HeatGuard

Sensing Risk Before Fire

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MSc. Integrated Product Design | Delft University of Technology
The Netherlands 2026

Design Thesis

by

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In partial fulfilment of the requirements for the degree of:

Master of Science
in Integrated Product Design

at the Delft University of Technology,

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Preface & Acknowledgements

This thesis marks my final work as an Industrial Design Engineer student. It has been a motivating and shaping journey, where I learned so much in the field of design and as a person. With great inspirations I found along the way both in the Netherlands and on my exchange in Sweden. I would not have missed it for anything.

Working on HeatGuard has taught me about my passions as a designer in integrated electronics in product design, what fuels my motivations, but also about me personally on trusting myself and my own judgements. Over the last 20 weeks I have been through the entire design process and I now know what I want as a designer: design products that bring electronics and people together.

Safety has been an interesting and challenging topic to me. It presented itself as broad and open to many problems and solutions, many opportunities that require an innovative design. I have landed on e-bike batteries and the invisible fire risk that forms within. A relevant topic to today's world that kept proving its interest to me throughout the project, with another article or picture about this problem weekly. This project showed me how I can tackle a broad topic like safety, and scope it down to a specific solution.

I want to express my gratitude to my mentors, without them this would not have been possible. I want to thank Gert Pasman for his support, great help and knowledge on the design process and helping me guide myself through the broad and complex scope of this thesis. When I lost the greater picture and got overwhelmed with ideas you helped me back on track. I want to thank Peter Kraaijeveld for his shared passion in the smart home and all the valuable brainstorm sessions that brought me great insights. Both your trust helped me chase my own ideas and passion, rely on my own judgements and grow as a designer.

A special thank you goes to Richard Snel and Alprokon for providing me with this great opportunity to work in the field of safety, their support and the amazing team that has been nothing but kind to me in this welcoming environment. The topic of safety has been super interesting to work with and seeing all the passion and knowledge from Alprokon has been nothing but motivating to me.

I want to thank my family and girlfriend for supporting me throughout the process and always having my back. Your support and interest have been valuable to me and pushed me to deliver this thesis. I can not wait to show you more fun projects in the future.

Finally, I want to thank all the participants and professionals who took the time to share their insights, knowledge and honest opinions. Their contributions and constructive feedback gave this project its meaning.

I hope you enjoy reading this thesis as much as I enjoyed writing it.

Executive Summary

Every day, people charge devices in their homes without realising the serious risks involved. Rechargeable lithium-ion batteries are generally safe, yet in 2024 alone, 250 to 300 domestic fires in the Netherlands were related to battery incidents [107]. On a regular basis dangerous accidents with e-bike batteries happen in the domestic environment [108, 128]. Public areas are even starting to ban batteries from their facilities and the fire department is increasingly creating awareness campaigns [26]. With the growing use of e-bikes and other rechargeable devices, this number and the urgency is expected to rise even more. Most existing safety systems detect fire or smoke, but at that stage it is often too late to prevent damage.

Before a battery catches fire, there is a phase in which it shows an irregular increase in temperature. Between the onset of this anomaly and full thermal runaway, there is typically a window of around 34 minutes in which intervention is still possible [58]. Current systems do not operate within that window, and limited research has focussed on prevention within the domestic environment through solutions that actively communicate risk to the resident.

This thesis addresses that gap. It proposes a domestic fire prevention system that monitors the temperature behaviour of rechargeable battery devices, interprets whether a pattern represents a developing risk, and communicates actionable information to the resident before that risk becomes irreversible. The new Alprokon platform 'Every Space Safe' creates a demand for an innovative design solution in the world of safety. Starting from the broad scope of safety, and moving through the Double Diamond design process, theoretical research, iterative ideation, and user tests, HeatGuard was developed.

HeatGuard is a safety system consisting of two components. The first is a physical sensing patch, applied to the e-bike battery, that senses the temperature rate of change and interprets it against learned and fixed thresholds. The second is a mobile application that translates and communicates the data into actionable information, so the user can respond safely to the developing risk of the e-bike battery.

HeatGuard is demonstrated as plausible and explored with users. Rather than a fully validated product, it establishes a set of design principles for thermal safety in rechargeable battery systems and forms a starting point for further development and testing under real conditions.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

My name is Stijn van den Boogaart, a master student in Integrated Product Design at Delft University of Technology in the Netherlands, Figure 1. My interests in design lie in the integration of smart sensing and embedded electronics within design, to bridge the gap between technology and human behaviour. I want to use technology as a tool to create comfort, awareness and control instead of a scary and difficult to understand machine. My vision in design is creating a bridge between the invisible and the tangible, translating something we cannot perceive with our senses, like temperature anomalies in batteries, into actionable interaction that we can use to improve our safety and awareness.

Designing safety is a never-ending topic as new risks are formed as fast as we can design solutions. With my client Alprokon I have found a good match to find an innovative solution within their new consumer platform: 'Every Space Safe'. A 20-week thesis project on a broad but fascinating topic, one that took extensive exploration before landing on a clear problem definition. Through research, expert meetings and stakeholder interviews, thermal safety in rechargeable e-bike battery systems emerged as the focus, and ultimately HeatGuard was designed.

HeatGuard centres on actionable communication and sensing technology, to detect and predict temperature changes within the battery itself. Paired with a mobile application, it informs the user directly with recommended actions for the safest response. HeatGuard senses the risk before the fire is able to develop.

Figure 1: Me

1.2 Alprokon

Alprokon, Figure 2, is a Dutch company that produces safety products for every space [9]. Their main products are astragals, see Figures 3 and 4. These are closing systems for double doors. This product, since early seventies, comes in different varieties and with an extra functional value like fire resistance, smoke, sound and/or burglar proof. Some other products provide for example roof safety and a safe escape. They are an innovative production company that is based in Barendrecht (NL) and distributes 95% of their products through dealers. Their passion for innovation and doing, making and testing things connects closely to my interests and curiosity in design.

The project brief Alprokon supplied is a means to their goal, the Big Hairy Audacious Goal (BHAG) in 2030; Everybody in the Netherlands knows Alprokon and understands their mission. Their mission statement:

"At Alprokon, we believe everyone deserves a safe space. Whether you're at home, at work, or visiting, we want you to feel carefree. That's why we do everything we can to make the Netherlands safer every day."

With their BHAG they want to expand from the B2B to the B2C market with a platform that provides all kinds of safety products in one place that support their mission and makes every space safe. This platform is called: "Every Space Safe". Besides the already familiar products like fire extinguishers and alarms, they aim for new innovative products that redefine safety and improve every space. That is where this thesis starts, with a clear goal and a mission.

ALPROKON.

Figure 2: Alprokon [9]

Figure 3: Astragal, provided by Alprokon [9]

Figure 4: Astragal closeup, provided by Alprokon [9]

1.3 Approach

This project is structured according to the Double Diamond design framework developed by the Design Council [38], consisting of four stages: Discover, Define, Develop, and Deliver. These phases form the basis of the design process and guide the transition from the research phase (Discover & Define) to the design phase (Develop & Deliver), as shown in the Figure 5.

Each phase of the Double Diamond presented a unique goal:

Discover
This phase was used to explore and understand the domestic safety landscape. Through desk research, expert meetings and stakeholder interviews, different types of safety, existing risks, current solutions and behavioural patterns were mapped.

Define
The insights from the discovery phase were used to define the core concepts of safety and Every Space Safe, and to create a problem definition. A set of selection criteria was developed to guide decision-making across risk categories and solutions. This phase narrowed the scope from a broad safety landscape to a specific design direction.

Develop
Within this phase, the solution was developed through sketching, prototyping and testing. User research and journey mapping provided information for the design of both the sensor system and the user interaction, translating the problem definition into a working solution.

Deliver
The final phase resulted in a concept validated through user evaluation, supported by a functional prototype designed to convey the intended user experience.

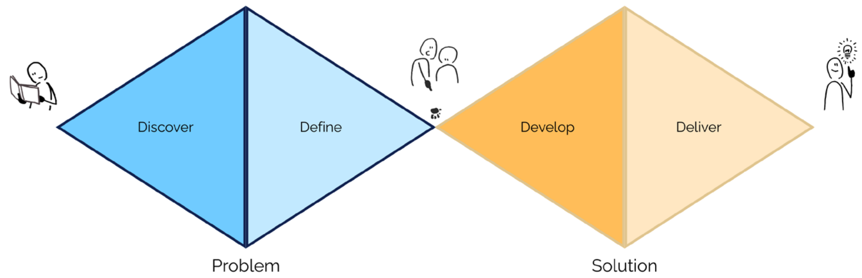


Figure 5: The Double Diamond approach

Personal approach

The approach of the double diamond in this process was used to take in as much information as possible, exploring as many areas as I could within the criteria I set of Every Space Safe. During the research phase I applied multiple divergence and convergence moments to understand and define a specific problem definition, as seen in Figure 6. Using multiple research and analysis methods I explored and evaluated on multiple areas of safety, I stayed curious for interesting design gaps and areas, documenting them in text and graphs.

A personal challenge in this process was my tendency to explore and drift off too much during the research phase, especially with such a broad design brief, making decision-making more difficult. That is why a structured and clear approach was essential for me to keep me on track and focussed when moving forward.

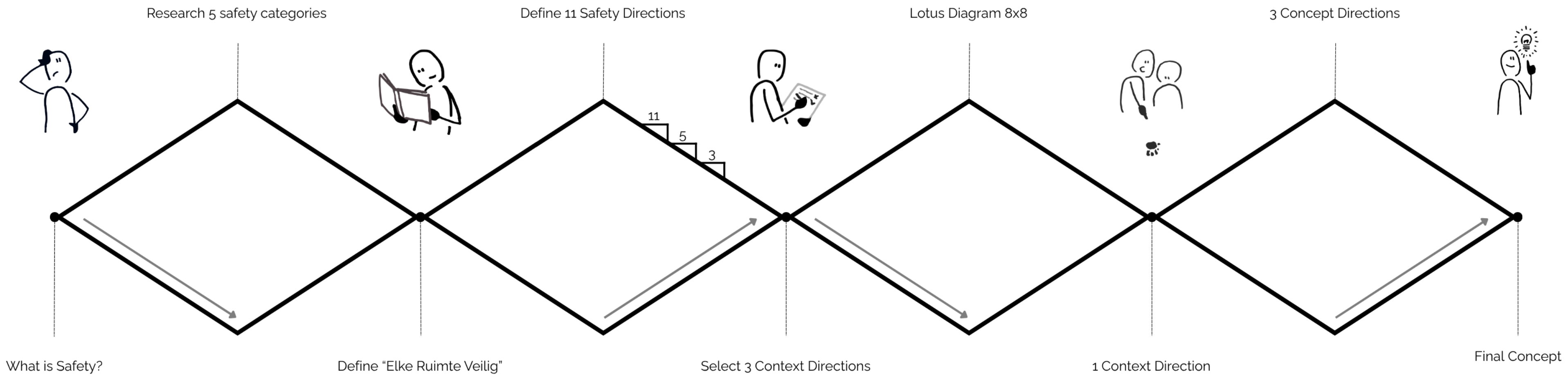


Figure 6: Personal research phase approach

AI statement

In this thesis, besides the applied approach and methods, I also used Artificial Intelligence (AI) tools to support my design process. I primarily used AI as a tool that acts as a sparring partner during brainstorming and to assist in rewriting text into academic British English. Secondly, I used AI as a development tool for the HeatGuard mobile application, through vibe coding and the generation of renders and images from my own artwork. The full overview can be found in Appendix L.

