dashboards across initiatives (E2) and frequent use of similar sensor data, projects repeatedly and independently develop new dashboards. A more efficient and scalable approach would involve creating standardized, modular dashboards as part of a broader measuring system, which could potentially be offered as a service.

A key factor in the design of dashboards is to deliver and visualize data in a locally relevant manner (Golumbic et al., 2019), since local interests often drive sustained participation (Rotman et al., 2012; Woods et al., 2018). Ideally, dashboards address the most pressing community issues and needs (Woods et al., 2018), emphasizing the importance of volunteers' contributions to increase their engagement (Rotman et al., 2012). User and expert interviews show similar findings. Enthusiasm for comparisons, such as with other users or areas, was highlighted by P1, E1, E2, and E4. The latter three referenced the "CurieuzeNeuzen in de Tuin" project, where participants received reports comparing the characteristics of their gardens to those of others.

2.4.12 Service: Mobile app

Since dashboards are currently often reached through web applications, E3 mentioned the desire for the development of a mobile-compatible application to increase platform diversity, a suggestion supported by Robinson et al. (2018). Mobile apps provide quick access to data, increasing participant satisfaction (Collier-Oxandale et al., 2022). Older participants may be less comfortable using mobile apps (Adler et al., 2020), but the web version can exist alongside.

Mobile applications also present opportunities for additional functionalities by using phone sensors, such as location tracking (Catlin-Groves, 2012) or photo uploads. They can serve as centralized platforms that defragment existing functions into a single platform while integrating new ones to satisfy participants' unmet motivational needs. These features can include troubleshooting, help pages (Skarlatidou et al., 2019), and communication options such as forums to interact with other participants (Baruch et al., 2016; Skarlatidou et al., 2019). Additionally, E3 highlights the potential for organizers to use mobile apps as a direct communication channel to send information and personalized notifications to participants in a more convenient way.

Key insights: service opportunities

Opportunity: Improved data quality
Data insights—through dashboards—are a motivator in citizen science projects, deliver feedback fulfilling the need for attribution and recognition, and they offer something unique, particularly for two main groups: “geeks” and those worried about the local environment. Further improving tools to explore and derive value from data increases user benefits.

Opportunity: Standardized dashboards usable across projects
Dashboards are developed repeatedly, whereas they do not change significantly. Incorporating locality and context applicability motivates.

Opportunity: Mobile app
An app increases functionalities of measuring instruments by using phone sensors; can serve as a central platform with various functionalities; and makes it easier to communicate with each other and organizers.

2.4.13 Business: Viable model

As described earlier, the reliance on short-term funding limits the longevity of projects. E1 observed that this dependence often results in initiatives failing to become self-sustaining, causing them to fade out and eventually cease. Enhanced scalability, modularity and durability of instruments could enable alternative financial models, such as renting instruments out, potentially resulting in a more sustainable platform.

When evaluating models, participant fees must also be carefully considered. E1 and E3 mentioned prices of about €20-30 to participate in a project, with E4 and P1 emphasizing this could act as a barrier to participation. As noted earlier, lower socio-economic groups are less likely to participate in citizen science (Pateman et al., 2021), risking skewed results and excluding vulnerable people who are most in need of environmental information, as they often live in areas with the most unhealthy conditions (Purcell et al., 2012). Research shows mixed opinions regarding participation fees. Asingizwe et al. (2020) found that participants do not expect monetary rewards, while Martin and Greig (2019) found that some participants were surprised to be charged a fee, though they admitted the amount was not substantial. Yet, completely dropping fees might not be beneficial, as they help to support projects and retain participants (Martin and Greig, 2019). E4 agreed, suggesting that a fee could act as a deposit, incentivizing participants to install, use and return the instruments. A middle ground is suggested, such as providing transparent communication about fee allocation or financial support for low-income participants (Martin and Greig, 2019; Woods et al., 2018).

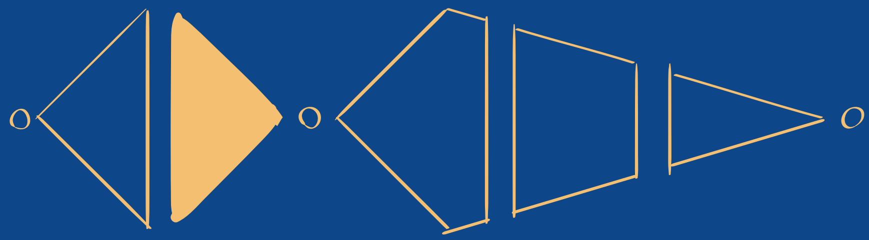
2.4.14 Business: Diversity

Citizen science participants are typically older, white, male, and highly educated (Paleco et al., 2021; Pateman et al., 2021; Wright et al., 2015). E1, E3, and E4 observed a similar trend, noting that older people for example explore new hobbies. Increasing diversity does not only extend citizen science benefits to previously uninvolved groups but also enriches the variety of contributions, which is essential for both the quantity and quality of data (Paleco et al., 2021). For example, a more diverse sample can help to mitigate spatial biases (Bird et al., 2014; Kays et al., 2021).

Key insights: business opportunities

Opportunity: Viable model
Current funding structures result in projects failing to be self-sustaining, causing them to fade out over time and stop. Improved measuring instruments could enable alternative financial models, such as renting instruments. Fee size should be considered, as it incentivizes and serves as a deposit.

Opportunity: Diversity
Participants are often older, white, male and highly educated. Including lower socio-economic groups gives them benefits and increases sample diversity, quantity, and quality.



3
Define

Building on the insights from the previous chapter, this section focuses on defining the project's scope, stakeholders, and use case scenario to establish a clear foundation for the design phases.

3.1 Project scope

Defining which opportunities will be addressed in this scope

Given the limited resources and time constraints typical of a graduation project, the scope of identified design opportunities has been refined to ensure feasibility and focus. An illustrated overview of the selected design opportunities that will be addressed in this project can be found in fig. 19, with increased saturation indicating greater emphasis on the issue. Since challenges overlap and lack rigid boundaries, the degree of intervention in each area became more defined as the project progressed. Scoping decisions were guided by the following considerations:

Firstly, the project focuses primarily on areas where industrial design engineering expertise (specifically in Integrated Product Design) can have the most impact. Therefore, more product-related opportunities, such as robustness, scalability, modularity, and reuse, were prioritized, along with installation help and troubleshooting, since they are partly addressed through physical features. These aspects all contribute to the development of a plug-and-play system. Ambient user communication was also included, as it focuses on one of the stakeholders of the instrument and must be physically implemented in a way that aligns with the overall design.

Secondly, to manage complexity and deliver meaningful outcomes, this project focuses on a few key challenges. By focusing on these, the project allows for more comprehensive development and iteration, avoiding efforts from being spread too thin across many aspects. Enhancing diversity was excluded as it is a rather high-level structural challenge, less relevant at the instrument level. Similarly, creating a viable business model is a broader issue that goes beyond improving the instrument itself. While developing an app and dashboard requires advanced, time-consuming programming, the conceptual exploration of what information these platforms should present and how they communicate with users will be addressed. Specifically, the integration of other functions into the app, such as installation, will be explored conceptually, while the dashboard will be excluded due to its limited relevance to this topic.

Thirdly, the scoped opportunities align with the company's expertise by focusing on challenges that match the strengths of supervising experts and available resources, maximizing the project's potential. As a result, developing standardized data protocols is excluded, as this requires collaboration with researchers and data scientists. Similarly, enhancing diversity is excluded because it heavily depends on project-specific communication strategies, better handled by communication experts. Finally, improving content quality is left out, as it involves developing messaging strategies and content frameworks.

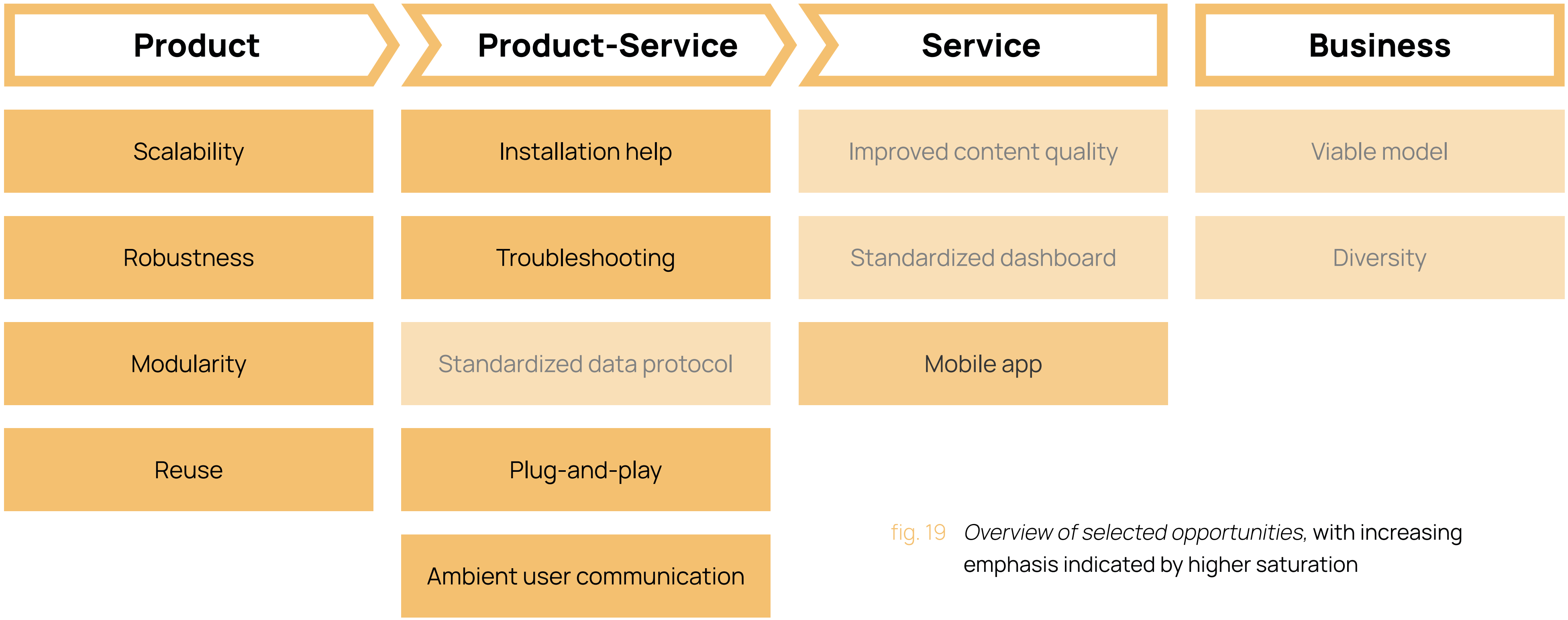


fig. 19 *Overview of selected opportunities*, with increasing emphasis indicated by higher saturation

3.2 Stakeholders

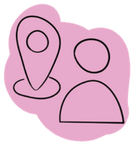
Who is involved, what do they desire in a new measuring instrument, and what opportunities mainly apply to them

3.2.1 Citizen scientists

Citizen scientists are the main stakeholders, as they interact directly with the product. Their motivations for joining and participating in citizen science have a diverse and individual underlying structure of motivations. Without their participation, citizen science would not exist, so a product should aim to address these various motivations.

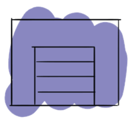
3.2.2 Researchers

Researchers are the second key stakeholder, often organizing and managing citizen science projects. They have their own set of motivations that the product should address, benefitting from instruments that facilitate their research efforts.



3.2.3 Local (civil) organizers

Local (civil) organizers seek to engage in citizen science, often to start public debates, such as those addressing local environmental health concerns. They typically lack the resources and expertise of research institutions in areas like technology, ethics, privacy, and scientific rigor but are superior in communication through strong connections within the local community.

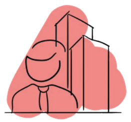


3.2.4 Instrument owner

The instruments are owned and distributed by a third party, who is committed to supporting citizen science. However, the development and maintenance of instruments must also be commercially viable. Their focus is on facilitating the instruments, and they ultimately benefit from increased interest in citizen science by improving indicated opportunities.

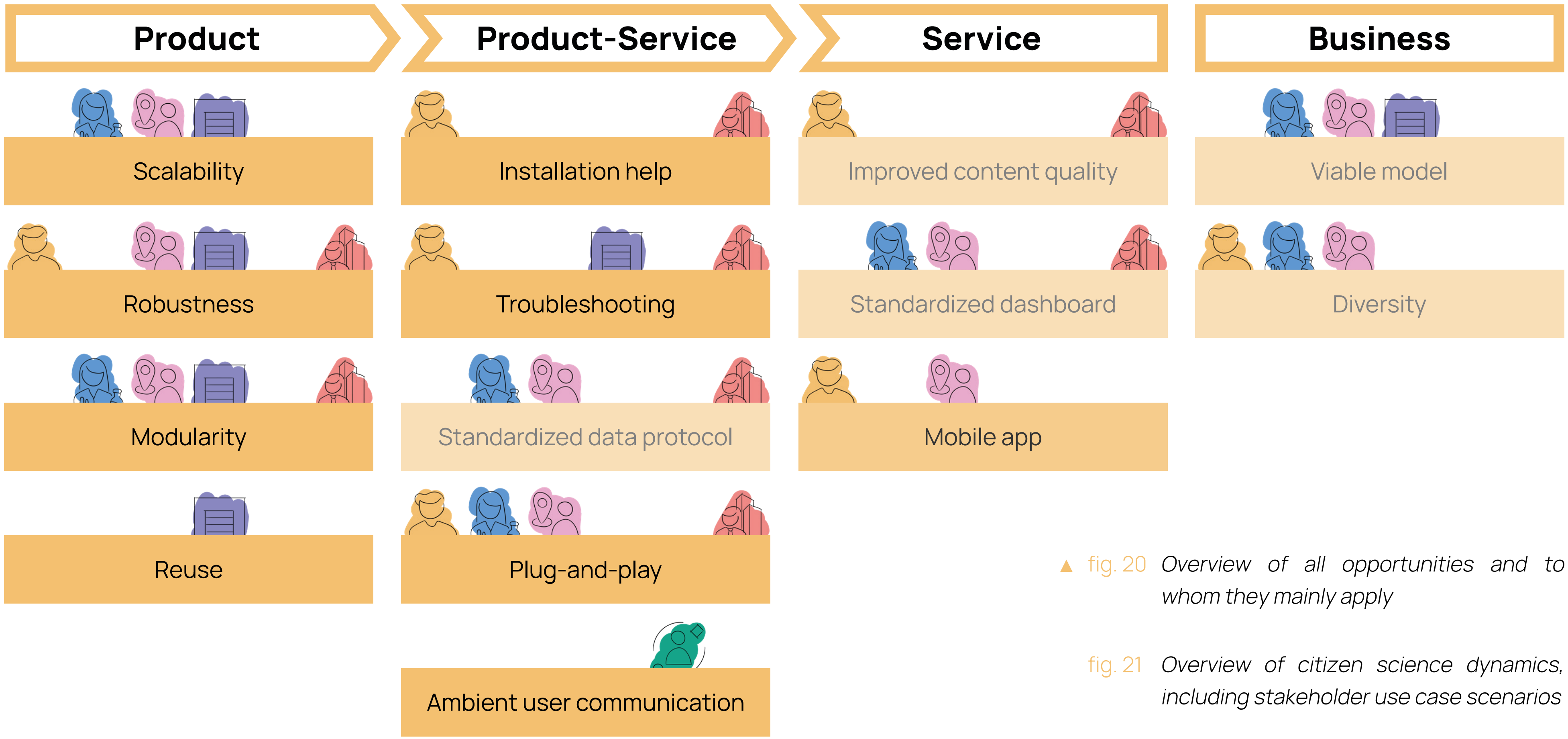
3.2.5 Ambient users

Ambient users have the right to be informed about the instrument and the data it records. Particularly significant in this scope are resisters, those who never used a measuring instrument and resist doing, and laggards, who might use one in the future.



3.2.6 Companies

Companies are potential new users who are creative in applying measuring instruments mainly for their own purposes. Although their primary interest is often their own benefit, the data they collect can still contribute to citizen science initiatives.

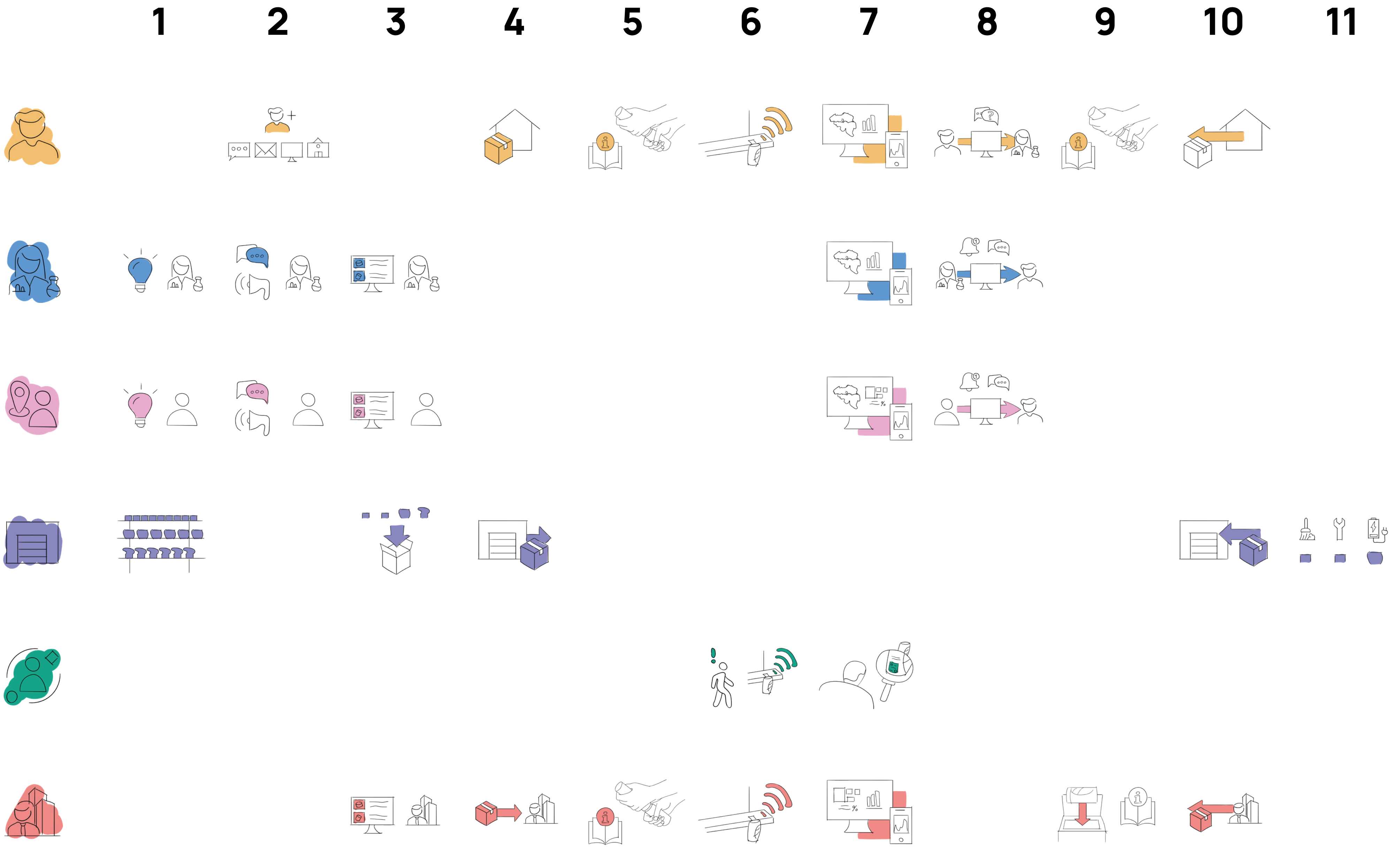


▲ fig. 20 *Overview of all opportunities and to whom they mainly apply*

fig. 21 *Overview of citizen science dynamics, including stakeholder use case scenarios* ▶

This page outlines all opportunities and the stakeholders they mainly apply to, while fig. 21 highlights the dynamics of a citizen science project, showing the use case scenarios for different stakeholders, their role in the process, and how they overlap.

The owner stores sensors while organizers plan citizen science projects (1). Organizers manage communication strategies themselves and engage participants via various channels (2). They select and order required sensors from the owner (3), who ships them to users (4). Users receive installation support (5), and instruments operate autonomously afterward (6). Ambient users are kept informed (6 & 7). Collected data becomes accessible and interactive in the online environment (7). Through the platform, organizers and users (except companies) can communicate with each other (8). After the process is done, users are guided in de-installing the instruments (9) and returning them to the owner (10), who cleans, repairs, and recharges them for reuse (11).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3.3 Context of use

To which context does this project apply

The instrument's proposed modularity allows for adaptation to a wide range of contexts for collecting citizen science data. To maintain focus while demonstrating this modularity, the project will focus on two specific research topics that serve as a blueprint for future applications: air quality and drought. These topics were selected as they are relatable to citizens, relevant to researchers, and align with current interests in citizen science.

The instrument is designed to function in outdoor residential settings, such as gardens for drought and balconies for air quality studies. To compare urban and rural settings, the instrument must be deployable in public natural spaces like parks and operate on battery power to ensure functionality in remote locations.

fig. 22 *Example of a typical garden setting*

fig. 23 *Examples of oudoor residential contexts*

A probe exploration was carried out to determine installation locations for the instruments. For reliable measurements, instruments should be fastened as firmly as possible, without requiring drilling. This resulted in soil, tree trunks, and (balcony) railings being desired locations, with the latter offering flexibility for attachment to a wide range of structures such as street lanterns or drainage pipes.

fig. 24 *Probe exploration: locations requiring hanging or sticking turned out to be unreliable*

Vision

Outlines the projects boundaries and addressed design parameters

Insights from the discover phase have been synthesized during the define phase to create a vision that will guide the design of a product-service system for contributory citizen science, specifically within the scope of monitoring air quality and drought. This vision summarizes key values and parameters of the design, defining the boundaries for the next phases and clarifying what will be addressed in this project. It serves as both a reference to ensure the design aligns with specific requirements and goals, and as a tool to evaluate project outcomes. Requirements are drawn from *preconditions* (representing existing demands) and **opportunities** (highlighting areas for improvement). For clarity, *italicized* text represents key values derived from preconditions or contextual demands, serving as guidelines when designing, while **bold** text highlights actionable design parameters addressed in this project.

The central element of the design is a **robust** physical measuring instrument equipped with various sensors to monitor air quality and drought in *outdoor residential and natural settings*. The instrument features **modular components** and adaptable *mounting options for soil, railings and trees*, enabling it to meet diverse project needs. Its modularity supports the various motivations of citizen scientists, including their desire to *contribute to science*. **Reuse** and repair are prioritized to extend the product's lifespan, reduce waste and enable cost-effective use of instruments across multiple projects. This approach also supports more sustainable business models, reducing dependency on short-term funding.

The system is designed to be **plug-and-play**, ensuring ease of use and accessibility for both citizen scientists and organizers, regardless of their technical and scientific expertise. It incorporates **interactive installation help** and **troubleshooting** to support users during setup, maintenance and repairs. Integrated data collection protocols automate processes to enhance academic rigor while maintaining *privacy and ethical standards*. These automated processes also improve **scalability** by minimizing manual tasks for organizers and eliminating the need for custom instrument development in each project. Also, **communication to ambient users** is incorporated to enhance *transparency* and trust.

The instrument is complemented by an online platform, compatible with both desktop and **mobile applications**. Among others, it integrates a data visualization dashboard that provides citizen scientists with real-time feedback, highlighting the significance of their contributions to the project. This addresses needs for *transparency, recognition and attribution*, with the ultimate goal of sustaining engagement. In addition, personalized tools for data exploration, enhanced features for comparison, and extended options for exploring data, the dashboard aims to improve data quality for citizen scientists. To reduce fragmentation, the platform integrates tools for *communication* with organizers and other participants and access to information resources.

By incorporating these requirements, the product aims to enhance the scientific and social impact of citizen science by better aligning with the practice of citizen science. It increases accessibility and application possibilities while empowering citizen scientists and organizers to collaborate effectively. This vison establishes a foundation for the next phase where detailed design and development will further refine and realize this vision.

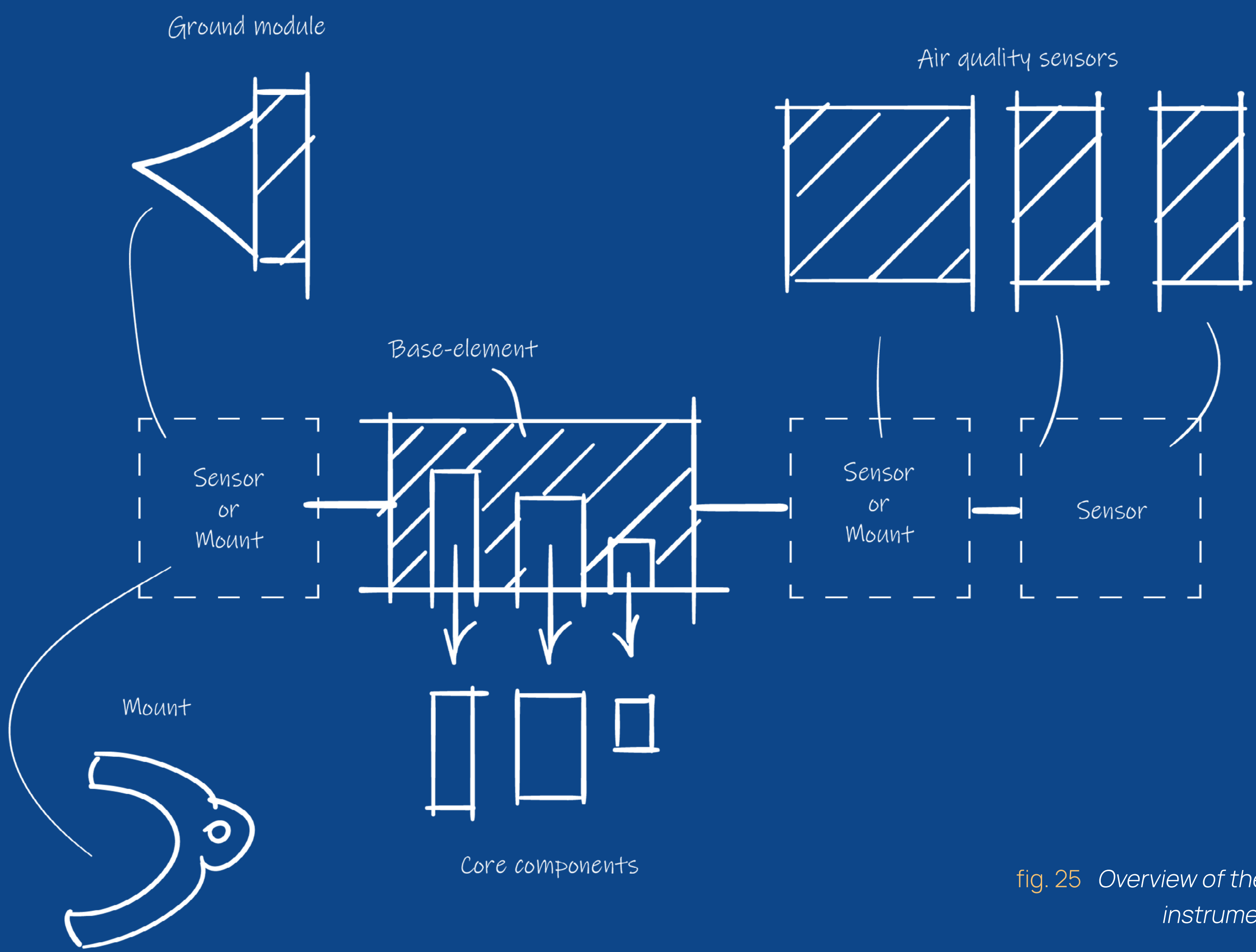
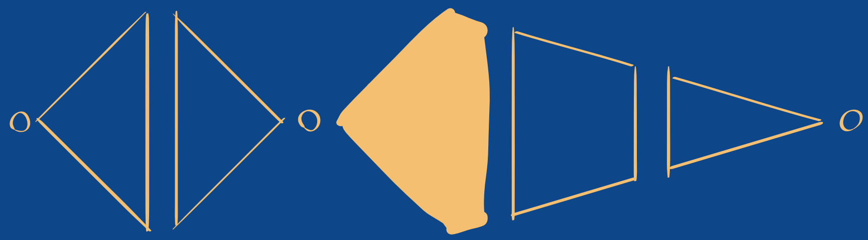


fig. 25 *Overview of the envisioned instrument structure*



4

Conceptualize

This chapter outlines the process of generating ideas and iteratively refining them into a cohesive preliminary design ready for further development.

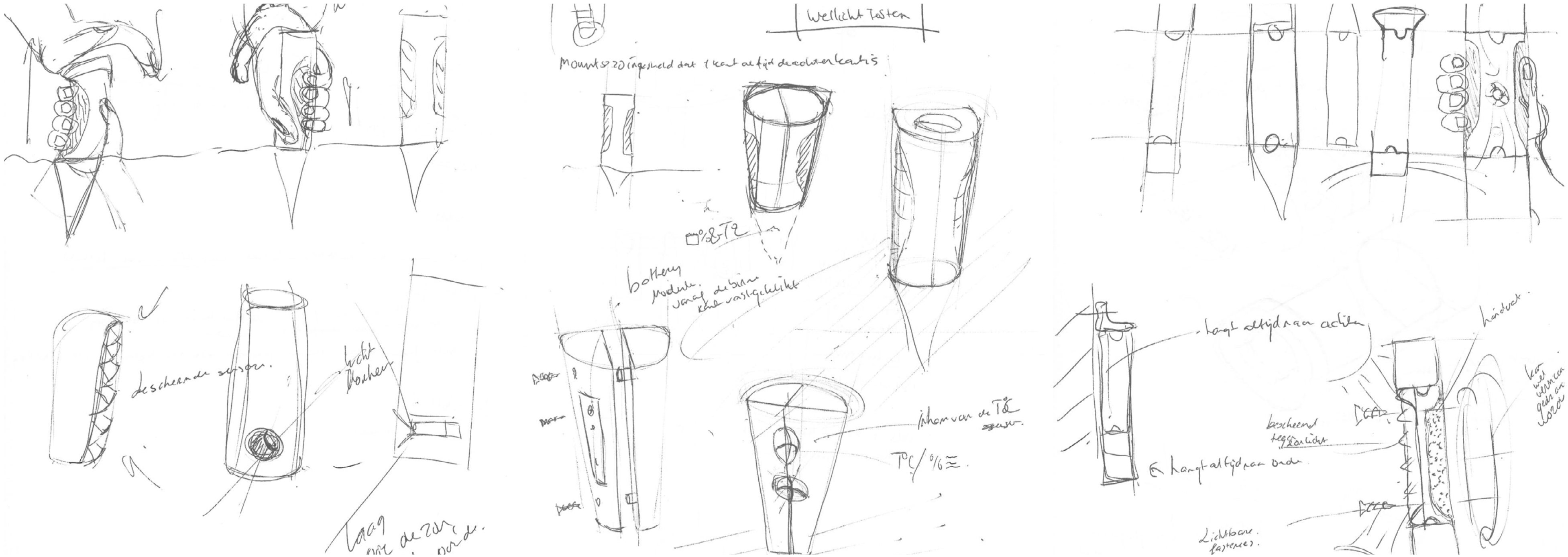
4.1 Concept exploration

Searching to interpret the vision resulting in different concept exploration

Brainstorming and sketching generated various interpretations of the vision. Initially, these tended to be superficial, leading to hasty and unjustified fundamental choices, such as settling on a cylindrical product shape without proper reasoning (fig. 26).

However, diversifying the approach enabled more effective comparison and evaluation of shapes and functionalities. Emphasizing different key product requirements or functionalities, such as easy installation and modularity, helped to assess different options. This resulted in seven concept explorations (fig. 27-fig. 33).

fig. 26 *Earliest sketches*



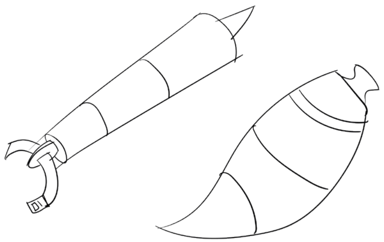


fig. 27 *Modules physically fit together in only one way, to simplify installation and prevent user errors.*

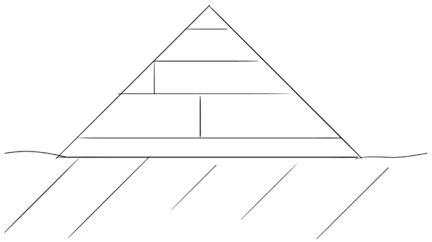


fig. 28 *Alternatively, a pyramid shaped variant indicates hierarchy and placement on its stable base.*

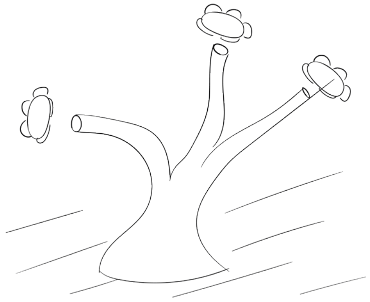


fig. 29 *An organic shape, such as a plant-inspired design with flower-like modules, would blend into garden contexts.*

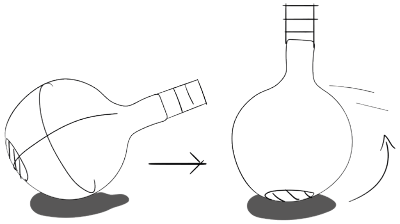


fig. 30 *Self-balancing instruments could enable optimal orientation, for example facing temperature sensors away from the sun to prevent direct radiation.*

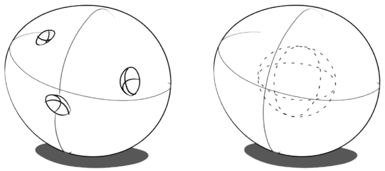


fig. 31 *Prioritizing robustness, a ball-shaped instrument can be thrown into the garden. Robust measurements can be done by averaging different sensors.*

While the shapes in fig. 27 and fig. 28 have limited modularity due to their fixed structures and lack of intuitive orientation for installation, they highlight that recognizable shapes can function as cues to connect components.

The concept in fig. 29, though aesthetically fitting for gardens, is overly specific to that environment, highlighting that scalable instruments should not be too specific, functionally and visually.

Instruments in fig. 30 and fig. 31 are not scalable to balconies, and their shapes can limit repair and modular functionalities. However, their ease of installation and automatic positioning are notable strengths.

The concepts seen in fig. 32 and fig. 32 are most promising, as they feature intuitive installation for both modules and the instrument in context; maintain modularity by using a base module suitable for electronics used across projects; and drawbacks are less prominent and more easily resolved compared to the others. Further investigation is required, among others to develop different mounting possibilities.

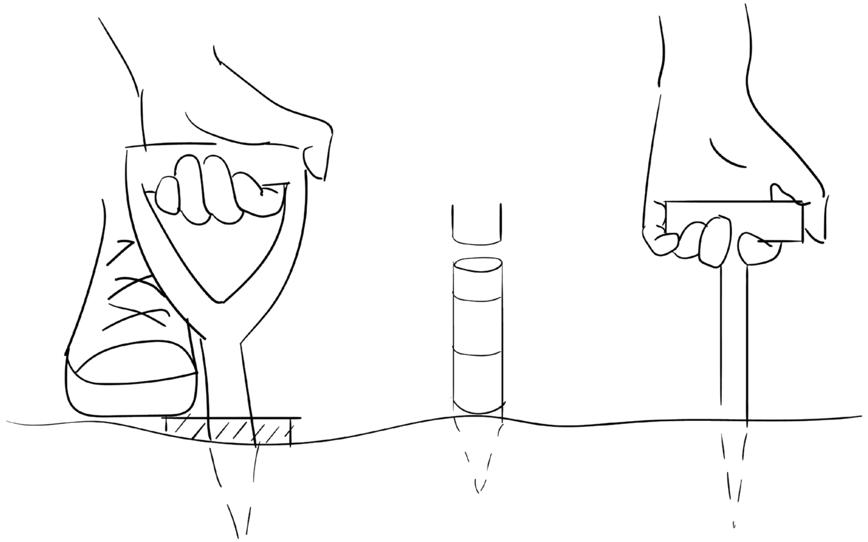


fig. 32 *Prioritizing easy installation and removal, this design features a grip that defines its shape.*

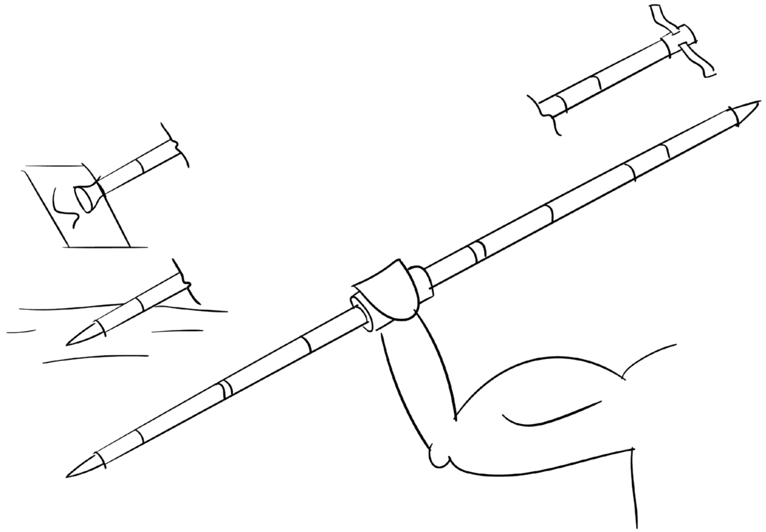


fig. 33 *Embodied by a spear, this design enables single-motion deployment and allows modules or mounts to be added or removed at both ends.*

4.2 Concept development

Further developing 2 chosen concept explorations leading to 3 design directions

Diverging from the two chosen explorations generated numerous possible concepts.