In each case, the input is supplied by me and the output critically assessed. AI was not used to generate any data or draw any conclusions for this thesis. All data is original and I, as the author, remain responsible for all outcomes.

1.4 Problem statement

The main challenge is that current domestic safety systems detect fire or smoke after a fire has already started. What they do not detect is the temperature build up that happens before. Rechargeable battery systems in e-bikes overheat before catching fire, following a pattern that is measurable but not perceptible to the human senses. There is a window between the first signs of abnormal heat formation and the moment of ignition in which intervention is still possible. Current systems do not operate within that window, which is the gap I aim to address.

This gap is shaped by everyday human behaviour. People leave devices charging and appliances running while their attention is elsewhere, not out of ignorance, but out of routines. Mechanical abuse to the battery is rarely perceived as a direct risk, dismissed as nothing serious, but can create significant internal damage. When you combine this invisible risk with a distracted and uninformed resident, you have the perfect conditions for domestic fires.

The relevance of this problem is growing, and people are starting to pay more attention. The number of lithium-ion batteries in the home is rising fast, driven by the increasing adoption of e-bikes, power tools, portable devices and home energy storage. There is a systemic increase in domestic energy density without a corresponding increase in safety measures.

The million-dollar question within battery safety is how to prevent the battery from going into thermal runaway at the cell level, and how to predict it at the first signs of internal damage. This thesis does not attempt to answer that question. It rather accepts that batteries can and will fail and designs a system around that reality. By translating the invisible dangers of rechargeable battery systems, I can guide the resident to act on this risk before it develops into an irreversible danger.

The Netherlands is a cycling-dense country, where a significant number of households own an e-bike or battery-powered bike. These bikes are used daily, charged in all kinds of places, exposed to a variety of abuses and a high fire hazard, see Figure 7. That combination makes it a real risk to design for.

This project addresses e-bike battery safety through a system that senses the early temperature rate of change increases in e-bike batteries, communicating actionable information to the resident in proportion to the actual risk level, and providing a clear guide for the user on how to respond safely.

Figure 7: E-bike battery burnt out [16]

CHAPTER 2

UNDERSTANDING SAFETY

This chapter starts the first phase, the discover phase, of the design process, see Figure 8. Discovering the background to form the fundamentals for this thesis. Understanding the landscape of safety means understanding safety. This definition of safety forms the criteria that ultimately guides the design choices made further in the process.

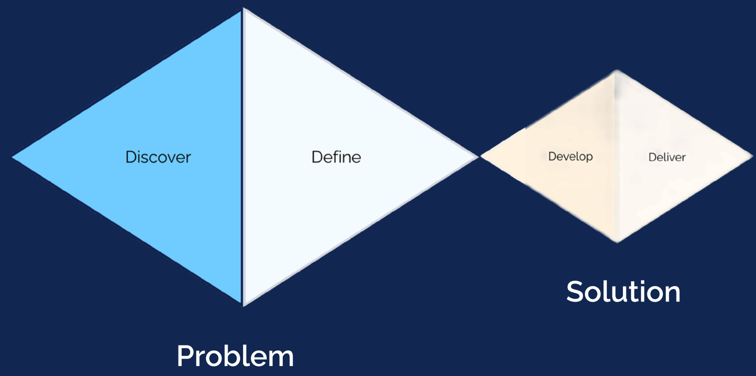


Figure 8: Discover phase

2.1 Safety

According to Maslow [92], another important motivator for survival, besides water, oxygen and food, is safety. Safety plays a crucial role in the happiness and quality of life for people. In research, safety is commonly defined as the absence of danger, injury or harm [125, 20, 133]. Yet, research by Raheemy et al. shows that safety is more than physical protection alone. It is not just about guarding yourself from external threats, it is also about safety as prevention, a condition of protection and the absence of harm [125]. Despite these studies, many definitions continue to prioritise physical risk management [20], while giving limited attention to the mental experience of feeling safe.

Safety is not just about controlling danger, but also about perception, awareness, and trust [69]. Everyday experiences, such as leaving your home with confidence or sleeping with the assurance that potential dangers will be detected, demonstrate that psychological safety in the home is strongly linked to physical safety. The person's susceptibility to harm and how they experience this danger strongly influence their behaviour in relation to risk [84]. When dangers are not recognised or understood, people may make decisions that ultimately increase risks, such as fire hazards or bad health consequences.

2.2 Objective and subjective safety

Physical and psychological safety can also be described as objective and subjective safety [149, 133]. Objective safety addresses the measurable safety, that is observable and can be argued for. Subjective safety are the feelings and emotions that people have with something or someone, their perspective on the situation, and control. This can be very different varying on the person, a feeling of whether someone feels safe at home can be different for neighbours in the same street, while the objective safety, burglary risk for example, is the same [122]. This difference does not only account for the residents themselves, but also for those closest to them who carry a sense of worry on their behalf. The resident wants to feel safe. Their loved ones want them to be safe.

Physical safety involves signalling danger and performing an appropriate response, including prevention, protection, and alarm systems [100]. The stakeholders that are interested in this type of safety are insurance and security companies, police or fire services. Emerging technologies, including IoT, smart systems and intelligent sensors, support this process by providing real-time and predictive detection of danger [110]. Translating physical risk assessments into accessible information through sensing and visualisation improves these systems in their level of awareness and effectiveness. Also, these smart systems are good at handling both objective safety and the subjective feeling of being safe at the same time.

2.3 Every Space Safe

Every Space Safe, Figure 9, can be divided into its three individual components, that each highlight a different perspective on safety. To structurally found the choices made in this thesis, I first must define what they mean.

Figure 9: Every Space Safe [9]

2.3.1 Every

Every does not literally mean every space. It refers to every space in which a preventable domestic risk can develop and where a design intervention can structurally reduce that risk. The selection of these spaces is explored and explained by desk research, stakeholder interviews and domestic sketching, later this chapter.

In this thesis, every means every space in the home where a rechargeable battery device, specifically an e-bike battery, is charged or stored. The location changes based on the routine of the resident, this means it can be a garage, a hallway, a living room or a bedroom. Moreover, the risk is not always fixed to one specific room, it follows the device. Because the home is seen as a safe space, the risks in house are often underestimated, and charging behaviour becomes automatic rather than attentive [51].

Every also implies safety for everyone within that space, not only the battery owner. Interestingly, I found a motivation of people living together that changes their risk acceptance, the “watch out” behaviour. People may accept risks for themselves, but not for people close to them or who they live with. This is not a central focus, but an interesting motivator that creates a sense of responsibility, which returns in the action matrix in Chapter 8.1.

Human factors research shows that routine behaviour, fatigue and distraction increase the likelihood of domestic accidents [18, 51], and this design highlights these behavioural limitations within the design and uses them to identify the moments and conditions in which risk is most likely to develop.

Every in Every Space Safe is therefore defined as every space in the home, in the Netherlands, where batteries are charged and stored.

2.3.2 Space

To clarify the spatial criteria of this design, I formed a definition of Space based on desk research on safety, the five identified risk categories, and the context sketching on both user and space level in this chapter.

A space is defined as an enclosed functional area within the house, that is characterised by recurring activities, technical properties and identifiable behavioural patterns. It is only focussed on internally generated risks that can form and develop within these spaces. A space is not only a physical boundary, but also a behavioural and risk containing environment. The behaviour of the resident is influential on the formation and development of the risk, the resident interacts with the space during its daily routines and that influences what the risks do or are.

In this thesis, the relevant spaces are those in which e-bike batteries are charged or stored, which can be a garage, hallway, bedroom or living room. These spaces are different in layout, materials and conditions, but the central activity remains the same: a battery is connected to a charger and left without supervision. That pattern creates a predictable risk moment in the different spaces, which in turn highlights the dangers of routine behaviour.

At the same time, a space is part of a larger whole. Risks and symptoms like smoke, heat, or electrical overload that begins in one room can affect another. This means that a connected set of rooms can therefore also be viewed as one functional space when activities and risks are transferred.

Space in Every Space Safe is the area around the e-bike battery and the room it is in, wherever the device is charged or stored is the space created that needs to be safe.

2.3.3 Safe

Building on the definitions of objective and subjective safety established in Chapter 2.2, Safe in Every Space Safe has a more detailed and elaborate definition.

Safety in this thesis is about prediction rather than reaction. It means the safety measure needs to recognise a pattern, condition or behaviour that can lead to danger and identify them before harm develops. It is more effective to act before an incident, to potentially reduce the risk, instead of after the fact. Therefore, it is important to know what is likely to happen. However, prediction does not mean perfectly foreseeing danger. It works within probabilistic boundaries, and these boundaries must be clearly set and communicated to the resident.

Objective safety in this design is about measuring and detecting the thermal activity, environmental conditions or behavioural patterns that can cause harm. The goal is to detect these risk factors before escalation occurs, within the prevention window that allows for intervention and gives the resident the awareness to act.

Subjective safety touches on the resident experiences and how the resident perceives risk. For this thesis, subjective safety must have its foundation in objective safety. False reassurance, a feeling of control that does not actually reduce the risk, is thus not considered safety. The design cannot simply create the illusion of safety, it must create the conditions for it, when something is safe or not, and communicate those conditions with actionable information.
Active, actionable feedback and clear communication about potential risks is created through the connected network systems in the house, and it should create awareness of the developing risk.

Safe in Every Space Safe means detecting a risk before it becomes dangerous, and making sure the resident knows about it in time to act.

2.4 Exploring the landscape of safety

To explore the landscape of safety, desk research was conducted to form five categories of domestic risk: burglary, fire, personal safety, chemical and gas hazards, and electrical hazards, Figure 10.

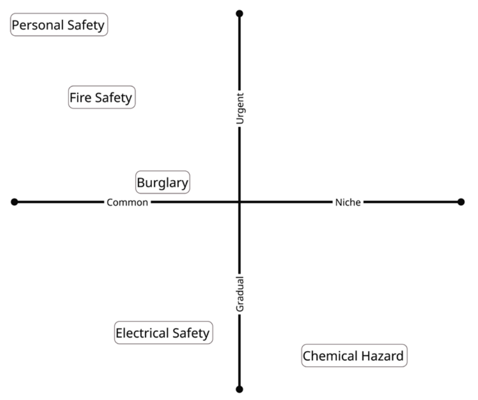


Figure 10: Graphic distribution of safety in Gradual vs. Urgent and Common vs. Niche

Each was analysed using the same structure of space, risk, need and solution. This made it comparable and presented me with a clear overview of all five categories, see Table 1. The full analysis is available in Appendix A.1.

Of the five, fire and electrical hazards surfaced as the most relevant. The two are closely linked, yet electrical hazards deserve separate attention because of a rising trend in domestic energy density too major to dismiss.

Around half of residential fires come from human action, routine behaviour, errors and a misunderstanding of how hazards form [115]. Early detection is therefore essential.

Category	Behavioural Influence	Prevention Window	Visibility	Solution Focus
Burglary	Low - Primarily External	Minimal	Moderate	Camera's, alarms, locks
Personal Safety	High - Routine, Fatigue	Minimal	Moderate	Mechnical, behaviour change
Chemical and Gas	Low - Infrastructure	Large	Low	CO detectors, air control
Fire	High - Human Error	Moderate	Low	Smoke / Heat detectors
Electrical hazards	High - Charging Behaviour	30 - 60 min	Low	Circuit breakers, surge protectors

Table 1: Safety Category comparison

Yet most systems respond to symptoms, like smoke or heat, rather than the conditions that cause them [32, 70, 146]. Within this landscape, the growing number of lithium-ion battery systems introduces a rising risk: thermal runaway. Under abuse, this can cause rapid fire development, explosions and toxic gas release [169, 171, 173].

Together, human influence, an actionable prevention window and the need for better solutions made fire and electrical hazards the strongest direction, see Figure 11.

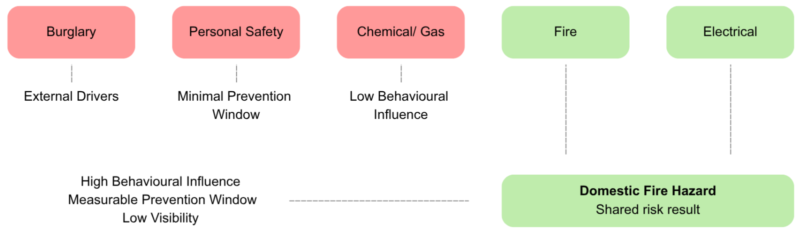


Figure 11: Direction; Domestic Fire Hazard

2.5 Sketching the domestic space

To validate these findings against the reality of daily life and domestic living, two contextual maps were created: one follows a resident through his evening routine, the other views each room as a risk environment, see Appendix A.2. Both maps independently arrived at the same high-risk spaces and reinforced the same conclusion that the hallway, kitchen, garage and bedroom have the highest overlap of behavioural risk and electrical hazard. It also highlights the human behaviour risks of being fatigued, distracted and having divided attention.

The human map sketches the spaces in the house where the user creates risk mainly due to the influence of human behaviour. Evaluating this understanding highlights that small risks can become larger due to divided attention or distractions. The main takeaway is that risks are "normalised" through familiarity and routines, people feel confident that nothing will happen since it has never happened before or since they are simple not aware of the dangers. Until something does happen, like a battery fire, see Figure 12.

The domestic map looks at the same spaces, but from the perspective of the home itself. In this view, the increasing energy density is identified as a common risk factor across the spaces. Charging and battery storage does not happen in one fixed location, it is rather an activity that happens throughout the house, dependent on the routine of the resident. Heat developed in one space can affect neighbouring areas. This supports the perspective that the domestic environment can not be viewed as separate spaces, but as a connected system in which local risks can affect the rest.

Figure 12: New York city apartment fire caused by electrical scooter parked inside [102]

2.6 Field research

I visited Gamma, Praxis and Hornbach to study what safety products are available to the regular consumer, see Appendix A.3. From my observations, the five types of safety as defined before can be recognised. A wide variety of product is available, yet the focus is on symptom management or mechanical protection / prevention, see Figure 13.

Moreover, the majority of available products is focussed on fire safety and burglary. This saturation in this section of the market reflects both the big demand for these products, the awareness that it brings and the pressure from regulatory parties as some are mandatory by law.
This leaves a big gap for active prevention, especially in the rising energy density in the home. Very few to no products target temperature development in battery systems. An interview with the Fire Department, for the full thematic analysis see Appendix A.4, highlighted the need and demand for safer battery systems, specifically home batteries. Due to the increase in solar panels and the disappearance of the net-metering arrangement [130], people are increasingly purchasing home batteries [129]. However, with bad installations and improper ventilation this can form a great risk. The fire department recognises this trend and express their concerns.

An interview with a General Practitioner (GP), the full thematic analysis is available in Appendix A.5, highlighted and reinforced the findings on personal safety that it is highly influenced by human behaviour. And that the prevention window is minimal, every item in the way has the potential to cause a tripping hazard and that can be instant. In accordance with the market findings in the hardware store, most solutions are mechanical and preventive, yet the GP and occupational therapist find solutions in changing the behavioural patterns. These findings confirm that personal safety, while relevant, does not offer the detection window that this design requires.

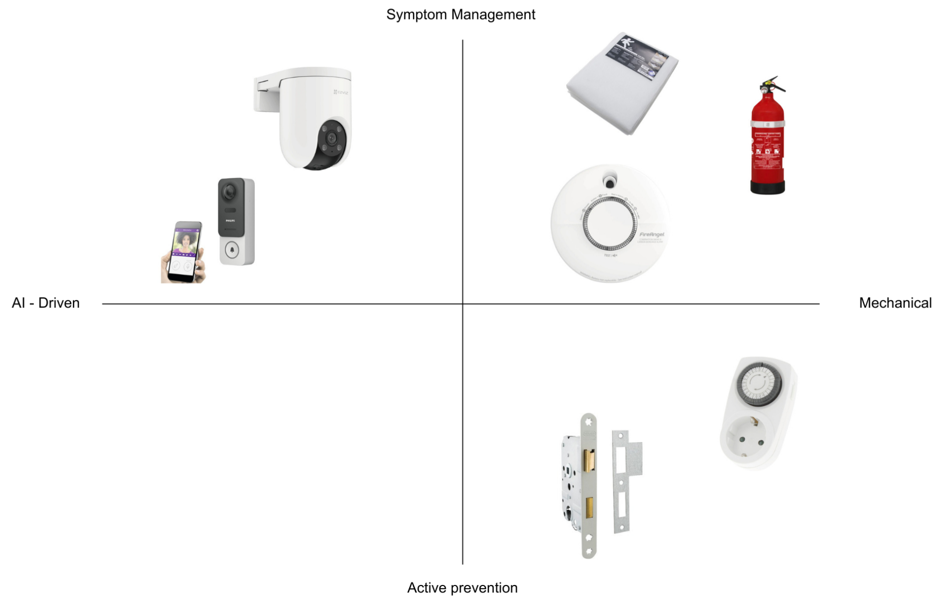


Figure 13: Comparing existing products, left to right: AI – Driven vs. Mechanical, bottom to top: Active prevention vs. Symptom Management [71, 72, 73, 74, 75, 76, 77]

2.7 Idea generation

The Lotus Diagram is a structured ideation method, Figure 14, in which a central theme generates eight surrounding directions, each expanded into eight sub-ideas represented by eight different colours [131]. The result is a matrix of 72 ideas clustered by 8 themes. This method allowed me to explore the landscape of preventive sensing in the home regarding thermal risk. Using these findings, I was able to understand what is possible and why rechargeable battery systems are the strongest fit. The full analysis of all the results and ideas can be found in Appendix A.6.

From the central theme, eight directions were selected to represent different domains in domestic fire risk. The eight note colours' only purpose is to link each central theme to the area where it is explored further. The coloured dots, however, are separate, and carry the voting categories.

Dot voting, Figure 15, highlights three recurring themes within the diagram:

First, Yellow, most devices do not stay in one place and are not charged in the same location at all times. This requires the system to be either portable or detect in a wider space. As charging behaviour is grounded in daily life practices, it is identified as a challenge to design for this irregularity.

Second, Blue, the lack of human supervision shows the influence of human behaviour into the development of risks. This routine behaviour lets devices be charged without the required attention of the resident to make it a safe practice.

Third, Red, invisible thermal risk was highlighted as the common risk mechanism. In different spaces in the house, heat develops and temperature can increase without the resident being able to detect it. Heat development is not instant, which demonstrates an opportunity to flag early thermal anomalies before the prevention window closes.