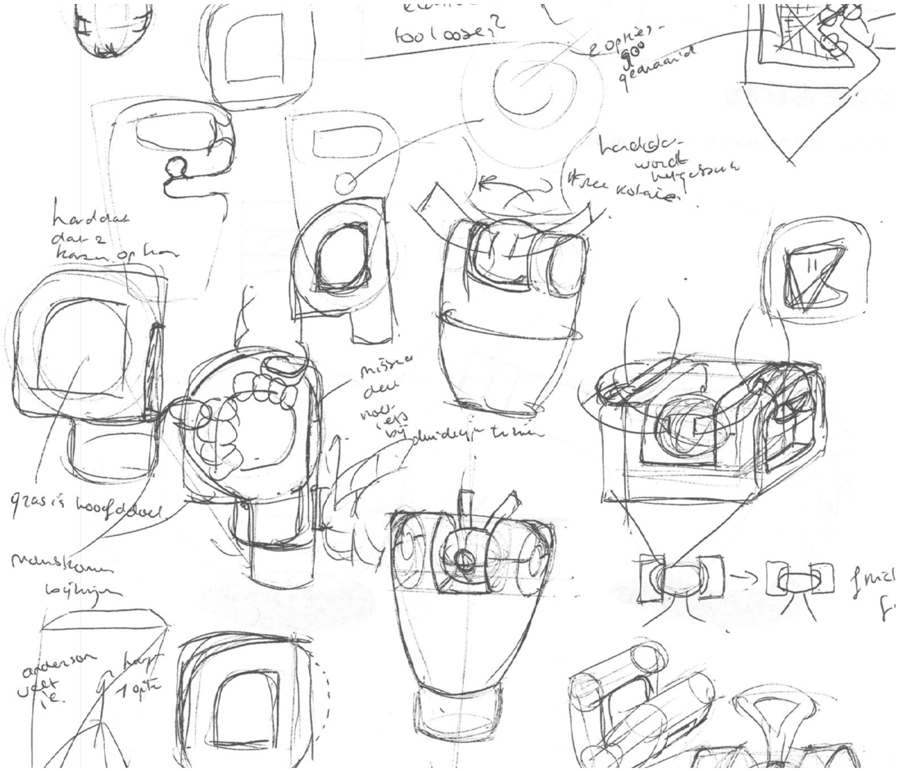


fig. 34 *Various sketches of grips*

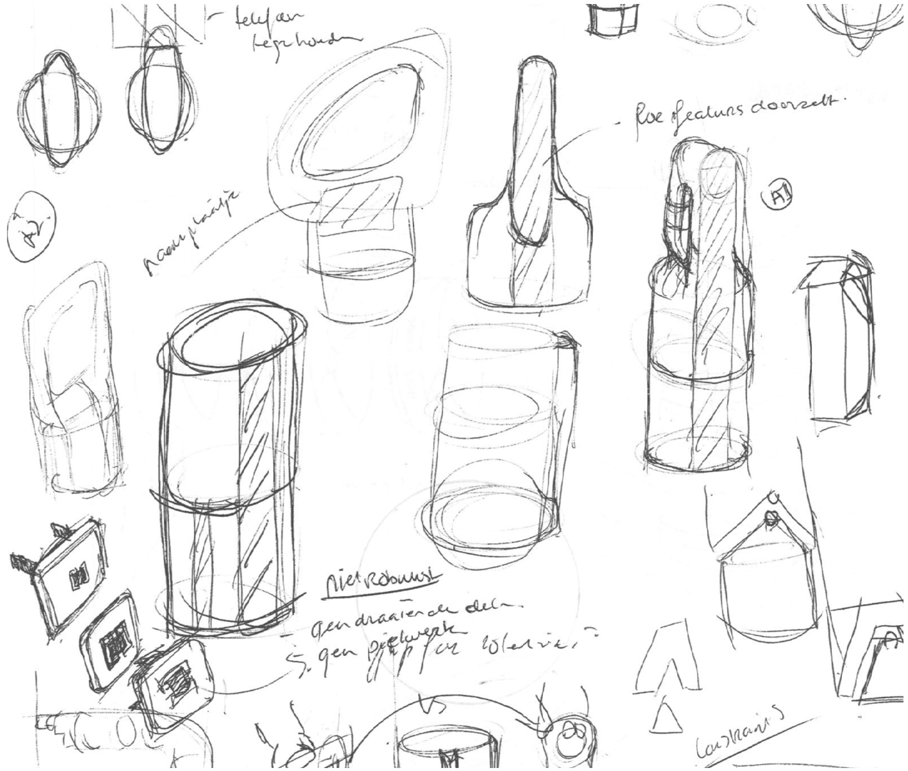
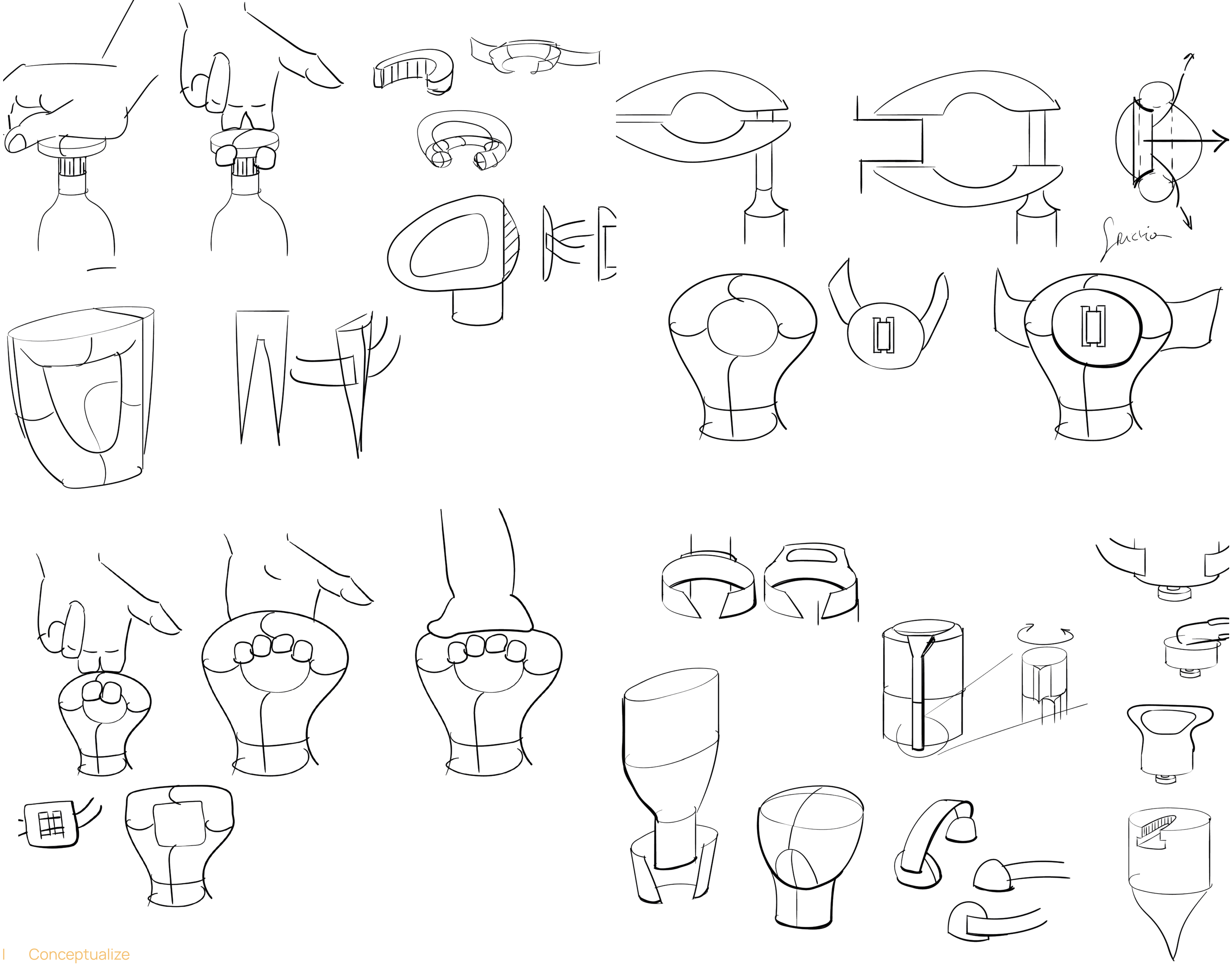


fig. 35 *Various sketches of mounting possibilities*



Moving from paper to 3-dimensional shapes enabled further exploration and refinement of various shapes and features. Foam models were created for a range of interesting ideas and proved to be ideal for rapid, iterative assessments. A few key insights are shown here, the full process can be found in Appendix A.

◄ fig. 36 *Sketches of various, more defined mounting features*

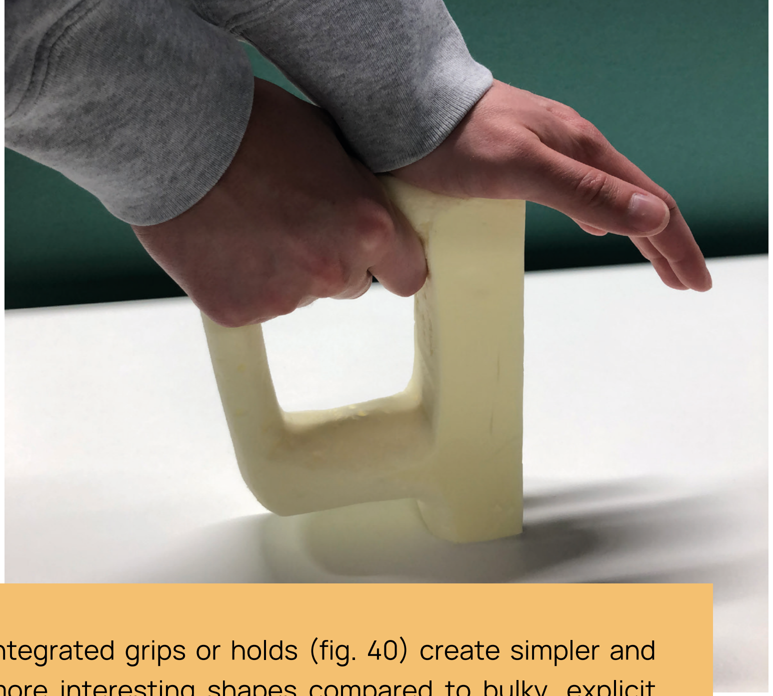


fig. 39

Volumes do not have to be large in size to communicate robustness, though they should avoid looking too thin to make a solid appearance. Subtle differences can make a difference between fragile (fig. 37) and robust (fig. 38) features.

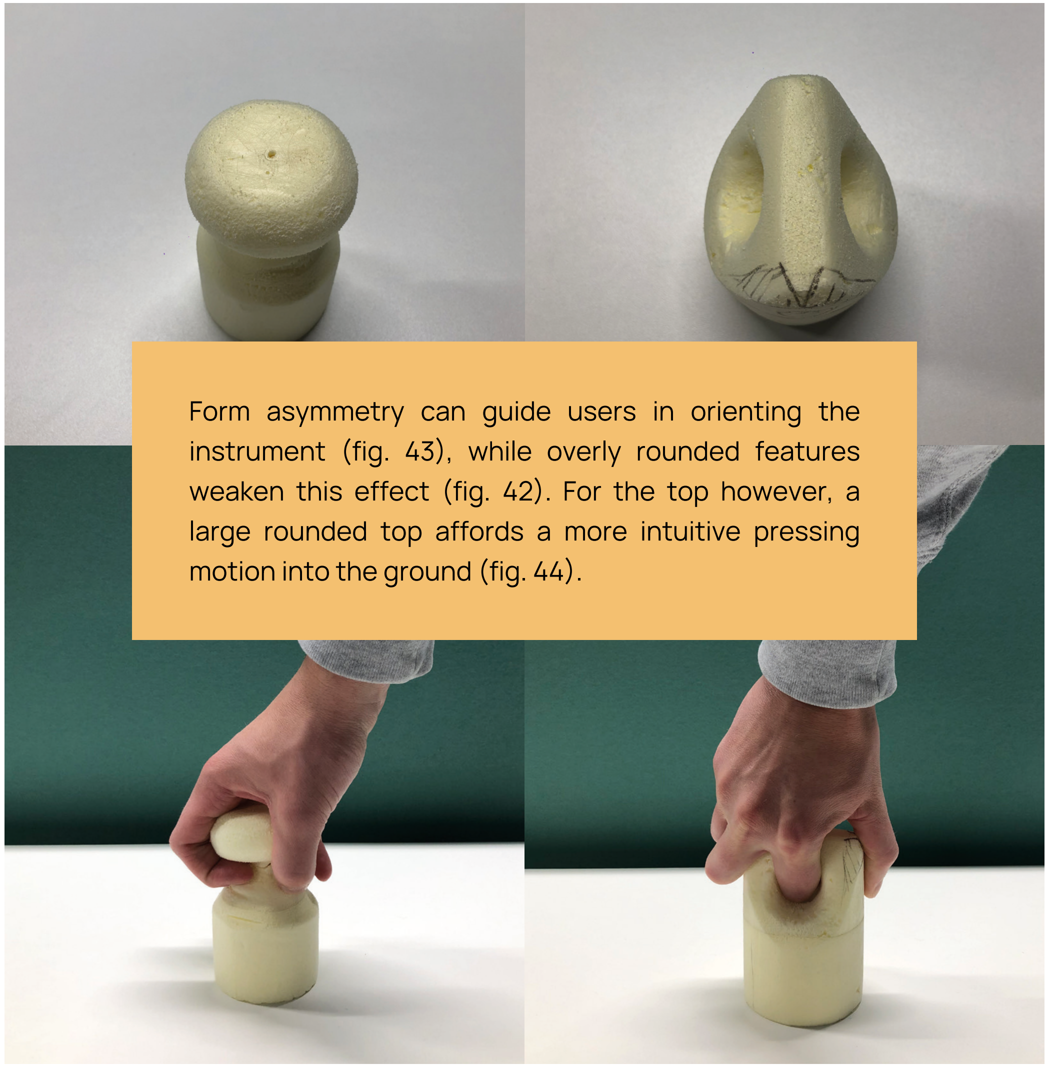
fig. 37

fig. 38

Integrated grips or holds (fig. 40) create simpler and more interesting shapes compared to bulky, explicit handles (fig. 39). Given the instrument's size, finger grips (fig. 41) are more appropriate than hand ones (fig. 39), which appear excessive.

fig. 40

fig. 41



Form asymmetry can guide users in orienting the instrument (fig. 43), while overly rounded features weaken this effect (fig. 42). For the top however, a large rounded top affords a more intuitive pressing motion into the ground (fig. 44).

fig. 42 fig. 43
fig. 44 fig. 45

Obvious metaphorical designs, such as the mushroom-inspired model, lack the impression of a well-considered product and feel simple.

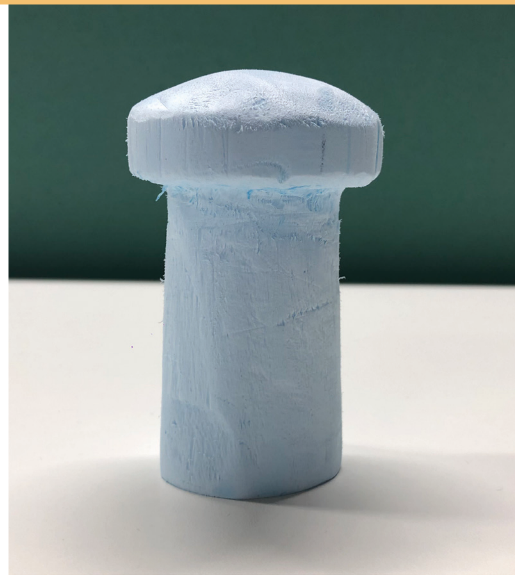


fig. 46

fig. 47

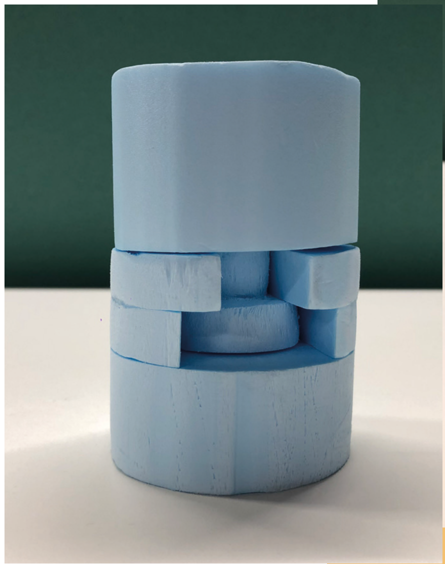


fig. 48

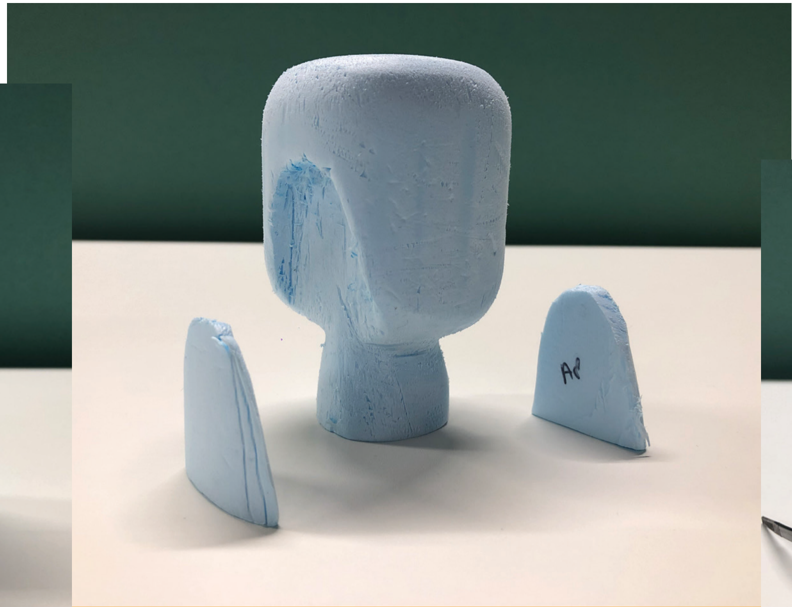
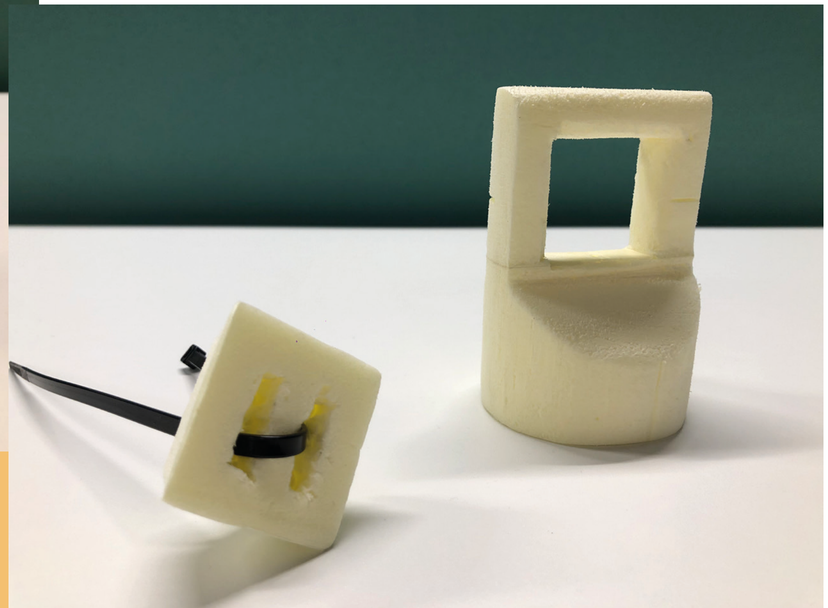


fig. 49



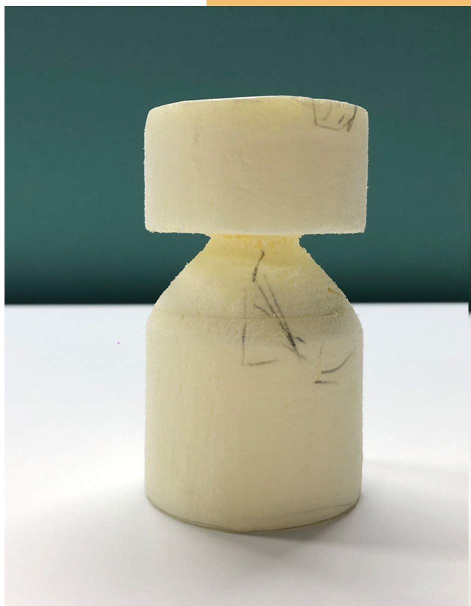
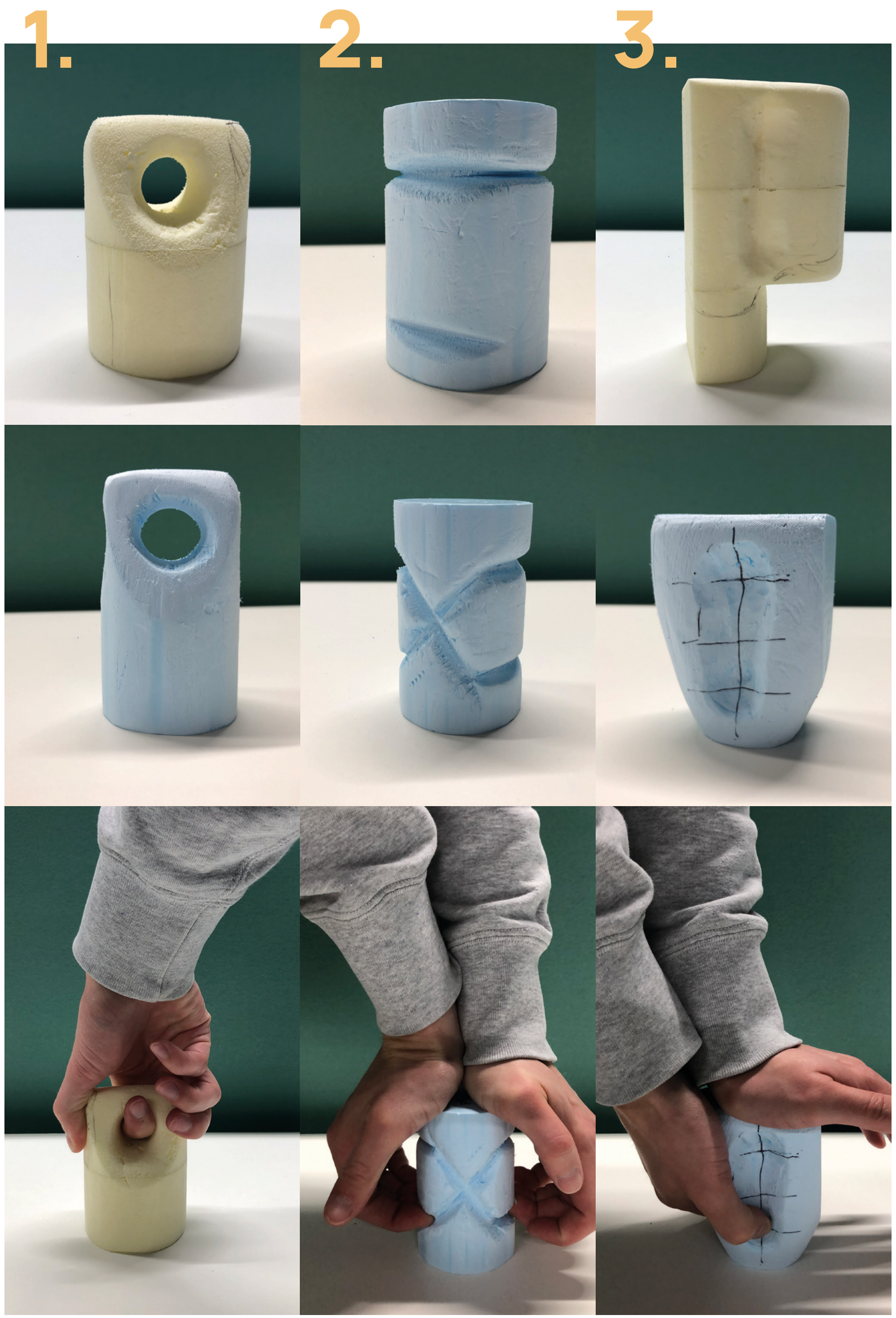


fig. 50 fig. 51

Sharp and straight cuts (fig. 50) feel harsh, whereas rounder (fig. 51), more organic shapes are perceived as more friendly and approachable. Some shapes allow for mounting features more naturally, while for others these mounts feel awkwardly attached.



Three promising models (fig. 52) were selected to be further refined into three distinct design directions. Given the large variety in citizen scientist motivations, different designs are expected to appeal to different participants. To explore this, directions 1 and 2 reflect two major groups identified in the discover phase. Respectively, they tailor to citizen scientists seeking to address concerns about the immediate environment, and those motivated by the technology and learning aspects. Since citizen science serves the public and is supposed to be available for everyone, the two designs aim to communicate approachability, inclusivity and accessibility.

The third direction takes a contrasting approach and serves as a provocative design probe to put the other two in perspective and highlight their differences. It helps to better define and assess features, functions, and aesthetics of each design direction while also exploring potential new interactions. The objective is not to choose one direction but to identify and combine the strongest elements from each.

While directions 1 and 2 are defined with a clear goal, the 3rd one is rather an outcome of the volume exploration, offering diversity and aiming to look beyond current users to see if a new design might appeal. To ensure these identities are effectively communicated, specific elements, such as the modules, are further defined through sketches and visualizations (fig. 53 and fig. 54).

fig. 52 *The foam models that led to the three distinct design directions*

◄ fig. 53 *Exploring module connections for further detailing*

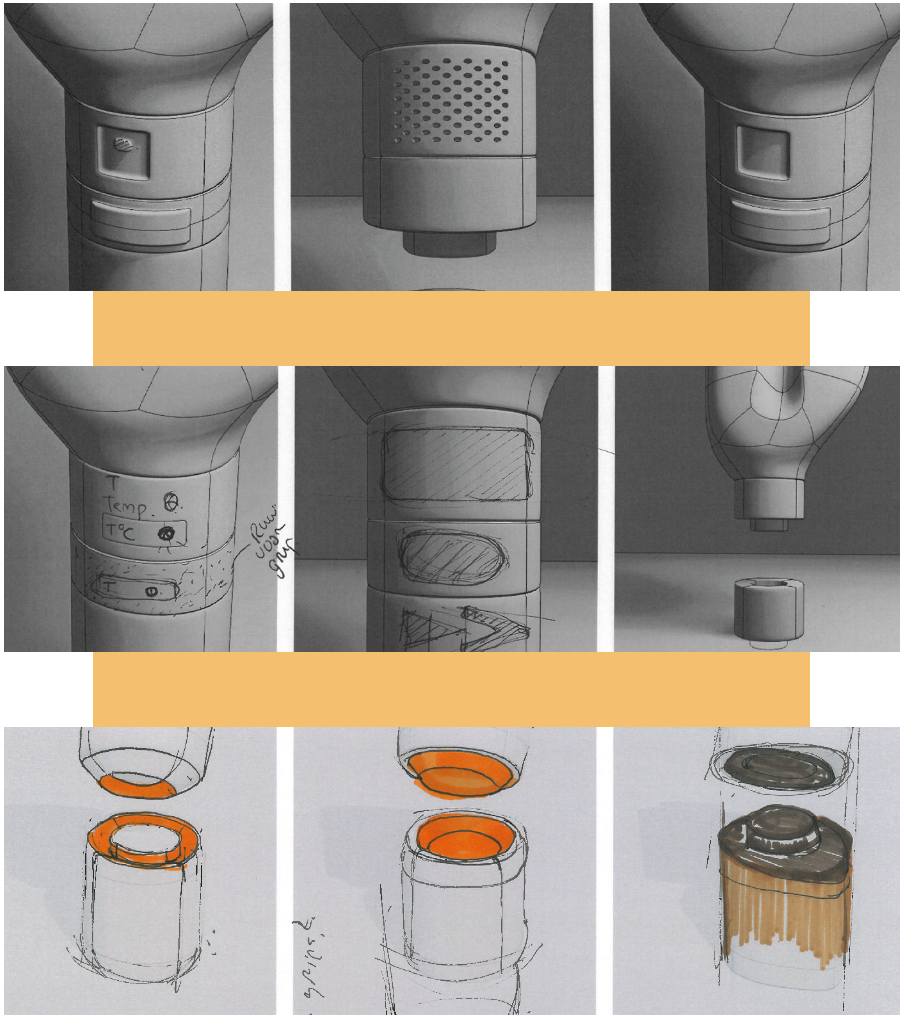


fig. 54 *Exploring module details*

4.2.1 Design direction 1: Friendly / approachable / comfortable

This design aims to be as simple, friendly, and approachable as possible, both visually and in terms of interaction. It features smooth, round, and simpler shapes, without too many details to reduce visual noise and be easy for the eye. Functional elements are more integrated in this design, instead of being very explicit. Colors are light, either pastel or saturated, and textures are minimized as much as possible or soft, to maintain a gentle appearance.

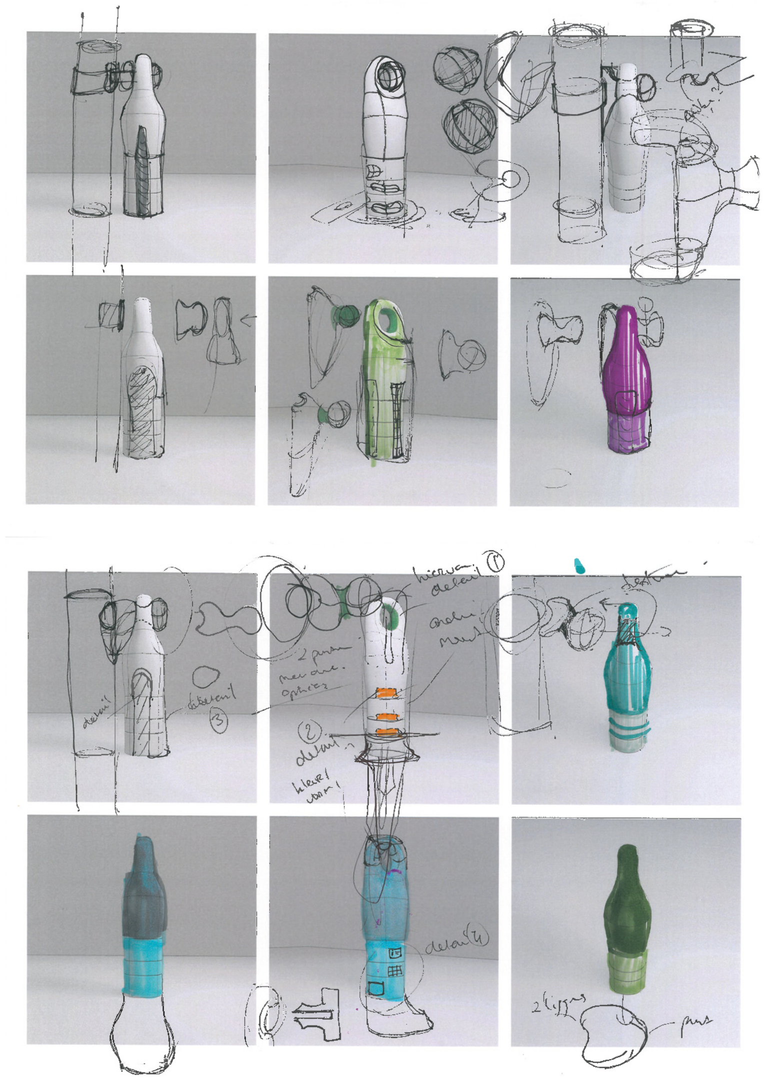


fig. 55 *Sketches of design direction 1*

fig. 56 *Toy stacker by Monti, featuring rounded simple shapes, with minimal visual details and light colors (Monti, n.d.)*

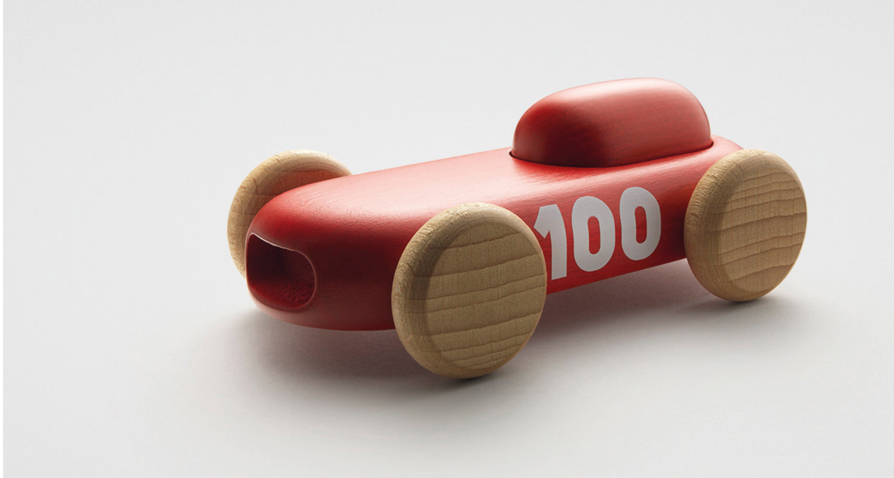


fig. 57 *Design of a toy car, a combination of basic rounded shapes (Permafrost Design, n.d.)*

fig. 58 *Friendly appearance of a speaker by Arthur Kenzo (Kenzo, n.d.)*

In practice, this is done by presenting the instrument in one single color, except for the mounting feature, which uses a deviating color to indicate where to fasten the mount. The interaction aligns with the instrument's overall identity: mounting should be very simple, ideally requiring just one click or push. The total has a toy-like appearance, as pushing the mount into the matching round slot is very intuitive.

The design's shapes flow into each other smoothly and create a calm visual impression, with minimal visible detail strengthening this characteristic. The sensors, for instance, are subtly integrated and simply indicated, avoiding any explicit explanation.

The cylindrical modules are free of textures and fit together in only one way. Color coding is used as a visual cue to guide the user in connecting them, similar to the mounting feature.

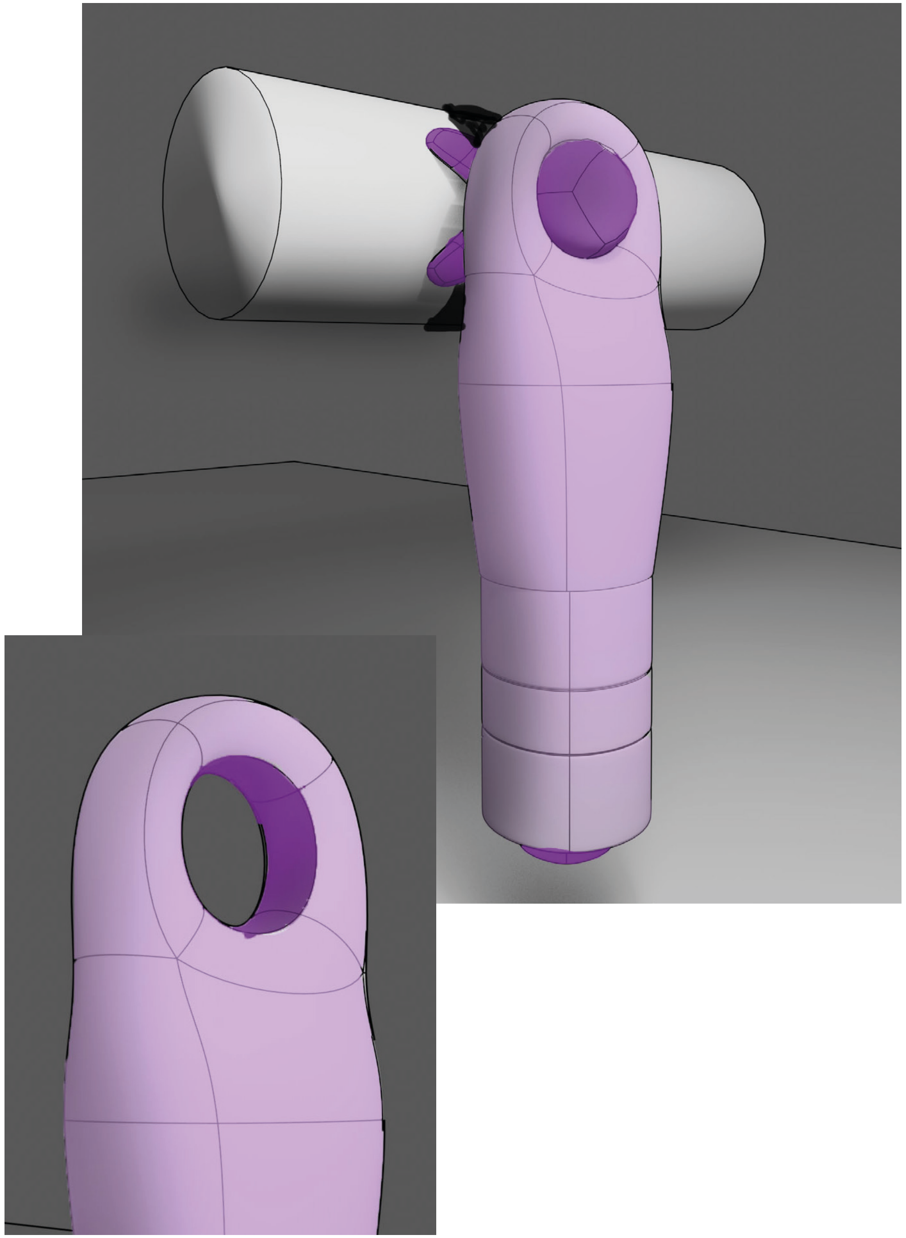


fig. 59 *Design direction 1, mounted on a horizontal railing using a simple color-coded feature*

fig. 60 *Instrument mounted on a vertical railing*

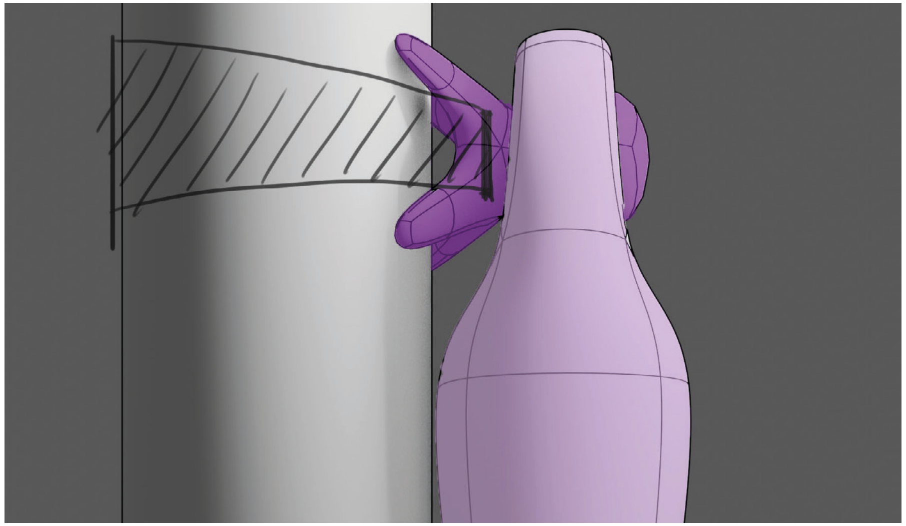


fig. 61 *Little visible details*

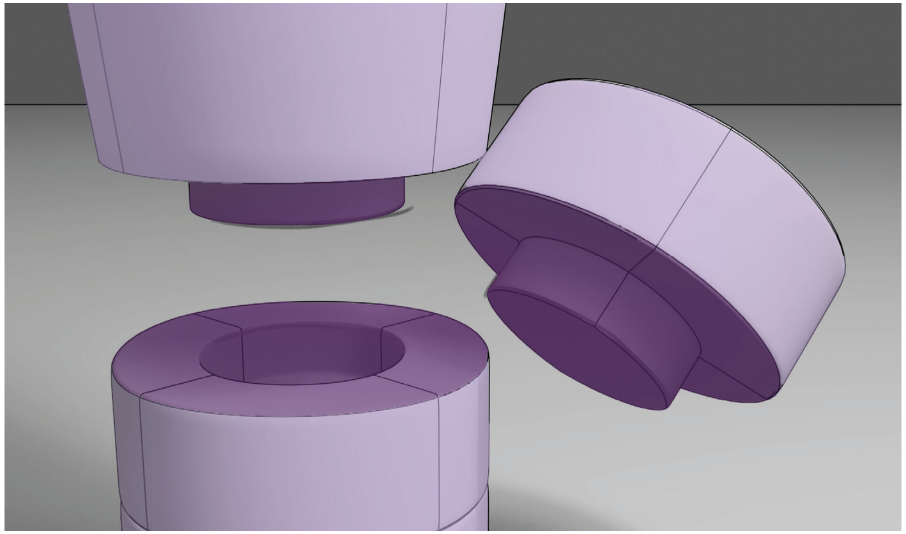


fig. 62 *Color-coded module connections*

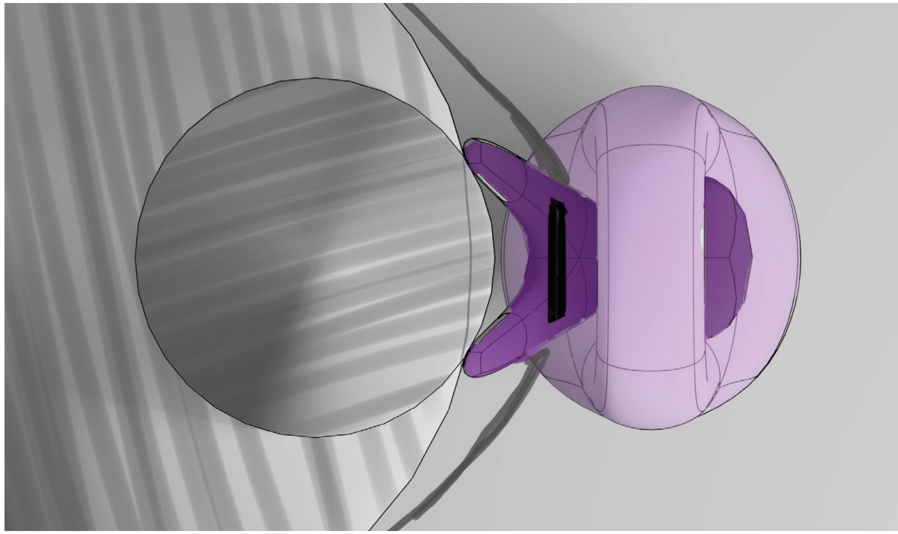


fig. 63 *Mounting possibilities for railings with different diameters*

4.2.2 Design direction 2: Adventurous / autonomous / raw

This design direction embraces more dynamic and interesting shapes, with sharper, more pronounced features that give the overall product a more adventurous appearance. Metallic, green, and wood-inspired colors, combined with natural material textures, reinforce this identity.

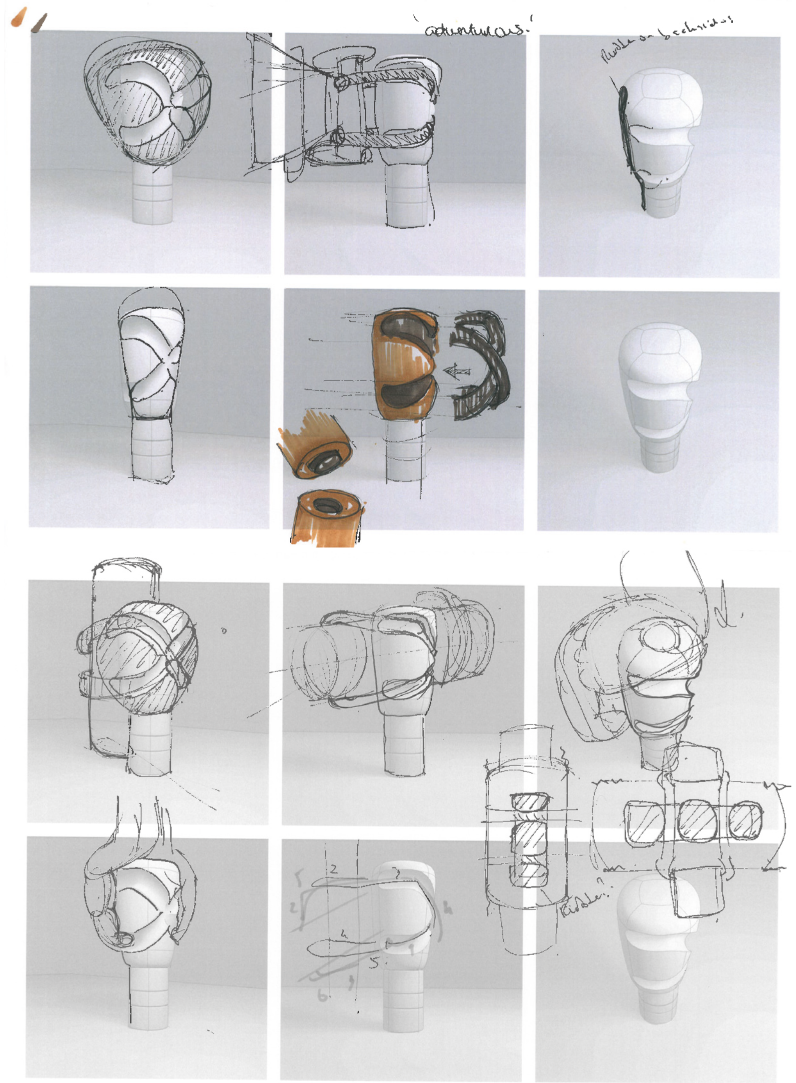


fig. 64 *Sketches of design direction 2*

fig. 66 *Explicit design detail indicating a USB connection (Eamin, 2020)*

fig. 65 *Unito coffee box set, incorporating an adventurous identity by using metallic, green and wood inspired colors and materials (Unito_store, 2024)*

In practice, an X-shaped mount allows for a more open and manual approach to fastening the instrument in context, while maintaining a certain orientation with defined front and back sides. The X-shape also becomes part of the design language and can be applied as a communicative signature across other elements of the design. Subtle colors indicate the mount without the need for explicit labels.