Figure 14: Scanned handwritten Lotus Diagram

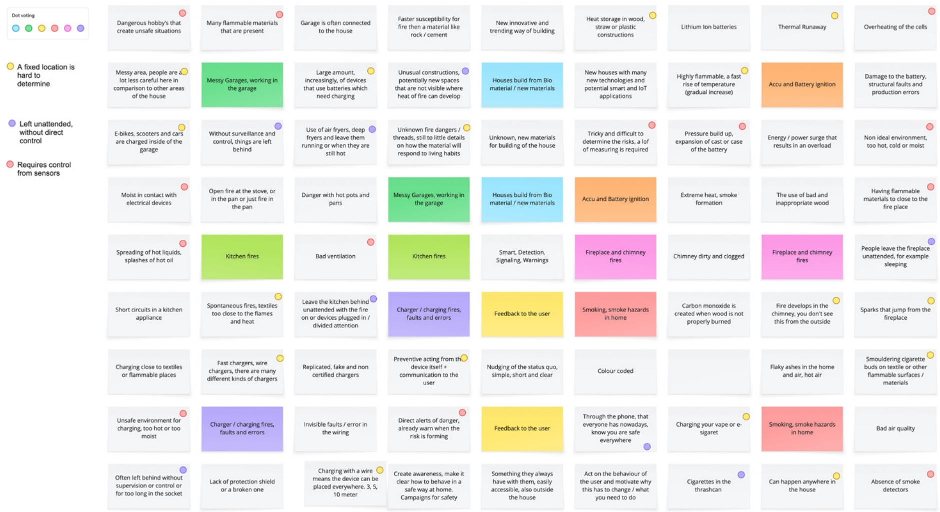


Figure 15: Lotus Diagram dot voting

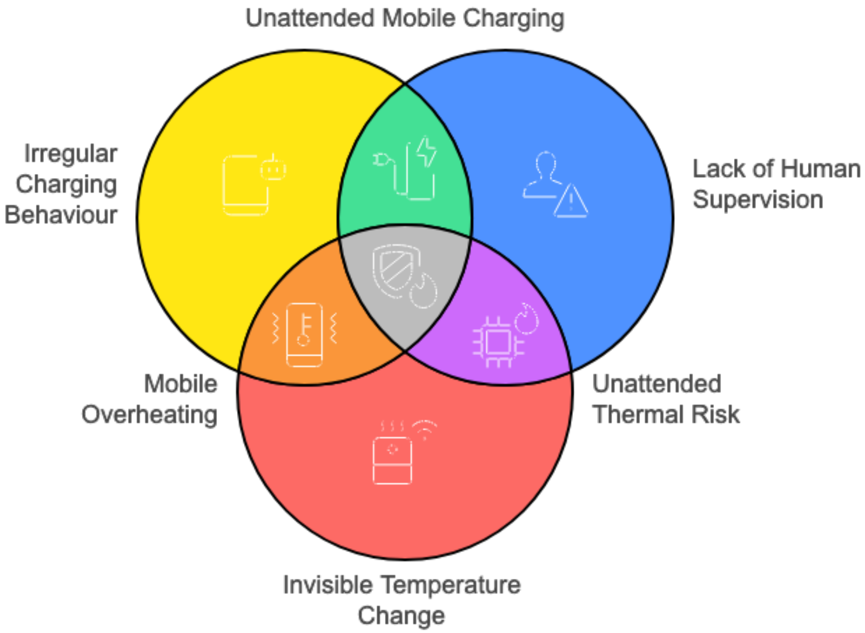


Figure 16: Patterns and challenges in thermal risks, image generated using Napkin [140]

Figure 16 shows a clear overview of how the patterns of the Lotus Diagram overlap and form new challenges that ultimately lead to thermal risk in the middle. It demonstrates the complexity of domestic fire hazards, the influence of human behaviour and the invisible nature of these temperature changes. It addresses the challenges and aspects that need to be considered when designing a system for this problem.

2.8 Smart trends

The full trend analysis is available in Appendix A.7. Three trends are identified and described here that are directly linked to rechargeable battery systems and collaborative communication.

Battery risks. Battery-related incidents are rising, this is seen in different battery systems, not just e-bikes, but also power banks and larger vehicles [5, 19, 162]. Fire department data from Utrecht shows approximately 20 callouts per year and rising specifically for e-bike battery fires [137]. This reflects a systemic increase in the number of high-energy batteries stored and charged in homes [107]. Figure 17 shows the increase of home batteries alone, which is flagged as a growing risk by the Fire Department, Chapter 2.6.

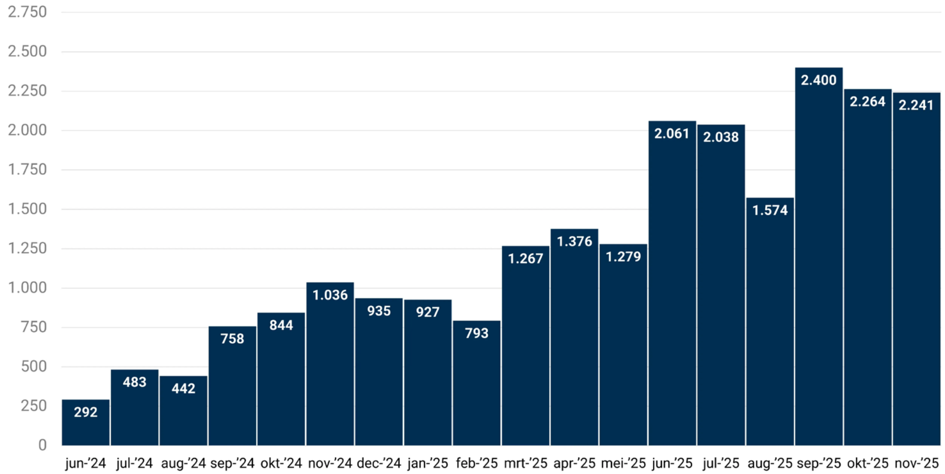


Figure 17: Total number of newly registered batteries in the Netherlands [99]

Of the battery incidents with a known cause, 72% occurred during charging [100]. A big reason is the rise in use of aftermarket chargers and converters, which are often uncertified or badly tested, as manufacturers increasingly ship devices without them for sustainability reasons [100].

AI-driven context understanding. New technologies are shifting the home from a passive space to an active, context-aware system [147]. Rather than responding to binary commands, systems start to learn behavioural patterns and respond to anomalies [123]. A system that learns what a normal charging cycle looks like can distinguish the abnormal, creating more reliable, predictive measurements and actionable communication to the user.

Collaborative sensing. The World Economic Forum identifies collaborative sensing as an emerging technology. These are connected systems that share data across individual devices to create a shared understanding of what is happening [176]. This is what turns a thermal sensor's reading into actionable, contextual communication like, whether someone is home, the room is occupied, or the device can charge unsupervised.

The identified trends serve two purposes. The first is pointing to an area where innovation is relevant, and the second is to identify emerging technologies that will form a technical starting point for this thesis. In combination with the identified market gap and the rising trend in domestic energy density, the trends support rechargeable battery systems as a dominant risk factor within the domestic environment, see Figure 18.

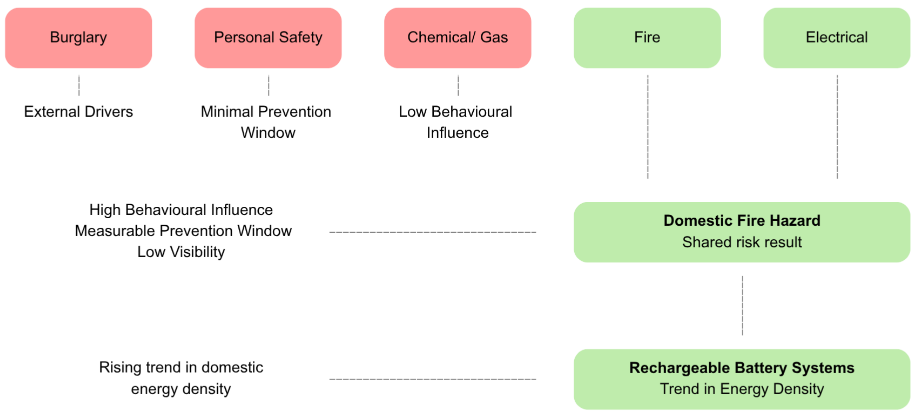


Figure 18: Rechargeable battery system focus

Chapter takeaways

Safety is more than the absence of danger. It is also about perception, awareness and trust. Objective and subjective safety are closely tied together, and both are important when providing safety in design. Yet false reassurance is not safety. The feeling of safety must be grounded in something measurable.

Every Space Safe is now defined in three parts. Every refers to the spaces in the home, in the Netherlands, where a rechargeable battery device is charged or stored by people living together. Space is the area around that device and the connected room it is located in. Safe means recognising a developing risk inside the prevention window, and communicating that risk to the resident with actionable information in time to act.

Following the research, interviews, trends and the exploration of the domestic safety landscape, I evaluated the findings against these definitions and criteria. What kept coming back was a pattern of the same combination in fire and electrical hazards. These hazards showed the strongest behavioural influence, a measurable prevention window and the lowest visibility to the resident. With a focus on the Dutch market that Alprokon situates itself in, trends highlight a rise in rechargeable battery systems and an increase in energy density. Especially due to the sustainability measures taken within the Netherlands to make everything greener, these battery systems are getting increasingly popular. This direction is identified as a substantial market and design gap.

With this explored safety landscape and the identified problems in rechargeable battery systems, I move into Chapter 3. There, using trend analysis and technical research, I will explain how these insights led to the design choice of selecting the e-bike battery as the main focus of this thesis.

CHAPTER 3

THE E-BIKE BATTERY

The insights from the first phase form the basis for the next step in identifying and creating the problem definition and solution, Figure 19.

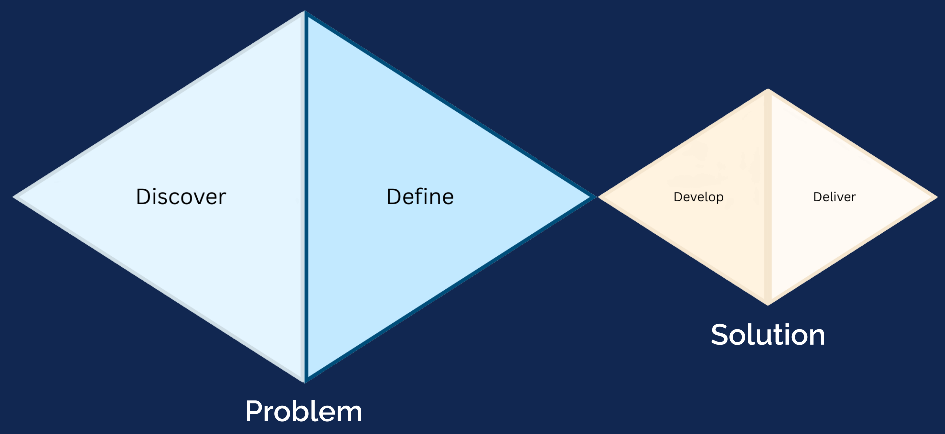


Figure 19: Second problem phase, Define

Figure 20: Removable e-bike battery [29]

First, I defined 11 potential problem directions. The full set is presented in Appendix B. These were evaluated against the criteria established in Chapter 2.3 and compared based on the findings of the preceding research. From this analysis, one direction was selected: electrical vehicles, batteries and electrically charged devices, Figure 20.

3.1 The biking country

As identified in Chapter 2, there are many different devices that include lithium-ion batteries, such as smartphones, tablets, home batteries, portable batteries and e-bikes. These all form a significant risk in the domestic environment when exposed to abuse. In the Netherlands, as the amount of bikes is rising, already exceeding the population, see Figure 21, and cycling is a part of daily routine. E-bike batteries are highly susceptible to all forms of abuse, see Chapter 4.2, and are regularly exposed to bad charging due to routine behaviour.

The number of e-bike sold in the Netherlands has more than doubled over the past decade, Figure 22, and with more people using them, the batteries come into more contact with abusive conditions. Where it used to be elderly riding e-bikes, today children, teens and adults use them for daily transportation. With 48% of the bikes in the Netherlands are electrical bikes, see Figure 23. And when these bikes are used without care, the damage on them increases and so does the risk for danger.

Figure 21: Trend graph of bikes in the Netherlands 2000 - 2023 [126]

Figure 22: Number of E-bikes sold in the Netherlands 2014 - 2023 [126]

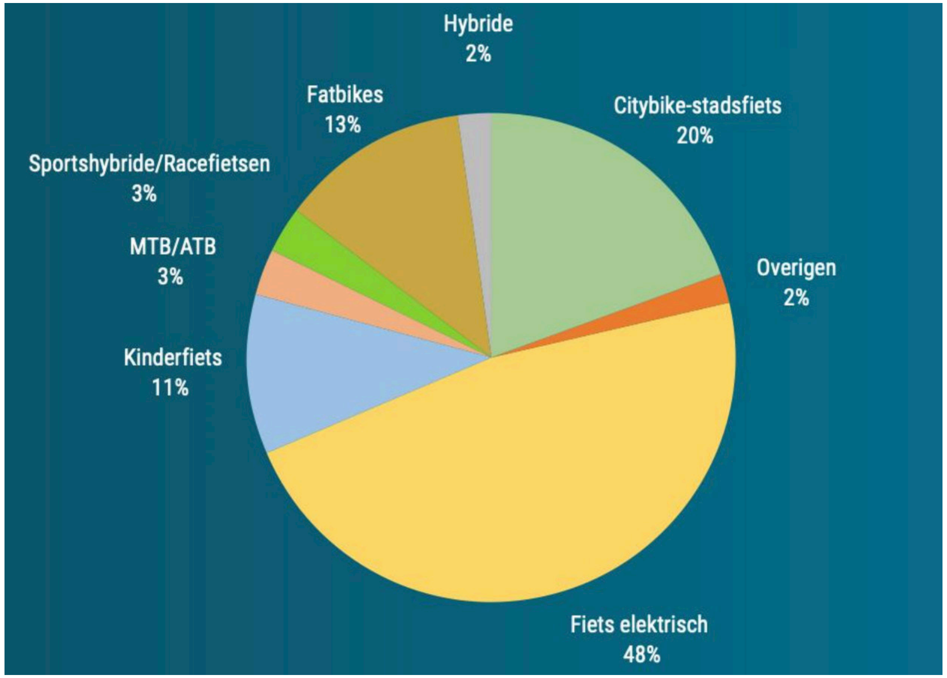


Figure 23: Graph of the market share in 2024 of the Electric Bike in the Netherlands [25]

3.1.1 The e-bike structure

E-bike batteries consist of multiple individual lithium-ion cells in parallel and series that, when overheating, can cause a chain reaction to overheat neighbouring cells. This exponentially increases the risk for thermal runaway and fires. The structure of the e-bike battery and the arrangement of the battery cells over the full length of the shell creates a need to sense over the entire shell, Figure 24. As one cell can go in thermal runaway, a single spot sensing method would not be enough. This creates a requirement for total length sensing, and the use of multiple sensors. In the design process this need to be considered.

As identified in Chapter 2.8, the trend research showed the dangers of aftermarket chargers and converters due to the decrease in supplied certified chargers. E-bike battery systems make use of an AC adaptor or power brick that converts the outlets high-voltage alternating current to the required low-voltage current. When faulty, because of abuse or the use of uncertified aftermarket power bricks, this can cause damage to the e-bike battery. However, as this power brick does not contain actual battery cells, it was decided that this part of the system is not in the scope of this thesis, and the design solution will focus on the e-bike battery alone.

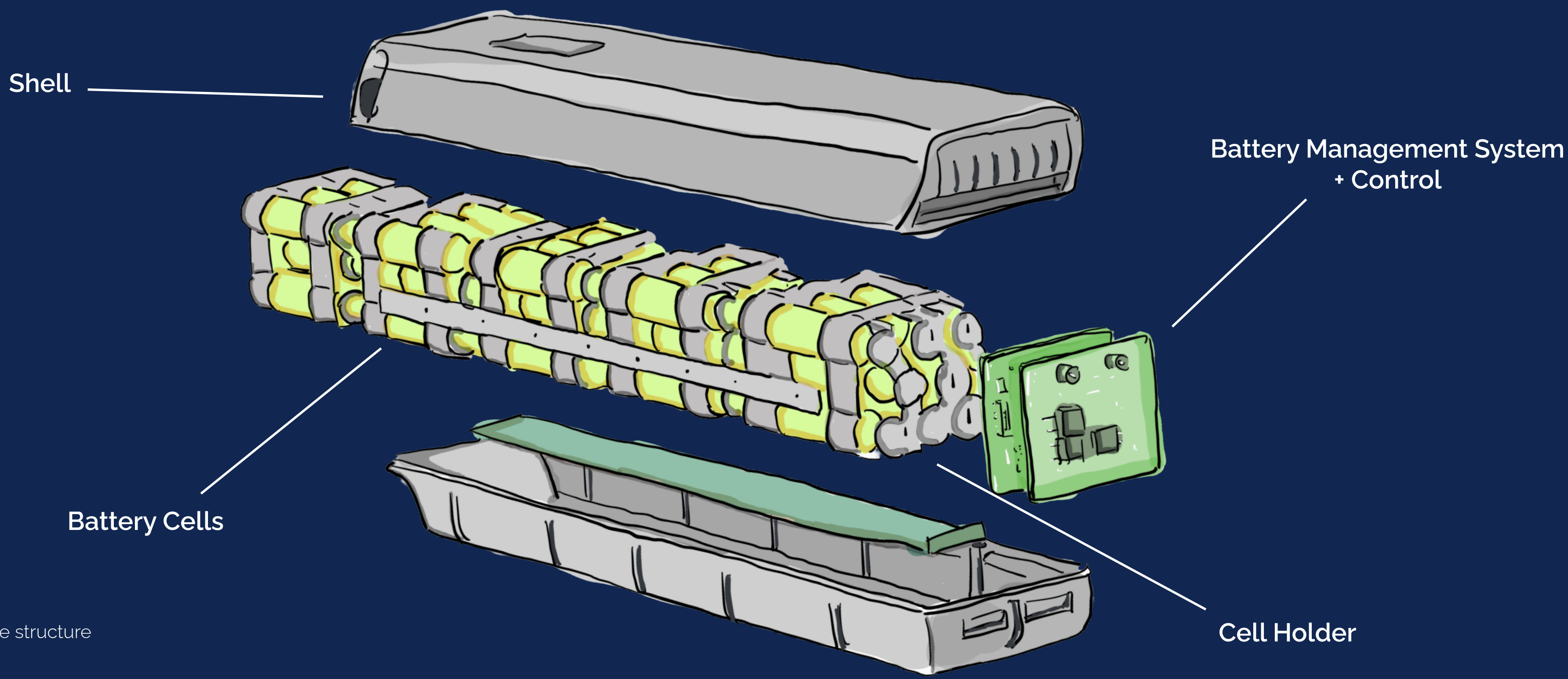


Figure 24: The e-bike structure

Amongst all rechargeable battery systems present in the Dutch household, the e-bike battery, Figure 26, presents the highest combination of risk danger, behaviour influence and abuse exposure. Therefore, it was decided to design for e-bike batteries, Figure 25.