Grip and surface textures communicate an adventurous identity, with rubber on the back providing stability against surfaces. Sensors are explicitly marked using text, icons or contrasting textures. Modules are not cylindrical and incorporate grips for enhanced tactile experience.

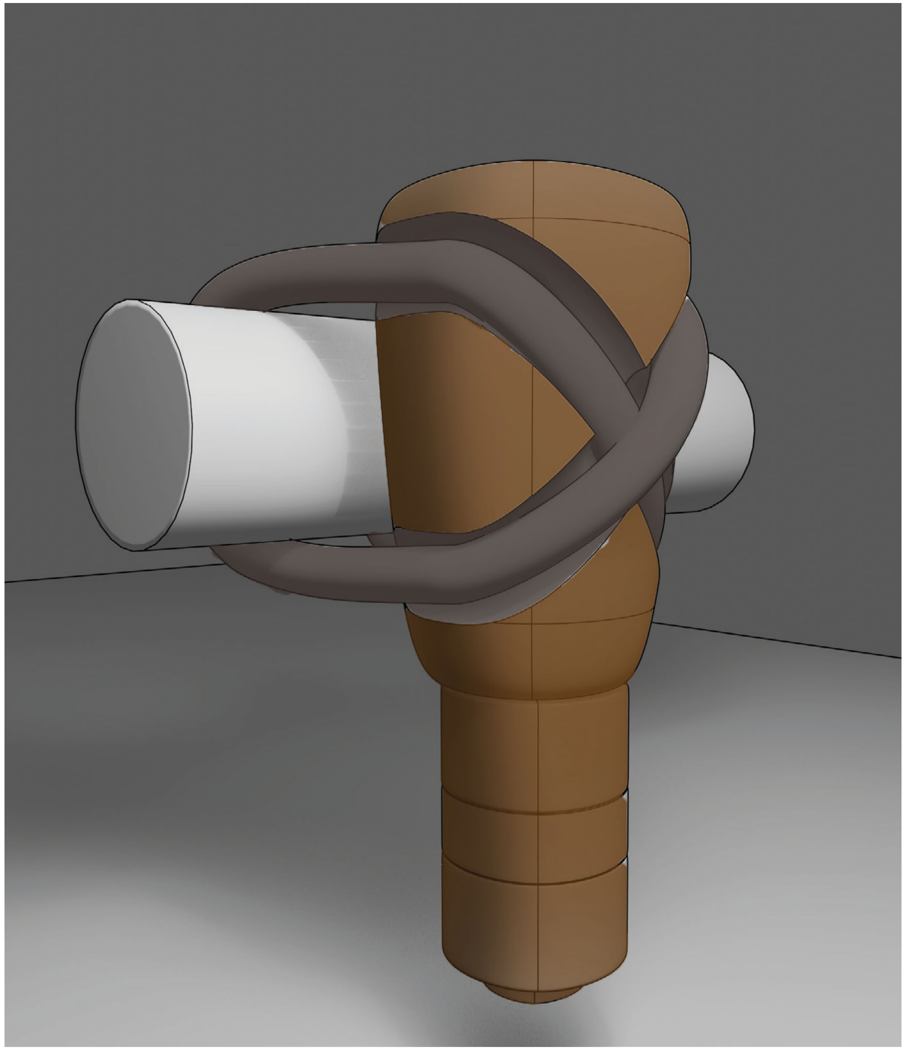
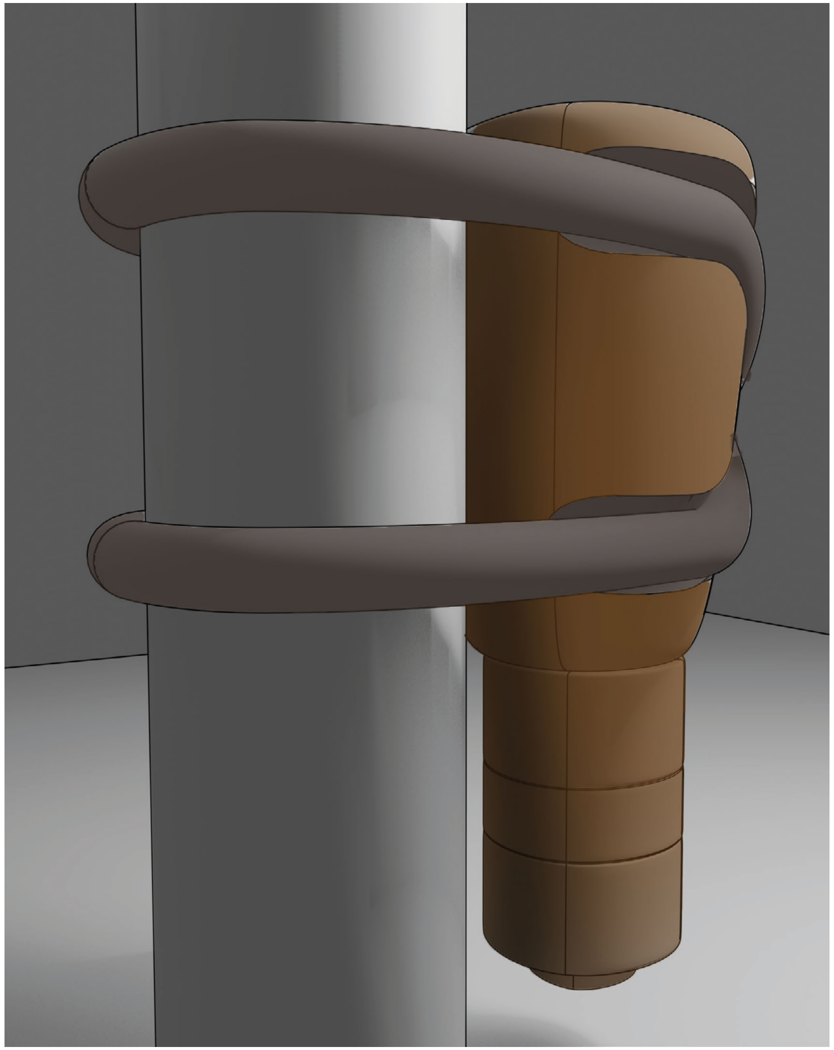


fig. 67 *Design direction 2, mounted on a horizontal railing by using the X-shape*

fig. 69 *Instrument mounted on a vertical railing*



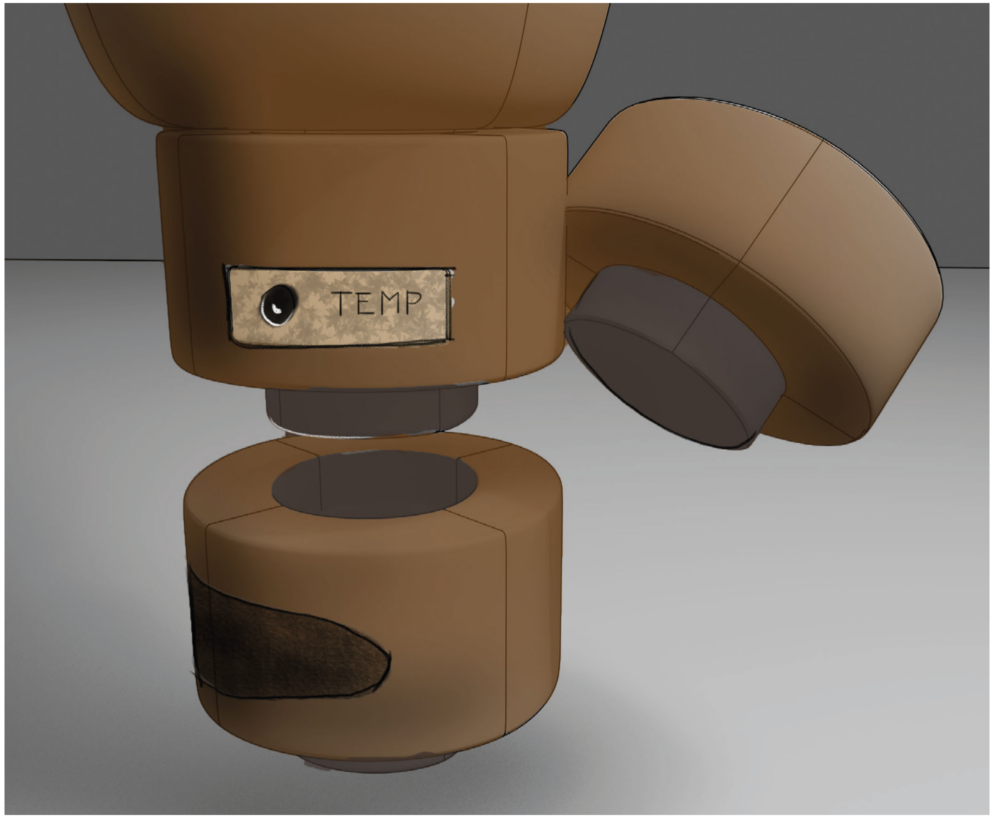


fig. 68 *Rubber grips and surface textures that communicate an adventurous identity*

4.2.3 Design direction 3: Technological / asymmetric / ambiguous

The third design direction has a rather modern and technological appearance, characterized by a neutral palette of black, white, and grey. The shape is asymmetric and features negative shapes: intentional cutouts that serve as distinct design elements that resonate with the product's form identity. The idea is that mounts, modules, and other functionalities complement and fill these negative spaces and complete the main shape. The specific mounting feature is an eye catcher. Incorporated textures are designed and parametric. Details are more basic, fine and sharply defined.

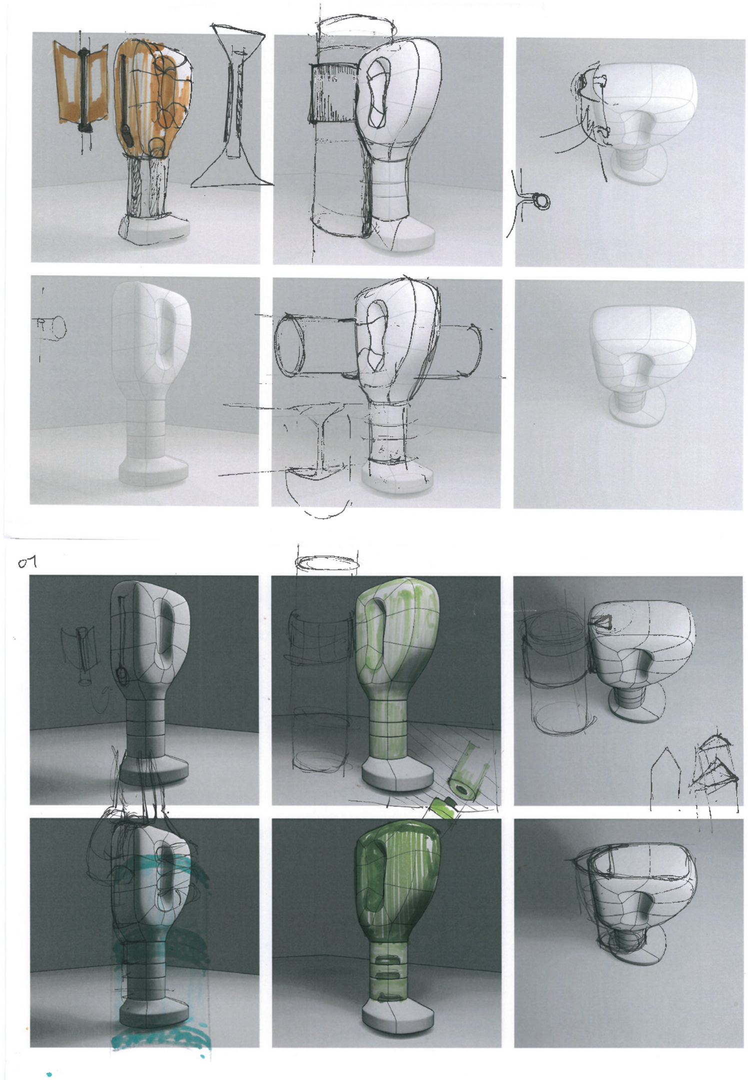


fig. 70 *Sketches of design direction 3*

fig. 71 *Freflow, a portible generator with similar "negative shape" feature, emphasized by designed, parametric textures (Worthington, 2019)*

fig. 72 *Vert!ca, a camera with basic, fine and sharply defined buttons and details (Lee and Choo, 2019)*

In practice, this means that the cutaway parts have colors different from the main body that corresponds with the modules and serve as visual cues that communicate an interaction.

Similarly, the mount feature has a contrasting color and appears to be more technical and interesting compared to the other designs. This feature represents a specific profile where different mounts can slide into, as long as they match its geometry.

The surface texture is molded directly into the instrument, maintaining material uniformity. Additionally, modules have a certain direction due to their asymmetry. Sensors are detailed more abstract and minimally, using a single icon or ridge only.

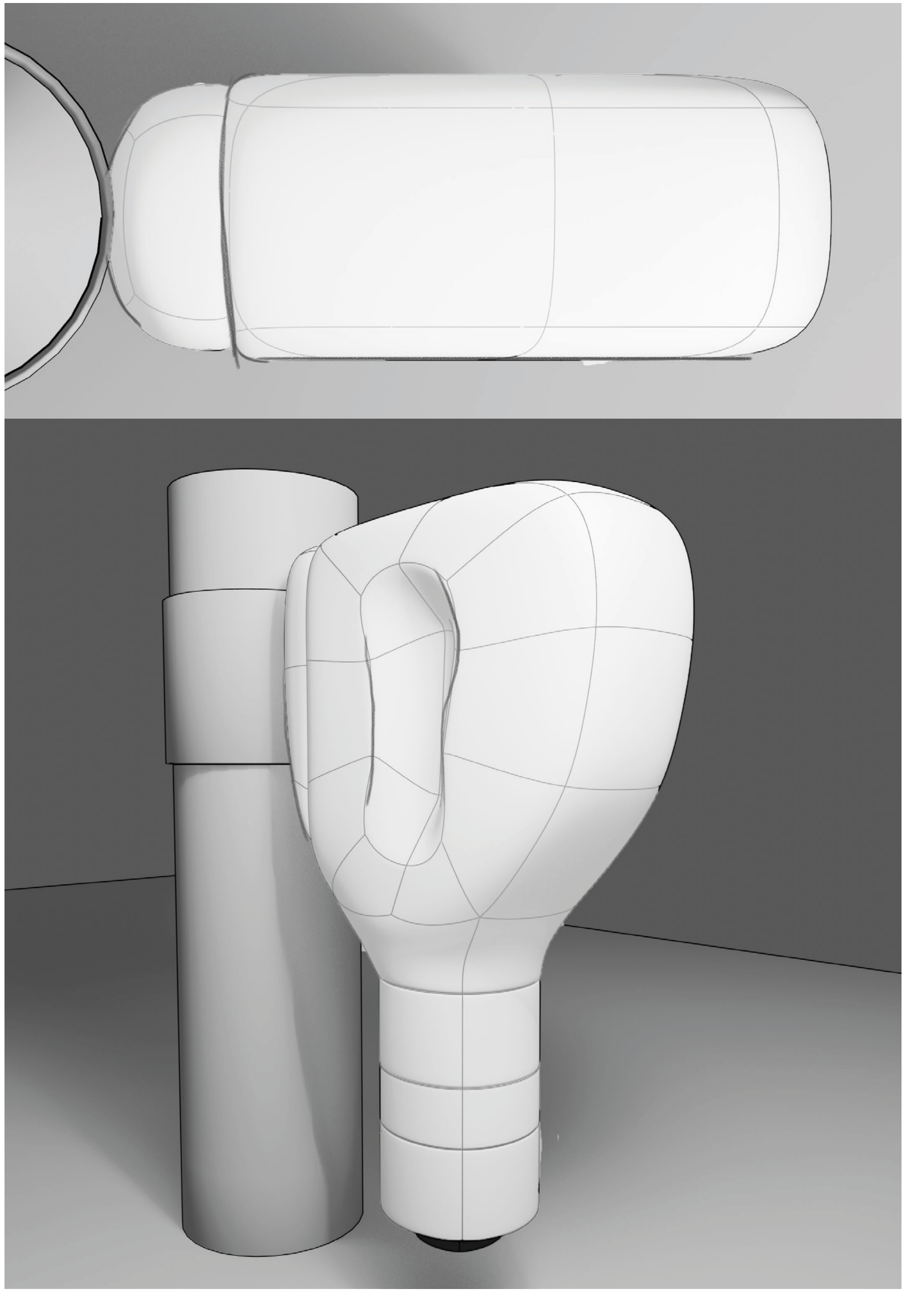


fig. 73 *Design direction 3, mounted on a vertical railing*

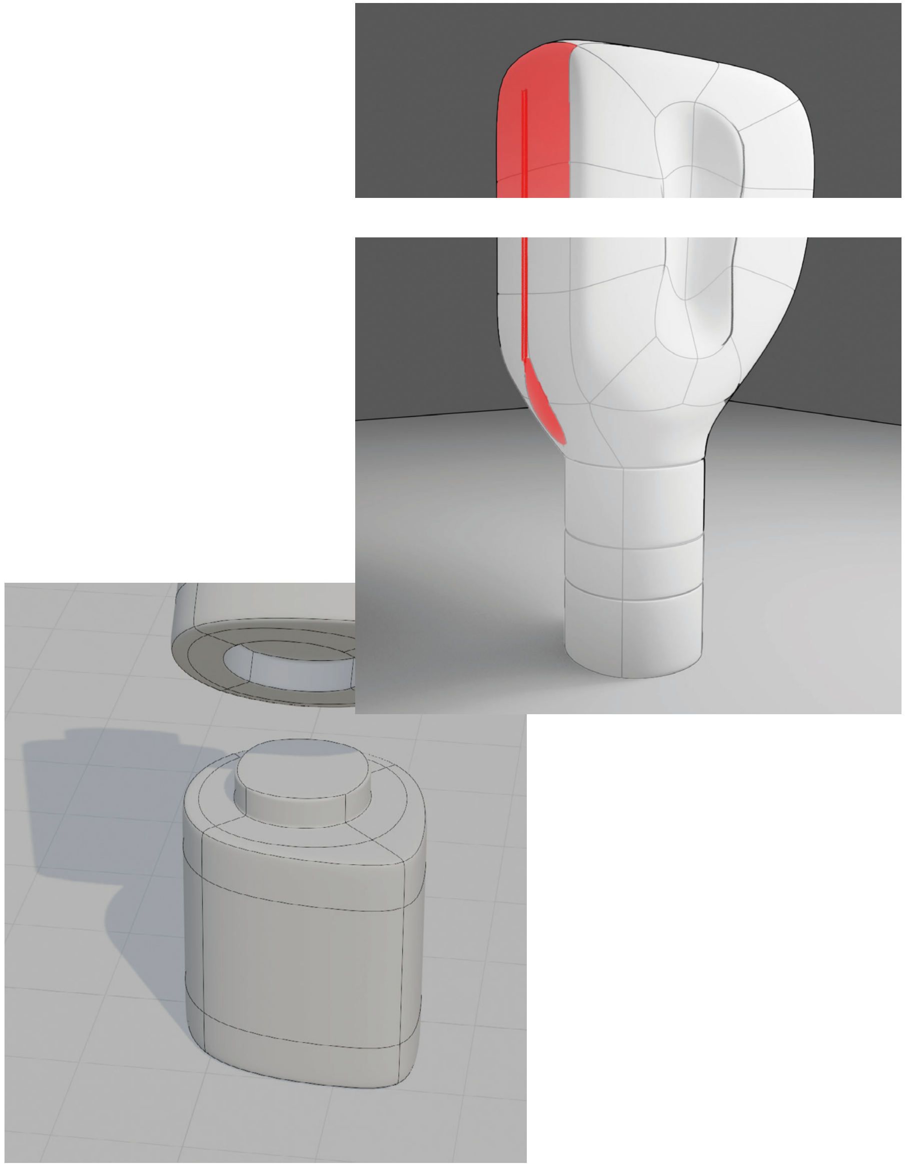


fig. 74 *Differently colored cutaway, serving as a cue for interaction (up) and modules with a specific direction for installing (below)*

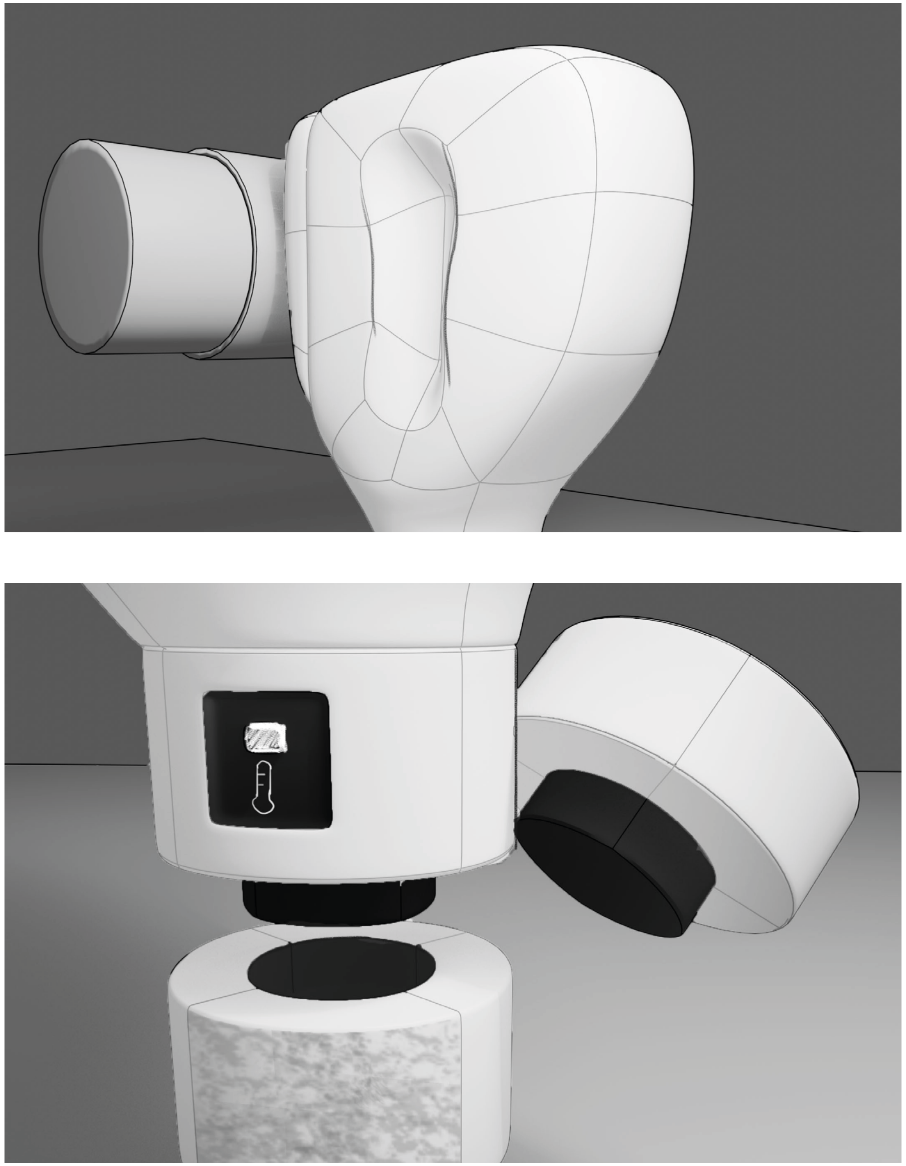


fig. 75 *Instrument mounted on a horizontal railing (up) and more abstract, minimally detailed modules (below)*

4.3 Design direction development

Describes the iterative process of developing design directions into a preliminary design

An analysis of the three design directions, conducted individually and with company experts, enabled to assess, filter and combine their strongest elements.

In design direction 1, the purpose of the ring when the instrument is mounted in soil is unclear and raises the question whether it is actually necessary for removal. A subtler ground module that allows it to be removed using a shovel, screwdriver, or fingers could be more practical. While the mount interaction is instantly clear, it is prone to detachment. Audio feedback could be integrated to confirm successful mounting. The organic, totem-like form conveys a friendly feeling that rhymes with the identity of citizen science. Considering its colors, while purple might not be the most suitable for fitting into the context, the use of intuitive color coding is powerful. Also, the perception of the shape 'observing' something through its hole, is a striking design language.

Direction 2 introduces an interesting mounting approach, but it lacks reliability. The X-shape adds character to the product, but might come across as aggressive and less appealing to citizen scientists. The design would be suitable for the garden context because of its natural appearance, although this is not true for balconies.

Direction 3 features an eye-catching mounting feature that consists of a profile supporting a variety of mounts, including future ones. However, the shape feels rough, heavy, and unfinished, with an awkwardly attached grip that appears to have not evolved naturally with the overall form. A more integrated grip—or removing it altogether—could improve this. The negative cutaway is distinctive and suitable for color coding, though care is needed to ensure the form remains complete on its own and not overly reliant on complementary parts. Therefore, the shapes should work both individually and combined.

General takeaways include maintaining a rounded top for ease of pressing into the ground and designing a functional soil module. The number of parts, particularly add-ons, should be minimized to prevent people from losing them. Cohesive form language across modules is essential to keep them visually connected, for example sharing shapes and details. It should be avoided that the instrument becomes an aesthetically unappealing "object on a pole". Moreover, simple shapes can be effective designs, as details can make them distinctive, though text should be avoided, using icons at max.

A few weaknesses and strengths emerged that informed the refinement of the three design directions towards a preliminary design.

–

Bulky shapes with unclear purposes

Unreliable mounting mechanisms

Necessity of a handgrip for removal

Design not inviting to be pressed

Cutaway shape feeling incomplete on its own

Shapes looking like one large cylinder or an 'object on a pole'

+

Design incorporates the users' perspective and not only the technical aspect

Friendly appearance, organic totem-like aesthetics

Color or form coding for mounts

A single future-proof profile for various mounts

Asymmetrical forms for proper orientation

Simple shapes can be made unique by detailing

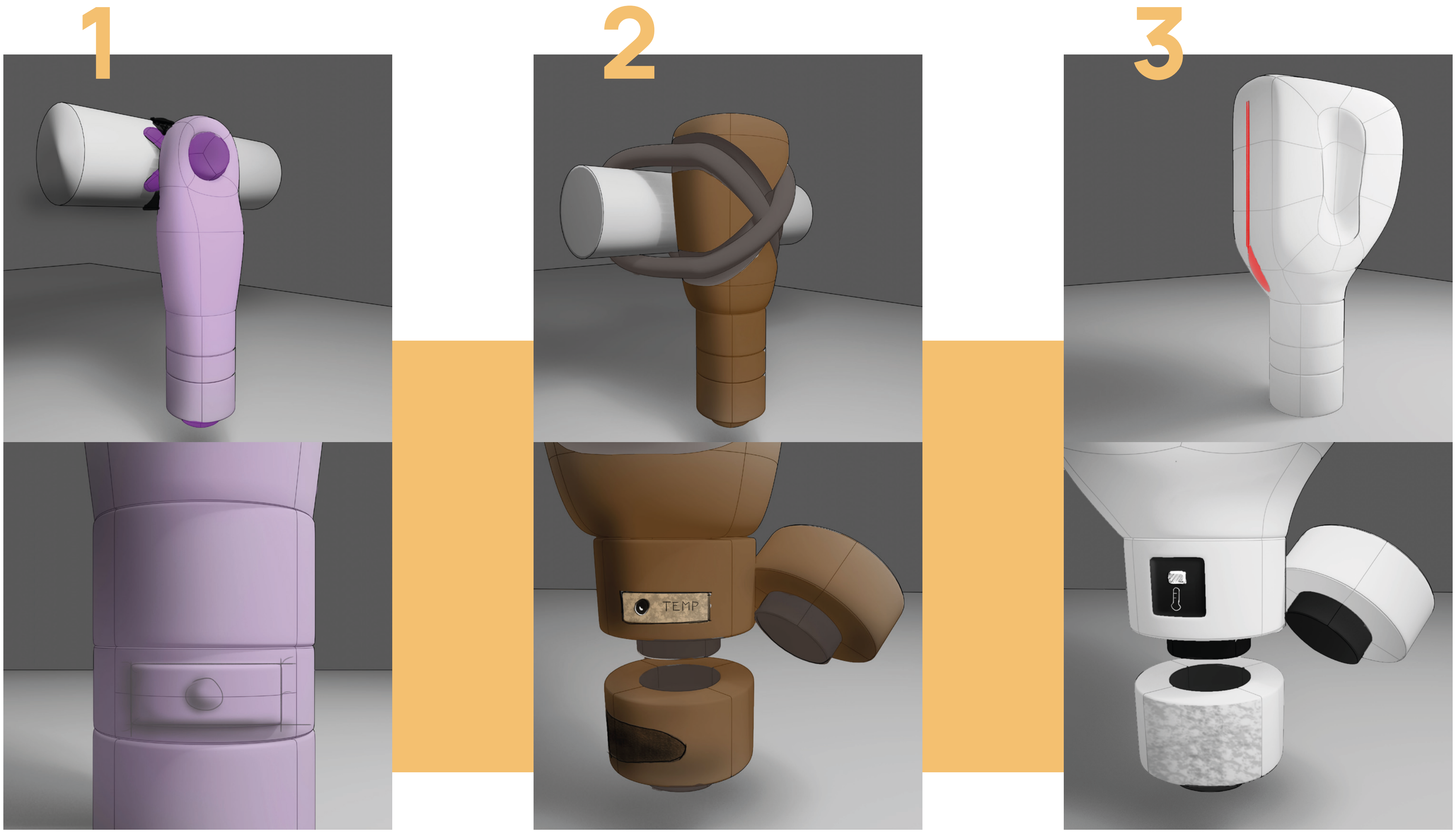


fig. 76 *Overview of the three design directions*

4.3.1 Iteration 1

The input from the analysis was translated into a totem-like form language to convey a friendly and approachable identity. The design is asymmetric, allows to be pressed into the soil, and inherently affords removal as well. However, incorporating the mounting feature felt forced as it did not integrate naturally with the overall shape. Additionally, the explicit human-like design risks appealing to a limited audience only, which reduces scalability. A friendly design does not necessarily have to resemble a human to be effective.

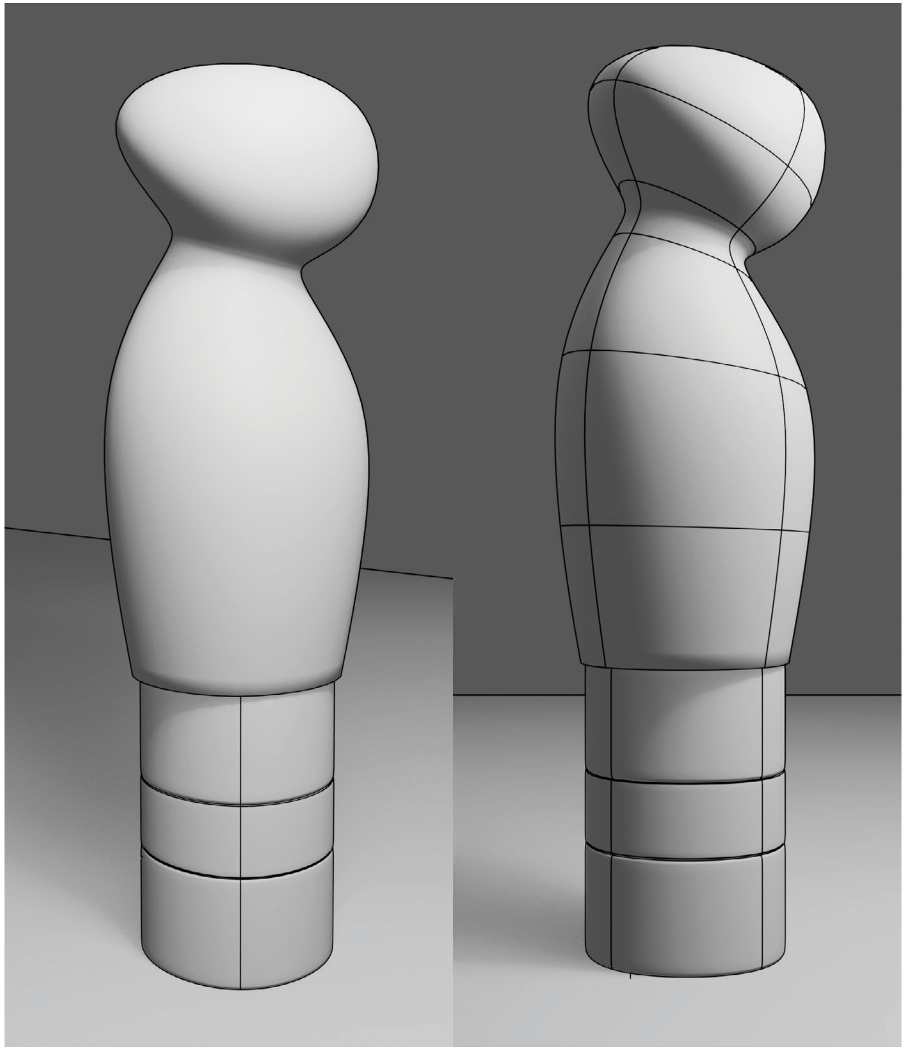


fig. 77 *Iteration 1: a human-like totem design*

4.3.2 Iteration 2

In response, the design shifted to a more abstract approach, aiming for a creature-like form that was concrete enough to evoke feelings but abstract enough to allow individuals to see what resonated with them personally. A more abstracted shape would aesthetically also fit in a larger variety of contexts. Examples of such abstractions include shapes that resemble an old man with a cane, or an owl (fig. 78); a bird pecking for bread crumbs, or a dove's tail (fig. 79); and a whale, or a sideways hummingbird (fig. 80).

fig. 78 *Abstract sculpture (anthonytheakstonsculptor, 2020)*

fig. 79 *Abstract sculpture (Hetty de Haan, n.d)*

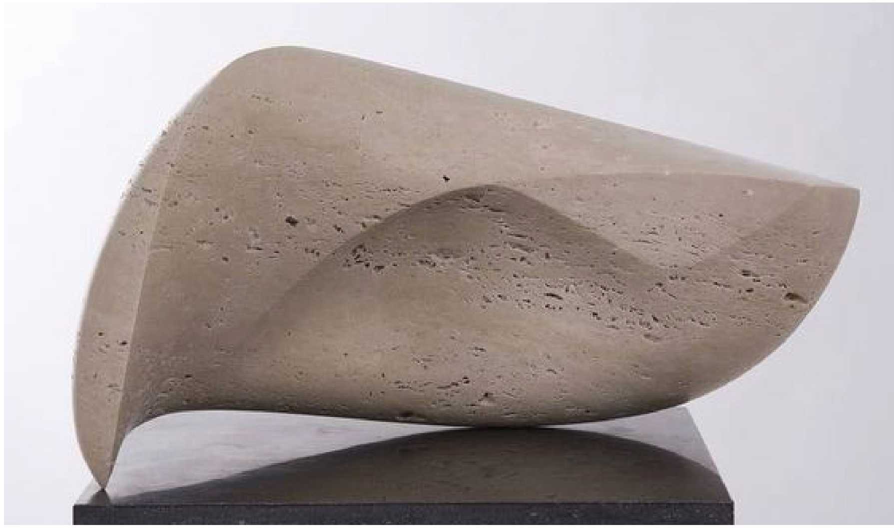


fig. 80 *Abstract sculpture (Saatchi Art, n.d.)*

Overly metaphorical designs were avoided, as even simple shapes can suggest an identity or expression (see fig. 84). Some designs conveyed more bear-like (fig. 81), others more bird-like characteristics (fig. 83), influencing their suitability for garden and balcony contexts.

Integrating the mount remained challenging, often feeling unnatural or added afterwards. Balancing design elements evenly in three dimensions was also difficult; features concentrated on the front side of the design decreased its overall appeal. The key challenge was to integrate features cohesively while avoiding the instrument looking like an “object on a pole”.

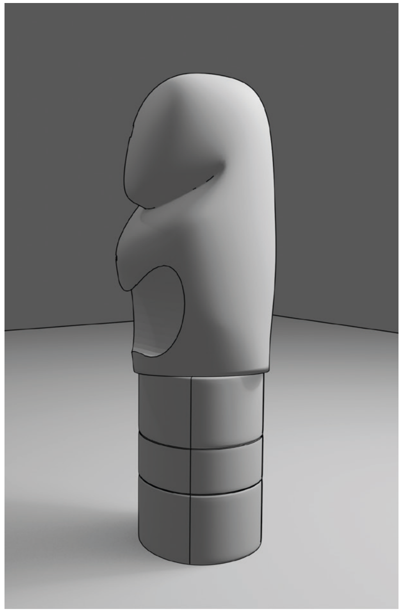


fig. 81

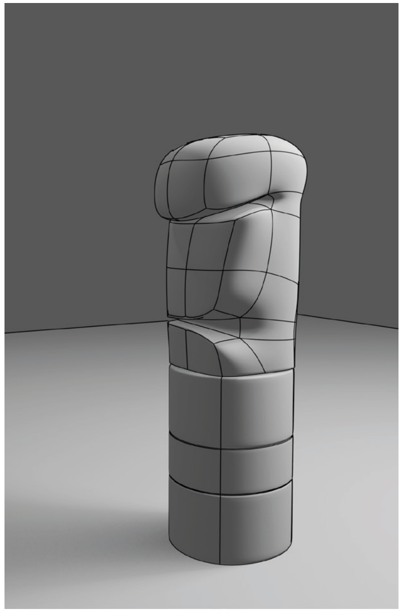


fig. 82

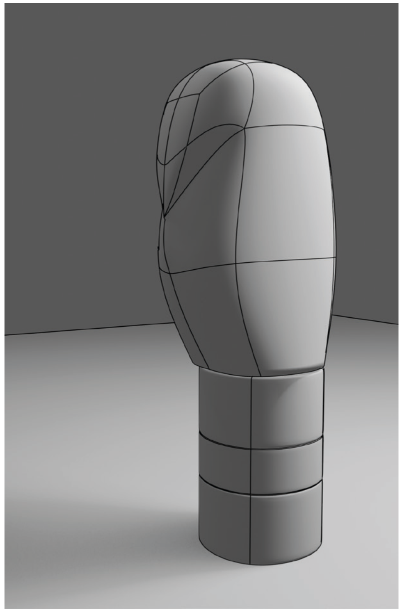


fig. 83

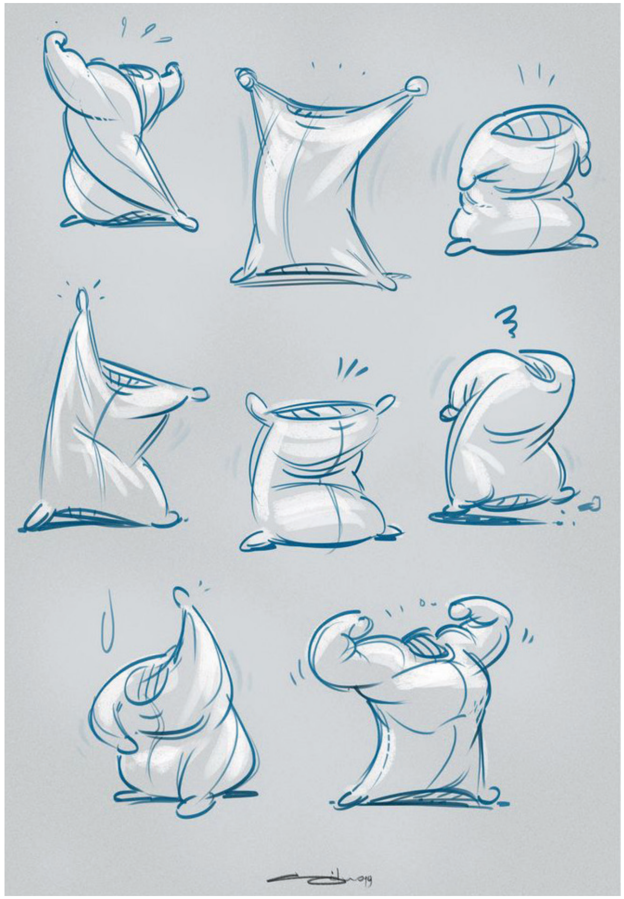


fig. 84 *Conveying emotions through a pillow sack only (Almaguer, n.d.)*

4.4 Preliminary design

A cohesive design ready to be refined and embodied

The third iteration brought everything together into a cohesive preliminary design. The negative cutaways appear naturally integrated and well-reasoned. Despite efforts to avoid explicit metaphors, some references remained; however they abstracted as much as possible.