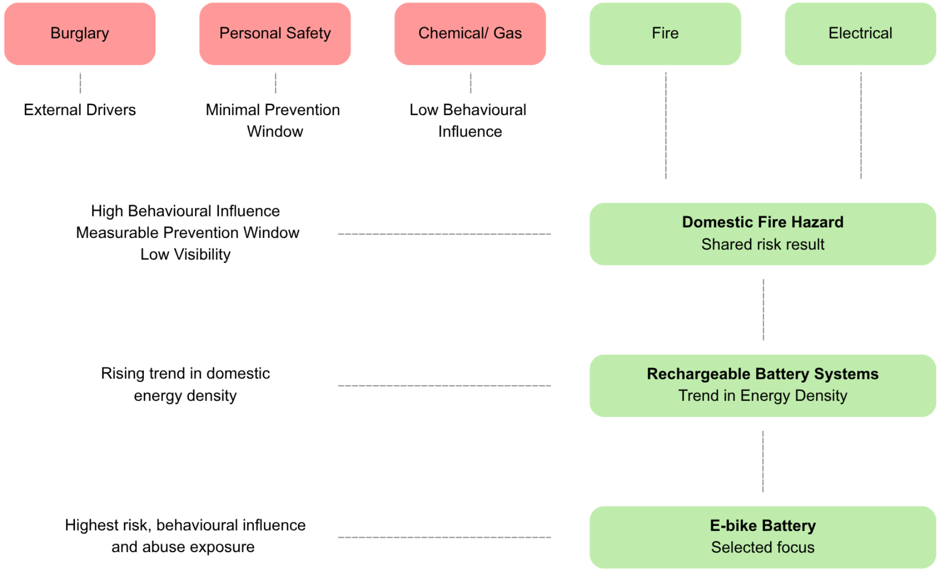


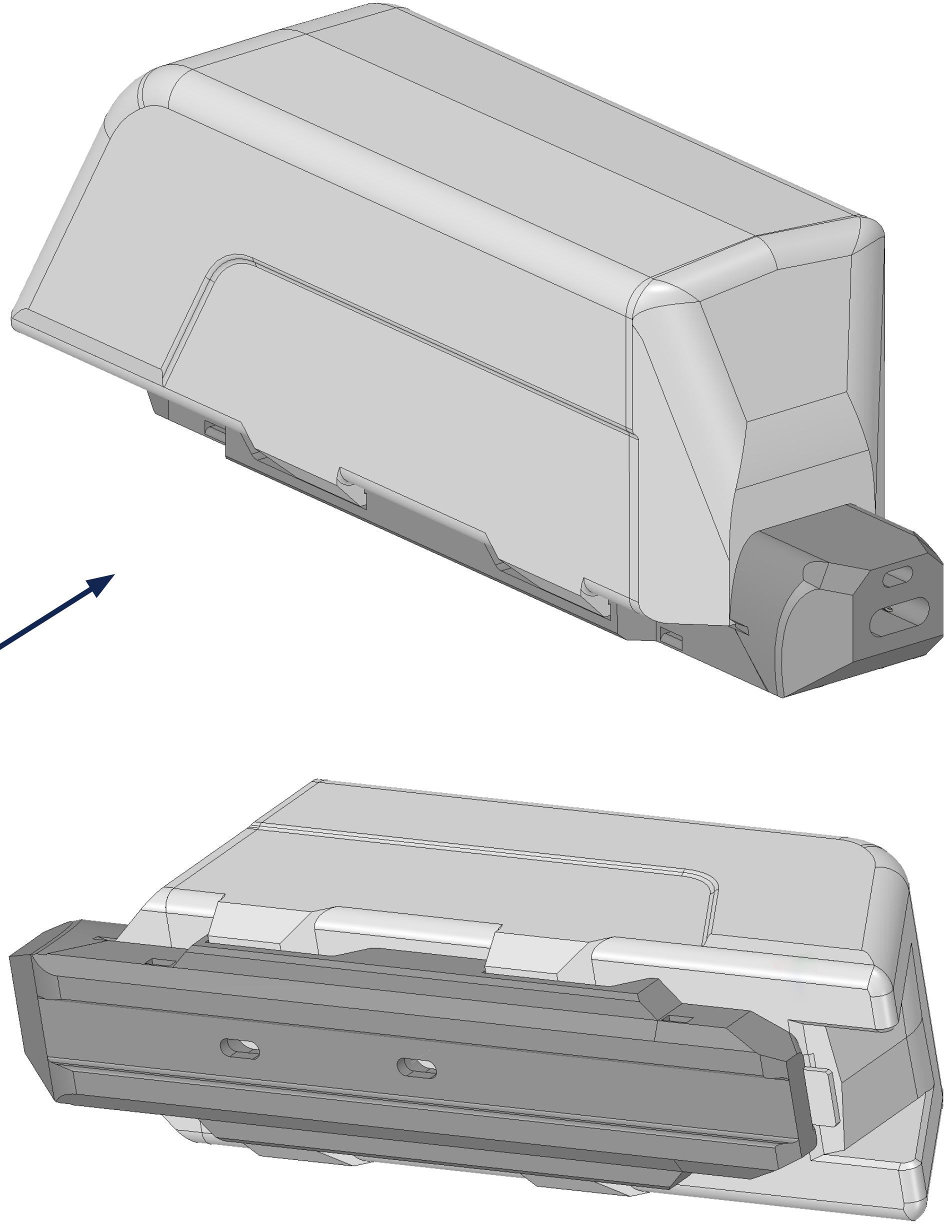
Figure 25: E-bike battery chosen as the problem focus

Figure 26: E-bikes in the Netherlands [107]

3.1.2 The battery model

The Netherlands has four common variations on the e-bike battery model [52]. The rear rack (removable from above or below), behind the seat tube, hidden in-frame tubing, and the fixed in-frame battery, see Figure 27 from top left to bottom right. Within these variations there are multiple different battery models. Each has its own attachment process, internal structure and charging method.
As a design reference for this thesis, I selected one model that I found to be representative of the e-bike models. The e-bike battery that mounts behind the seat tube, top right in Figure 27. It has an attachment system on one side and an exposed shell on the others, see Figures 28 and 29. The fundamental sensing principles and design solutions created in this thesis form the basis and foundation for designing for other battery systems.

Figure 27: four e-bike battery bike variations [52]


Figures 28 and 29:: MK2 E-Bike Battery Pack for 40 Cells and BMS ebike by butchja on Thingiverse [28]

Chapter takeaways

Biking is part of daily life in the Netherlands. There are more bikes than people. E-bike sales have more than doubled over the past decade, and fatbike interest has increased significantly in the past five years, in close correlation to the increase in domestic battery fires [107]. What was once most popular amongst the elderly is now more interesting for children, teenagers and adults under ordinary, often careless conditions and use.

Of the eleven problem directions defined in Appendix B, the e-bike battery emerged as the device with the highest combination of risk severity, behavioural influence and abuse exposure in the Dutch home. Internally, the cells sit in series and parallel along the full length of the shell, so a single overheating cell can create a chain reaction that ignites or damages neighbouring cells, requiring full coverage sensing to be safe.

In the Netherlands there are four common versions of the e-bike battery model, however, within those there is a wide variety of models. Several were highlighted and ultimately one of the e-bike battery models was selected as the design reference. I take this to be representative of the e-bike models and will use this model throughout this thesis. The principles developed can be used in the design of and to translate to the other battery models and systems.

Chapter 4 moves into the cell structure itself and the staged progression of thermal runaway, into the real mechanism behind the risk and the boundary conditions for the solution.

CHAPTER 4

THERMAL RUNAWAY

Figure 30: Thermal runaway in action [106]

4.1 What is thermal runaway

Thermal runaway (TR) is a self-accelerating failure process within lithium-ion batteries in which the internal heat generation gets larger than the cell's ability to dissipate it. This results in an uncontrollable temperature increase that can lead to fire, explosion, or the release of toxic and flammable gases, see Figure 31 [57]. Once the process of TR is triggered, the temperature can reach several hundred degrees within seconds [58]. What makes TR especially dangerous, and therefore even more relevant to the domestic environment, is the combination of the invisible threat and suddenness. From an external perspective and to the human senses nothing changes, however, internally the electrical and thermal behaviour of the battery affects the cell's structure [58].

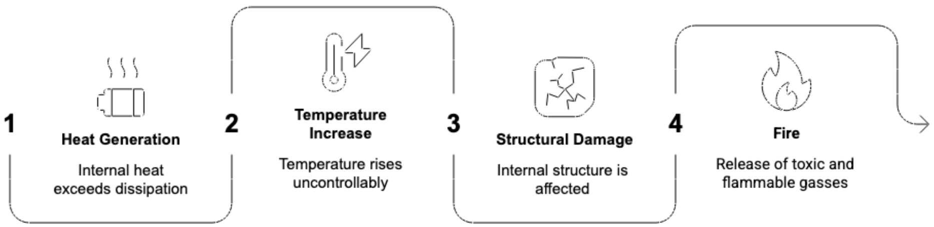


Figure 31: Thermal runaway process, image generated using Napkin [140]

Over the past decade, this problem has received an increase in interest, driven by incidents such as the Boeing 787 Dreamliner battery fires, Tesla Model S fires, and Samsung Galaxy Note 7 explosions. These all highlighted the urgency for a better understanding and prevention of battery failures on a larger scale [57, 179]. This trend is directly relevant to this study, as the same batteries that started this interest rise are now present in everyday products, yet without the preventive safety structure or visibility.

4.2 Causes and conditions

Thermal runaway can be caused by three main categories of abuse: mechanical, electrical, and thermal, see Figure 32 [57, 58, 179].

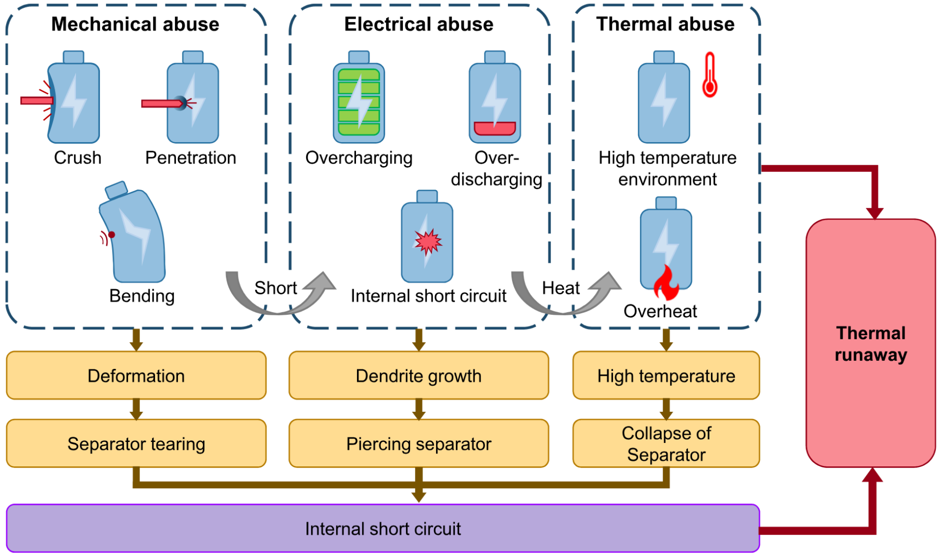


Figure 32: Thermal runaway causes as described by Ghandily et al. [57]

Mechanical abuse occurs when a battery sustains physical damage like crushing, penetration, or significant impact. This can result in internal damage that can cause internal short circuits that generate concentrated heat within the cell.

Electrical abuse involves conditions like overcharging, overdischarging, or short-circuiting. Overcharging increases the voltage beyond safe levels which can form excessive heat, while short-circuiting causes a sudden surge of current and a dangerous temperature spike [180].

Thermal abuse means an exposure to temperatures that are outside the battery's safe operating range. Extreme high temperatures accelerate the internal reactions, while extreme low temperatures can increase the internal resistance. Both are damaging to the internal structure and increase the risk of thermal runaway [57, 87].

In all three abuse categories, the State of Charge plays a significant role for the level of danger [180]. Higher charge levels, so a fuller battery, create more intense internal reactions, which means a shorter prevention window [57, 58].

It is important to realise that besides the three categories of abuse, there is another type that is specifically tied to the human side, behavioural abuses. Actions like charging an e-bike battery overnight in a garage or using an uncertified aftermarket charger that does not have the safety mechanisms required to prevent overheating or overcurrent. These routine behaviours introduce an increasing risk by combining a lack of human attention with electrical stress. This thesis does not focus on the specific dangers of electrical stress and detecting faulty charging, however, it does acknowledge the impact of these aftermarket chargers and its relation to human charging behaviour. It is viewed as a cause for abuse rather than a direct risk.

4.3 The domestic operating context

The normal operating temperature for lithium-ion batteries is generally described as being between 15 ˚C and 35 ˚C, with optimal performance concentrated in a smaller range of approximately 20–30 ˚C [59, 119]. Any long deviations beyond this range, either higher or lower, negatively affect battery capacity, power output, and cycle life [87, 90]. Even passive storage at temperatures above 25 ˚C has been shown to affect long-term battery life, independent of whether the battery is active [7].

In 1.2 minutes of charging it is possible to measure the battery's temperature as it increases linearly [7]. Within the domestic environment the temperature conditions are not equal nor unique. Different spaces in the house have a different temperature range. And especially during the summer, the temperature can reach non-optimal temperatures for these batteries. As most people are not aware of these increased temperature risks, we do not perceive a space as unsafe when the sun is directly heating it. Neither are the spaces designed to hold several charging systems that each have their own optimal temperature. Nor do we see or know when the battery could overheat. This absence of temperature supervision and unawareness in the domestic environment is precisely the gap that this problem definition addresses.

4.4 Staged progression

Thermal runaway is not a single spontaneous event. It happens in a chain of predictable and measurable reactions, that each have its unique characteristics. Ghandily et al. [57] map this progression by using specific temperature thresholds for lithium-ion cells, Figure 33. Normally, under good conditions, batteries function between 20–40 ˚C. When they are subjected to abuse, internal degradation begins at approximately 50–65 ˚C. As the temperature continues to rise, to about 70 ˚C, the next threshold is reached, which starts further breakdown of the internal structure. After more chemical reactions between 100-300 ˚C, the process accelerates towards total energy release above 300 ˚C.

Figure 33 shows these stages and stepwise describes what is happening, each step indicates a new phase and a higher level of risk.

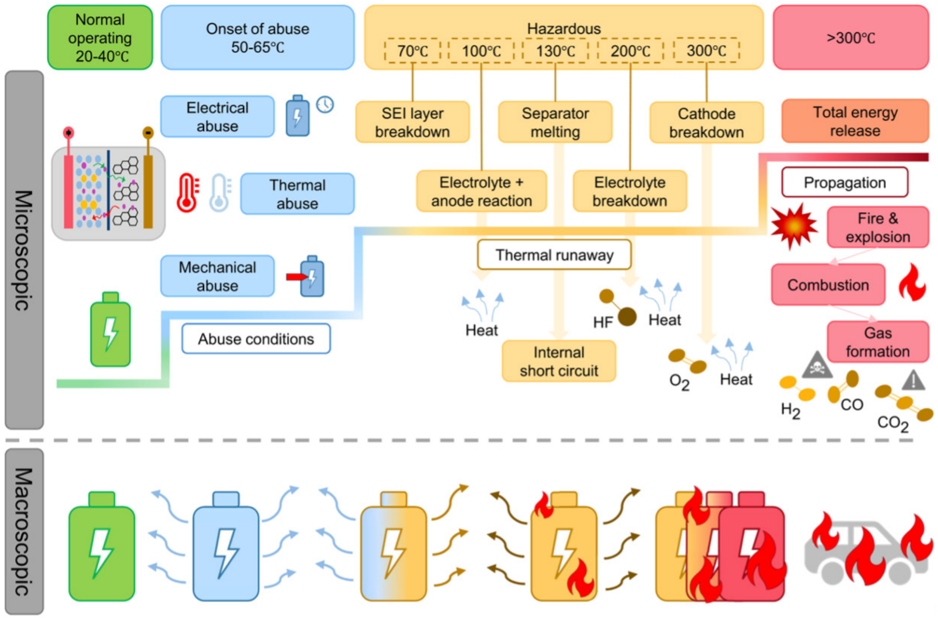


Figure 33: Thermal runaway stages [57]

Gu et al. [58] additionally describe this temperature based mapping with a five stage time based and mechanical model derived from experimental observation, Figure 34 and 35.

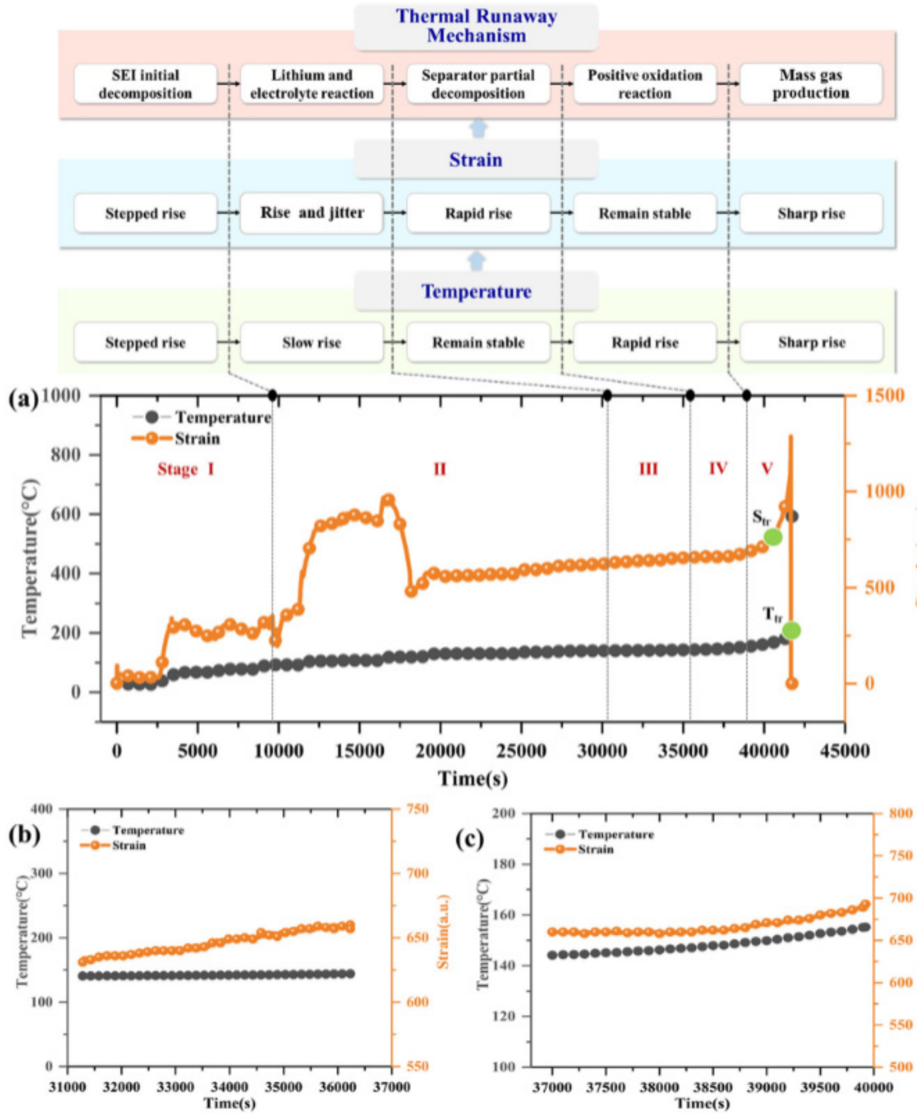


Figure 34: Thermal runaway 5 stage model [58]

In Stage I, strain and temperature rise together in correlation. Stage II is the start of the internal decomposition, which produces gas that causes the cell to expand and bulge. Stage III starts an important process, the temperature remains stable, but the strain increases. Yet the mechanical condition of the battery has already changed drastically. Stage IV reverses these conditions, temperature starts to rise exponentially, while strain stabilises. Finally, Stage V is the point of irreversible thermal runaway, where both temperature and strain spike as mass gas production and total energy release occur simultaneously.

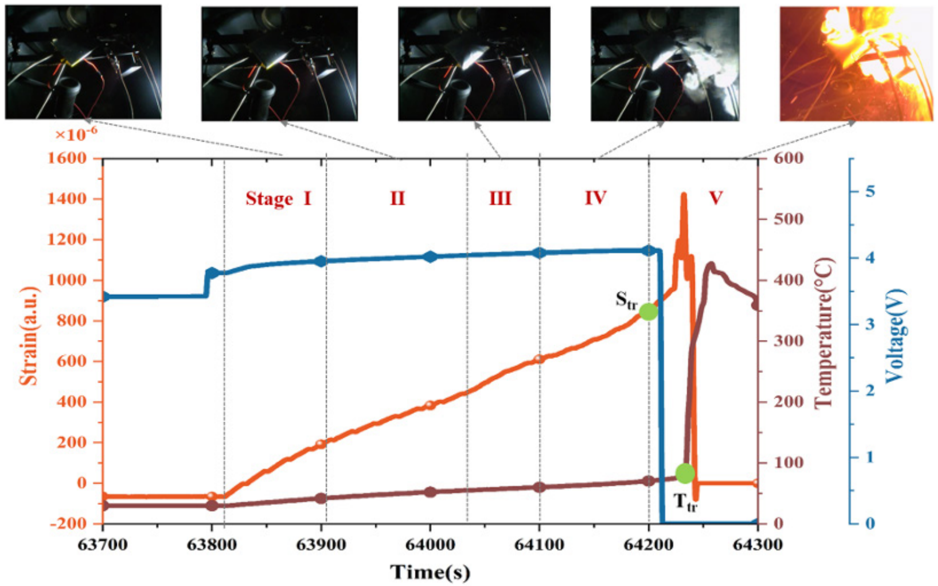


Figure 35: Thermal runaway strain in the 5 stages [58]

What makes this model important for this thesis is not the use of strain as measurement method, as strain gauges cannot be used on sealed consumer devices. However, it confirms that thermal runaway progresses through a set of predictable stages that can be used to detect the development of thermal runaway. This interval between the starting stage and the final irreversible stage is the prevention window in which the system will operate.

4.5 Detection methods and external temperature sensing

Currently the most used methods for detecting thermal runaway rely on gas, sound, power or temperature signals, each with their own limitation in the domestic environment [58, 179]. Gas-based techniques can detect gases like CO, CO_2, and CH_4 released from internal reactions only once the battery is already badly damaged. Sound can be detected from the release of these gases through safety valves or holes in the shell; however, these are suscseptible to ambient noise in the home [58]. Voltage-based methods detect overcharging, undercharging and power anomalies to measure the health of the battery. However, voltage-based measuring requires the system to be in direct contact with the internal electronics and this is not realistic as detection must happen through sealed consumer devices.

This thesis therefore relies on external temperature sensing. Temperature sensing presents a 0.57 hour window from detectable temperature change to irreversible damage [58]. This is measured under simulated abuse conditions, where a high temperature and thermal runaway are forced. In a domestic scenario this will be very different, damage can develop gradually over time which means the prevention window will be different. This however requires more research and elaborate testing to fundamentally prove and determine the exact time window. In this thesis the feasibility is plausible and theoretically demonstrated.