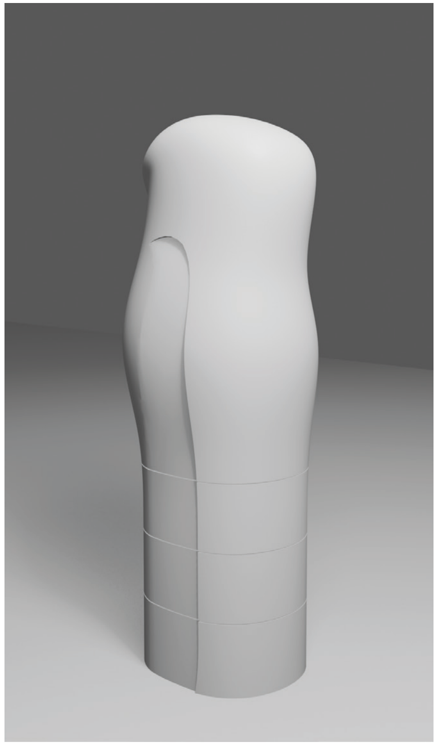


fig. 85 *Isometric back view*

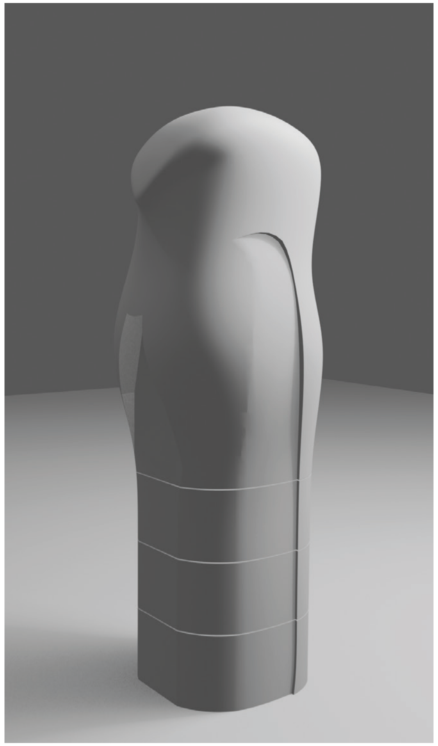


fig. 86 *Isometric front view*

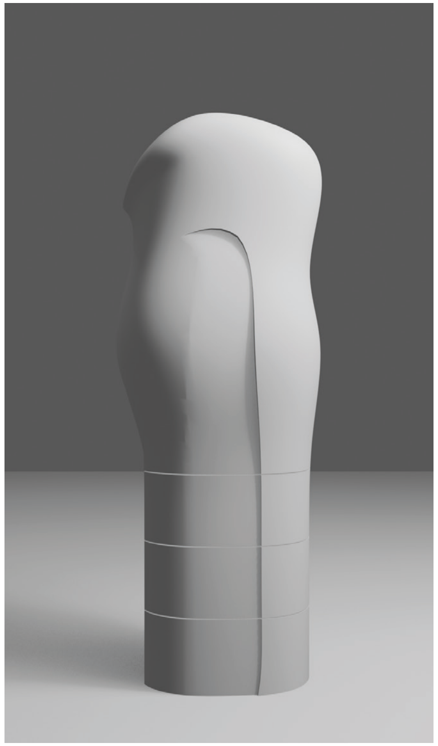


fig. 87 *Side view*

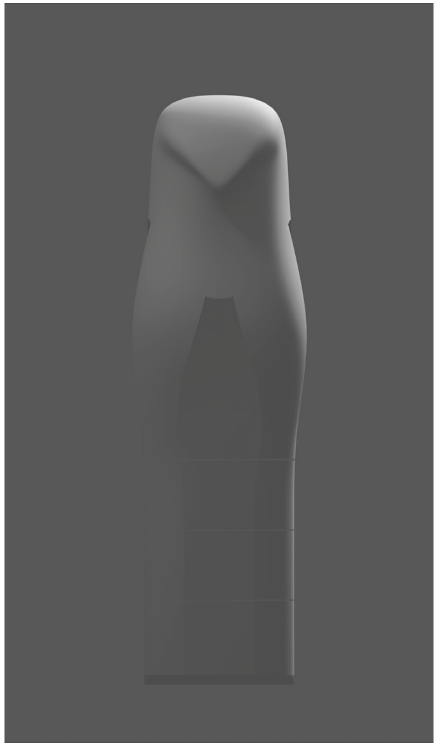
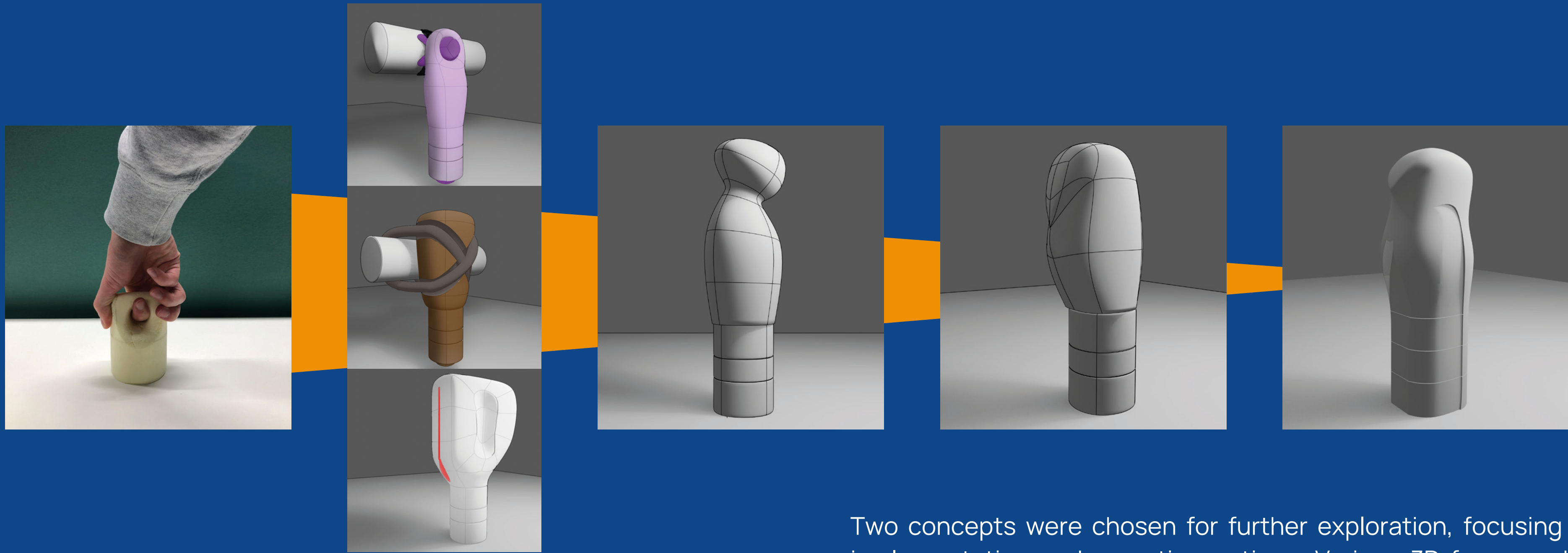


fig. 88 *Front view*

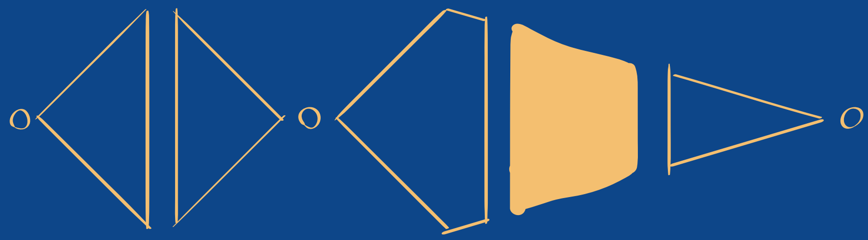


Key insights: Conceptualize

This phase began with brainstorming and sketching to explore different interpretations of the vision. Seven concepts emerged, each addressing key functionalities of the instrument. Discovered challenges included limited scalability and context applicability due to overly specific designs, while other valuable insights highlighted the importance of easy modularity, simple shapes, and recognizable features as visual cues for interaction.

Two concepts were chosen for further exploration, focusing on implementation and mounting options. Various 3D foam models were created to better understand form, scale, and interaction. Key insights included the realization that shapes do not need to be large to appear robust, and that more elegant integrated (finger) grips are preferred over bulky explicit (hand) handles. Asymmetry was found to support intuitive instrument orientation, while sharp, straight cuts felt harsh compared to more rounded, organic shapes that convey friendliness and approachability. Mounts should appear reliable and well-integrated, instead of awkwardly attached.

From there, three distinct design directions evolved: one friendly and approachable, another adventurous and autonomous, and a third technological and asymmetrical. Iterative development gradually integrated more functional, natural, balanced and abstracted features. By the third iteration, a cohesive preliminary design emerged, ready for further refinement and embodiment.



5
Embody

This chapter focuses on further refining and embodying the preliminary design by addressing various partial solutions—such as shape details, functional mechanisms, and aesthetics—that combine to form a cohesive and complete final design.

5.1 Base module geometry

Improving the geometry of the design

The design was validated with company experts, leading to significant improvements. Harsh and uneven edges were smoothed and rounded to achieve the desired sculpted effect, making the instrument more aesthetically pleasing and easier to produce. The mount feature, which previously ended abruptly, was rounded to better align with the overall aesthetic. The sharp "beak" was revised, as it evoked a strict, hawk-like impression that conflicted with the intended friendly and approachable form language.

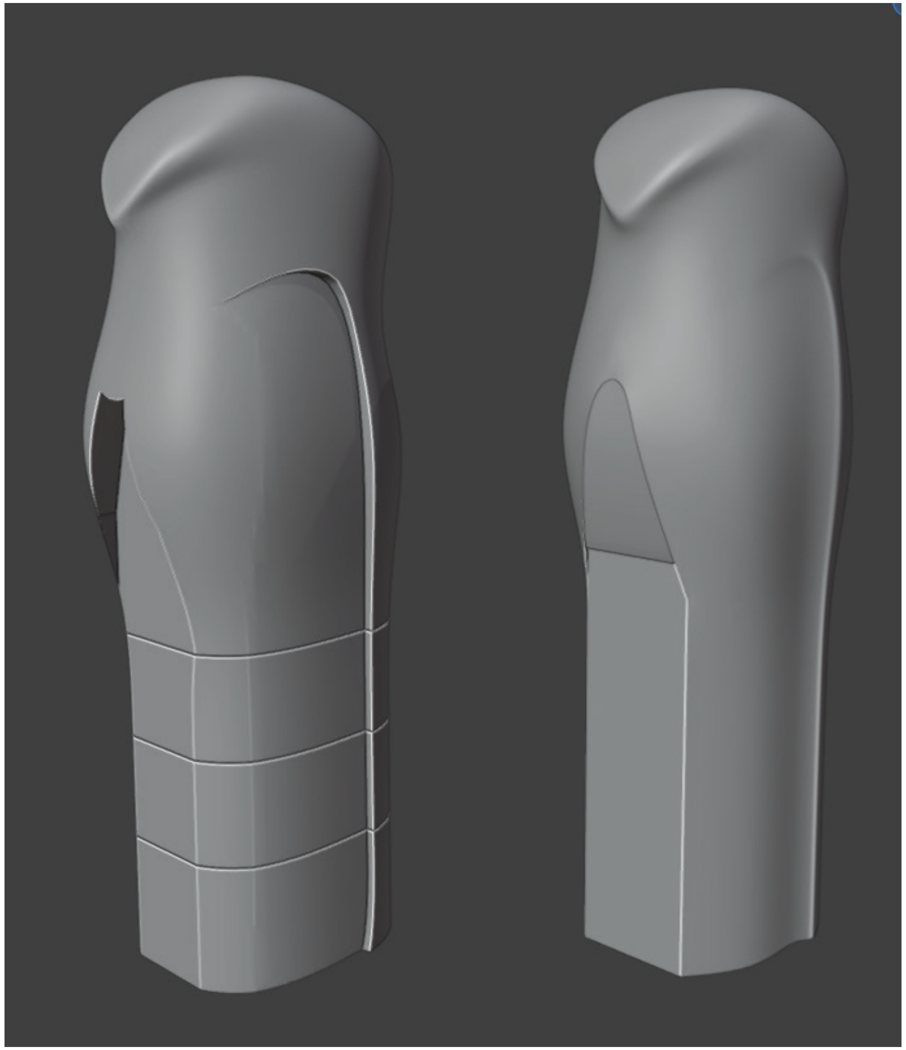


fig. 89 *Moving towards a smoother and more simply defined design*

Different head shapes were explored, ranging from abstract to more sharply defined. The fully rounded ones felt unsettling and failed to convey friendliness. A less defined shape was ultimately chosen to more subtly suggest identity.

fig. 90

The instrument's size of (length x width x height) 70 x 60 x 125 mm is determined by its electronic components and evaluated through 3D-printed models. It is derived by repeatedly subdividing a simple, mathematically defined form, resulting in an organic, but parametrically definable design.

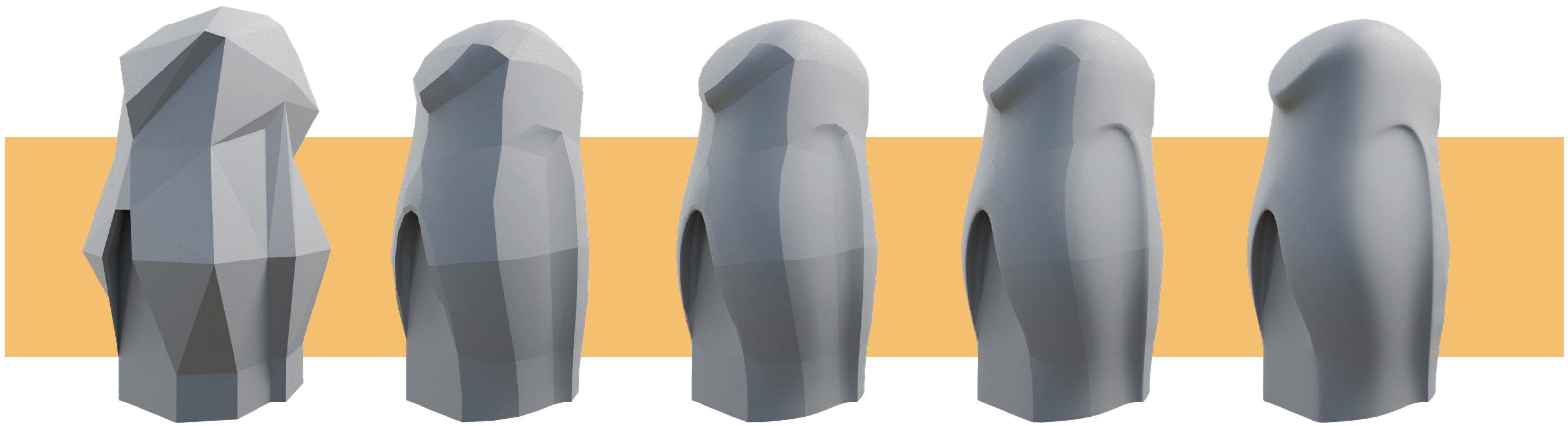


fig. 91

5.2 Back surface texture

Exploring the texture on the instrument's back

A key challenge in the conceptualization phase was to avoid a "creature on a pole" appearance, which was tackled by design elements that prolonged the shape and made it one whole. A texture on the back added more dimension to the product, beyond simple shapes and surfaces, while adding tactile cues to guide the user in fastening the modules. It also aims to improve ergonomics by steering towards a specific grip orientation. Using a molded texture eliminates the need for additional finishing steps and supports mono-material production for improved recyclability.

Various textures were explored, including both mathematical and organic ones. Geometric patterns, such as dots and lines (fig. 92), felt artificial and clashed with the smooth, friendly form language, while organic patterns, like feathers (fig. 93), were overly literal and hard to manufacture. Ultimately, a Turing pattern was selected, which describes how stripes and spots arise in nature due to (chemical) crystallization. A Voronoi variation (see fig. 96) of this pattern was chosen because of its mathematical definability, manufacturability, and abstraction possibilities, aligning with the design's overall approachable identity.

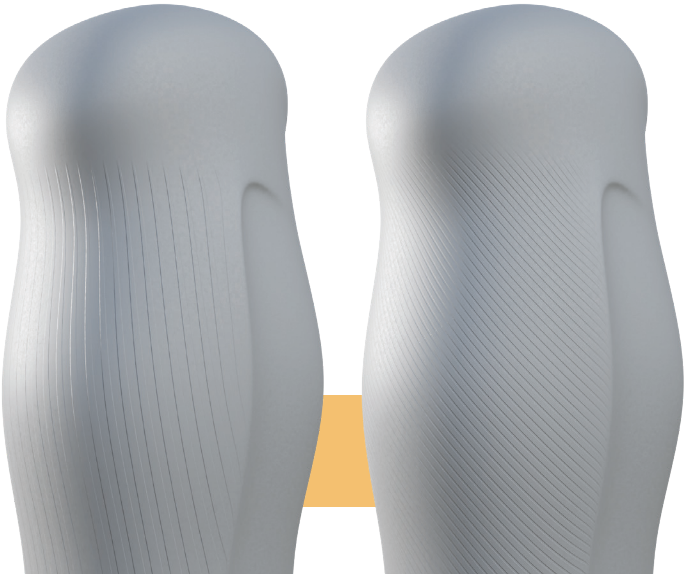


fig. 92 *Two geometric patterns*

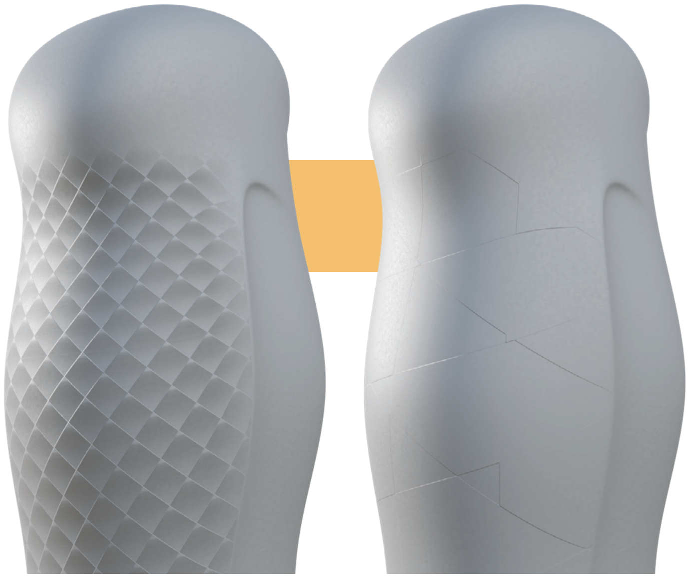
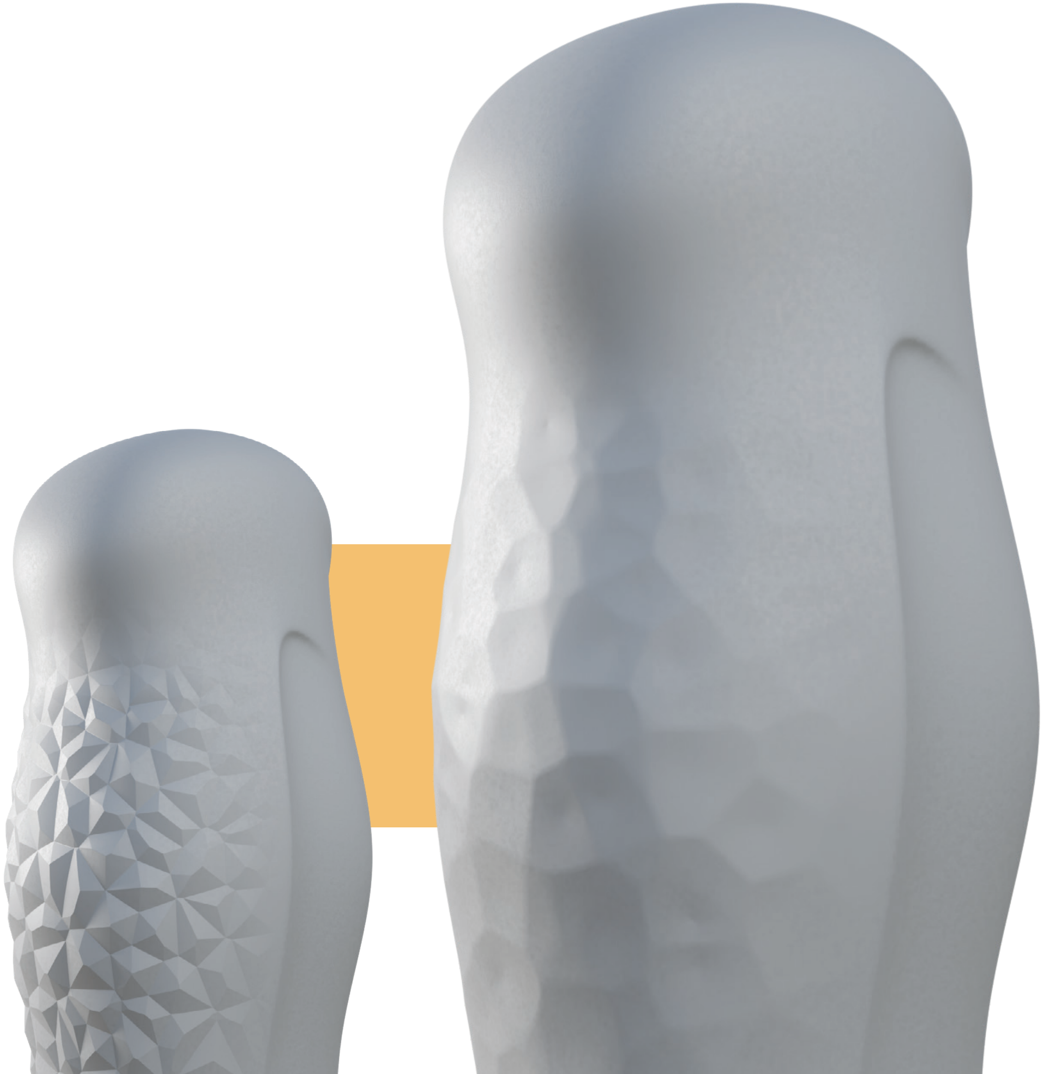


fig. 93 *Two (abstracted) organic patterns*

fig. 94 *Voronoi pattern on a Giraffe's skin (Giraffe Conservation Foundation, 2024)*

fig. 95 *Crown shyness, a natural phenomenon where leaves do not interfere (Osterloff, n.d.)*

fig. 96 *Instrument with voronoi pattern (left), tweaked to the more friendly final one (right)*



5.3 Sensors and module design

Selecting the sensors within scope and designing their modules

5.3.1 Sensor selection

To ensure modularity, distinct sensor modules were designed alongside a base module that houses core components essential for all projects, including a microcontroller, modules for data storage and transmission, and a battery. Different projects can connect different desired sensor modules to the base module while also incorporating a mounting system for fastening in context.

Designing the additional modules required in-depth sensor exploration to map their data output, required technology, and optimal physical measuring conditions. Given the project's focus on drought and air quality, the selection of sensors was narrowed down to allow detailed development and to create a blueprint for future modules.

Sensors were chosen from a list of available citizen science sensors published by the Flemish government (Agentschap binnenlands bestuur, n.d.), and evaluated against six key criteria seen below.

1) Context applicability – The most important parameter: the sensor measures the context of air quality and drought.

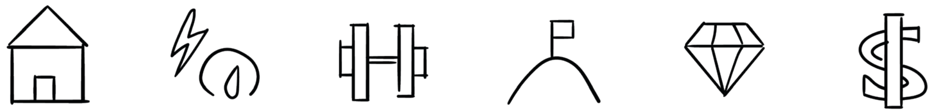
2) Power consumption & data rate – Power efficiency is key for battery life. Factors such as measuring intervals, on-sensor data processing, and data rate determine energy use. Sensors with high data output or energy consumption, such as cameras, are unsuitable.

3) Robustness – Sensors must be durable, reliable and low-maintenance.

4) Scalability – Only automated, active sensors are suitable; passive sensors requiring manual tasks, like Palmes tubes, were excluded.

5) (Scientific) Value – Citizen science sensors may not always prioritize scientific precision, but preferably provide as useful data as possible. Two factors are considered: the value of citizen measurements compared to professional sensors, and the relevance of local measurements versus regional ones.

6) Price – While cost is less important, extremely expensive sensors are unsuitable for an affordable, scalable instrument.



SENSOR	1	2	3	4	5	6	All
Touch	red	green	orange	green	orange	orange	red
Distance	orange	green	green	green	orange	green	red
Atmospheric pressure	red	green	green	green	orange	green	red
Movement	red	green	green	green	orange	green	red
(Soil) temperature	green	green	green	green	green	green	green
Soil moisture	green	green	green	green	orange	green	green
CO (carbon monoxide)	red	green	green	green	red	green	red
CO2 (carbon dioxide)	red	green	green	green	orange	orange	red
Water flow	red	green	orange	green	orange	green	red
Decibel	red	green	orange	orange	orange	orange	red
Light intensity	green	green	green	green	red	green	red
Location	orange	green	green	green	orange	green	green
Humidity	red	green	green	green	green	green	red
NH3 (ammonia / air pollutant)	green	green	green	red	red	orange	red
NH4+ (ammonium / water pollutant)	red	green	orange	orange	orange	orange	red
NO (Nitric oxide / air pollutant)	red	green	orange	orange	red	orange	red
NO2 (Nitric dioxide / air pollutant)	green	green	green	orange	orange	orange	green
NO3 (Nitrate / ground pollutant)	red	green	orange	orange	orange	orange	red
O3 (Ozone / air pollutant)	green	green	orange	orange	red	orange	red
Passage count	red	green	green	green	red	green	red
PH-value ground	red	green	orange	orange	orange	green	red
PM 1 / 2.5 / 10	green	red	orange	green	orange	orange	green
SO2 (Sulfur dioxide / air pollutant)	green	green	orange	orange	red	orange	red
Wind direction	orange	green	red	orange	red	green	red
Wind speed	orange	green	red	orange	red	green	red

fig. 97 *Overview of evaluation and selection of sensors*

A complete and detailed evaluation of the sensors can be found in Appendix B, an overview and key examples are outlined here.

In the evaluation table (fig. 97), green indicates sensors that meet criteria with minimal challenges and are suitable for implementation, yellow highlights uncertainties or the need for adjustments or alternative methods; and red identifies unsuitable sensors. Individual criteria are assessed and combined in the final column to determine if a sensor is included.

With regard to the first criterion, some sensors, such as distance or location, can provide supporting data for other sensors (e.g., instrument placement height), but do not directly address the project's scope. Similarly, sensors for ground and water pollution are excluded for this reason.

Most sensors consume little power or can be adapted to do so. However, exceptions like the particulate matter (PM) sensor require constant power, making them unsuitable for battery operation.

In terms of robustness, many sensors, such as off-the-shelf circuit boards, are durable and easily integrated into modules. However, others, like wind direction and speed sensors have a higher risk of failure due to rotating components.

Many sensors lack sufficient sensitivity to produce (scientifically) valuable results, such as the active NH3 sensor, while its passive counterpart is not scalable due to required manual tasks. Others, like UV index sensors, offer little added value for localized measurements due to the availability of regional-level data.

Based on these evaluations, (soil) temperature and moisture sensors were selected to monitor drought, while air temperature, NO2 and PM sensors were chosen for air quality measuring. The following sections detail their considerations and implementation, while chapter 5.6 focuses on the electronic components more in-depth.

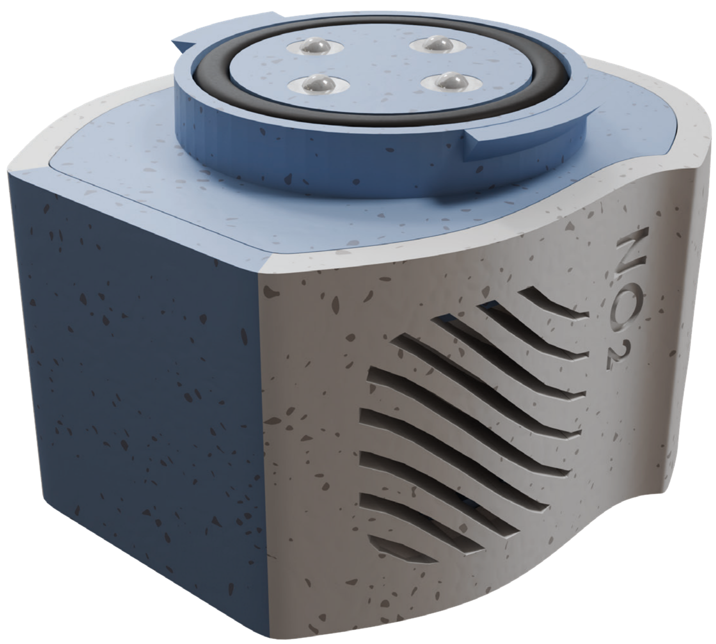


fig. 98 *Close up of the NO2 module*

fig. 99 *Connected NO2 module*

5.3.2 NO2 module

The NO2 module is designed to measure air quality and houses only an NO2 sensor. In collaboration with a mechanical expert from Dott Achilles, specific features were considered to ensure functionality while remaining at a watertightness rating of at least IPx4, protecting the module from splashes of water from all directions. Since the module does not actively draw in air, the risk of water ingress is limited. Structured air vents, such as louvers (fig. 100), will be integrated to allow airflow while preventing water intrusion. The sensor is mounted upside down to prevent water from pooling on its surface.

The design language emphasizes the module's data collection function, enhancing user transparency and engagement while also informing ambient users about its purpose. Horizontal perforations, commonly associated with air-related products (fig. 101), were selected to visually signify the module's air measurement function and to distinguish between the roles of different modules. However, to align with the overall aesthetic of the instrument, these perforations were refined from standard straight lines into a more stylized design. The module is approximately 30 mm tall, accounting for the sensor height (16.5 mm), housing thickness, module connections, and airflow clearance.

fig. 101 *Elongated striped perforation as design language for air-related products such as wall mounted vents (Ventilatieshop.be, n.d.) and air conditioners (Eurgeen, n.d.), and a more stylized convection heater by Huang Peng (Peng, n.d.)*

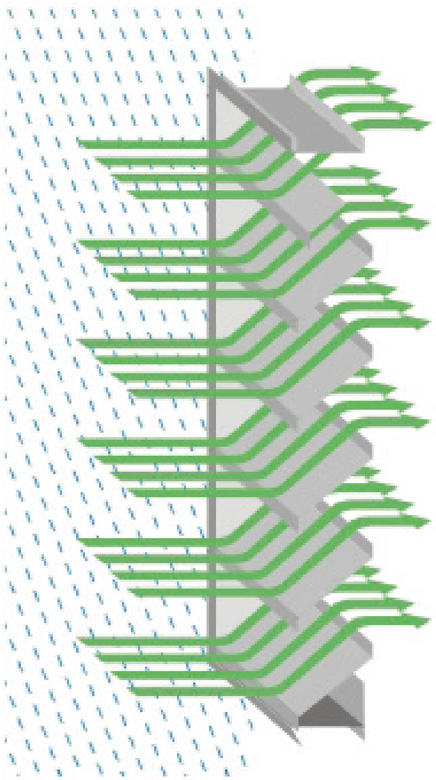


fig. 100 *Louvers, enabling air flow while blocking water (Conaire, n.d.)*

fig. 102 *Fine, mesh-like perforation as design language for audio products such as microphones (RØDE, n.d.) and speakers (JBL, n.d.)*

fig. 103 *Connected closing module*

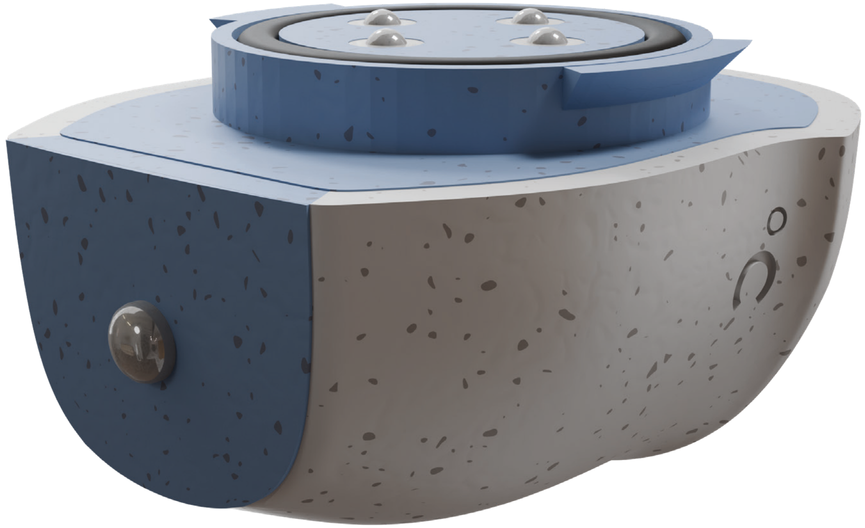


fig. 104 *Close up of closing module*

5.3.3 °C module

The °C module functions as an end module, sealing the open connection inherent to the modular system to ensure watertightness while completing the instrument's form. It houses an air temperature sensor commonly used across projects. Placing the sensor in this module instead of the base module improves repairability and simplifies replacement. The sensor's explicit visual integration aligns with the overall design language of clearly communicating its measuring function, which is consistent with the other modules. Although functionally the module could be smaller, the height of approximately 28 mm serves to enhance grip strength and visual appeal.

5.3.4 Soil module

The soil module aims to monitor drought by integrating soil moisture and soil temperature sensors, along with an air temperature sensor, as it also functions as an end module. The capacitive soil moisture sensor is overmolded to turn it into a solid pin, ensuring robustness and easy insertion into the ground. The module, with a height of 23 mm, features a flattened bottom that serves as a physical stop to indicate correct installation depth and allows for removal from the soil by enabling the use of a shovel or fingers to lift it.

fig. 105 *Connected soil module*

fig. 106 *Connected PM module*

5.3.5 PM module

The PM measures air quality and functions as an end module as well; similar to the previously described end modules, it therefore houses a temperature sensor next to a PM sensor. The PM sensor requires a constant intake of air, resulting in high energy consumption that cannot be sustained by a battery, necessitating a grid power connection. Despite this limitation, the sensor is popular in many citizen science initiatives, among others those funded by the European Union (see chapter 2.4.2). To appeal to this existing user base, the PM module has been included in the project scope with a dedicated grid power connection. Given that the sensor's power demand is an exception, the overall system remains battery-powered. For most cases this is most suitable, and it keeps the instrument simple. Future iterations may reconsider a grid power module if demand increases.

To ensure watertightness, the PM module incorporates the same features as the NO2 module, such as upside-down sensor mounting and structured air vents. However, since the PM sensor actively draws in air, the air inlet was enlarged, based on mechanical expert advice, to prevent a suction effect caused by under pressure. Its size (length x width x height) is approximately 9 x 9 x 14.8 mm.

5.4 Color

Exploring the instrument's colors

The instrument's colors were selected based on several considerations. Functionally, (1) a light color minimizes the impact of direct radiation on temperature measurements by reflecting sunlight. However, (2) lighter colors can quickly appear dirty in outdoor settings. The design also aims for the instrument to stand out slightly, drawing attention and possibly sparking conversation, (3) which demands colors that contrast with the context of use. Finally, an important aspect of the design is to use color as a design cue to signal affordances for interaction. Examples of such 感性デザイン (eng: Kansei design) or "emotional design" include the color-coded components in the Fairphone 5 (fig. 107) and the drill by Tactile Inc. (fig. 108). To achieve this, (4) interactable features of the instrument are highlighted with bright accent colors that contrast with the main color.

fig. 107 *Color-coded components for intuitive installation (Fairphone, 2023)*

fig. 108 *Use of color to indicate interactability (Tactile Inc., 2023)*

The number of used colors was intentionally limited, as fewer colors were found to enhance a friendly and approachable appearance during concept development. Initially, various greens paired with contrasting bright accents were tested to blend in with garden environments. Complementary colors like red were compared with analogous ones, such as yellow, to soften the overall effect. While this worked well for garden environments, it was unsuitable for less natural contexts, such as balconies.

White and lighter colors were examined for their neutrality, offering a broader contextual fit while still creating contrast with a bright accent color. Experimenting with (split-)complementary and analogous harmonies showed that these would highlight the instrument but risked appearing dirty more quickly. To mitigate this, darker shades were also explored, which felt more robust but are more prone to being heated by sunlight. Ultimately, light grey was selected as the main color, balancing visibility and robustness. This was paired with a light blue accent to highlight elements while easing in with the light grey.

fig. 109 *A selection of palettes and harmonies from the color exploration*

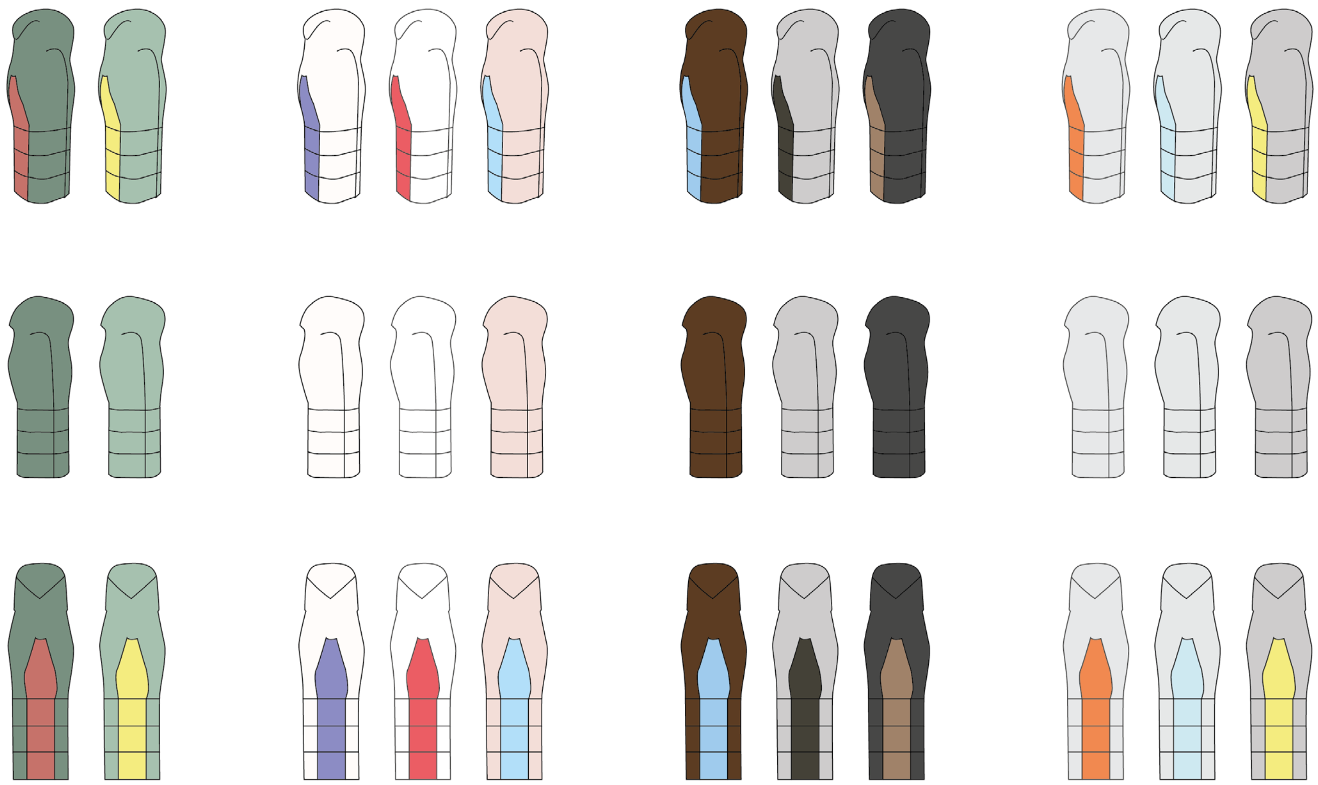


fig. 110 *Comparing instrument colors with autumn or winter garden contexts*

fig. 111 *Comparing instrument colors with less natural contexts*

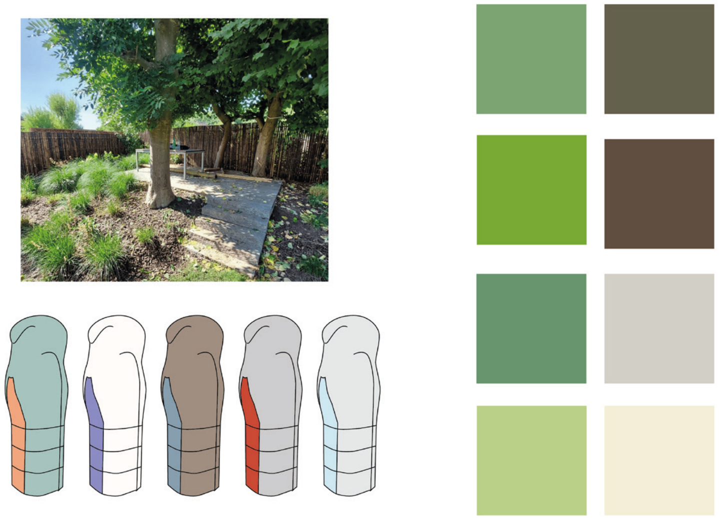


fig. 112 *Comparing instrument colors with spring or summer garden contexts*

5.5 Material and production

Describing the selected materials and how they will be manufactured

5.5.1 Material selection

The instrument's material must meet several requirements, including being watertight (IPx4) and UV-resistant to withstand outdoor environments; look and feel robust while remaining lightweight; and be scalable while remaining cost-effective. A hands-on evaluation of various material samples and their properties in collaboration with company experts identified plastic to be most suitable. Further research explored environmentally friendly plastics, including mass-balanced (partially recycled), bio-based, biocomposite, post-industrial and post-consumer variants (fig. 113). Despite claims of sustainability, many of those plastics combine components with different properties and qualities, often resulting in non-monomaterials that are harder to recycle. Some are characterized by speckles (fig. 114), which can be a result of included biofibers. While not inherently environmentally friendly, such materials can enhance product longevity by masking wear and damage from frequent use. Concealing this damage can support prolonged use, which indirectly enhances sustainability. Speckled materials are particularly suitable for the instrument's context, as it communicates the spirit of citizen science—often addressing societal issues—while masking splashes of dirt.

fig. 113 *Exploration of different "environmentally friendly" materials and colors*

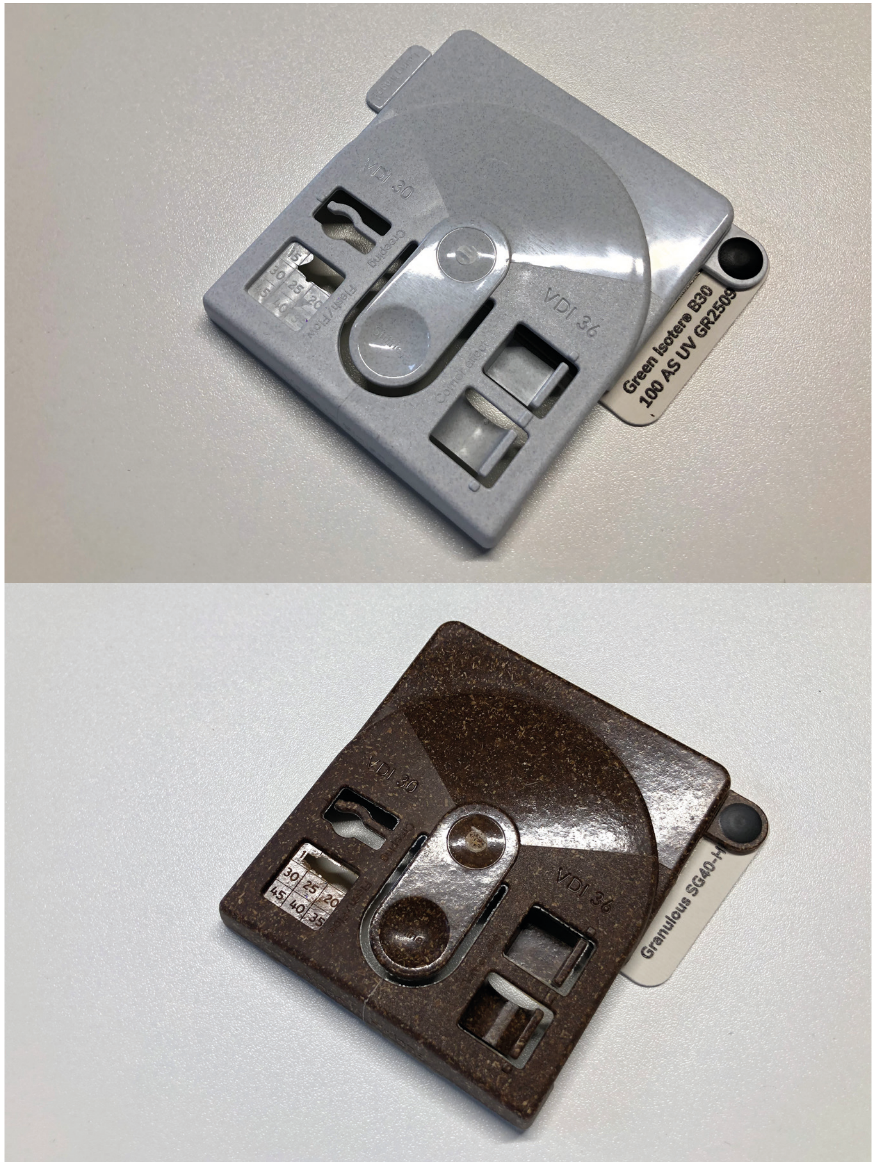


fig. 114 *Materials suitable to incorporate in the instrument for their grey color (above) and a speckled characteristics (below)*

5.5.2 Color production

In discussion with a company expert, three methods for integrating different colors were considered.

The product can be manufactured from a single material and painted in an additional surface finishing step. However, this method has significant drawbacks, including limited durability, particularly in mounting areas where damage can expose the base material (fig. 115). Painting also increases production costs and has a negative environmental impact, as it contaminates the material and complicates recycling.

Two-component (2K) injection molding allows two different materials or colors to be combined in a single process using a chemical bond (fig. 117). The bright blue color could therefore be molded over the main color. While this increases robustness and can save an additional finishing or assembly step, it contaminates the materials, making recycling impossible.

Using double-walled material, two separate parts are produced and assembled afterwards. While this can be slightly more expensive, it allows for separation of materials for recycling. Since the bright blue color is used for both the mounting feature as well as the module connections, they can effectively be combined in one assembly step (fig. 118), which makes it the most suitable method to produce the instrument.

fig. 115 *Damaged paint causing the base material to be revealed*

fig. 116 *An example of ultrasonic welding: a car seat belt (Alpha, n.d.)*

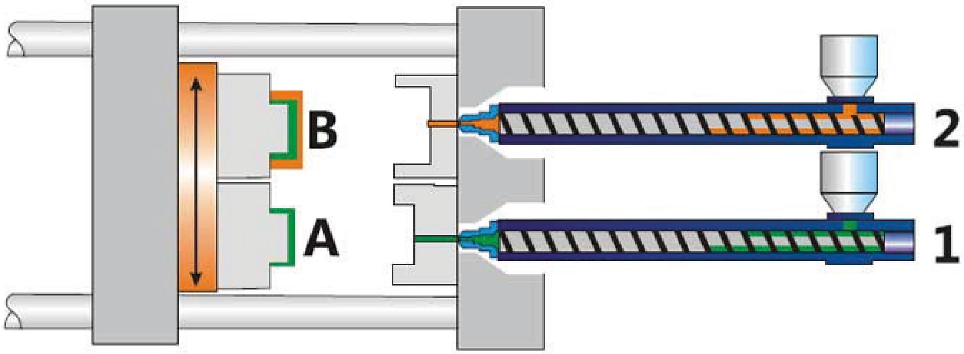


fig. 117 *Schematic overview of the principle of 2K injection molding (VDL, n.d.)*

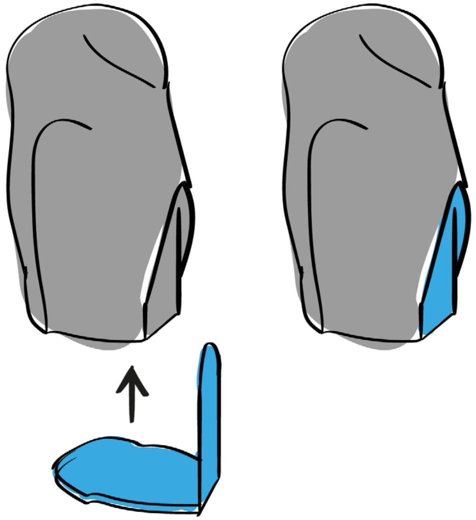


fig. 118 *Individually produced parts will be assembled*

5.5.3 Module manufacturing

The geometry of the main shape requires it to be molded from two separate parts, which are joined afterwards using ultrasonic welding (fig. 116). This process minimizes the visibility of the parting line and ensures watertightness. The line is positioned along the nose and front, creating a symmetrical solution and partially camouflaging it with the texture on the back (fig. 119).

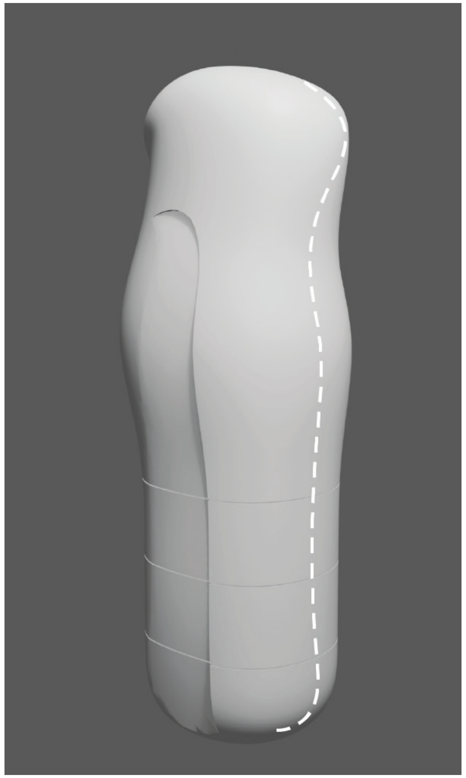


fig. 119 *The proposed parting line between the base module parts*

The bottom cap, containing the module connection, is fastened using screws and a sealing to maintain robustness and watertightness. Internally, it features a molded structure that serves as a frame to which the interior of the instrument, including all electronic components, is attached to enhance repairability (fig. 120).

Modules can generally be produced as a container with two lids, eliminating the need for visible parting lines or the production of multiple components. However, more complex modules require an approach similar to the base module. A material thickness of 2 mm has been specified as sufficiently robust based on evaluations with a company expert.

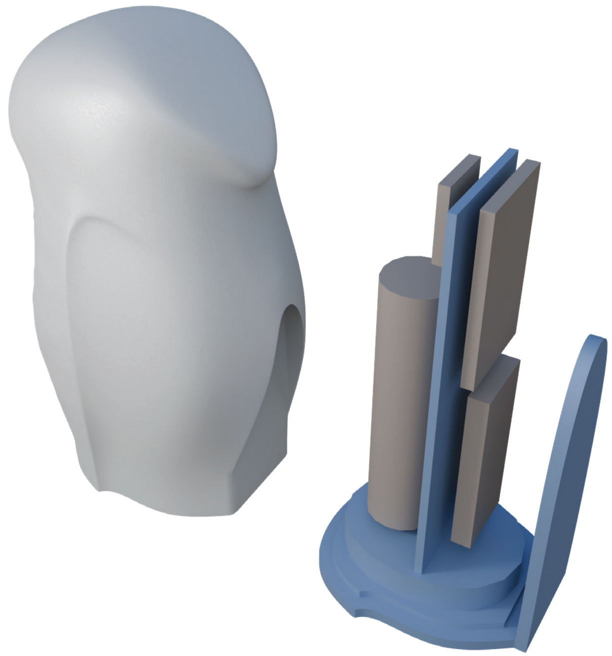


fig. 120 *The internal structure with volumes representing electronics*

5.6 Electronic components

Listing the included electronic components in base and sensor modules

This section covers the electronic components integrated into both the base module and additional modules, along with key considerations for specific technologies and components. Estimations and assumptions are used to outline dimensions, price and performance. For complete and detailed reasoning, please refer to Appendix C and Appendix D.

5.6.1 Base module

The base module houses essential components required for all projects and includes connections for both mounting and additional modules.

Microcontroller
To manage the instrument's processes, a microcontroller is included. Highly energy-efficient options with extended sleep functionalities are available, with the final selection to be determined by an electrical engineer.

Data storage
The instrument integrates local data storing serving as a buffer before transmitting to the online environment. Several options for embedded memory are all relatively cheap, but a slightly larger, more expensive option is implemented: an SD card, as it enhances recoverability if the instrument breaks or fails to transmit data to the online platform. Storage capacity depends on the used sensors and their measuring intervals. For example, when including all the sensors for both air quality and drought, recording data every minute generates approximately 17280 bytes per day (see Appendix E), adding up to around 63 MB over a 10-year period.

Power
As the instrument needs to operate in remote and outdoor environments, it will be powered using a battery. A rechargeable Li-Ion battery is compact and allows for long-term use. To roughly determine the order of magnitude of the battery capacity, power consumption of included sensors is calculated in Appendix E. Excluding the grid powered PM module, a 18500 type, 1500 mAh battery would be able to sustain measurements at one-minute intervals for nearly 9 years. The duration of benchmark projects rarely exceeds 4 years, which is why the battery aims to at least outlast that timespan. To accommodate potential future additional modules, a 18650 type 2600 mAh battery will be used.

Recharging the battery is best handled by the owner or distributor of the instruments to ensure safe procedures and maintain a plug-and-play system. The instrument will also be pre-activated by the distributor, eliminating the need for citizen scientists to manually turn it on. It will continuously measure but only transmit data when installed. Although not included in the scope of this project, future iterations should implement the possibility to grid-power the instrument, further increasing its application possibilities.

Data transmission

Technologies to transmit collected data to the online environment each have their own advantages and weaknesses and are evaluated through many parameters, including bandwidth, coverage, power consumption, cost, mobility, latency, indoor penetration, security and redundancy. Given the instrument's limited data needs and static outdoor operating conditions, LPWAN (Low-Powered Wide Area Network) technologies with existing infrastructures, such as LTE-M and NB-IoT, are most suitable. For a complete overview of the considerations, see Appendix C.

Both technologies are extremely energy-efficient, but where LTE-M supports higher availability in Europe, mobility, and higher data rates, NB-IoT is the better option outside Europe and typically cheaper. Based on both current (Appendix E) and future demanded data rates, LTE-M is the most suitable and robust solution. An example of a chip that incorporates this technology is Telits' NE310G1 (fig. 121).

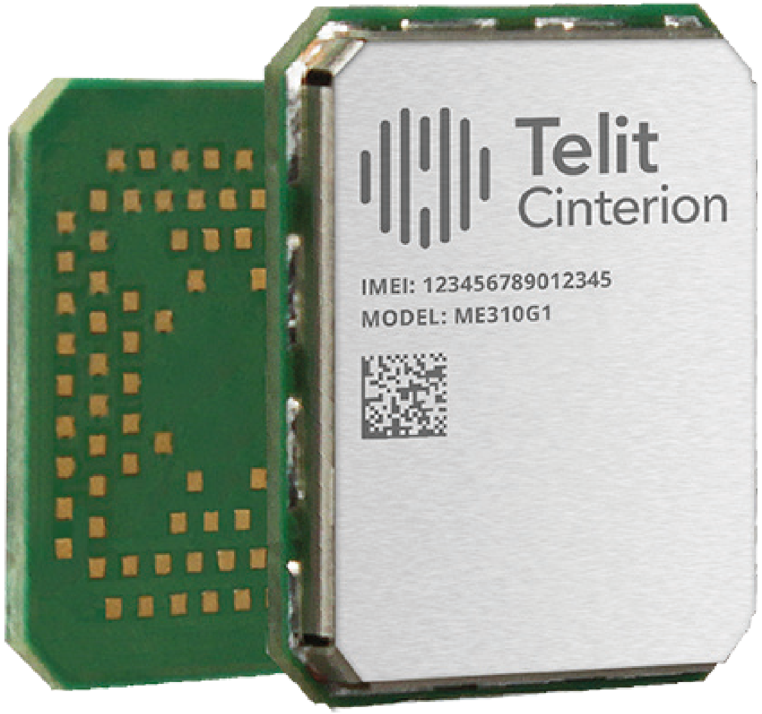


fig. 121 *Telit cinterion's ME310G1 LTE-M data transmission module (Telit Cinterion, n.d.)*

5.6.2 NO2 module

Based on earlier sensor selection (see Appendix B), Alphasense's NO2-B43F sensor (fig. 122) is currently the best option to implement.

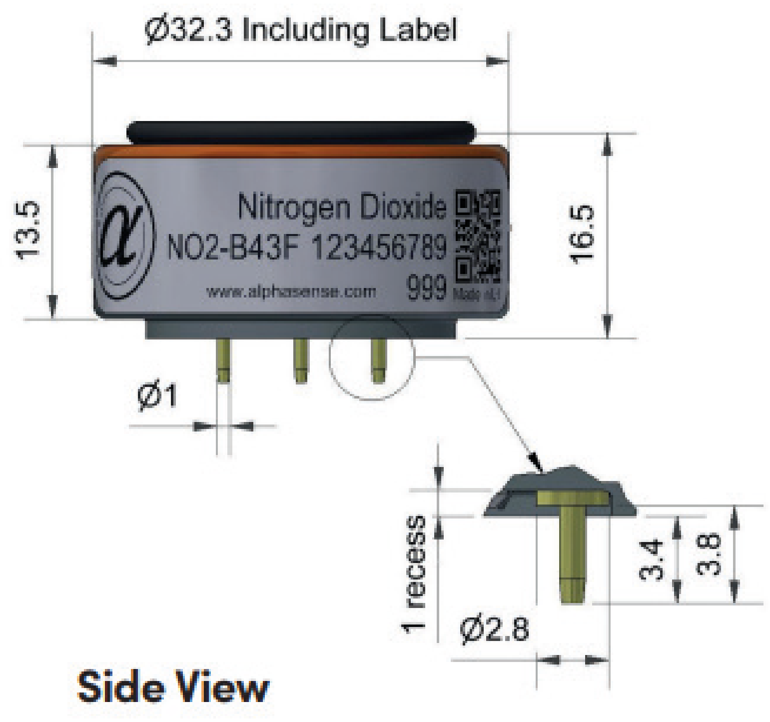


fig. 122 *Alphasense's NO2-B43F sensor*

5.6.3 °C module

The temperature sensor in the °C end module comes in different (waterproof) probe shapes and sizes off the shelf (fig. 123).

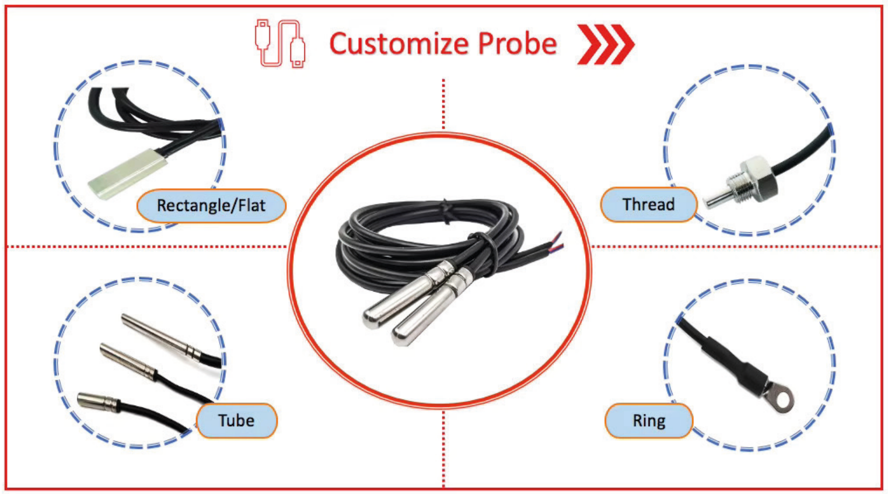


fig. 123 *Customizable temperature sensor probes (Alibaba, n.d.-f)*

5.6.4 Soil module

Sensors for soil moisture often come in blade-shaped designs (fig. 124), however, they can be custom overmolded in various ways (fig. 125). As the ground module is also an end module, it contains a temperature sensor as well.

fig. 124 *Off-the-shelf capacitive soil moisture sensor (Alibaba, n.d.-b)*

fig. 125 *Overmolded capacitive soil moisture sensor (Evvos, n.d.)*

5.6.5 Particle matter module

Based on earlier sensor selection (Appendix B), Alphasense's OPC-N3 sensor (fig. 126) is the best option to implement. As the PM module is also an end module, it contains a temperature sensor as well.

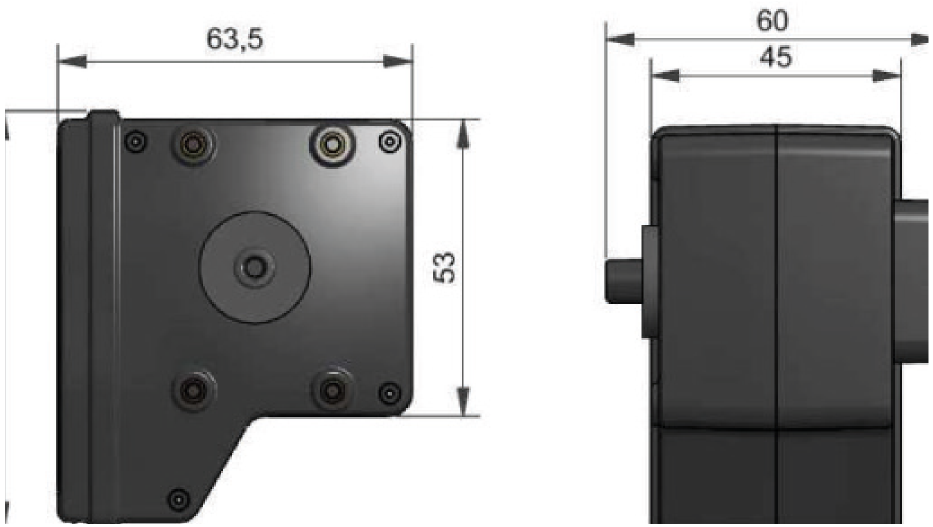


fig. 126 *Alphasense's OPC-N3 particle matter sensor (Alphasense, n.d.-b)*

COMPONENT	DIMENSIONS (MM)	UNIT PRICE (€)
Base module		
Microcontroller (Alibaba, n.d.-h)	44 x 18 x 5	1.85
LTE-M module (Symmetry Electron-ics, n.d.)	18 x 18 x 2.6	13.00
SD module (Alibaba, n.d.-i)	42 x 24 x ~3	0.25
SD card (Alibaba, n.d.-e)	"	0.50
Battery (Li-Ion type 18650) (Alibaba, n.d.-c)	ø 18.6 x 68.2	1.45
NO2 module		
NO2 sensor (Alibaba, n.d.-d)	ø 32.3 x 16.5	90.00
PM module		
PM sensor (Alibaba, n.d.-a)	60 x 60.3 x 75	~400.00
Temperature (Alibaba, n.d.-f)	ø 6 x 10	0.50
Soil module		
Soil moisture (Alibaba, n.d.-b)	98 x 23	0.30
Temperature (Alibaba, n.d.-f)	ø 6 x 10	0.50
Endmodule		
Temperature (Alibaba, n.d.-f)	ø 6 x 10	0.50

fig. 127 *Included electronic components and their characteristics*

5.7 Module connection

Exploring the connecting mechanism between modules

5.7.1 Mechanism exploration

Various mechanisms were evaluated to securely connect modules while meeting a few key criteria: watertightness (to prevent damaging electric connections), ease of use, reliability (firmness of the connection), simplicity (ease of production), robustness (resistance to breakage), scalability (compatibility with future modules), and aesthetic appeal.

A bayonet lock uses interlocking pins and slots to connect modules with a quick twist, typically requiring less than a 90° turn (fig. 129). The connection is secured through friction or compliant materials.

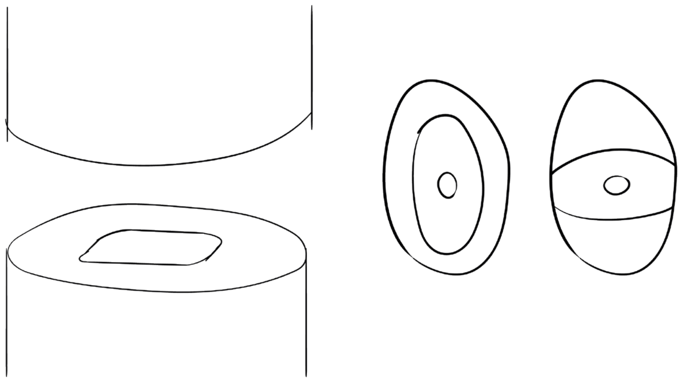


fig. 128 *Bayonet lock*

fig. 129 *Simple friction-secured bayonet lock design as seen in the Aeropress coffee maker*

Quick-release mechanisms self-lock when components are pushed together and are easily unlocked by retracting the locking element through a simple interaction.

fig. 130 *Quick-release mechanism* ▶

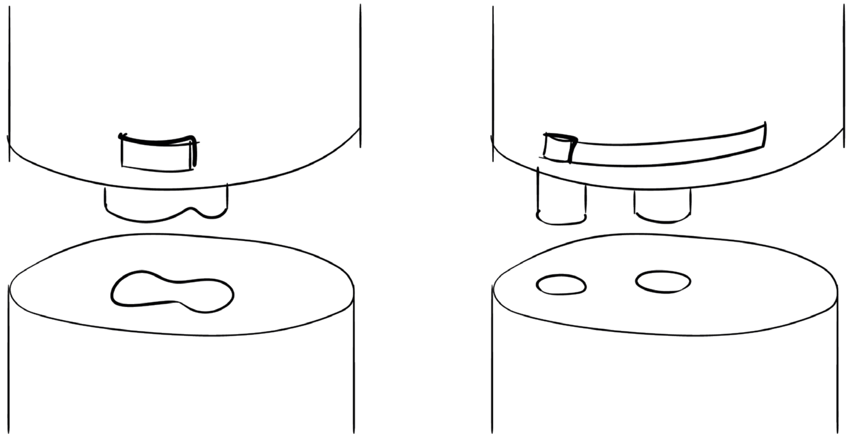


fig. 131 *Working principle of a quick-release mechanism*

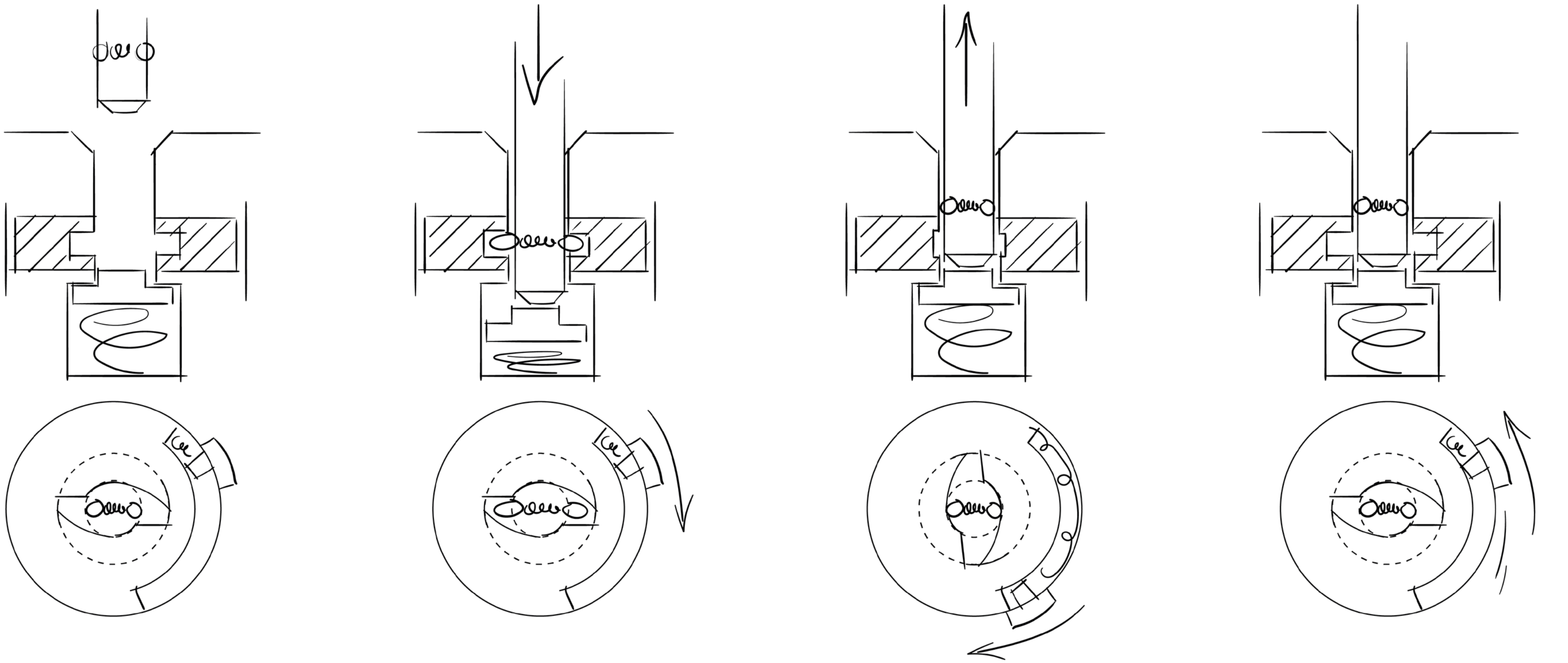


fig. 132 *Magnet-based connection*

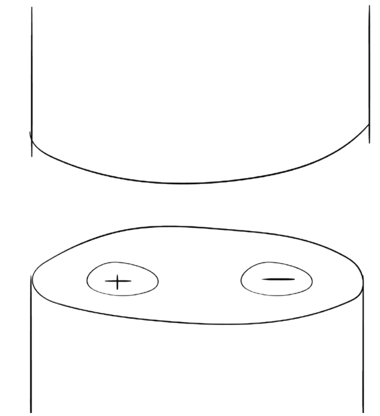
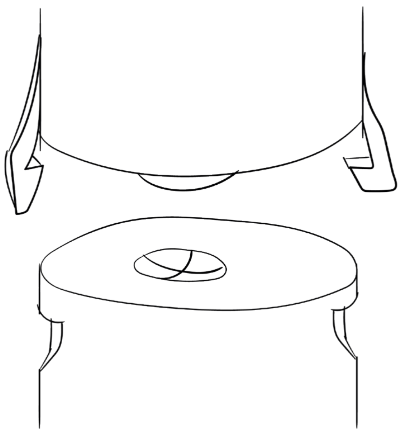


fig. 134 *Snap-fit connection*



Snap-fits rely on flexible components that interlock when pushed together, and are unlocked by a manual interaction.

fig. 135 *Screw thread*

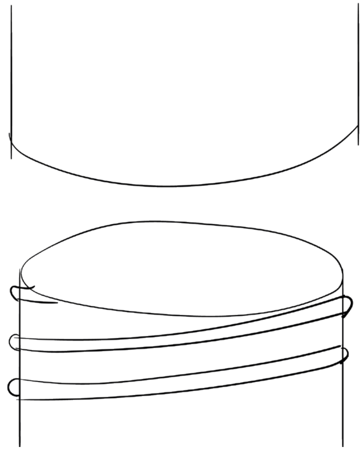
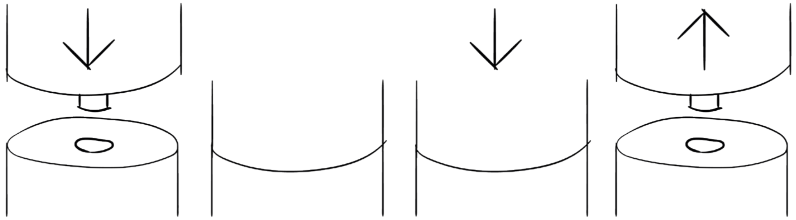


fig. 133 *Push-push mechanism*



A push-push mechanism locks modules with a push and releases them after a second push, similar to the mechanism in ballpoint pens.

Guided spring-loaded locks, push-push mechanisms and magnets are most intuitive, as they incorporate (visual) alignment and automatic locking through simple interactions. Snap-fits provide additional visual guidance but rely on small features that are less robust and visually unappealing. Quick-release and push-push mechanisms are more complex, having additional components that increase the risk of breakage. Magnets, though intuitive, are easily disconnected and therefore unreliable.

Screw and bayonet locks are simple and functional mechanisms to create watertight locks, however they are less intuitive compared to the others because modules are harder to align. Screw threads, in particular, are less visually appealing, time-consuming to fasten, and lack feedback to indicate how tightly they should be secured.

5.7.2 Mechanism design improvements

Bayonet locks are the most suitable option due to their balance of functionality and usability. To enhance intuitiveness, ポカヨケ (eng: poka yoke) guiding mechanisms are integrated, which aim to avoid mistakes by preventing, correcting, or drawing attention to human errors as they occur (fig. 138 and fig. 139). Next to tactile feedback of module textures and visual cues of shapes and color coding, bayonet locks have distinct male and a female parts with physical constraints that prevent incorrect installation (fig. 137). Additionally, an audible and haptic "click" reassures the user that the connection is secure. Validation with a mechanical expert confirmed that this "click" can be achieved through the geometry of the bayonet lock, eliminating the need for additional parts and allowing the mechanism to be molded directly into the design.

fig. 136 *Physical constraints are intuitive, as they are ingrained in human behaviour from a young age, for example when playing with a shape sorter (In den Olifant, n.d.)*

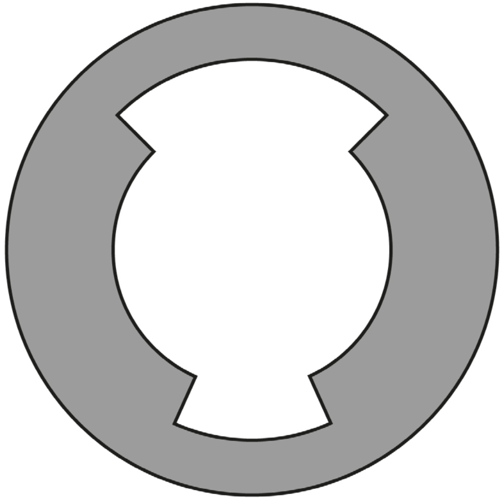


fig. 137 *Outline of the instrument's female side of the bayonet lock, physically constraining for a single orientation only*

fig. 138 *Example of ポカヨケ, an asymmetrically shaped SIM card that can only be inserted in a single way*

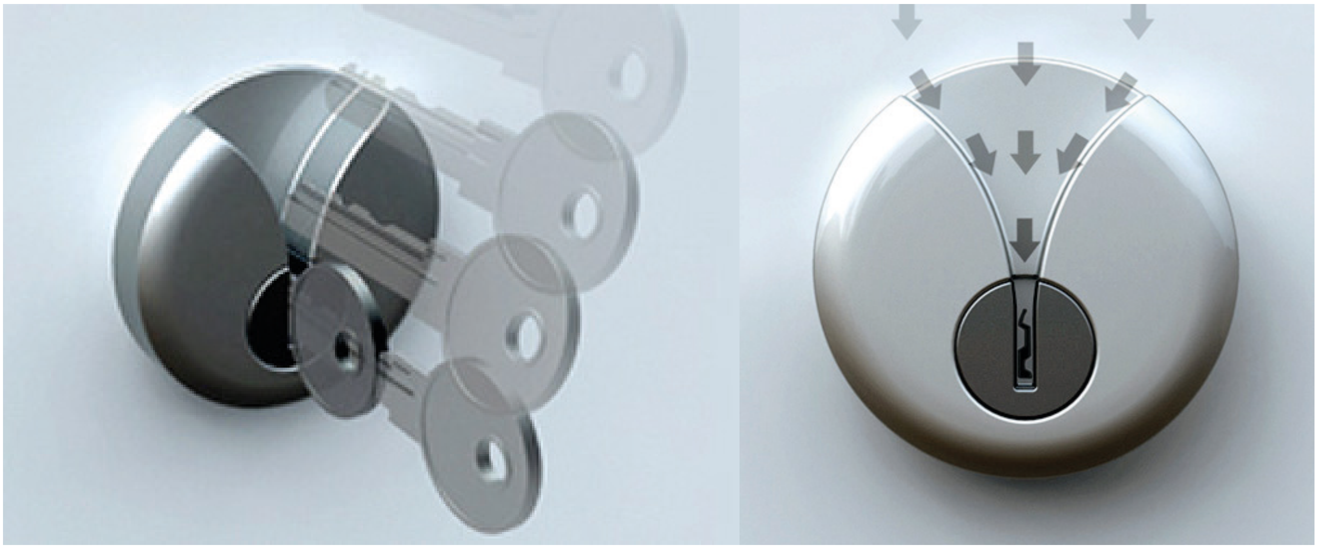


fig. 139 *An easy to find door lock, as designed by Junjie Zhang (Zhang, n.d)*

5.7.3 Electrical connection

Spring-loaded pogo connectors (fig. 140) are incorporated into the design to ensure a robust electrical connection, counteracting slight misalignments and maintaining reliable contact when used together with a compressible O-ring.

5.7.4 Watertight seal

Two O-ring variations were analysed to ensure a watertight seal: axial seals, compressed between two flat surfaces, acting as a gasket; and radial seals, compressed perpendicular to their axes, sealing between the inner and outer surfaces of two cylindrical parts (fig. 141). While both are reliable, the axial seal was selected for its ability to minimize the required vertical space.

fig. 140 *Electrical connection using pogo pins* (Amazon, n.d.-b)

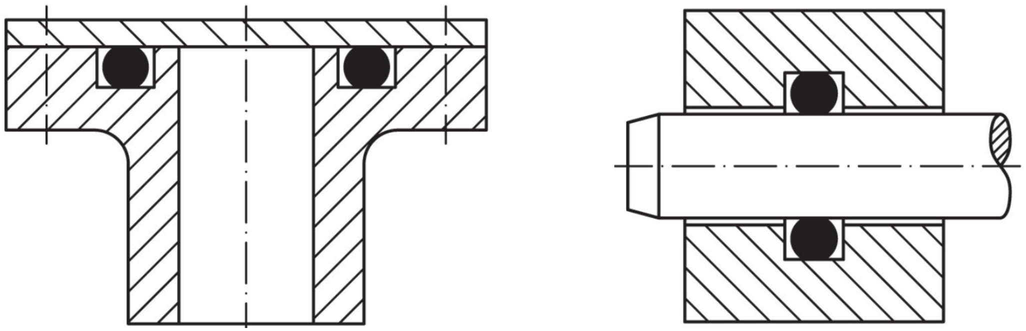


fig. 141 *Axial (left) and radial (right) O-rings (Anyseals NV, n.d.)*

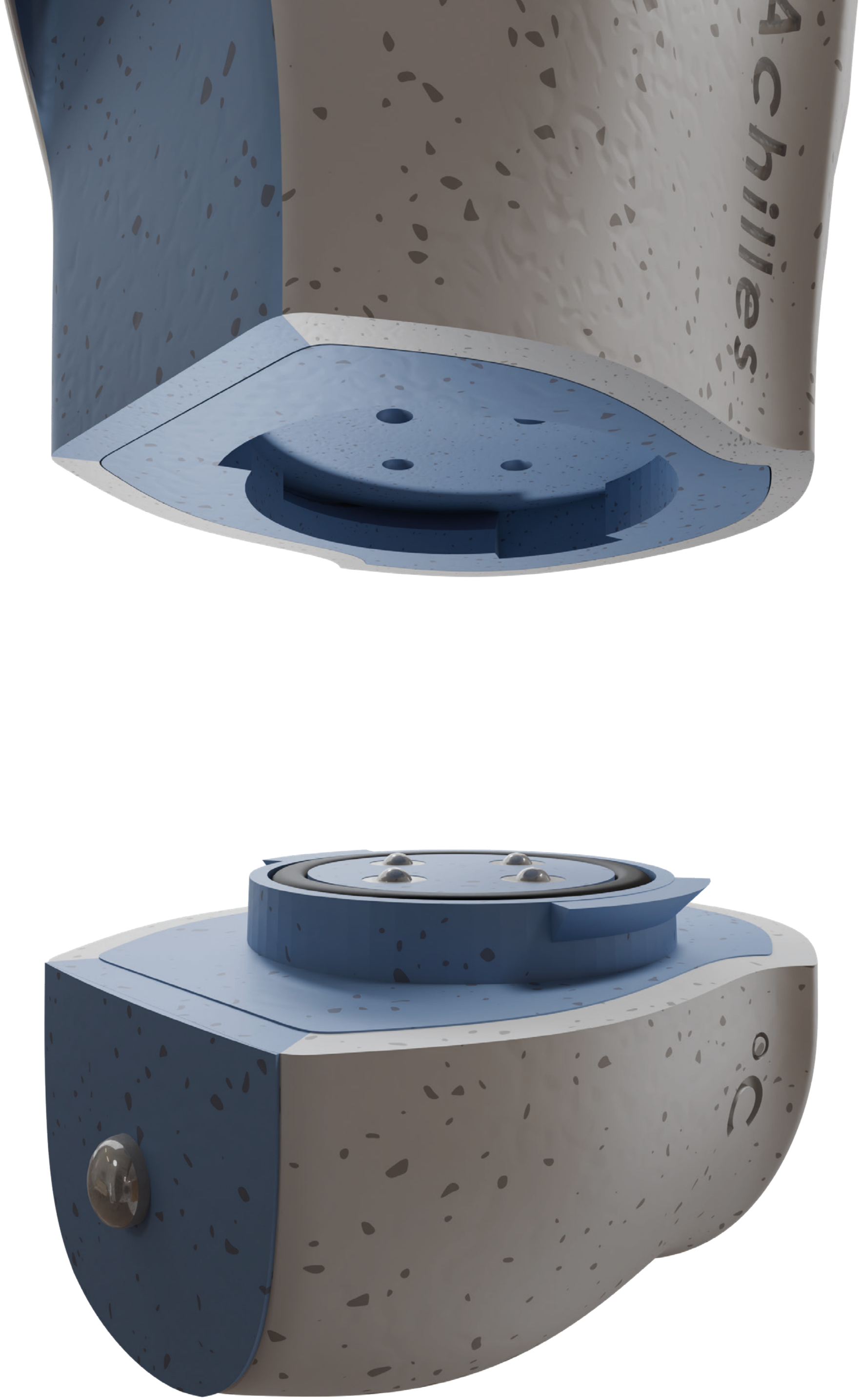


fig. 142 *Implemented bayonet lock*

5.8 Mount

Describes the integration of the mounting feature

The base module incorporates a mounting feature designed to support various fastening options in different contexts, increasing scalability alongside the soil module, which secures the instrument in the ground. The mounting feature, integrated into the front of the base module, is designed as a "negative shape" cut out from the main shape, with the mount forming a complementary shape to complete it (fig. 143). Unlike the soil module, which connects electrically as an end module, the mounting feature contains no electronics.

To narrow the scope, one specific mount was selected to be developed, excluding the windowsill clamp that was included in the use context. This allowed to focus on other design elements while still validating the mounting mechanism. Future iterations will include the clamp.

fig. 143 *An example of a "negative shape" that is completed by a complementary shape: Sweeper & Funnel by Kochański (Kochański, n.d.)*

The mounting feature relies on a rail-based mechanism with a specific profile, allowing mounts to slide in and secure via friction fit. This profile ensures compatibility with various (future) mounts, as new designs can adapt to the system (fig. 148). To enhance strength and provide tactile and auditory feedback, integrating a snap-fit mechanism (fig. 144 and fig. 145) was considered.

fig. 144 *Example of shape-integrated snap-fit* (ZacSimmo, 2021)

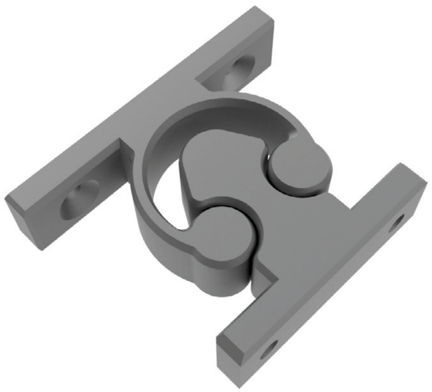


fig. 145 *Example of shape-integrated snap-fit* (Ecosupply, n.d.)

fig. 146 *Although adopting a more technical look, the Nintendo Switch features a comparable rail system that allows to attach a variety of accessories (Nintendo, n.d.).*

However, integrating and concealing snap-fit components within the housing proved to be complex. A ball-plunger mechanism, providing similar feedback, was ultimately selected (fig. 147). Although it is a separate component that needs to be assembled, it is simple and aligns with the instrument's overall design language of transparent and explicit communication of functionality.

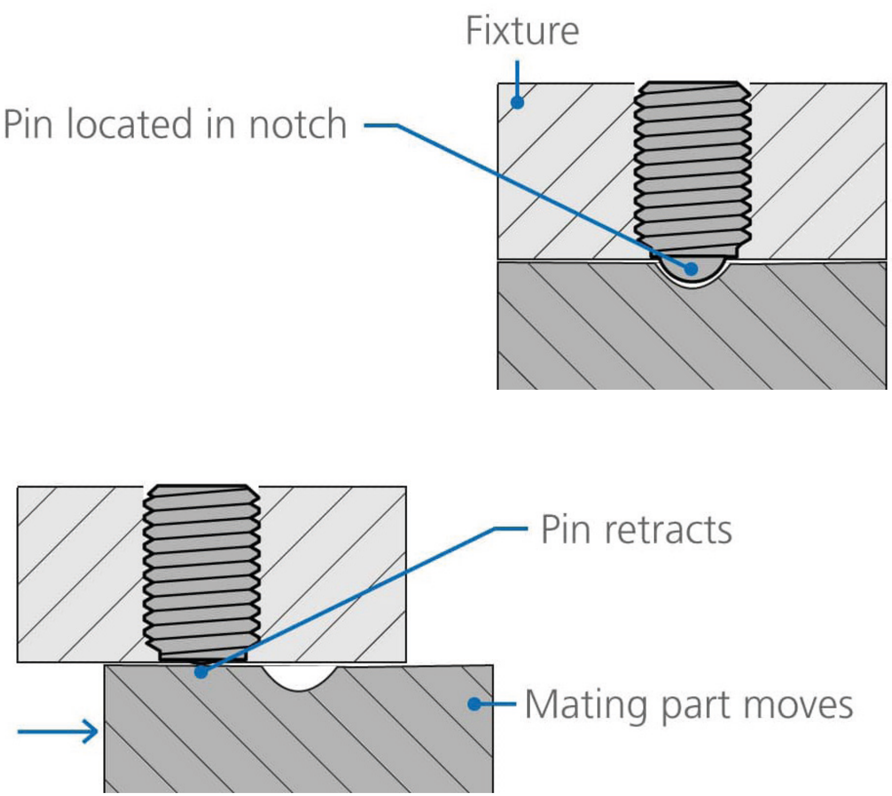


fig. 147 *Working principle of a ball plunger (Rencol, 2024)*

fig. 148 *The specific profile that can be the basis for a variety of mounts*

fig. 149 *The mount allows for attachment to railings with small and large diameters, both horizontal and vertical*

fig. 150 *The instrument's mounting feature: completing the "negative shape" witih the complementary shape of the mount*

5.9 Ambient user communication

Describes the integration of communicative elements in the main shape

To ensure transparency, the instrument provides communication for ambient users to inform them about its purpose, the type of data it records, and how the data will be used. Stickers were initially considered to display this information, for example, using a URL or QR code, but this presented several challenges. Frequent reuse across various projects, changing the associated information, makes universal links unreliable over time. Stickers are susceptible to weather conditions and require frequent manual replacement, risking to being placed incorrectly, which reduces scalability and robustness. Additionally, they lack sustainability and do not align with the instrument's stylized design language.

The redesigned solution integrates subtle, robust labeling directly into the instrument. Each module is labelled with its specific function, such as "NO2", explicitly communicating its purpose. The distributor's name, currently depicted as "Dott Achilles", is integrated into the base module, offering ambient users a starting point for further details. For instance, the distributor's website can provide comprehensive sensor information.

fig. 151 *Labeling and communicative elements of modules*

5.10 Online platform

Describing the features of the online platform

The physical instrument is complemented with an online platform that further enhances user-friendliness, robustness and scalability by streamlining interactions across the complete system and providing accessible information. Compatible with mobile and desktop devices, maximizing its functionality and inclusivity, the platform offers citizen scientists essential project information and support to use the instrument. While this chapter describes key functions, additional features—such as a forum to enhance the feeling of being part of a community—can be incorporated to align with participants' motivations found in the research phase.

5.10.1 (De-)Installation help

The platform offers step-by-step assistance in installation and disassembly through an interactive, user-friendly manual that aligns with research findings. The process is broken down into smaller, manageable steps to reduce complexity and prevent users from skipping any steps. It provides instant feedback to avoid mistakes and correct errors where necessary (fig. 152). Users can revisit steps (fig. 156), and the manual incorporates images, illustrations, and videos that correspond with the situation to demonstrate correct actions and assist in proper instrument placement (fig. 153). The manual also allows for input in a scalable way, such as noting installation height (fig. 155), and when integrated into the platform with mobile application compatibility, it can use the phone's features. For example, the camera can be used to upload photos of installed instruments (fig. 154), and GPS functionality can set the instrument's location. After use, citizen scientists receive disassembly instructions, including guidance on cleaning and repackaging if required.

To touch upon educational motivations and deepen understanding, additional information is available through interactive elements such as "info" icons and underlined terms that show explanations when clicked (fig. 153). All information is documented and accessible in a searchable wiki or dictionary, altogether contributing to a plug-and-play system.

fig. 152 *An example of a user error in the first "CurieuzeNeuzen" project: participants forgot to close off their Palmes tubes to end measuring, before returning them (CurieuzeNeuzen, n.d.-b)*

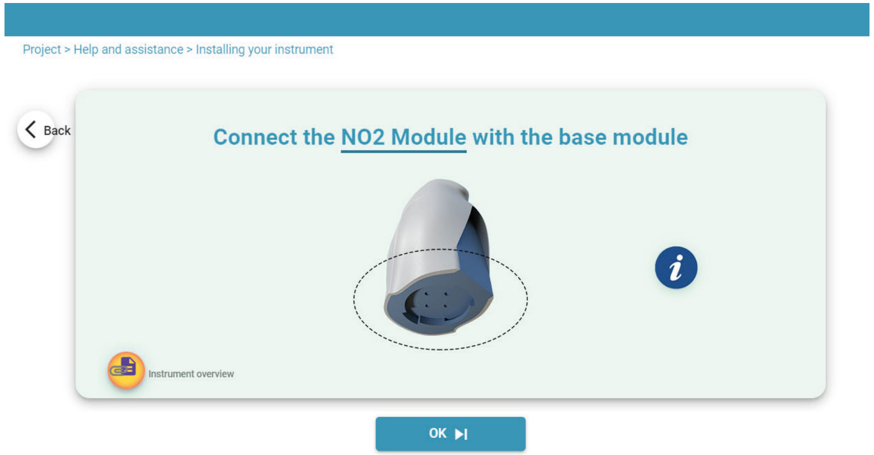


fig. 153 *Possibility to show corresponding media and underlined terms, desktop version inspired by Decizone (n.d.)*

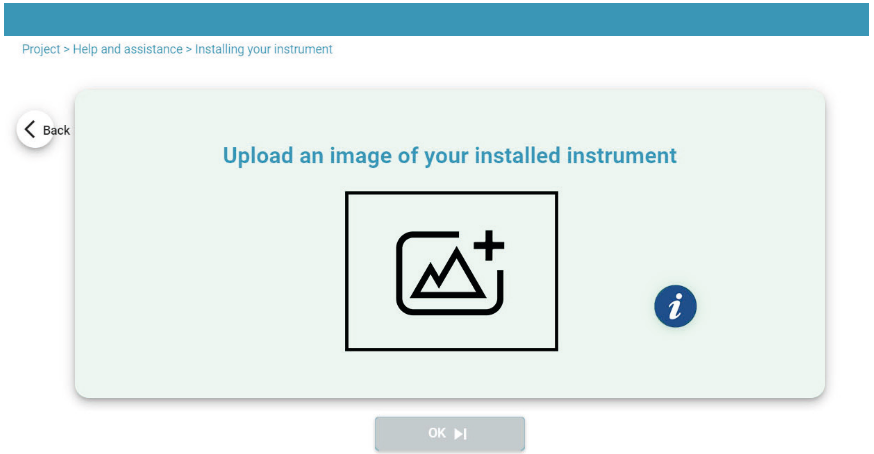


fig. 154 *Possibility to upload images in a scalable way, desktop version inspired by Decizone (n.d.)*

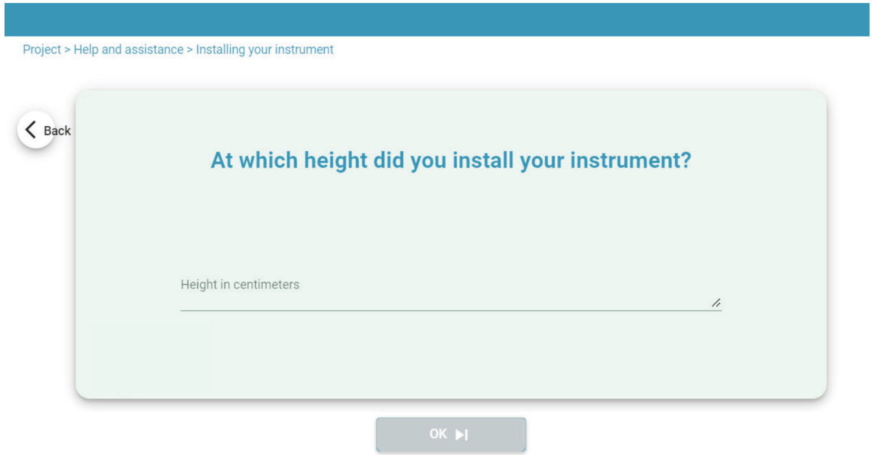


fig. 155 *Possibility to note information in a scalable way and implement mandatory steps, desktop version inspired by Decizone (n.d.)*

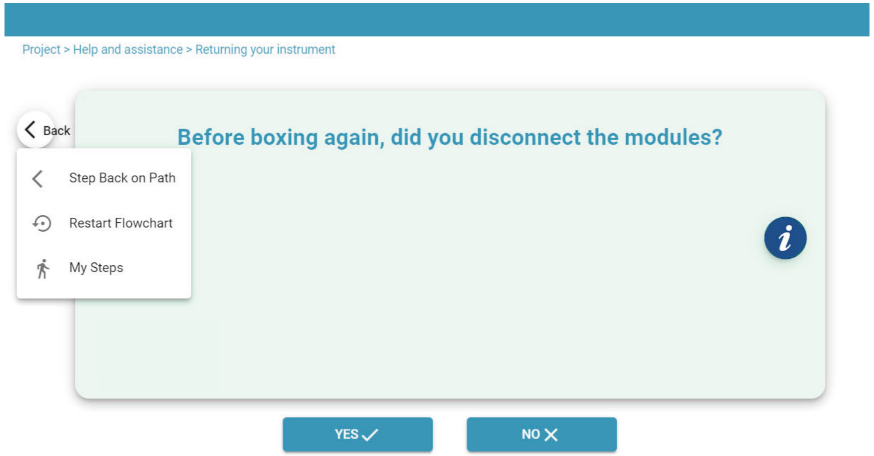


fig. 156 *Possibility to return to previous steps and the implementation of "info" icons, to give additional information or link users to external sources, desktop version inspired by Decizone (n.d.)*

5.10.2 Troubleshooting & repair assistance

The platform includes interactive troubleshooting functions to help participants diagnose and solve simple common issues themselves, such as faulty installation or lost connection. This enhances the system's scalability as there is no need for manual organizer intervention. For more complex repairs, instruments are sent to the distributor for safe repair or replacement, minimizing participant frustration.

5.10.3 Data visualization

Effective data visualization can significantly increase motivation by showing citizen scientists the impact of their contributions. Therefore, the platform includes a dashboard with graphs, timelines and other visualizations of real-time data in context. Offering comparisons between participants or areas and personalized data reports further increases engagement. To address educational needs, adding GIS map overlays allows users to explore results on their own.

Passive hooks, such as weather events, draw participants to the platform, while active personalized notifications can further boost engagement. For example, users can set custom conditional alerts, like a reminder to water plants if it has not rained for a week. These adhere to individual needs and enhance intrinsic motivation. Users may also browse recommended or community-created alerts.

5.10.4 Contact

The platform facilitates communication between participants and organizers, contributing to the friendly and approachable identity of a project and defragmenting communication by combining it all in one channel. Organizers can send notifications, information, and questionnaires, while participants can reach out through in-app contact options. Notifications can be made customizable, incorporating distinct designs to help convey different levels of importance or types of information.

Key insights: Embody

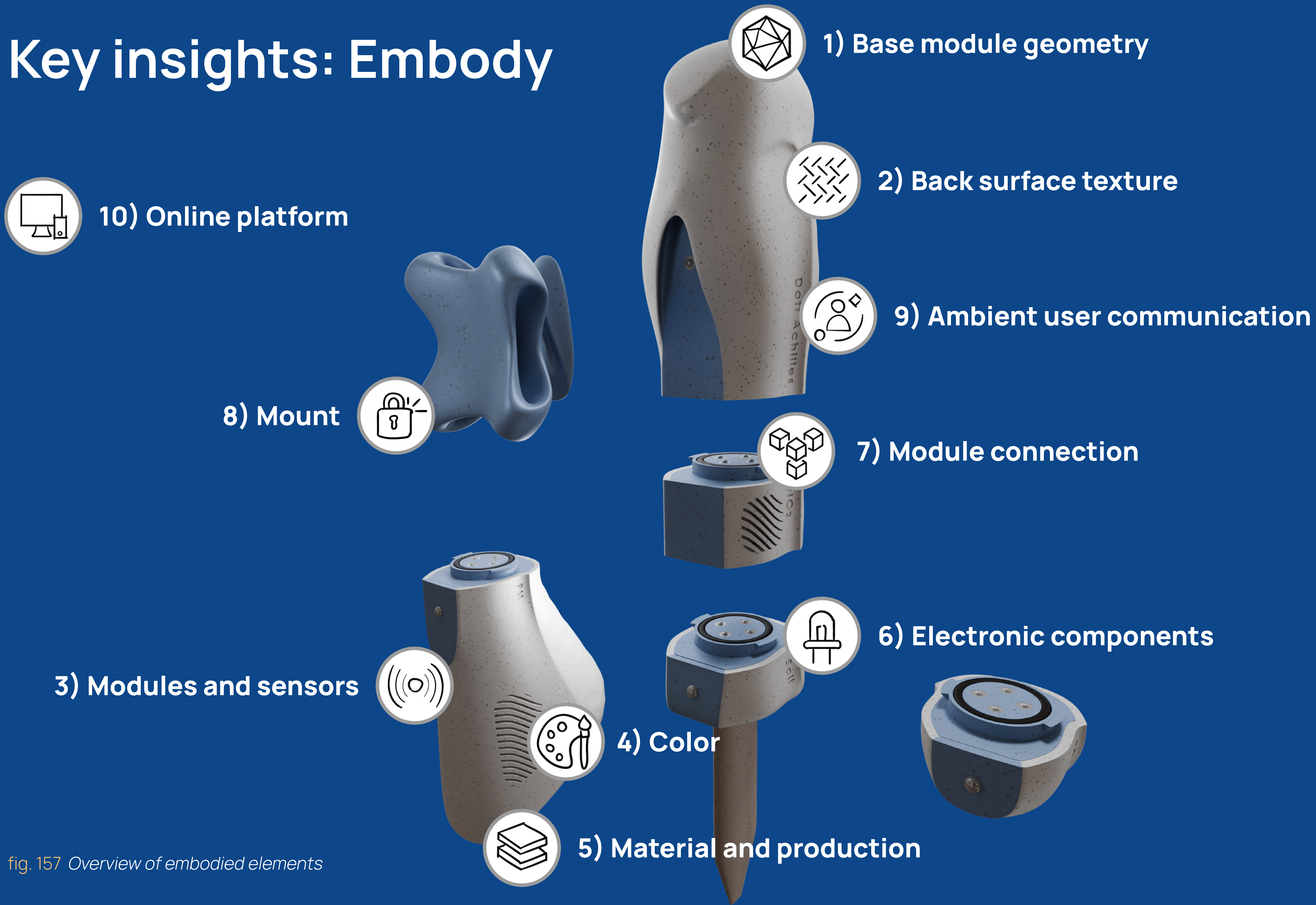


fig. 157 *Overview of embodied elements*

6 Validate

This chapter focuses on validating the product through user and expert evaluations conducted with a prototype. The insights gained from these evaluations are described, followed by recommendations to refine and optimize the final design.

6.1 Validation setup

Explains the objectives, methods and focus of the validation

6.1.1 Objective

Although this graduation project follows a holistic approach to developing a measuring instrument for citizen science, the validation phase primarily focuses on assessing usability, particularly the installation of the measuring instrument. This aligns closely with the overarching goal of enhancing participation and engagement in citizen science. Given resource and time constraints, evaluating installation usability is the most feasible and impactful aspect of the product system. Expert interviews will provide supplementary feedback on certain aspects of the product but are rather to inform than to validate, while other aspects will remain outside the scope of this phase. Feedback from both potential users and experts will be synthesized to evaluate the scoped requirements and inform recommendations for future product iterations. This validation therefore has the following objectives, as seen on the right.

Evaluate whether the proposed product features and interactive manual enable users to successfully install the instrument for air quality and drought monitoring.

Gather qualitative feedback on user experience and overall satisfaction.

Assess the extent to which the design meets predefined requirements.

Identify areas for improvement for future iterations.

Below (fig. 158), the requirements to be validated through the usability study with potential citizen scientists are shown in solid; those that can only partly be validated or are only evaluated through expert reviews are hatched; and requirements not addressed in this phase are displayed transparently. Those initially not included in the vision are excluded from the overview.

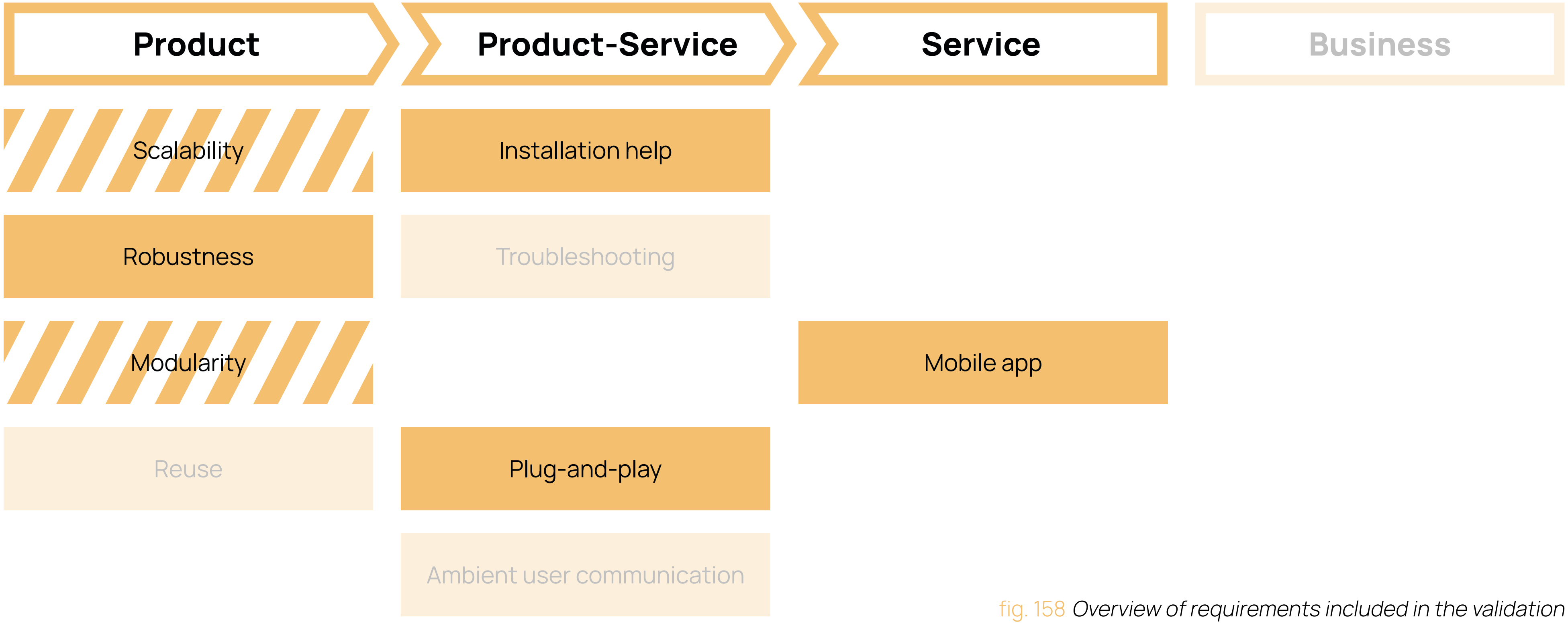


fig. 158 *Overview of requirements included in the validation*

6.1.2 Part 1: Usability study

Setup

Participants were recruited from the researcher's personal and professional network, ensuring diversity in technical expertise and familiarity with similar instruments. As citizen science is ideally accessible to all, no strict in- or exclusion criteria were applied.

Materials for the study included a physical prototype of the measuring instrument and a Wizard-of-Oz-style mobile app, simulating interactive feedback (see chapter 6.2).

The study was conducted in participants' own residential outdoor settings, including participants with and without gardens, to test installation in diverse locations such as soil, railings, and trees.

Data collection and analysis

The data sources used for analysis are observation notes, photos of participant interactions with the device, and transcriptions of interviews. A thematic analysis approach was used to identify recurring patterns.

No.	Worked with citizen science?	Worked with electronic measuring instruments?	Technical skills	Gender	Garden
P1	No	No	Less than average	F	N
P2	Yes (bird counts)	Yes (indoor CO2 meter)	Not really	F	Y
P3	Yes (ObsIdentify)	No	About average	F	Y
P4	Yes (bird counts)	No	Technical profession	M	Y
P5	No	No	Not really, average	F	Y
P6	No	Yes (indoor temperature and humidity sensor)	Technical profession	M	Y
P7	No	Yes (decibel meter)	Handy, but not with electronics	M	Y
P8	Yes (indoor energy use project)	No	Not really	F	Y
P9	No	No	Not really	F	N
P10	No	No	Technical background	M	N

fig. 159 *Characteristics of participants in the usability study*

Procedure Usability study	01) Introduction	02) Baseline questions	03) Usability task	04) Post-task interview

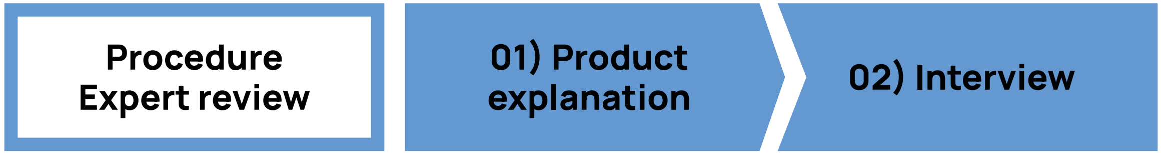
Participants are welcomed, and the purpose of the study is explained, after which written consent is obtained. Then, the concept of citizen science, the instrument's purpose, and its relevance within the context of citizen science are explained.

Participants are provided with the prototypes of the physical instrument and interactive manual. They are told that the task involves measuring air quality and drought, and they are instructed to install the device independently for the two scenarios, without external assistance.

Participants are asked to follow a think-aloud protocol, verbalizing their thought processes during the task. Significant events are noted, including difficulties with understanding instructions, physical challenges, errors, and deviations from correct procedures. Photos of installation attempts are taken for later analysis.

Before executing the study, participants' familiarity with citizen science, similar measuring devices, and technical skills is assessed with the following questions: (1) Have you participated in citizen science before? (2) What is your experience with electronic measuring instruments? (3) Do you consider yourself technically skilled?

A semi-structured interview is conducted to gather feedback on overall impressions, challenges, successes, manual clarity and usefulness, suggestions for improvement, and the device's design.



6.1.3 Part 2: Expert review

Setup

This part of the study involves two experts recruited through Dott Achilles' professional network; one of them is the client. Both have professional experience in the field and were previously interviewed during the discover phase, identified as E1 and E3 (detailed profiles can be found in chapter 2.2). They are provided with the instrument prototype and supporting documentation, explaining the functionality and rationale behind the design and development. The review is conducted one-on-one with the researcher.

Procedure

Experts are welcomed, introduced to the purpose of the review, and given an overview of the product's development, functionality, and design. Then, feedback is gathered through open-ended questions in an unstructured format, allowing for in-depth exploration of their insights. Focus areas include the feasibility of the design for real-world use, identification of flaws or areas for improvement, and suggestions to improve the product.

Data collection

Notes are taken on key insights during discussions and thematically analyzed to identify recurring themes or actionable recommendations.

6.1.4 Limitations

The validation phase is subject to several limitations that impact the generalizability of findings. Most significant is the small sample size of the usability test. Also, the limited number of experts resulted in feedback rather than true validation. However, as the client is included among the experts, their input still provides a valuable perspective on the product's functionality. Another limitation is the use of aesthetic prototypes rather than fully functional instruments, which may affect evaluation of the product. The selection of participants is subject to bias, as the potential users were recruited from the researcher's network. Lastly, the researcher's presence during usability tasks could have influenced participants' responses.

6.2 Prototype

Introduces the prototype used in the usability study

Two prototypes were developed to support the validation objectives: a physical model of the measuring instrument and a Wizard-of-Oz-style mock-up of a mobile app incorporating the interactive installation manual.

6.2.1 Measuring instrument model

The first prototype provides a tangible representation of the device and its physical functionality, allowing participants to interact with it. It is tailored to the specific aspects being validated; therefore, it does not contain any electronics but solely focuses on the instruments' aesthetics and interactable features. These include the texture on the back, colors, module connections, and mechanisms for guiding and feedback. As it offered embodiment early on in the design process, it is iteratively developed throughout the project.

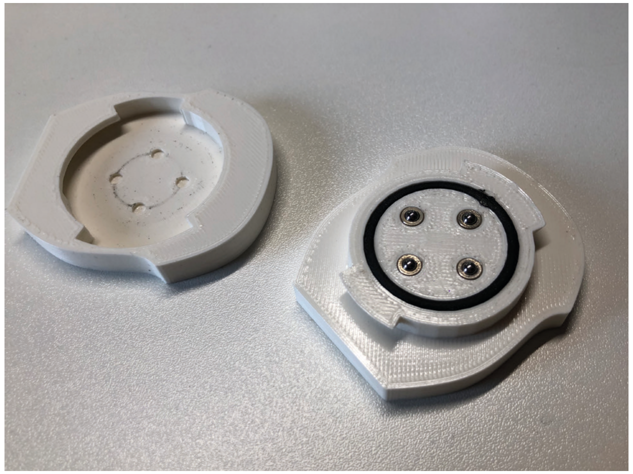


fig. 160 *Early module connection mock-ups*

fig. 161 *Iteratively exploring dimensions and features using 3D prints*

fig. 162 *First 3D print, produced using SLS*

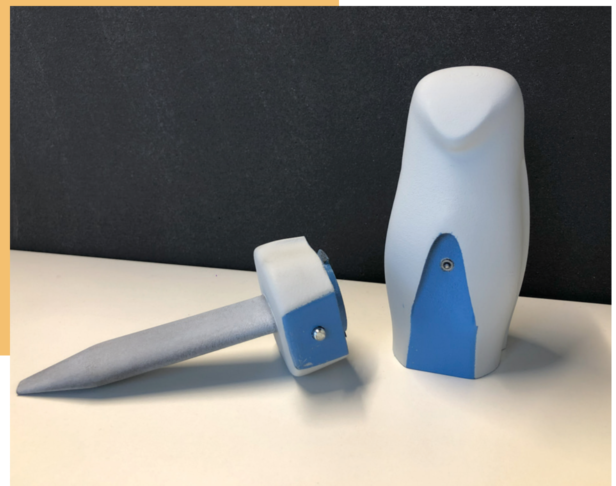


fig. 163 *Prototype used in the usability study, disassembled, mounted in soil, and on a railing*

6.2.2 Mobile application mock-up

The second prototype is used alongside the physical measuring instrument and simulates proposed app functionalities related to installation, such as breaking instructions into smaller, manageable steps; providing instant feedback; showing corresponding media; using the phone's features to assist in installing; and offering access to additional information. The mock-up consists of an interactive PowerPoint presentation that is adapted to a mobile phone to allow participants to experience the intended functionality realistically. For the complete sequence refer to Appendix G.

fig. 165 *The compass included in the manual*

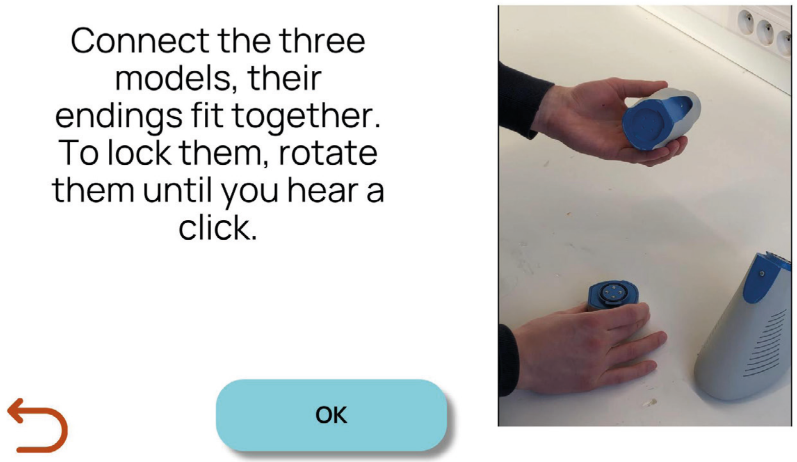


fig. 164 *Step including a video how to connect the modules*

fig. 166 *Simulation of a mobile app incorporating an interactive manual*

6.3 Results

Synthesizes the validation insights and how they relate to the requirements

6.3.1 Usability study insights

Participants appreciated the robustness and weight of the instrument, though the size of the PM module was sometimes seen as a drawback
Out of 10 participants, 9 assessed the instrument to be robust. One participant (P7) expressed concern about potentially damaging the instrument, while another (P3) doubted the robustness of the colored coating. P2 particularly highlighted the soil pin's sturdiness. However, the PM module was noted to be too large, feeling unbalanced (P7), visually unappealing in the garden (P5), and 'too heavy' for the relatively small mount (P1).

Design features and visual cues worked well to guide assembly in general but less successful for actual module connection
Participants P1, P3, P5, P6, P7, and P9 highlighted the effectiveness of matching blue colors for module placement. Some participants explicitly noticed the directional cues of the bayonet lock (P3, P4, P7, P10), others relied on trial and error (P8) or failed to recognize the cues initially (P04, P07). Suggestions for improvement included adding explicit alignment markers, similar to those in camera systems (P4, P8). All participants were trying to connect the modules through rotation, but no one managed to connect them without at least a few tries, indicating that more efforts can be done to make the connection self-searching.

A straightforward interpretation of the design aesthetic was absent, with participants interpreting the shape in various ways
While 4 participants (P1, P2, P3, P4, P10) described the instrument to look like a bird or penguin, other interpretations included a stone (P6), a bone (P9), a dinosaur or elephant leg (P7), or purely functional with no symbolic meaning (P5, P8). P7 said, "I'm thinking in terms of animals because of the organic shape." This shows that the shape is abstract enough for people to see different things, but it does not universally evoke the feeling of identity.

Correct feedback that corresponds with an expected interaction was proven to be very important for user confidence
Even though participants generally found module connection easy (explicitly mentioned by P1, P2, P5, P6, P9, P10), several emphasized they were confused when not hearing a "click", despite this being mentioned in the manual (P2, P3, P4). Additionally, participants experienced the PM module being too tough to install (P1, P3, P7, P9). Though this is an unintended effect of the prototype's quality, the result when it is not functioning as intended is remarkable.

Mounting the instrument in soil was effortless, but hanging it was slightly more challenging, particularly because of the inconvenient tie-wraps

Participants reported that pushing the instrument into the soil was straightforward; however, mounting for air quality was more challenging, particularly because of the use of tie-wraps (P1, P2, P3, P6). It led to some participants experimenting with diagonal mounting (P1, P9) or creating less sturdy installations (P2, P8, P10). P1 and P2 asked explicitly for more examples in the manual that show various mounting techniques. Despite these challenges, P2 noted that the adjustable length of the tie-wrap was a useful feature since it would fit various contexts.

fig. 167 *A participant pushing the instrument into the soil*

fig. 168 *A participant pushing the instrument into the soil*

fig. 169 *Participants creating less sturdy installations*

fig. 170 *A diagonally mounted instrument*

Most participants reported being confident in installing the instrument correctly, even if this was not the case
Except for P2 and P6, all other participants were confident they had installed the instruments correctly. However, for P4, P8 and P9, their orientation was incorrect. Steps in which the users were asked to confirm aspects were mentioned to be valuable, with P02 and P04 explicitly mentioning the possibility to check their actions. P04 for instance, corrected an error after identifying a discrepancy between the reference image and the instrument (fig. 171).

Using an interactive manual that combines text and media was appreciated, despite varying opinions
The interactive manual received positive feedback overall. Participants appreciated its simplicity (P1, P3, P6, P7) and its visual media (P2, P3, P4). P6 said, "the interactive manual works because it is harder to skip steps, and you can do it at your own pace. With IKEA manuals, you sometimes have leftover screws at the end". Five participants found the amount of text too much (P2, P4, P5, P6, P7), with P2, P4 and P6 explicitly preferring videos, while others (P5, P6, P8) mentioned to prefer the text being included, allowing them to read at their own pace. Participants P3, P5, P7 and P8 suggested partially hiding (additional) information to improve readability. Suggesting it is useful to incorporate various approaches to reach the same goal.

While product features helped to orient instruments, even with a supporting manual, orientation can be difficult — Participants oriented the instrument using the pointy "beak" (P2, P4, P7, P8) and colors (P2, P5). However, while the orientation of the instrument itself was clear, using this to correctly install the instrument in context was more difficult. No participants were struggling with installation in soil, but hanging it away from the sun was challenging (P1, P4, P5, P6, P8, P9). Additionally, the use of indoor reference images led some participants (P1, P3, P9) to believe the instrument should be installed indoors, which stressed the importance of appropriate reference images.

fig. 171 *The moment right before the participant noticed a mistake*

fig. 172 *A participant sucessfully mounting the instrument*

6.3.2 Expert review insights

Engagement and user experience

Both E1 and E3 view the instrument as fitting well in the citizen science domain, with E3 stating, "It has everything I was searching for in an instrument." While both recognize its ease of installation and user-friendliness as key strengths, E1 noted that automating tasks (e.g., during installation or measuring) also reduces tasks to be executed by users. Although this can lower the barrier for potential participants, it may reduce engagement among participants that seek more active involvement. E3 shared this concern, similarly experiencing participants that want to take on more tasks in current projects.

To address this, both experts suggested incorporating a layered engagement approach: offering a low barrier for initial involvement while facilitating users to take on additional responsibilities. This could include becoming an ambassador for the project, organizing or informing others, or using tools for deeper exploration of the data. This could attract participants but also sustain engagement on various levels.

Modularity and adaptability

The instrument's modular design was valued for its flexibility, but both experts identified limitations. E3 highlighted that NO2 modules cannot be combined with soil modules due to differing installation requirements, with the NO2 modules needing placement at a height of 1.5-2 meters, requiring the use of multiple instruments.

Both experts highlighted challenges with continuous measurements, such as those for sound, which require more frequent measuring intervals, higher data rates, and increased power consumption, demanding grid power and enhanced data modules. Further investigation is needed to make data and power components interchangeable or modular as well.

Additionally, E3 stressed the need of developing additional mounts, such as those for window sills, to enhance the instrument's applicability. The current mount profile was deemed suitable to do so.

Scalability

E3 suggested that renting instruments could significantly reduce costs and enhance scalability. However, ensuring connectivity and streamlined application would require the involvement of an IT specialist, a responsibility proposed to be managed by the distributor.

E1 noted that generalizing the instruments risks excluding users that prefer discreet designs. Additionally, dedicated designs often build a reputation for being reliable in specific applications. To build credibility and scalability, E1 suggests targeting researchers and local governments, as they are key decision-makers in choosing such instruments.

6.3.3 Evaluation of requirements

In fig. 173 on the next page, the requirements to be validated through the usability study with potential citizen scientists are shown in solid; those that can only partly be validated or are only evaluated through expert reviews are hatched; and requirements not addressed in this phase are displayed transparently.

Robustness: Met
Participants agreed that the instrument was physically robust, considering it is still in a prototype phase.

Installation help: Mostly met
The interactive manual was positively received, particularly for its combination of text and media and easy-to-use step-by-step guidance. While participants felt confident in installing the instrument, errors in some cases suggest room for improvement in refining the steps and incorporating preferences for text and media.

Plug-and-play: Mostly met
Design features, visual cues, and incorporated feedback helped to guide participants effectively in reaching their goal. However, further refinements can optimize usability for the module connection.

Mobile app: Mostly met
Though few mobile app functionalities were validated, its added value effectively supported participant tasks, for example, for interactive installation.

Scalability: Evaluated to be met
Due to limited validation, compliance with the scalability requirement cannot be fully assessed. Nonetheless, introducing the instruments in practice to increase scalability was evaluated as promising by experts, particularly by the client.

Modularity: Evaluated to be mostly met
Due to limited validation, compliance with the modularity requirement cannot be fully assessed. Nonetheless, participants were mostly able to install the instrument for two different scenarios. However, custom fastening methods, such as tie wraps hindered participants when hanging the instruments on railings and trees, highlighting the need for a dedicated trap to enhance modularity. Although facing some challenges for actual implementation, experts evaluated the instrument's modularity to be promising.

Troubleshooting: Not validated
The practical implementation of this requirement overlaps with interactive installation help and was therefore not validated in this scope. Future development of actual instructions has to be validated.

Reuse: Not validated
Long-term validation of real instruments is required to validate actual reuse of instruments. Current prototypes do not support this type of evaluation.

Ambient user communication: Not validated
Validation of this requirement involves real-world settings, consulting ambient users to assess communication effectiveness.

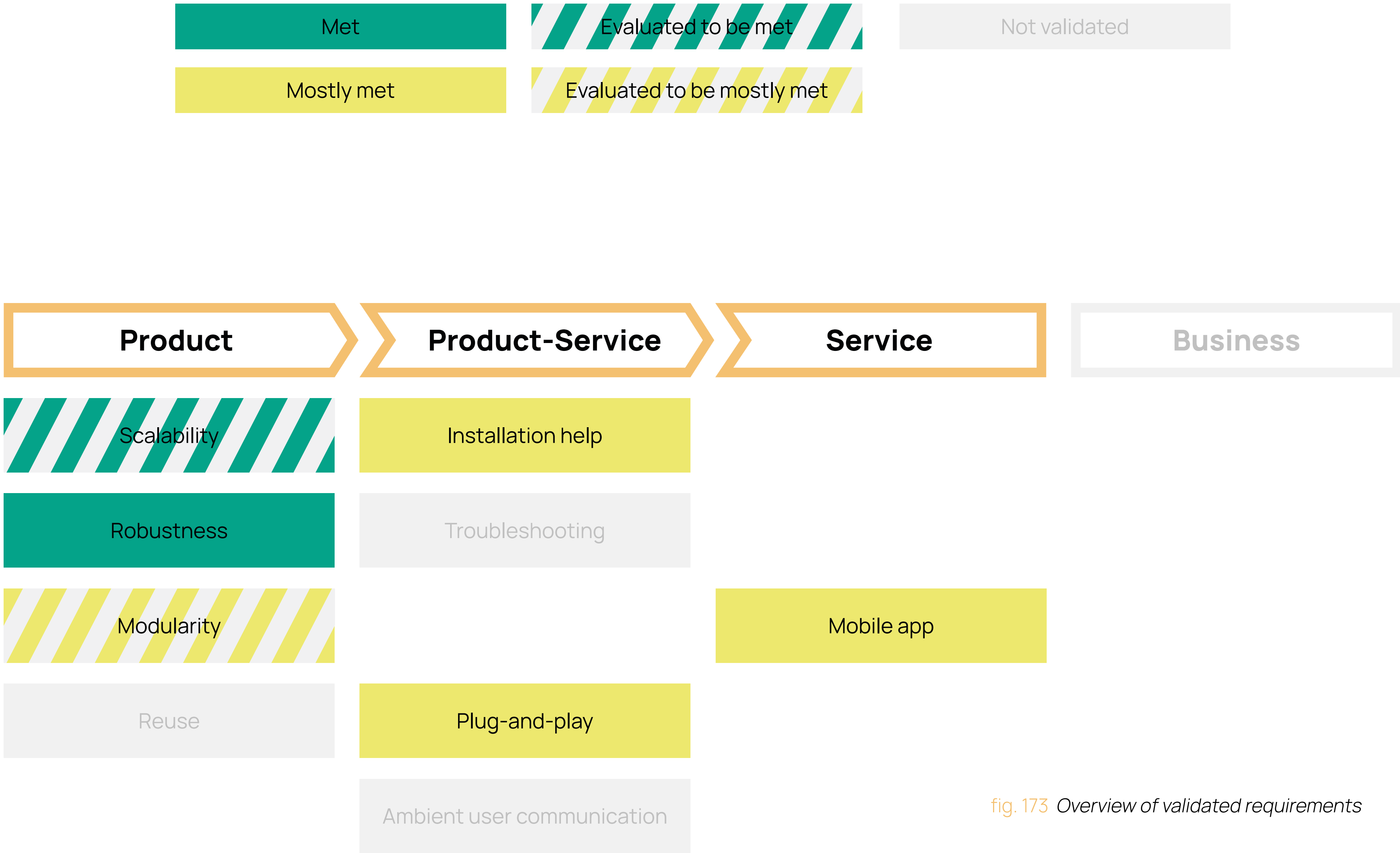


fig. 173 *Overview of validated requirements*

6.4 Recommendations

Listing recommendations for future steps and implications

STEP 1

Immediate improvements to the prototype and product

- Refine the bayonet lock mechanism to make it more guiding, self-searching, and intuitive
- Design a dedicated strap mechanism with an adaptable length to fasten the instruments
- Refine installation instructions for citizen scientists (e.g., show more possible fastening methods)
- Develop a windowsill mount

STEP 2

Further embodiment and field test validation

- Develop the interior of modules and techniques to produce them
- Investigating watertightness of connections
- Investigate the integration of calibration for sensors
- Test the connectivity of instruments
- Investigate sensor installation requirements together with researchers
- Investigate standardized data protocols and data formats together with researchers
- Investigate how long sensors and modules will last
- Investigate the modularity of data transmission components
- Investigate robustness of materials in real-world contexts over longer use
- Scale usability tests to longer-term field tests with a larger sample in different weather conditions
- Investigate an end-of-life recycling plan to support sustainability

STEP 3

Expanding functionality and accessibility

- Develop a mobile app
- Develop a dashboard (including functionalities and tools to improve content quality for citizen scientists)
- Develop layered engagement in the online platform for citizen scientists
- Develop new modules and sensors
- Develop a grid-power module

STEP 4

Long-term scalability and sustainability

- Create a marketing strategy introducing instruments into the field
- Increase diversity, for example, by investigating accessibility options such as text-to-speech
- Create a viable business model

Key insights: Validation

This validation chapter evaluates the usability of the measuring instrument prototype, with a particular focus on its installation process. It aims to determine whether users can successfully install the instrument for air quality and drought monitoring using an interactive manual. Expert feedback complements this validation, offering additional insights into product functionality and areas for improvement.

A usability study was conducted with ten participants of varying technical expertise. Using a physical prototype and a Wizard-of-Oz-style interactive manual simulating interactive feedback, participants were asked to install the instrument independently in outdoor settings while following a think-aloud protocol. Data was collected through observation, photos and post-task interviews, providing insights into user experiences, challenges, and suggestions for improvement.

Expert reviews highlighted the instrument's potential within the citizen science domain, emphasizing strengths such as ease of installation and modularity. However, challenges related to continuous measuring and sensor placement were identified. The findings from both the usability study and expert feedback stressed the need to further refine the installation process and improve product features.

The chapter concludes with recommendations in four stages: (1) immediate improvements to the prototype and product; (2) further embodiment and field testing; (3) expanding functionality and accessibility; and (4) long-term scalability and sustainability. These steps will guide future development to optimize its functionality and make it ready for widespread use in citizen science.

Final result

Outlines the final result of this graduation project

The final design of the citizen science measuring instrument represents the project result of a modular, scalable, and user-friendly product-service system. Designed to enhance citizen science engagement while adhering to its core principles, the system combines a physical measuring instrument with an integrated online platform. Together, they aim to expand citizen science applications and broaden their societal and scientific impacts.

Central to the design is a robust, modular measuring instrument capable of adapting to diverse research contexts, from urban balconies to rural gardens and public parks. The instrument incorporates customizable sensor modules and diverse mounting options, allowing deployment in soil, on tree trunks, and on railings (fig. 174). This flexibility ensures accessibility for citizen scientists from diverse backgrounds while promoting reuse across multiple projects, enhancing sustainability. As a result, it supports alternative financial models, such as rental systems, reducing reliance on short-term funding and making the system more accessible to resource-constrained organizers.

fig. 174 *Typical rural and urban installation contexts*

The instrument prioritizes usability through the integration of 感性デザイン (Kansei design), which guides users intuitively in interaction. Features such as color-coded connectors (visual feedback), textured back surfaces (tactile feedback), and click sounds upon secure attachment (audio feedback) create a plug-and-play system (fig. 175). ポカヨケ (poka-yoke) principles further simplify interaction by ensuring that mounts and modules can only be assembled in the correct way, eliminating errors during setup. These elements make the system accessible to both citizen scientists and local organizers, regardless of their technical expertise.

The aesthetic design of the instrument balances stylization and abstraction, creating a product that is visually appealing, approachable and friendly, while abstract enough to fit a wide range of users and aesthetically adapt to diverse contexts. While speckled material enhances its aesthetic compatibility with natural and urban settings, it also camouflages minor damages, ensuring long-term reuse and durability (fig. 175). The design language explicitly communicates the instrument's functionality: for instance, temperature sensors and air inlets are visibly marked to clarify their purpose to participants while simultaneously informing and reassuring ambient users (fig. 177). This transparency aims to enhance trust and acceptance, addressing potential concerns about the instrument's role and data collection.

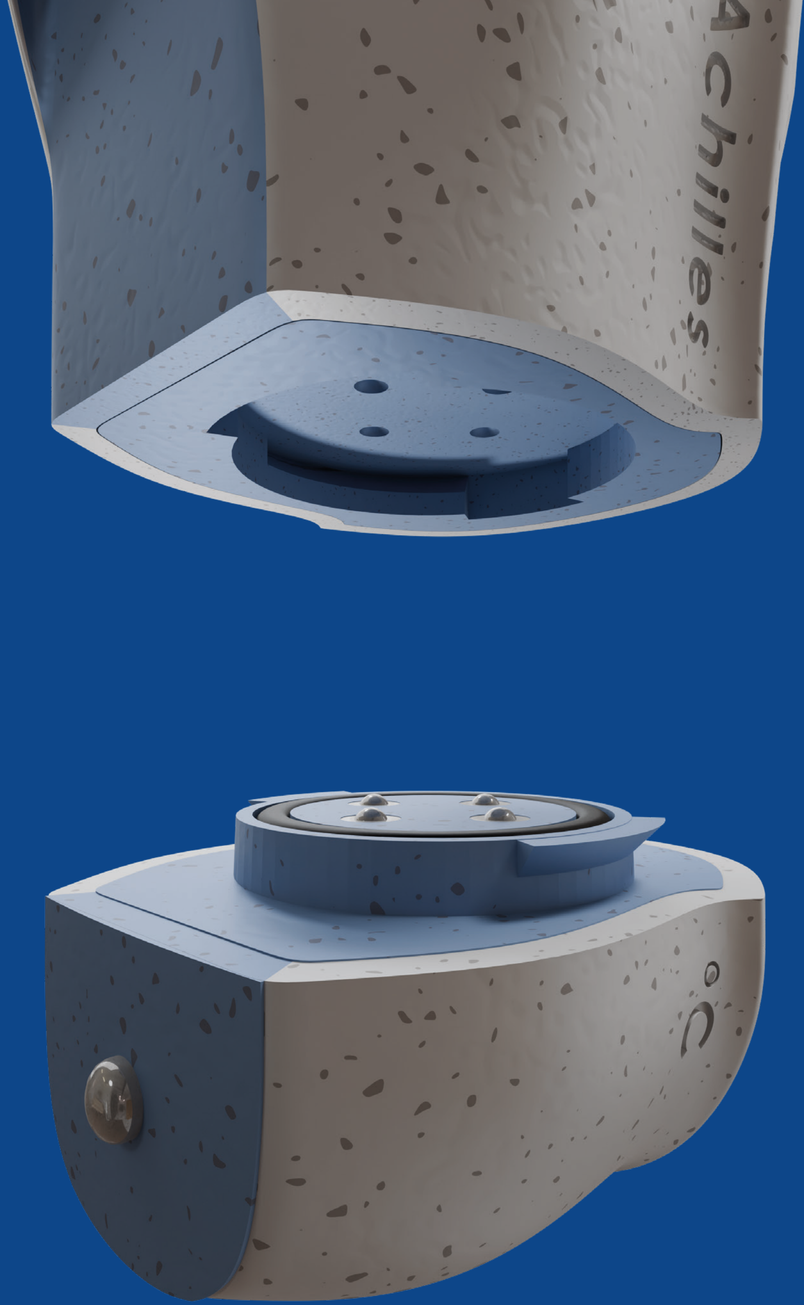


fig. 175 *The module connection, in speckled material, incorporating visual, tactile and audio feedback,*

An online platform, accessible via desktop and mobile applications, complements the physical instrument. The platform provides participants with real-time data visualization, tools for comparing and exploring data, and personalized feedback to recognize participants' contributions and sustain their motivation. Interactive installation and troubleshooting aids further enhance usability and scalability, for example, allowing participants to upload photos of installed instruments or to use phone sensors to assist in optimal placement (fig. 176). These features reduce the workload on organizers while supporting participants to confidently install, maintain, and use the instrument.

This final product addresses critical challenges faced by current citizen science initiatives through design. It creates a system that empowers citizens and supports local organizers, enhancing participation in citizen science and maximizing its scientific and societal impact.

fig. 176 *Interactive manual that makes use of the phone's sensors to assist in optimal placement*

fig. 177 *Overview of preliminary idea's instrument structure*

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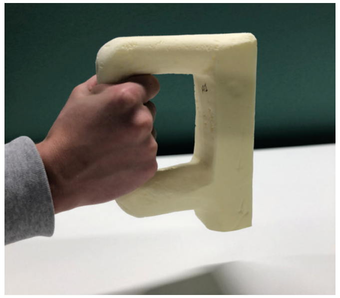
Appendices

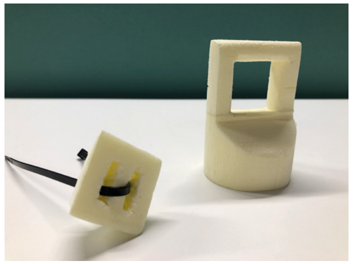
Appendix A

Concept development foam models

A1)

- Bulky thing
- No interesting shape, straightforward and blocky
- Is comfortable to hold, for pushing into the ground it is probably good
- There is a lot of space for components
- Not quite aesthetic
- Communicates a clear shape
- Flat side makes sure it fits a wall well, is quite intuitive
- Probably slides easily with regard to mounts
- Very large, a lot of geometry you don't use
- The idea of a grip is good, but has to be more integrated

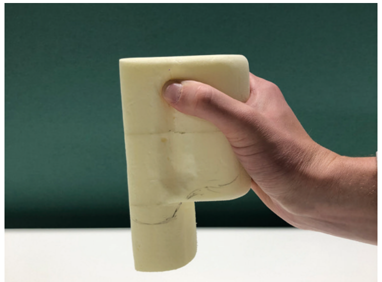



A2)

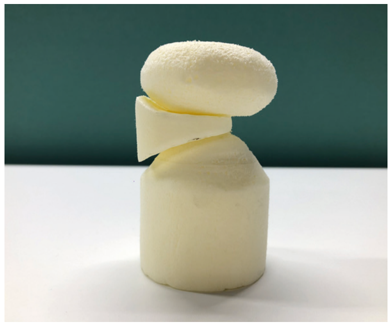
- Still somewhat bulky
- More suitable for pulling than pushing
- Function conveys well
- Mount feels more like and unintended attachment
- This would be more aesthetic when rounded
- Will not be supported against the wall and hang slanted
- Is very symetric, maybe problematic when orienting the thing
- Is scalable, can be smaller to fit a finger or larger to fit a hand
- A12 is more aesthetic compared to this one, more organic and better fits the garden context.
- Feels farfetched
- Idea that it works in the garden and with an attachment in other contexts is nice


A3)

- Rounded feeld better in the hand with more gip
- Still feels bulky
- Very clear what the function is, pressing down is intuitive
- Quite simple, not very wlel integrated
- Questionable whether this would look pretty in the context
- Volume allows to fit components in
- How do you hang this thing?
- To much focused on 1 interaction, giving problems with other mounts
- Idea that you can pull and oush easily is nice

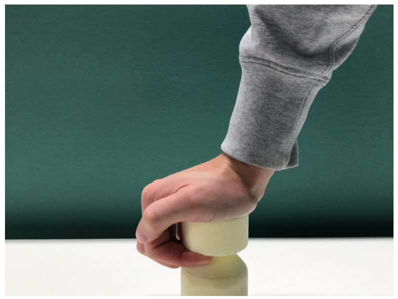



A4)
- Grips can be larger, not sure if the hole for the thumb is useful because you do not need that much power
- Nice integration of the grip
- Can be streamlined further
- There is a clear orientation and space for a mount feature
- Interior space is very efficient, no weird corners etc.
- Is not quite as ergonomic as intended, size of the holes might change
- Grip that is integrated is easier to manufacture
- Maybe make the holes closer to the palm of the hand, too large now
- Flat top helps to push into the ground
- Flat front side can be made matching with a mount f.e.
- More organic form would prabably better fit the garden. But maybe changing color and texture can be deviating enough to make it a product that can start a conversation




A5)
- More extended possibilities to grab compared to A4, which allows only to hold in 1 or 2 directions. Also push with fingers or hands etc.
- Not a very interesting shape, quite simple, does not intrigue
- Mount is very intuitive, maybe work with a color band that matches with the color of the mount.
- Mount can be clicked, possibly with extra fastening
- Can be made such that it fits a straight wall
- Possibilities for other mounts as long as they have the circular shape
- Interior up in the shape is limited due to small connection in the middle
- Thicker connection might make it more robust
- Use of mount is little effort, it is the same shape
- Mount does not really fit form family, is a separate shape now, maybe they can better fit together
- No orientation of the instrument

A6)
- A6 feels more powerful, able to exert more strength with fingers because they 'stick' better
- Very easy to use when pushing
- Maybe look at the dimensions to make it more comfortable for fingers
- Mounts are more aesthetically pleasing as they will fit seamlessly.
- A bit rougher compared to A5, but also looks more robust
- No orientation of the instrument

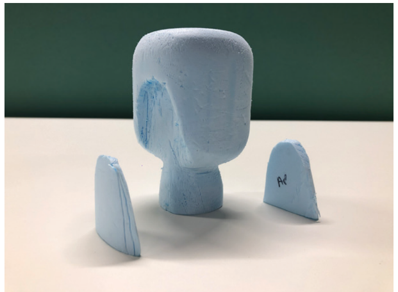



A7)

- No orientation of the instrument
- Asymetric, also in pulling
- Simple design, feels like a walking cane, but organic
- Might not be the most useful shape, interior wise
- Would suit the garden, more interesting shape compared to A6 for example
- Focuses more on pushing and pulling, is not so easily mounted to other things

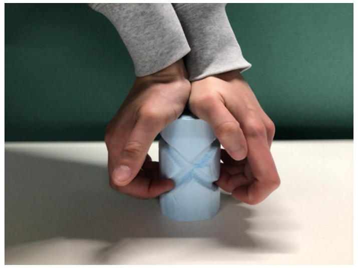

A8)

- Shapes are very recognizable, and obviously fit in the holes
- It has to be fastened, that is not so obviously done now, because they loosely hang in there now
- A grip can be designed to only attach when it needs to be removed from the soil, but has to be developed separately.
- Interesting shape
- No orientation currently



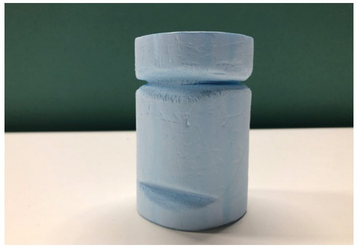
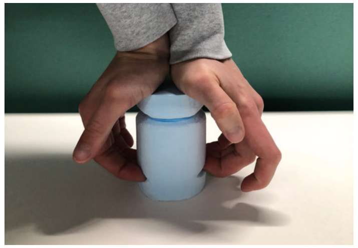
A9)

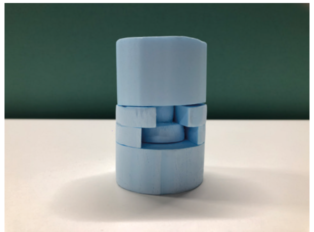
- A shape that offers a certain affordance for finger grips. Also offers possibilities to attach different mounts.
- More of a general feature that has multiple functions
- With a better integration, this would be an interesting non-everyday shape
- Can converge a bit more, making it more dynamic
- Isn't this hard to make watertight?
- Mount can be something like a cross that falls exactly inside, which makes it easier to hang it.

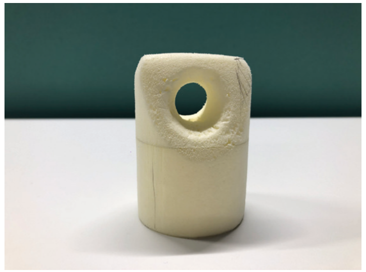
A10)

- Mount can be something like a cross that falls exactly inside, which makes it easier to hang it.
- The aesthetic version of A9
- Simple and quite symmetic, has little orientation, might be hard when fastening the shape.
- Hanging it can be hard, it especially with loose cables

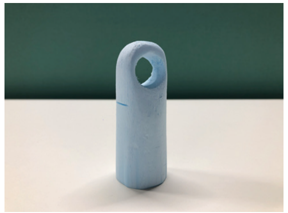


A11)
- Clear what needs to happen
- Mount is robust, especially when it clamps or clicks
- There are possibilities to change to only let it fit in one way
- Shape is not necessarily compact and simple
- Very straightforward and clumsy, not aesthetic.



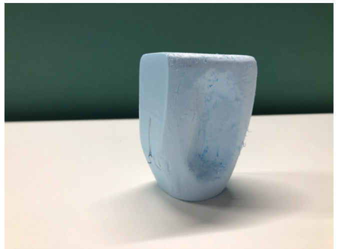
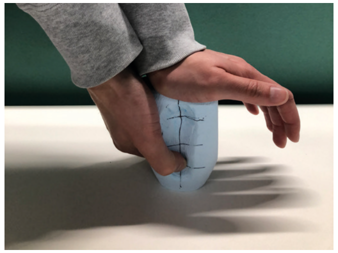
A12)
- Shape is robust
- Clear how to interact with it, pulling with a finger, not sure if a finger is strong enough to pull the shape from the soil
- Simple straightforward shape
- Not really a connection for other mounts, except using spheres that for example locks in the ring
- Is this something to put in the garden? Maybe yes
- Mounts are easier than for A13 and A14, because this one is still kinda summetric
- Maybe dents on the side to offer more grip when inserting

A13 & A14)
- Mounts are harder to realize because they don't really fit the organic shape and the instrument will probably slant when hanging.
- Both are inutive, it is clear how to interact with them
- A13 looks less robust than A14, both less than A12
- Better to have slightly larger shapes, to appear more robust

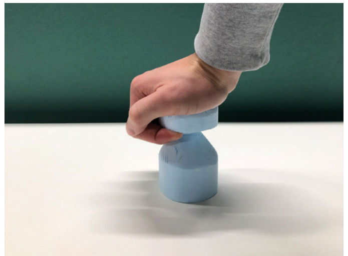


General findings
- Does not have to be large to be robust
- Don't make features too small for electronics
- Integrated grips can make interesting shapes and limit product complexity
- Useful when there is asymmetry or if the product has a direction to orient it, so prevent overly rounded shapes
- Explicit handles or grips are overkill, grips should be integrated more
- A full hand is too large for the instrument, better design for finger grips
- Idea that a product has a feature that works in the garden and with an attachment transforms into a hanging variant is nice
- Pulling with fingers and the top of the instrument should remain flat to press it into the ground.

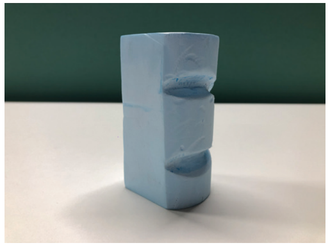
Iteration two
- A4 but one that is compacter and with a deeper grip
- A6 with a more rounded top
- A9 but with deeper holes, a direction, and a way to attach a clamp
- For A12 focus more on the grip to be pushable, and is more comfortable in the hand, also think about specific orientation

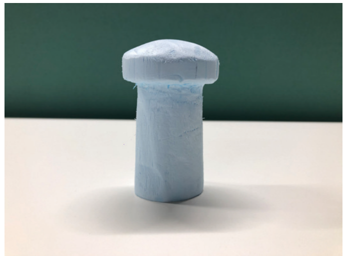
B4)
- Shape more natural than A4 and more compact
- Shape cut is maybe a bit random
- One can shape the grip itself, letting it point in a certain direction

B9)
- Shape cut is a bit random to give direction
- Being a bit smaller is not necessarily more robust
- With this material and a rope, the isntrument is not tightly fastened, maybe including other materials it does
- Rounded cutouts give more hold compared to the sharp edge
- Top can converge to show what the front side is



B7)
- Top can converge to show what the front side is
- Does not feel more robust, maybe fillet should be smaller
- More organic, better




B12)
- More comfortable compared to the first iteration
- Hard to make a shape from this, especially one that gives direction to it
- Still hard to make a mount for it, easily feel pasted on there

B15)
- More organic
- Looks a lot like a mushroom, fits in the garden, but is overly explicit, also can not be hanged because of that

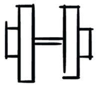
Appendix B

Sensor exploration

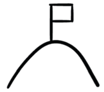
Sensors were selected from a list of available citizen science sensors, published by the Flemish government (Agentschap binnenlands bestuur, n.d.), and evaluated using six key criteria.

1) Context applicability – The most important parameter: the sensor must provide meaningful insight into air quality and drought.

2) Power consumption & data rate – Power efficiency is key for battery life. Factors such as measuring intervals, on-sensor data processing and data transmission size determine energy use. Sensors with high data output or energy consumption, such as cameras, are unsuitable.



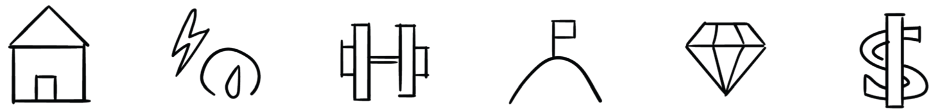
3) Robustness – Sensors must be durable, low-maintenance and reliable.



4) Scalability – Only automated active sensors are suitable; passive sensors, like Palmes tubes, that require manual tasks are excluded.

5) (Scientific) Value – Citizen science sensors may not always prioritize scientific precision, but preferably provide as useful data as possible. Two factors are considered: the value of citizen measurements compared to professional sensors, and the relevance of local measurements versus regional ones.

6) Price – While cost is less important, extremely expensive sensors are unsuitable for an affordable, long-term instrument.



SENSOR	1	2	3	4	5	6	All
Touch	red	green	orange	green	orange	orange	red
Distance	orange	green	green	green	orange	green	red
Atmospheric pressure	red	green	green	green	orange	green	red
Movement	red	green	green	green	orange	green	red
(Soil) temperature	green	green	green	green	green	green	green
Soil moisture	green	green	green	green	orange	green	green
CO (carbon monoxide)	red	green	green	green	red	green	red
CO_2 (carbon dioxide)	red	green	green	green	orange	orange	red
Water flow	red	green	orange	green	orange	green	red
Decibel	red	green	orange	orange	orange	orange	red
Light intensity	green	green	green	green	red	green	red
Location	orange	green	green	green	orange	green	green
Humidity	red	green	green	green	green	green	red
NH_3 (ammonia / air pollutant)	green	green	green	red	red	orange	red
NH_4^+ (ammonium / water pollutant)	red	green	orange	orange	orange	orange	red
NO (Nitric oxide / air pollutant)	red	green	orange	orange	red	orange	red
NO_2 (Nitric dioxide / air pollutant)	green	green	green	orange	orange	orange	green
NO_3 (Nitrate / ground pollutant)	red	green	orange	orange	orange	orange	red
O_3 (Ozone / air pollutant)	green	green	orange	orange	red	orange	red
Passage count	red	green	green	green	red	green	red
PH-value ground	red	green	orange	orange	orange	green	red
PM 1 / 2.5 / 10	green	red	orange	green	orange	orange	green
SO_2 (Sulfur dioxide / air pollutant)	green	green	orange	orange	red	orange	red
Wind direction	orange	green	red	orange	red	green	red
Wind speed	orange	green	red	orange	red	green	red

Touch
Can be either a physical button or capacitive touch. They are not really required to investigate the context, they are at best there to support other sensors. Their power consumption is very low; can be made robust, but are also prone to failure if physical; don't require additional effort; are accurate and can be very cheap on their own but might require casing redesign.

Distance
Can for example be ultrasonic or inductive. They use limited power if they don't have to measure continuously. They are robust as long as they are protected within the instrument's casing and do not require additional effort and they are a few euros off-the-shelf (Tinytronics, n.d.-i). They are not really valuable in measuring the scoped context, however, they might be valuable in automating the measuring process. For some sensors it might be important to know how far they are located from other objects to take measuring uncertainties into account, for example for temperature sensors.

Atmospheric pressure
Digital barometers are small and only a few euros off-the-shelf (Tinytronics, n.d.-c). Their impact on measuring the desired context is questionable, on the contrary they are very accurate (+-0.5 hPa) and often combined with humidity and/or temperature sensors (Tinytronics, n.d.-b). Since they are digital they are very robust and can easily be implemented. The data output is simple and energy consumption low.

Movement
Often a pyroelectric infrared motion (PIR) sensor (Tinytronics, n.d.-e). It is only a few euros off-the-shelf; has a very low working current (15 μA); simple on/off data output; and is active. However, it doesn't really contribute to getting insight in the context.

(Soil) temperature
Temperature sensors are excellent to investigate the context. In benchmark product was seen that temperature can differ locally and is used to investigate dryness and urban heat islands. The 'Samen Meten' dashboard similarly measures temperature (RIVM, n.d.-b), which is a governmental platform for sharing environmental data collected through citizen science initiatives.

They can also come in waterproof versions; have simple data output; are completely passive and only consume energy when they are powered to read them (Tinytronics, n.d.-g). They are very robust and can be implemented in various ways and also very cheap, only 1-2 euros off-the-shelve. They can have an accuracy of around 0.0625 °C (Tinytronics, n.d.-b). The only challenge is that, to measure actual temperature, the sensors shouldn't be affected by direct radiation from the sun, or conduction by the heated element. Therefore they are often housed in a Stevenson screen (Barani, n.d.). Whether this is possible in practice is questionable, therefore the instrument should prevent this as much as possible, for example by incorporating light reflecting colors or preventing light from reaching the sensor. According to the World Meteorological Organization, temperature sensors should measure at a level of 1.25 to 2 meters above surface level to count as official measurements (World Meteorological Organization, n.d.). The influences that cause a deviation from the actual temperature should be taken into account by researchers.

Soil moisture
Will be a capacitive sensor, can also be passive which is very energy efficient (Tinytronics, n.d.-d). It doesn't require any additional effort and can be robust if correctly integrated. It is very applicable to the context. According to Liu et al. (2020) (Liu et al., 2020) the amount of moisture in the soil is the main factor that influences how ecosystems experience

dryness stress, affecting plant growth and productivity. To achieve a higher accuracy however, calibrating sensors is desired (Jiménez et al., 2019).

CO (carbon monoxide)
Carbon monoxide binds 240 times stronger with hemoglobin than oxygen, banishing the latter from the blood and this can be dangerous. Aside from forming spontaneous in the atmosphere, it also forms outdoor by industries and traffic, but it is mostly a problem indoors (Vlaams instituut gezond leven, n.d.-b).

It is also not mentioned by the RIVM report for measuring air quality by citizens (Wesseling et al., 2016), which is an advisory report from a governmental body assessing scientific value for various cheap and compact sensors. The (type of) sensors described in the report are investigated because of their potential application in citizen science initiatives, since CO is not mentioned, its value is questionable.
There are cheap options that cost a few euros off-the-shelf, with a long lifespan and simple data output (Tinytronics, n.d.-h). However, they are not really sensitive, namely >20 ppm, where 0.10 ppm is the approximate atmospheric value (National Oceanic and Atmospheric Administration, n.d.).

CO2 (carbon dioxide)
An acceptable level of carbon dioxide does not necessarily mean the air is healthy as there is no correlation between other particles (Vlaamse overheid departement zorg, n.d.). Therefore it is not suitable to determine air quality, it is also not covered in the RIVM report for citizen measurements (Wesseling et al., 2016). Scientific value and costs are unknown.

Water flow
Water flow is obvious related to dryness, when we are speaking of rivers that replenish water. For small volumes, they are available for a few euros off-the-shelf; output simple data and they are quite accurate as well. However, these small scale sensors are not suitable for larger water volumes. Even though the topic is applicable, it doesn't make a lot of sense to measure this in the context as described currently.

Decibel
Even though outdoor volume levels have a significant effect on our health (RIVM, n.d.-a), they are not related to air quality or dryness.

Light intensity (lux or UV)
According to Belnap et al. (2008), increases in UV will likely lead to lowered productivity and increased mortality in biological soil crusts, reducing their ability to contribute to soil stability. Therefore it would be applicable to the context of measuring dryness.

Sensors for both UV and lux are a few euros off-the-shelf, and they export simple data and are robust modules that can be integrated (Tinytronics, n.d.-a, n.d.-j). Their scientific value is questionable as, according to the datasheets, they are inaccurate (up to 1.5 times the actual value at max). Isolation of a factor as light intensity is also difficult under field conditions since low air temperature and high relative humidity are usually associated with low light intensity (Penfound, 1931). When aiming to isolate, specifically constructed shade shelters are required, causing extra effort.

Location
Location is, just as distance, not necessarily a sensor that measures the context, but it can be valuable information that supports other sensors. As opposed to distance, determining location can be done with modules

that are already implemented in the instrument: the data transmission module. Depending on the type of network or technology determining this location is less or more accurate and also requires less or more power. To be of value, a quite accurate location might be required.

Humidity

Humidity itself is not an air pollutant, even though it changes air conditions for other pollutants. Sensors are often combined with temperature sensors, are very cheap and deliver quite accurate measurements (Tinytronics, n.d.-f). Nonetheless, one can question how valuable it is in context, also when other pollutants can also be measured.

NH3 (ammonia / air pollutant)

Ammonia is an interesting substance for measuring air quality. It is covered in the RIVM report and on the 'samen voor zuivere lucht' website, which is a project by Interreg European, partnering RIVM and Vlaamse Mileumaatschappij (Samen voor Zuivere Lucht, n.d.-a; Wesseling et al., 2016). From there, however, it becomes clear that ammonia can be measured using passive samplers, which is not desirable for the project's scope. According to the RIVM report, it can also be measured using active sensors, but their sensitivity is insufficient and only suitable for environments with high concentrations such as cow sheds.

NH4+ (ammonium / indicator for water pollution)

Ammonium is an indicator for ground pollution but more commonly for water pollution because of the flushing effect that the ground has towards surface water reservoirs (RIVM, n.d.-d). It is therefore not really applicable to the scope of the proposed instrument. Accuracy, robustness, scientific value and price are unknown.

NO (Nitric oxide / air pollutant converts to NO2)

NO does little harm to one's health and has a short life span as it reacts with oxygen and ozone to NO2 (RIVM, n.d.-d). It is mentioned in the RIVM report and included in the "Samen Meten" dashboard under NOx, but different from NO2 it is not mentioned to be measured by citizens (RIVM, n.d.-c; Wesseling et al., 2016).

NO2 (Nitric dioxide / air pollutant)

Measuring NO2 is valuable in the set context, as it has a negative effect on one's health, causing irritation and inflammation of the lungs, throat, eyes and nose and it can be measured easily (RIVM, n.d.-c; Vlaams instituut gezond leven, n.d.-d). The RIVM report and 'samen voor zuivere lucht' also cover measuring NO2 by citizens (Samen voor Zuivere Lucht, n.d.-c; Wesseling et al., 2016).

It can be done passively, using Palmes tubes, and actively, using sensors. The former is relatively cheap and also quite accurate, but has two major disadvantages. Real-time measurements are not possible, which can decrease engagement, and Palmes tubes have to be manually investigated in the lab, which is a time-consuming task, greatly reducing the scalability of the instrument.

Active sensors on the other hand are less accurate and more expensive: 200 euros off-the-shelf (Wesseling et al., 2016). The RIVM reports mentions that Alphasense's sensors are barely capable to deliver valuable measurements, given that the sensors use the dedicated Alphasense IST board. Calibrating the sensors would increase their accuracy, but in practice they appear to be quite volatile and sensitive to humidity and ozone. The report mentions that differences of ± 20 μg/m3 at least, and preferable ± 10 μg/m3, should be measured to make them any valuable. According to the same report, Alphasense's sensor is capable to measure 5-10 ppb (9.5-19 μg/m3), which is just in the desired sensitivity range. The sensor uses 5 μA in standby mode but can be incorporated in a circuit with a sleep time. When measuring, the sensor draws 0,15 mA and when simultaneously writing 2,15 mA, but this is only for a short period of time, retaining energy efficiency (Alphasense, n.d.-a).

NO3 (Nitrate / indicator for ground pollution)
Nitrate is a substance that is formed in—or added to—the ground (RIVM, n.d.-d). It often flushes towards surface water and reacts with oxygen, whereby the latter is removed from the water. For air quality and dryness it is less significant to measure.

O3 (Ozone / air pollutant indicator)
Ozone is an unstable gas that reacts with other substances in the environment. High in the atmosphere it protects the earth from UV radiation. Ozone on living height is produced indirectly, through radiation on other pollutants as Nox, causing irritation and other health complaints (Vlaams instituut gezond leven, n.d.-c). Both the RIVM report and the 'Samen Meten' dashboard do not include it, therefore measuring by citizens might not be useful enough (RIVM, n.d.-e; Wesseling et al., 2016).

Passage count
Even though passage count, which can be done by lasers or motion sensors, is cheap, robust and outputs simple data, it is not so interesting to design for in this context because of the lack of connection with dryness and air quality.

pH-value ground
A change in soil pH affects nutrient availability, in turn affecting plants, in turn affecting dryness. However, measuring this might be too indirect as plant health is determined by many factors. There are off-the-shelf components costing around 70 euros that output simple data and have an accuracy of +-0.2 pH, but they require calibration and installation in the soil, reducing user-friendliness (AtlasScientific, n.d.).

PM1 / PM2.5 / PM10
Particle matter, or PM for short, is fine dust in the air that affects functioning of the lungs, heart and vessels and is therefore very applicable to the target context (Vlaams instituut gezond leven, n.d.-a). The RIVM report and 'samen voor zuivere lucht' describe the possibility for citizen scientists to measure PM (Samen voor Zuivere Lucht, n.d.-b; Wesseling et al., 2016), however there are some challenges.

Official measuring methods require a PM sensor that actively takes in air from the environment, gathering dust on a filter. After 24 hours the filter is weighed and the amount can be calculated. Cheaper sensors, still in the range of a few hundred euros, do not weigh the parts, but optically estimate them, causing additional measuring uncertainty. An additional disadvantage of the optical measuring method is that parts emitted by traffic are not detected, as they are often smaller than 0.1 μm.

A sensor manufactured by Alphasense gives the most accurate results and is able to measure parts with a diameter between 0.3 and 15 μm. In contrast, the SPS30 sensor by Sensirion, while costing about a tenth of the price (Sensirion, n.d.), has a narrower measurement range (0.3 – 1.0) and estimates PM4 and PM10 values based on PM1 and PM2.5 data instead of directly measuring them. According to Wesseling et al. (2016), a sensitivity of at least 5 to 10 μg/m³ is recommended. The SPS30 barely meets this threshold only for PM1 and PM2.5, whereas the Alphasense sensor datasheet does not specify sensitivity or accuracy.

Because of the constant intake of air, the sensor uses a lot of energy (180 mA). It contains a stand-by mode, but then still uses quite some energy (<45 mA). Briefly turning on for a moment is also undesired as it has a startup time of about 60 seconds (Alphasense, n.d.-b). Therefore, to implement this sensor, grid power is required since it would not last long on battery. With a battery capacity of 2600 mAh, the battery would be drained after almost 58 hours.

SO2 (Sulfur dioxide / air pollutant)

SO2 is an air pollutant that is emitted when burning fossil fuels. 95% of SO2 in the air is coming from human activity, and it can exaggerate citizen's existing health complaints. Nonetheless, the concentrations of SO2 are relatively low, and are not expected to create severe smog (Samen Meten, n.d.). Measuring it will mostly be only an indication of air quality. It is also not described in the RIVM report and therefore its significance of implementation in the instrument is questionable (Wesseling et al., 2016).

Wind direction & speed

The direction of the wind is not an indication of air pollution but it definitely influences local air quality. However, sensors require moving parts that can rotate freely, limiting robustness. In addition, wind speed and direction is measured on a national level, for example by the KMI (KMI, n.d.-b). Therefore the additional value that local measurements offer is limited.

SUBSTANCE	TYPICAL CONCENTRATIONS	SENSITIVITY (MINIMAL DIFFERENCE TO MEASURE)
NO2	Hour: 5-200 µg/m3 Year: 15-45 µg/m3	~5-20 µg/m3
PM 10	Day: 5-70 µg/m3	~5-10 µg/m3
PM 2.5	Day: 5-50 µg/m3	~5-10 µg/m3

(Wesseling et al., 2016)

Appendix C

Data transmission technology exploration

The technology for data transmission that will be implemented in the instrument is important to consider, as it will be a determining factor for other design choices. For example, data size limitations can result in exclusion from certain data types, or power consumption determines whether it is suitable to operate on battery. There are numerous technologies, each having their own (dis)advantages and to find the optimal data transmission protocol, many parameters have been considered.

Selection criteria

Bandwidth and data throughput

Refers to the maximum amount of data that may be sent across a connection (Mitrofanskiy, 2024). In case a lot of information needs to be send, for example video data from cameras, a protocol with a higher bandwidth is required compared to when small data packets are send.
The proposed instrument requires limited bandwidth and throughput as there are no large data transmissions such as photos or videos in the current scope. Sensor data coming from temperature sensors are within the order of magnitude of several bytes per measuring interval. This means that power-consuming technologies with high bandwidths and data are not required.

Coverage

It's important that the type of network is available in the areas where the instrument will be deployed, but also has a certain range (Ho, 2023; Mitrofanskiy, 2024).

In this scope, it is useful if the instrument uses infrastructure that is already set up, such as cellular networks. If besides Belgium, the instrument will be deployed in other places, coverage should be considered because of availability of different networks, especially outside of Europe.

Power consumption

Refers to the power that the instrument will use when transmitting of receiving data, but also when it is idle (Dinkevich, 2024; Ho, 2023).
For a battery-powered instrument, low power consumption is of utmost importance. Thereby not only looking at the power required to transmit and receive (Tx/Rx), but also the power used when idle. Preferable it even has the option to go into deep sleep mode, to extend life span even further.

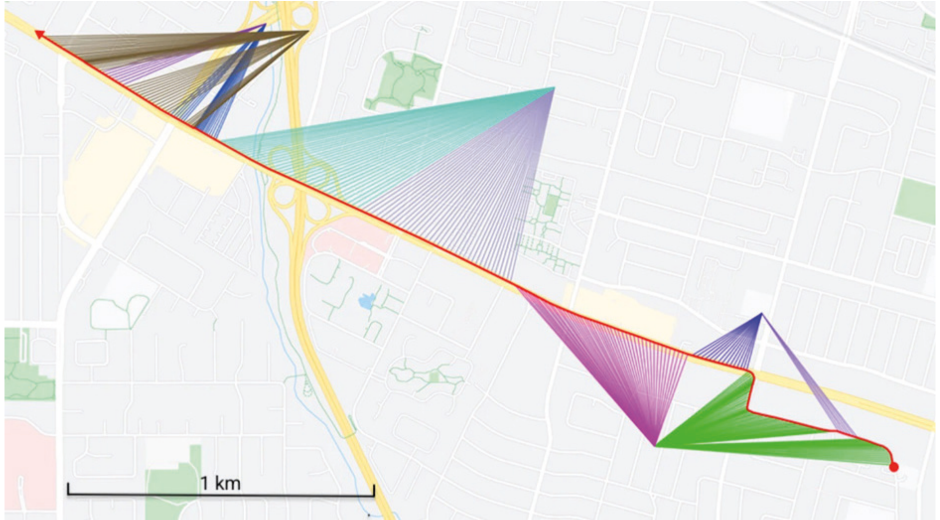
Cost

Cost of the technology is partly a trade-off between upfront costs and ongoing fees of the network. It depends among others on the complexity of the system, but also on the available infrastructure of the protocol (Dinkevich, 2024).

Of course, the intended instrument should be as cost-efficient as possible, but robustness is more important, meaning the technology in the first place should be suitable.

Mobility

Is a device meant to be operating while moving? In that case faster data transmission is required. Moving speeds matters as well, certain technologies track devices more accurately and over longer distances (Ho, 2023). The image below shows how a device will need to seamlessly switch between stations or cell towers frequently when moving (using a cellular technology). A short journey requires quite some switches in a short journey and slower technologies are not capable of doing this kind of switching. When it moves out of range of a tower, it will increase the power to stay connected. The instrument in this scope is static and does not require to move.



(Michael Bosson, 2023)

Latency
Some protocols offer a minimal delay, but others prioritize for example battery life and communicate less frequent.

A delay in sending the data to the online environment will not a problem, data is only semi real-time and data might be send only a few times or once a day to reduce power consumption.

Indoor penetration
Where lower frequency protocols generally work well indoors, higher frequencies might struggle to connect indoor or underground.
Since the instrument in this scope will be used outdoor, penetration is not a big deal.

Security
Cellular networks offer robust encryption in their protocols, to prevent unauthorized access, but other networks can be vulnerable and might require additional security measures. Firmware updates allow to improve security while operating, but protocols with limited bandwidth might not be able to deliver them (Ho, 2023).

Safe data transmission is favourable because it might also include sensitive location data. Even if there is another way to share location data with the online environment, future modules might still collect sensitive data.

Redundancy
Refers to the backup options that protocols offer. Cellular networks often allow switching between providers and roaming. It can increase connectivity, but is especially important if downtime has to be diminished. Downtime now and then shouldn't be that big of a problem, as long as the measurements are send to the online environment. If that interval is daily, the protocol can spend the day transmitting the data.

The figures on the next page give an idea of the various technologies that could be used and their specifications. The left covers data transmission technologies in general, the right one lists common IoT networks.

Technology	Range	Power Consumption	Data Rate	Applications
2G (retired)	Wide	Moderate	Low	Basic data transmission (no longer widely deployed)
3G	Wide	Moderate	Moderate	Mobile broadband internet access (being phased out)
4G	Wide	Moderate	High	Mobile broadband internet access, industrial applications
5G	Wide	Moderate to High	Very High	High-bandwidth, low-latency applications (evolving technology)
Bluetooth	Short	Low	Low	Sensors, wearables
Cellular Networks (NB-IoT, LTE-M)	Wide	Very Low	Low to Moderate	Remote sensors, wearables, asset tracking
LoRaWAN	Wide	Very Low	Very Low	Remote sensors, meters, smart cities
Satellite (GNSS)	Global	N/A (powered externally)	Moderate	GPS tracking, remote asset monitoring
M-Bus	Short (wired)	Very Low	Low	Building automation, meter reading
PLC (Power Line Communication)	Medium (over existing power lines)	Low	Moderate	Smart meters, industrial automation
Ethernet	Limited (wired)	Low	High	Real-time control, constant data flow
Mesh Protocols (Zigbee)	Extended (mesh network)	Low	Moderate	Smart homes, building automation
RFID	Short (reader proximity)	N/A (passive tags)	Very Low	Inventory management, access control
Wi-Fi	Short	Moderate	High	Home automation, smart appliances

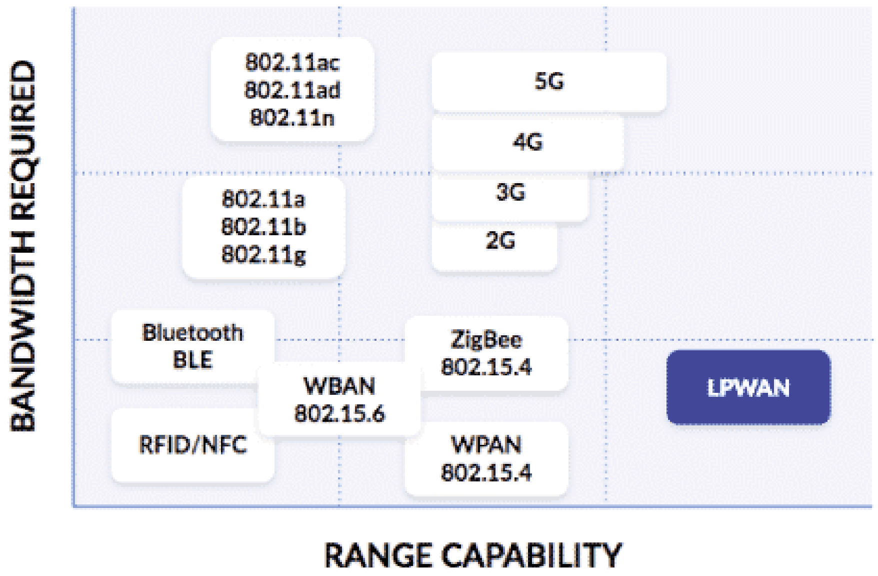
(Dinkevich, 2024)

Connectivity Type	Coverage	Data throughput	Idle Power	Rx/Tx Power	Power Save Mode	Power Supply	Module Cost
Cellular	Global	Up to 130 Mbps	As low as ~1.5 mA	As low as ~110 mA	As low as ~3 µA	As low as 2.75 V	As low as 7€
WiFi	<400m	Up to 1.3 Gbps	~30-100mA	~130-250 mA	~1.5 mA	As low as 3 V	5-10€
Bluetooth	<700m	Up to 3 Mbps	As low as 35 mA	As low as 2.7 mA	As low as 1 µA	As low as 1.7 V	7-10€
Zigbee	<300m	Up to 1 Mbps	15-20 mA	40-135 mA	As low as 2 µA	As low as 2.1 V	10-15€
LoRaWAN	15km	0.24-37.5 Kbps	N/A	As low as 5 mA	1.8 µA	As low as 2.4 V	8-12€
Ethernet	Limited by cable	Up to 10 Gbps					
M-Bus	<km	Up to 100 Kbps (Wireless M-Bus)	~2 mA	As low as 10 mA	As low as ~1 µA	As low as 2.3 V	
PLC	1 km cables	Up to 575 Kbps	100-240 mA	100-240 mA	N/A	N/A	As low as 35€

(Ho, 2023)

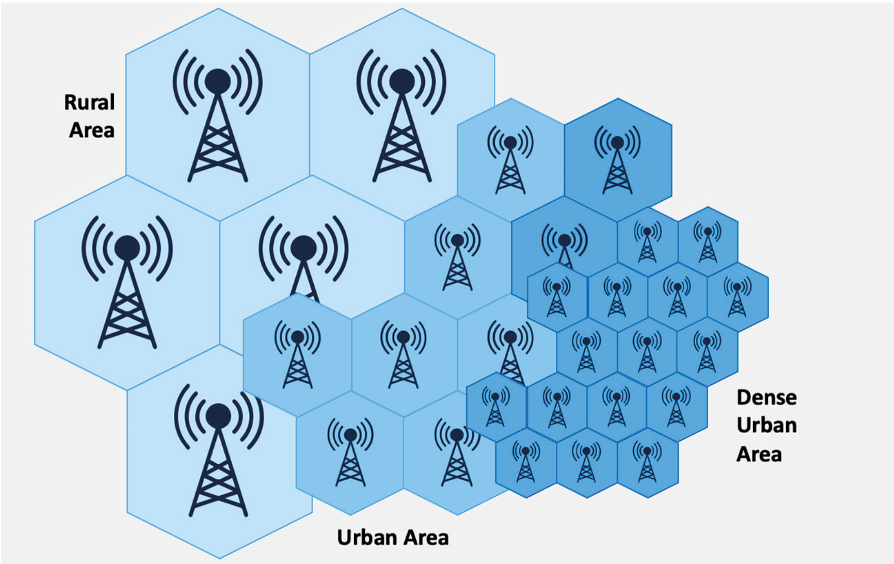
LPWAN technology

When filtering technologies according to the set requirements or considerations, a few common IoT solutions remain: NB-IoT, LTE-M and LoRaWAN. They all belong to the category of LPWAN (Low Powered Wide Area Network) technologies. It's a broad term encompassing various protocols, both proprietary and open-source, that share two common characteristics. As the name suggests, they are low power, and thus operate on small, inexpensive batteries for years, and they operate in a wide area, typically more than 2 km in urban settings (IoT For All, 2024). These characteristics make LPWAN an excellent choice for long-term monitoring, but it comes with the cost of small data sizes.



(IoT For All, 2024)

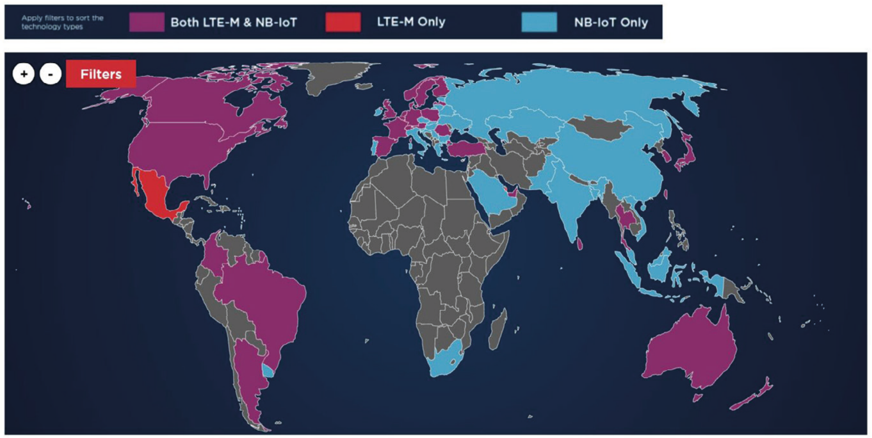
NB-IoT stands for NarrowBand-Internet of Things. LTE-M is short for Long Term Evolution for Machines, which is the simplified term for eMTC LPWA (enhanced machine type communication low power wide area) technology. They are both cellular IoT technologies, meaning they operate on a network that facilitates communication over area divided in cells. A technology known for communication with among other mobile phones under the umbrella terms 2G, 3G, etc. (Ho, 2023).



(Aldinger and Mikuda, 2023)

NB-IoT and LTE-M differ in availability and coverage. NB-IoT can be deployed on both 2G (GSM) and 4G (LTE) networks, while LTE-M is solely for 4G. On the contrary, LTE-M is already compatible with the existing LTE network, while NB-IoT requires specific hardware. Both are planned to be available on 5G.

Operators typically deployed LTE-M first in countries that had LTE coverage already (Michael Bosson, 2023). It's easier to upgrade an existing LTE tower to support LTE-M than to add NB-IoT support. However, if LTE is not supported already it is cheaper to put up new NB-IoT infrastructure. Another factor to consider is that companies like Huawei are pretty invested in NB-IoT intellectual property (IP) and support its rollout.



(Michael Bosson, 2023)

Roaming agreements between network operators allow customers to access partner networks in other countries, for LTE-M there are already agreements in place, while NB-IoT is far behind.

NB-IoT and LTE-M have energy-saving features that help devices last longer between charges (Mitrofanskiy, 2024). However, power consumption in both technologies heavily depends on transmission frequency and size and connection distance. In the field, under normal conditions using LTE-M will on average have a lower power consumption, but if devices experience a lot of obstructions or data has a relative long travel distance, NB-IoT would be preferred. Therefore it is hard to compare the two (Michael Bosson, 2023). They consume about 110 mA when transmitting and receiving (Tx/Rx) and ~3 μA when in power saving mode. The two can be also switched off to reduce power, however this is only efficient when sending less than once a day (Thingsdata, 2023).

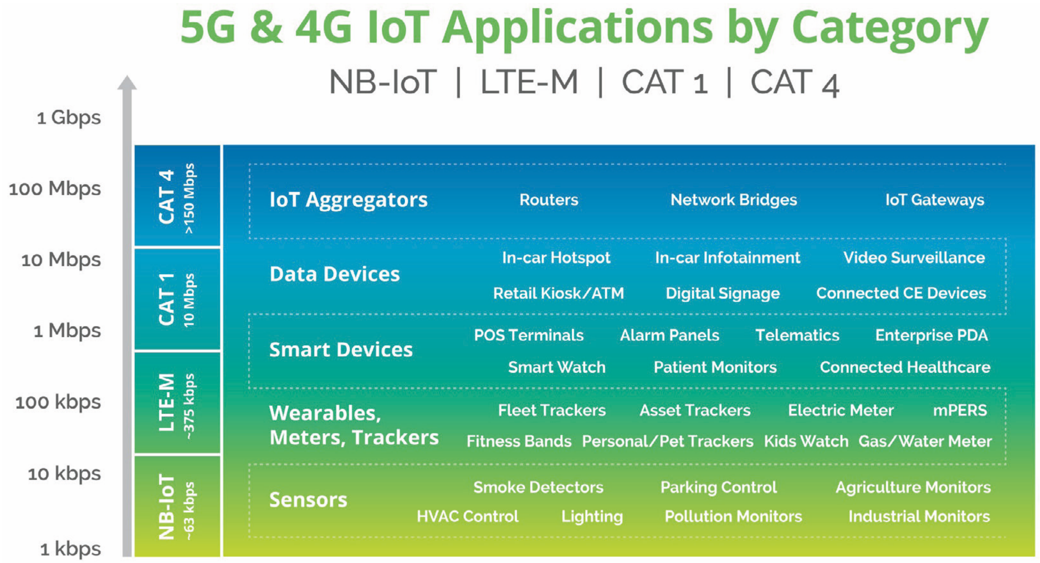
A significant difference between the two is mobility. While LTE-M is able to switch between cell towers frequently, NB-IoT is not capable of doing this efficiently. When it moves out of range of a cell tower, it increases power (Tx) to stay connected, and when it disconnects it must register with the network again, increasing power consumption. The proposed instrument does not require to be moved frequently and therefore both technologies would be suitable (Helppi, 2022).

The main trade-off is within data rates and cost. Up- and downlink speeds for LTE-M are higher than for NB-IoT (uplink: 159 Kbit/s vs 7 Mbit/s, downlink: 127 Kbit/s vs 4 Mbit/s) (IoT For All, 2024; Michael Bosson, 2023), but LTE-M modules are slightly more expensive, as chipsets incorporating the NB-IoT protocol are simpler (IoT For All, 2024).

Comparison table: NB-IoT vs LTE-M

	NB-IoT	LTE-M
Uplink and downlink speeds	Low (Kbit/s). LTE Cat NB2 offers max 159 Kbit/s uplink and 127 Kbit/s downlink.	High (Mbits/s). LTE Cat M2 offers max 7 Mbit/s uplink and 4 Mbit/s downlink.
Coverage/Penetration	Great coverage and penetration.	Great coverage and penetration.
Global availability	Good availability. Requires new infrastructure. Cheaper to roll-out than LTE.	Great availability where LTE already exists. Built on existing LTE technology.
Roaming capability	Technically possible, but basically non-existent in reality. Check regions of interest.	Good roaming availability. Check regions of interest.
Module costs	Typically cheaper than LTE-M.	Typically more expensive than NB-IoT.
Power saving features	PSM and eDRX support.	PSM and eDRX support.
Mobility	No handover when moving, only suitable for static devices.	Suitable for static and mobile devices.
Freedom to leave	Typically no SMS support. Not good for freedom to leave and eUICC (eSIM).	Supports freedom to leave and eUICC (eSIM).

(Michael Bosson, 2023)



Data rates for LTE CAT 1, CAT 4, CAT M1 & CAT NB1 and their possible applications giving an idea of the required data rate (IoT For All, 2024)

Another possibly suitable technology is LoRa, a technology that depends on a LoRaWAN, which is a type of LPWAN as well, specifically designed for IoT (Ho, 2023), just as LTE-M and NB-IoT.

The main advantage of the network is that it uses unlicensed frequency bands, so you don't pay for the data. Even though there are LoRaWAN providers scattered throughout the world, in most cases, IoT manufacturers still need to deploy their own infrastructure rather than attaching to an existing one and there are also no roaming agreements (Ho, 2023). Compared to LTE-M and NB-IoT, LoRaWAN can send information over larger distances (Narrowband, n.d.).

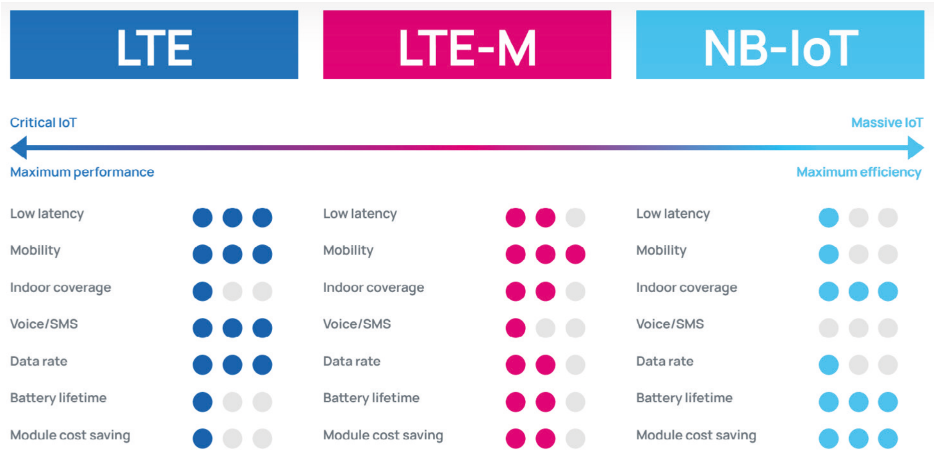
LoRaWAN uses even less energy, ~5-15 mA for receiving (Rx) and ~120 mA for transmitting (Tx) (Thingsdata, 2023). Additionally, as long as nothing is sent, the module is not active either, it doesn't need to maintain a connection and therefore also doesn't use power. Again, the energy efficiency also depends on the coverage of the network and the amount of information that is sent.

A disadvantage of the network is limited messaging capacity, lower then cellular IoT technologies. Maximum message size is about 54 Bytes (Thingsdata, 2023), similar to a 50 character text, which can be enough when only sending some sensor information. Sending smaller messages is faster and costs less power. Even though frequencies are not licensed there are limitations. In the Netherlands for example, the Radiocommunications Agency enforces a so-called duty cycle limitation, meaning signals should not be send too often and the intensity of the signal is limited, with a maximum of 20 mW .

When considering the currently required data rate, but also requirements for future potential module extensions, the coverage of the network and the availability of current infrastructure, LTE-M appears to be the most suitable and robust solution.

	LTE	LTE-M	NB-IoT	LoRa
Spectrum	Licensed	Licensed	Licensed	Unlicensed
Bandwidth	20 MHz	1.4 MHz	180 kHz	125 – 500 kHz
Bidirectional Data Transfer	Full duplex	Half duplex & full duplex	Licensed	Unlicensed
Peak Data Rate	10 Mbps (DL) 5 Mbps (UL)	1 Mbps (DL) 1 Mbps (UL)	250 Kbps (DL) 230 Kbps (UL)	50 Kbps (DL) 50 Kbps (UL)
Typical Daily Throughput	Limited only by battery, radio signaling condition and commercial terms (e.g., monhtly data volume, amount of messages/size per period)			~ 200 B (DL) ~ 200 kB (UL)
Max. Coupling Loss (vs. GSM)	144 dB (0 dB)	156dB (+12 dB)	164 dB (+20 dB)	157 dB (+13 dB)
Module Cost	› $10	‹ $10	‹ $5	‹ $7
Battery Lifetime	3 – 5 years	5 – 10 years	10+ years	10+ years

Characteristics of the compared technologies (IoT Creators, n.d.)



(IoT Creators, n.d.)

Appendix D

Battery and data storage exploration

Battery

As the instrument has to operate in public and more remote places, access to grid power is often absent. But even around the house, grid power would not always be suitable to power the instrument. The required cables take up space and are exposed outside risking wear and a cable reduces watertightness. When depending on grid power, there is a risk of power disconnection, deliberately or accidentally.

Therefore a battery would be the most suitable option, coming with its own disadvantages. The major ones are limited capacity (mAh) and demand for recharge. The integrated sensors and their power use eventually determine what battery would be suitable, but it can also work the other way around, in which battery capacity limits the sensor choice. For the current scope, a battery module is designed to be default, but leaving the possibility to implement grid power in the future.

Empty batteries are inevitable eventually. Recharging them could be done by either the citizen scientist, the organizer or the owner/distributor. Tasking the former 2 saves the owner time and power. However, this does not really rhyme with the characteristic of a plug & play, and users and organizers already have quite some tasks. Additionally, it risks user mistakes and might require more complex features to ensure a user-friendly interaction. Considering that the instruments have to be returned to the distributor anyway, he is most suitable to execute the charging process, ensuring it happens in a safe and correct manner.

The application requires a rechargeable battery that has minimal self-discharge, is safe and preferable has a high specific energy (to reduce the size), resulting in a Li-ion battery to be the most suitable. For example the instrument used in the 'Curieuzeneuzen in de tuin' project features a common 18650 model Li-ion battery (3,6 V; 2600 mAh; 65 mm x D:18 mm) that is able to power three temperature sensors and a capacitive soil

Specifications	Lead Acid	NiCd	NiMH	Li-ion[1]		
				Cobalt	Manganese	Phosphate
Specific energy (Wh/kg)	30–50	45–80	60–120	150–250	100–150	90–120
Internal resistance	Very Low	Very low	Low	Moderate	Low	Very low
Cycle life[2] (80% DoD)	200–300	1,000[3]	300–500[3]	500–1,000	500–1,000	1,000–2,000
Charge time[4]	8–16h	1–2h	2–4h	2–4h	1–2h	1–2h
Overcharge tolerance	High	Moderate	Low	Low. No trickle charge		
Self-discharge/ month (room temp)	5%	20%[5]	30%[5]	<5% Protection circuit consumes 3%/month		
Cell voltage (nominal)	2V	1.2V[6]	1.2V[6]	3.6V[7]	3.7V[7]	3.2–3.3V
Charge cutoff voltage (V/cell)	2.40 Float 2.25	Full charge detection by voltage signature		4.20 typical Some go to higher V		3.60
Discharge cutoff voltage (V/cell, 1C)	1.75V	1.00V		2.50–3.00V		2.50V
Peak load current Best result	5C[8] 0.2C	20C 1C	5C 0.5C	2C <1C	>30C <10C	>30C <10C
Charge temperature	–20 to 50°C (–4 to 122°F)	0 to 45°C (32 to 113°F)		0 to 45°C[9] (32 to 113°F)		
Discharge temperature	–20 to 50°C (–4 to 122°F)	–20 to 65°C (–4 to 149°F)		–20 to 60°C (–4 to 140°F)		
Maintenance requirement	3–6 months[10] (toping chg.)	Full discharge every 90 days when in full use		Maintenance-free		
Safety requirements	Thermally stable	Thermally stable, fuse protection		Protection circuit mandatory[11]		
In use since	Late 1800s	1950	1990	1991	1996	1999
Toxicity	Very high	Very high	Low	Low		
Coulombic efficiency[12]	~90%	~70% slow charge ~90% fast charge		99%		
Cost	Low	Moderate		High[13]		

Characteristics of commonly used rechargeable batteries (Buchmann, 2016)

moisture sensor for about 10 years (TOMST, n.d.).
For the battery, a standard model can be used, having two options. According to appendix FIXME a 1500 mAh battery is enough for almost 9 years of use with one-minute measuring intervals. A 18500 type (D:18,5 x 52,8 mm) battery, costing €1.46 would therefore be sufficient (Alibaba, n.d.-g). However, in the future when more or more energy consuming modules are possibly going to be added, it would be useful to include a 2600 mAh 18650 type size (D:18,6 x 68,2 mm), costing €1.44, which could last 15 years (Alibaba, n.d.-c).

Data storage

The data produced by the sensor is stored to bridge the time until the data is send to the online environment and offers the possibility to still retrieve the information in case wireless data transmission no longer works. The size of the data that needs to be transmitted depends on the output format of the specific sensor and measuring interval. When the interval is determined, storage size can be determined in turn. The KMI gathers information about the weather every hour (KMI, n.d.-a); benchmark products as the instrument from the “Curieuze neuzen in de tuin” project every 15 minutes (TOMST, n.d.); and instruments within the RIVM measuring network are calibrated every 60 minutes (RIVM, n.d.-b). This applies to the execution of measurements and local storage, it does not mean that gathered data will be send to the online platform every 15 minutes, which can for example also happen once a day.

Appendix E

Power consumption and data rate calculations

Component	Included	Bytes per measurement	Standby power use (mA)	Power use (mA)	Duration of measurement (s)	Total standby power use (mAh/y)	Total power use - always powered (mAh/y)	Total power - 10s measurements (mAh/y)	Total power - 30s measurements (mAh/y)	Total power - 1m measurements (mAh/y)	Total power - 5m measurements (mAh/y)	Total power - 15m measurements (mAh/y)	Total power - 1h measurements (mAh/y)
Soil temp	1	2		1	0,1	0	8760	87,6	29,2	14,6	2,92	0,973333333	0,243333333
Air temp	1	2		1	0,1	0	8760	87,6	29,2	14,6	2,92	0,973333333	0,243333333
Soil moisture	1	1		5	0,1	0	43800	438	146	73	14,6	4,866666667	1,216666667
NO2	1	1		2,15	0,1	0	18834	188,34	62,78	31,39	6,278	2,092666667	0,523166667
PM	1	6		180	60	0	1576800	9460800	3153600	1576800	315360	105120	26280
Microcontroller	1		0,0001	0,011		0,876	96,36	9,636	3,212	1,606	0,3212	0,107066667	0,026766667
Data (Rx/Tx)	1		0,003	110		26,28	963600	54,41505882	18,13835294	9,069176471	1,813835294	0,604611765	0,151152941
Stand by						27,156		24,4404	26,2508	26,7034	27,06548	27,12582667	27,14845667
Total w/PM	6	6	0,0031	119,161		54,312	1043850,36	890,0314588	314,7811529	170,9685765	55,91851529	36,7435051	29,55287627
Total w/o/PM	7	12	0,0031	299,161		54,312	2620650,36	9461690,031	3153914,781	1576970,969	315415,9185	105156,7435	26309,55288
Battery lifespan (y)							0,00099212	0,000274792	0,000824372	0,00164873	0,008243084	0,024724995	0,09882342

Bitrate/s NB-IoT	170000		Max measuring	1		Battery capacit	2600

Bytes per measurement	Measuring interval (min)	Measurements per day	Bytes per day	Bits per day	Sending duration /d (s)	Sending duration /y (s)	Power use transmitting /y (mAh)	Standby /y (s)	Power use idle /y (mAh)
12	60	24	288	2304	0,013552941	4,946823529	0,151152941	31535995,05	26,27999588
12	15	96	1152	9216	0,054211765	19,78729412	0,604611765	31535980,21	26,27998351
12	5	288	3456	27648	0,162635294	59,36188235	1,813835294	31535940,64	26,27995053
12	1	1440	17280	138240	0,813176471	296,8094118	9,069176471	31535703,19	26,27975266
12	1/2	2880	34560	276480	1,626352941	593,6188235	18,13835294	31535406,38	26,27950532
12	1/6	8640	103680	829440	4,879058824	1780,856471	54,41505882	31534219,14	26,27851595

Appendix F

Informed consent form

Delft University of Technology
HUMAN RESEARCH ETHICS
INFORMED CONSENT FORM

Designing a Measuring Instrument to Improve Citizen Science Participation

You are being invited to participate in a research study titled "*Public Participation Powered by Design: Developing a Measuring Instrument to Enhance Citizen Science Engagement*" This study is performed by Paul Roelen, a Master's student at TU Delft, in collaboration with Dott Achilles as graduation company. The purpose of this research is to explore how a newly designed measuring instrument system can enhance participation in citizen science projects. The findings will be used to validate current efforts, and further develop the product.

Your role in the study
We will be asking you to interact with a prototype of a measuring instrument, attempt to install it in a simulated real-life setting, and provide feedback on this process. You will receive a list of set instructions and will operate with a mock-up of a measuring instrument and accompanying mobile interactive installation guide. You will receive further instructions prior to the study. The process will take approximately 45 minutes and will include a semi-structured interview to gather insights about your experience and opinions. During the interview audio will be recorded for transcribing purposes.

Data Collection Management and other risks
We will collect the following personal data: (1) observational data (e.g., actions during the task); (2) feedback provided during the interview; (3) any demographic information shared voluntarily (age). All data will be anonymized, with details removed or pseudonymized, and will never be shared with third parties without prior consent. Data will be securely stored on password-protected devices and accessible only to the researcher. Data will be used for research purposes, including publications. You might experience light emotional discomfort if tasks feel challenging or frustrating. We want to emphasize that the prototype is being tested, if you experience these feelings it is due to the instrument's pitfalls.

Your participation in this study is entirely voluntary and you can withdraw at any time. If you withdraw, any identifiable data collected up to that point will be deleted. You are free to omit any questions. You have the right to request access to and deletion of your collected data until two weeks after participation, before the publication of the thesis report. In case of any questions, contact:

Paul Roelen
Faculty of Industrial Design Engineering
Delft University of Technology
Landbergstraat 15
2628 CE Delft, Netherlands

EXPLICIT CONSENT POINTS

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated [*12/01/2025*], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves: • I will receive instructions about the tasks and the device that I will test and evaluate. • I will interact with a prototype of a measuring instrument and attempt to install it in a simulated real-life setting and; • I will be interviewed to provide feedback. The audio of the interview will be recorded for transcription purposes and will be destroyed afterwards. • During the study my hands interacting with the instrument can be photographed.	☐	☐
4. I understand that the study will take approximately 45 minutes	☐	☐
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
5. I understand that taking part in the study involves the following risks: • (1) You might experience mild emotional discomfort if the tasks feel challenging or frustrating. • (2) A potential data breach could occur, linking collected data (age, audio recordings, and photographs) to me. I understand that these will be mitigated by: • (1) Emphasizing that the prototype is being tested, and any frustration experienced reflects the instrument's shortcomings, not participant performance. • (2) Ensuring that none of the data is shared with the company, except for anonymized photos and age. Only synthesized results will be shared with them, in the same format as presented in the thesis report. Data will be securely stored in encrypted folders and locked cabinets at the researcher's home. • (3) The ability for you to stop the study at any point without any consequences.	☐	☐
6. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) such as my name and age and associated personally identifiable research data (PIRD) such as audio recordings and photographs with the potential risk of my identity being revealed to the researcher only. No PII or PIRD will be made publicly available un-anonymized unless explicit consent is given.	☐	☐
7. I understand that the following steps will be taken to minimise the threat of a data breach, and protect my identity in the event of such a breach: • All data will be stored according to a data management plan that was approved by the TU Delft Human Research Ethics Committee (HREC) • The data will be locally stored in an encrypted folder on the researcher's computer. • The data will be pseudonymized. Every participant will receive a unique identifier.	☐	☐

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
• This informed consent form will be stored in a locked cabinet in the researcher's home. • Audio recordings and photographs will be locally stored in an encrypted folder on the researcher's computer. • Photographs are anonymized, only my hands will be visible.		
8. I understand that personal information collected about me that can identify me, such as my age. My name will not be shared beyond the researcher.	☐	☐
9. I understand that the (identifiable) personal data I provide will be destroyed after publication of the study results.	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
10. I understand that after the research study the de-identified information I provide will be used for further development of the device, publications, reports and presentations.	☐	☐
11. I agree that my responses, views or other input can be quoted anonymously in research outputs.	☐	☐
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE		
12. I give permission for the de-identified data (interview results, age, photographs) that I provide to be archived in the TU Delft repository so it can be used for future research and learning. I understand that the audio recordings will not be uploaded to this repository.	☐	☐
13. I understand that access to this repository is open.	☐	☐

Signatures

______________________	________________	_______
Name of participant [printed]	Signature	Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Paul Roelen	________________	_______
Name or researcher [printed]	Signature	Date

Study contact details for further information:

Paul Roelen

Faculty of Industrial Design Engineering, Delft University of Technology

Landbergstraat 15, 2628 CE Delft, Netherlands

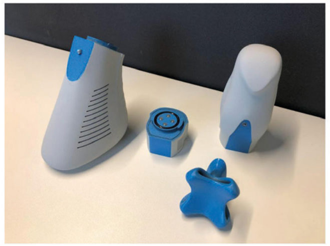
Appendix G

Mock-ups of interactive manuals

Interactive manual: Installing your instrument

Let's start!

Do you have these components?



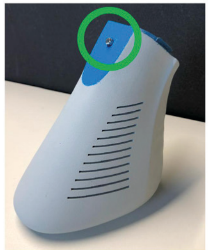
YES, I have all the components

NO, I'm missing some

The component you see here is the base module, which contains the technology to power the instrument and send the recorded data

OK

The component you see here is the PM module, which contains sensors for both PM (particle matter) and a temperature sensor, which is the metal pin button (green ring).



Learn more: PM

OK

The component you see here is the NO2 module, which contains only a NO2 sensor.

Learn more: NO2

OK

Connect the three models, their endings fit together. To lock them, rotate them until you hear a click.

OK

Does your instrument now look like this?

YES, it does

NO, it looks different, maybe show again how they fit

You successfully connected the required modules! Now we want to install the instrument to make it ready for measuring! The instrument is pre-powered, so it is already measuring. The measurements will be saved as soon as you finish this manual.

Learn more: instrument power

Let's install the sensor!

To measure outdoor air quality, the instrument must be installed hanging in the air, we are going to do that using the mount seen here.

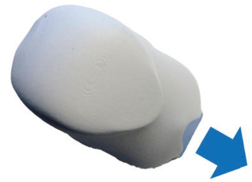
OK

For the best measurements, the temperature sensor (the metal button pin in green) is best placed outside of direct sunlight. Therefore, we are going to face the instrument away from the sun as much as possible.

OK

The placement orientation can help. Since the sun rises in the east and sets in the west through the south, the instrument is ideally faced north. Place your phone on the ground and use the compass on the next page to find the ideal direction, it is okay to deviate from that, only make sure that the sun does not directly shine on the temperature sensor. **Press OK when your phone is on the ground.**

OK



OK, I have the orientation

You are going to fasten the mount, so that it points in the right direction. Make sure the mount points upward, the instrument is going to slide into it. From above

OK, show me how

Fasten the mount with the cable tie, so that it hangs securely. This example shows a vertical railing, but you can also fix it on a horizontal railing with the different holes on the mount.

DONE

You can now hang the instrument on the mount, when you hear a click, the mount is locked

YES, I heard a click

Is your instrument installed like this?

YES!

I don't think so, can I start over?

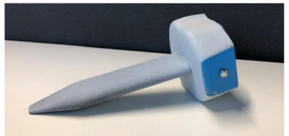
I want to contact the organizer

Congratulations, the sensor is installed and is measuring, you're supposed to see its measurements from tomorrow 8 pm

Interactive manual: Installing your instrument

Let's start!

Do you have these components?



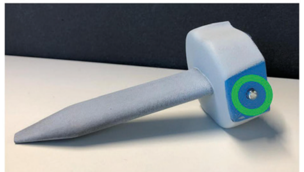
YES, I have all the components

NO, I'm missing some

The component you see here is the base module, which contains the technology to power the instrument and send the recorded data

OK

This is the soil module it contains a soil moisture sensor and a temperature sensor (the metal button pin in green)



OK

Connect the two models, their endings fit together. To lock them, rotate them until you hear a click.

OK

Does your instrument now look like this?

YES, it does!

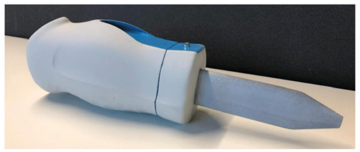
NO, maybe show again how it's done

You successfully connected the required modules! Now we want to install the instrument to make it ready for measuring! The instrument is pre-powered, so it is already measuring. The measurements will be saved as soon as you finish this manual.

Learn more: instrument power

Let's install the sensor!

To measure soil moisture, the instrument must be installed in the ground, we are going to do that using the pin that you see on the soil module



OK

For the best measurements, the temperature sensor (metal pin button in green) is best placed outside of direct sunlight. Therefore, we are going to shield the sensors on the front of the instrument from the sun.

OK

The placement orientation can help. Since the sun rises in the east and sets in the west through the south, the instrument is ideally faced north. Place your phone on the ground and use the compass on the next page to find the ideal direction to make sure that the sun does not directly shine on the temperature sensor. **Press OK when your phone is on the ground.**

OK

OK, I have the orientation

Now push the instrument in this orientation into the ground, until the bottom is against the soil, so that you cannot push the instrument further down with your hands.

DONE!

Is your instrument installed like this?

YES!

I don't think so, can I start over?

I want to contact the organizer

Congratulations, the sensor is installed and is measuring, you're supposed to see its measurements from tomorrow 8 pm

Appendix H

Initial project brief

Personal Project Brief – IDE Master Graduation Project

Name student 　　　　 **Student number**

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title The design of a measuring instrument that improves citizen science participation

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

The project will take place in the domain of Citizen Science, where the public engages in scientific research, stimulating collaboration between citizens, scientists, and policymakers. So called `citizen scientists' engage in various stages of the scientific process, including data collection, analysis, and publication, contributing to new knowledge and understanding. Its a flexible approach that can be applied within the contect of numerous disciplines. Organizations like Scivil in Flanders supports these projects by connecting stakeholders and enhancing their impact.

There are two primary stakeholder groups for this project, one of them being academic researchers. They often design and steer the citizen science projects, and benefit from the extensive data collected by citizens. However, they can also gain from enhanced public engagement and the democratization of the scientific process, leading to better public understanding and appreciation of science. Citizen scientists, being the other primary stakeholder group can also benefit. Interesting aspects to investigate are to learn about science and contribute to research, experience social cohesion and personal joy, and draw attention to local issues to influence policies on various levels. Governments and policymakers are also involved, they benefit from societal advances and can utilize project findings to shape policies.

Currently, the impact of citizen science's advantages is limited because participation of citizen scientists is limited. Dott Achilles, a Mechelen based design company, wants to take the opportunity to improve the current citizen science process. They gave me the assignment to design a measuring instrument that helps to increase participation in such projects by addressing to the needs of both researchers and citizens.

→ *space available for images / figures on next page*

image / figure 1 Example of a measuring instrument from the 'curieuze neuzen in de tuin' project (De Standaard)

image / figure 2

DESIGN FOR our future

TUDelft

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

Citizen science projects currently face several challenges. Scientists struggle to engage large numbers of participants, involve specific target groups, ensure diversity, and sustain long-term engagement. Additionally, developing measuring instruments is extensive and expensive, causing numerous functional, usable and scalable limitations. Ineffective science communication, crucial for motivating, educating, and retaining participants, leads to inaccurate data collection, which is worsened by low usability of measuring instruments. These reasons cause an excessively high threshold for participants to join, reducing the number of participants and limiting contributors to those with strong intrinsic motivation, which negatively impacts the effectiveness and efficiency of citizen science projects.

Opportunities to improve the citizen science process lie in designing a user-friendly measuring instrument that lowers the threshold and increases incentives for participants to join, while enhancing data quality and quantity for researchers, ultimately broadening the application of citizen science and its advantages, benefitting all stakeholders. Addressing these opportunities while adhering to the principles of citizen science, such as mutual benefits, public data sharing, and ethical considerations, will ensure that the advantages of citizen science are retained and that participants are informed, valued and acknowledged.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Design a measuring instrument to improve citizen scientist participation in a citizen science project context, that addresses to the needs of both researchers and citizen scientists

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

First, I will conduct literary research on the motives and incentives of participants in citizen science projects to understand their reasons for participating. In parallel, I will do context mapping, including interviewing participants and professors in the field to gather insights into the strenghts and weaknesses of the current citizen science approach and function analysis of benchmark measuring products. This all will help identify the desired type of measurements and instrument features.

Next, I will combine the insights from the different researches with the principles of citizen science to create a list of requirements for the overall process, but specifically the measuring product within this process. Then, I will start ideating using brainstorming, -drawing and -writing, starting either with the product itself or the service context in which it will be used. After choosing a design direction and selecting a concept, I will detail (product life cycle, eco-checklist), prototype, and validate the concept iteratively with researchers and users (usability evaluation, experience prototyping), adjusting as needed to create a final prototype (3D and physical modelling, technical documentation).

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a ***kick-off meeting, mid-term evaluation meeting, green light meeting*** *and* ***graduation ceremony****. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	15 Jun 2024
Mid-term evaluation	6 Sep 2024
Green light meeting	1 Oct 2024
Graduation ceremony	6 Dec 2024

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

This project appeals to me because it deals with real-life limitations, unlike many academic projects. I am enthusiastic about broadening citizen science application, enhancing social cohesion. Achilles Design offers me the expertise I seek, especially in manufacturing.

I aim to show my **holistic view** on the design process, balancing the big picture with finer details. Throughout my studies, I improved my **problem-solving** skills, emphasizing **iterative design** and **prototyping** from **various perspectives**, which I believe are crucial for **detailing** a product. Combined with **critical-thinking**, is what makes a product **robust.**

I also want to showcase my **collaborative** skills and **storytelling** abilities, often supported through **visualizing** complex components. In addition, I will highlight both **cognitive** and **physical ergonomics.** Regarding manufacturing, I aim to demonstrate my skills in **Arduino and electronics, 3D CAD (Blender or SolidWorks), physical modelling, materialization,** and if applicable, **photography.** Furthermore, I want to enhance **engineering, materialization** and **product lifecycle management,** to cover a product from concept to end-of-life.

Personal goals I seek to further develop are **business** skills, to take a prototype one step further and focus on value proposition. I want to refine my **aesthetics** and **sustainable design** capabilities. I also want to take a **natural / 'intuitive' / emotional** design perspective, and focus on **stakeholder communication,** for both customers and clients.