Chapter takeaways

An interesting gap found in this chapter is the absence of temperature supervision and unawareness in the domestic environment. We do not capture a battery overheating with our human senses until it is too late. Thermal runaway can happen in any lithium-ion battery, regardless of the product. Any sealed consumer product holding these rechargeable batteries can therefore create a risk. The failure process develops through predictable stages, each with measurable thermal characteristics. A prevention window of around 34 minutes exists and can be designed for.

The system has to measure the battery's temperature externally, through its shell. Previous work explored internal measurements of the battery's temperature under simulated conditions, making external measurements unexplored, yet interesting.

The next chapter uses this knowledge to begin conceptualisation, creating solutions for the thermal risk problem.

CHAPTER 5

CONCEPTUALISATION

With thermal risk as the identified problem, and thermal runaway explored and explained, I continue with conceptualisation, Figure 36.

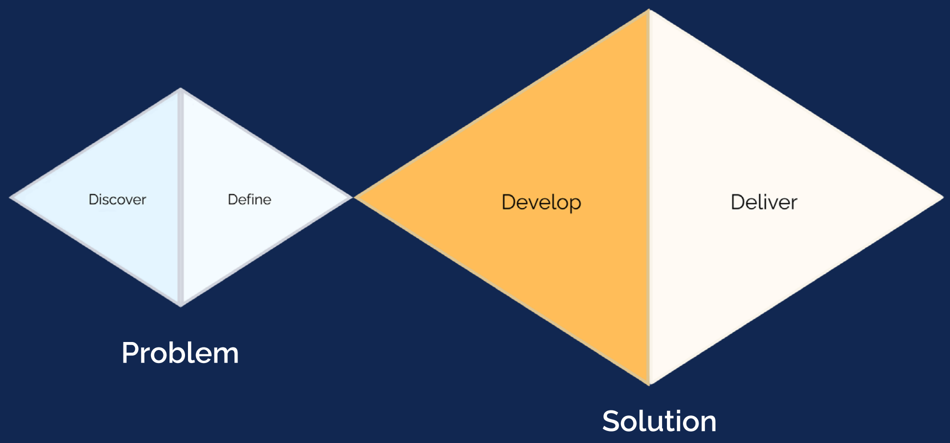


Figure 36: Develop stage of the Solution phase

5.1 Design Sprint

As seen in Figure 37, I developed three concepts using the first three days of the Sprint methodology by Knapp, Zeratsky and Kowitz [88]: understanding the problem and mapping the challenge (Monday), generating individual solutions through sketching (Tuesday), and selecting the strongest directions through structured decision-making (Wednesday), Figure 38. Each concept addresses the same problem direction from a different sensing angle, challenging the issues in the domestic category and e-bike batteries in other ways.

Figure 37: Design Sprint

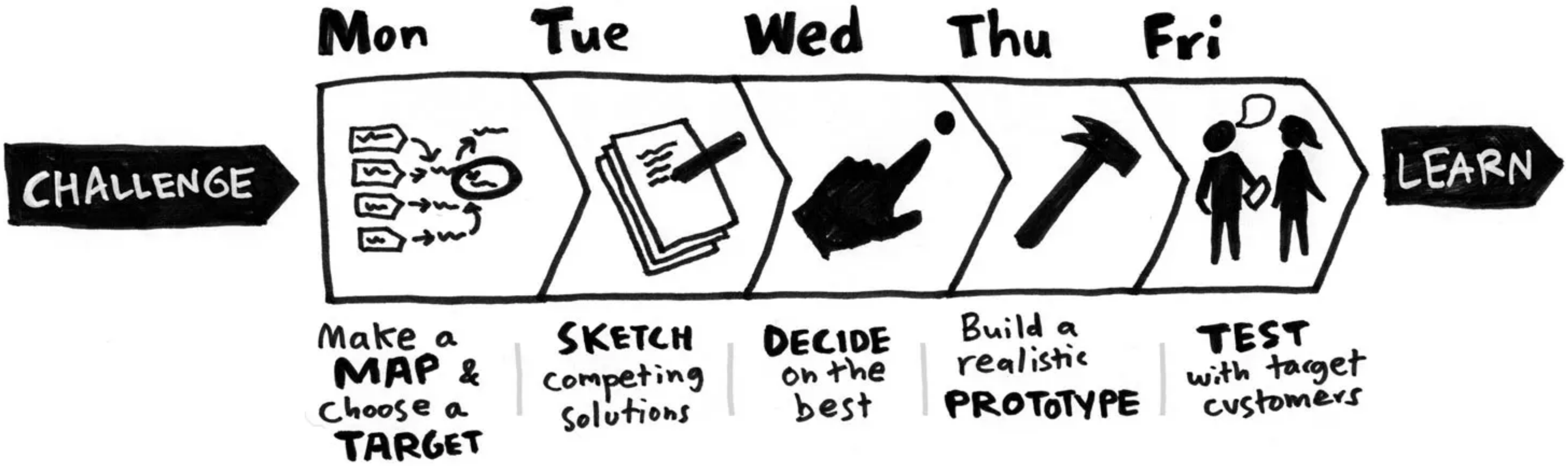


Figure 38: Sprint stages by Knapp [88, 89]

5.2 Gekko Imaging (1)

Description
The first concept, Gekko Imaging, Figure 39, can be placed on the wall wherever the space requires, directly challenging the issue of cluttered household spaces that could block the viewing path to the charged device. Thermal imaging cameras detect heat signatures, hot spots and thermal patterns. Moreover, the resident can plug their charger into the sensor, so the same wire that powers the device is also used to actively prevent overheating by closing the connection when needed.

How does it work?
Gekko Imaging works in two spatial layers. The primary layer is a safety perimeter of approximately two metres around the plugged-in device, tracking temperature and rate of change to identify abnormal heat signatures and distinguish normal use from elevated risk. When the risk is significant, it cuts power to delay or revert more temperature increase. The secondary layer is over the entire room, detecting anomalies from other sources to inform the user of any other abnormal heat patterns.

Advantages
- Thermal imaging allows for detecting other and multiple heat sources.
- Has an active prevention system that disconnects power when needed.
- Flexible wall placement allows for optimal wall placement to work around cluttered areas that can block the viewing path.

Disadvantages
- A single device is actively connected, all the others are only monitored.
- False flagging heat spots, this requires advanced contextual awareness.
- Each time the device is relocated, repositioning is required.
- It requires a clear line of sight to the device, so objects blocking the signal can create unreliable measurements.

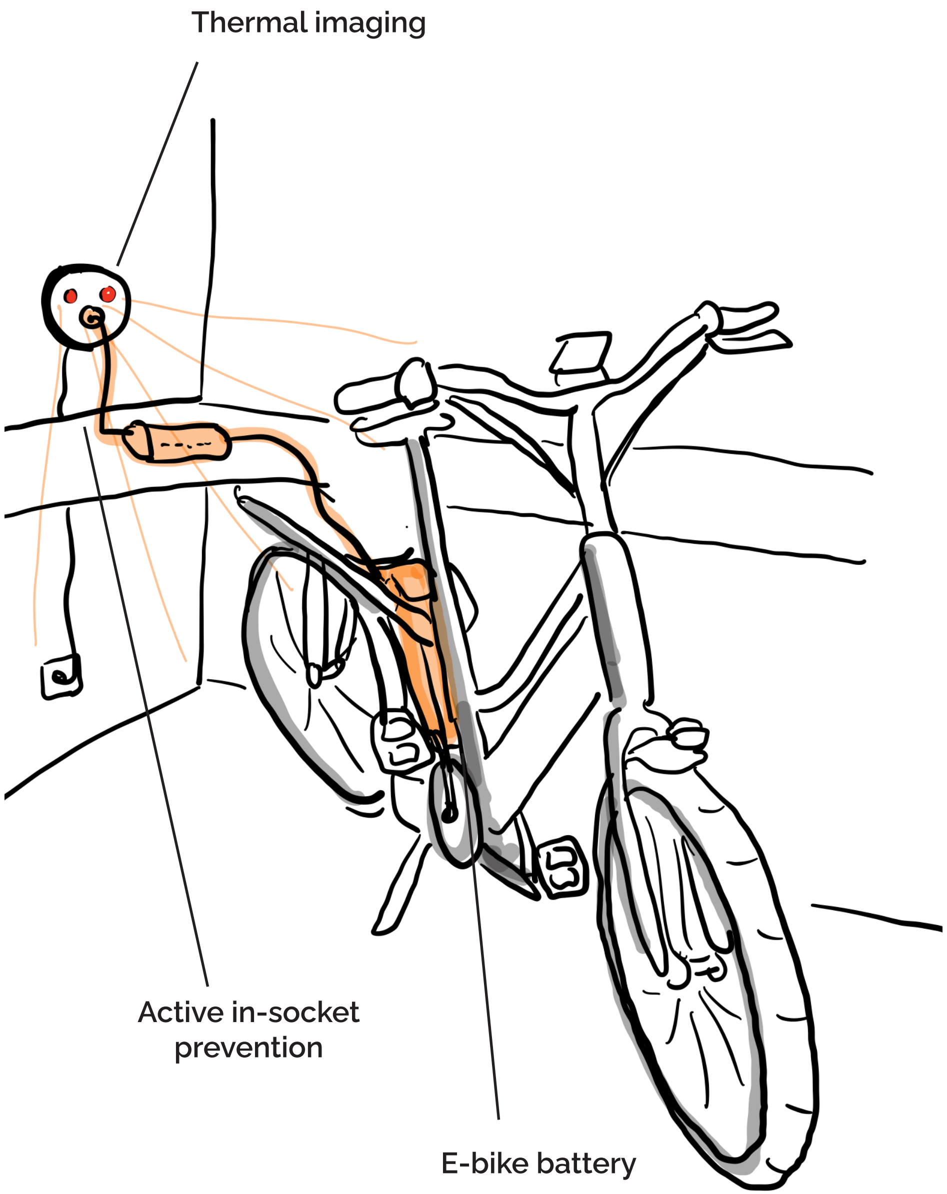


Figure 39: Gekko Imaging

5.3 Sensing Plaster (2)

Description

The second concept, The Sensing Plaster, as seen in Figures 40 and 41, uses contact sensors placed directly on the device's shell at the battery cells location. It eliminates the need for line of sight, correct spatial placement, and removes the challenge of cluttered spaces. It only requires correct placement on the battery upon installation.

The concept focusses on timely detection and actionable communication through proportional and levelled notifications, enabling informed response before the prevention window closes. As batteries can be moved outside the house and thermal runaway can develop without charging, it allows for continuous measurement outside of charging routines.

How does it work?

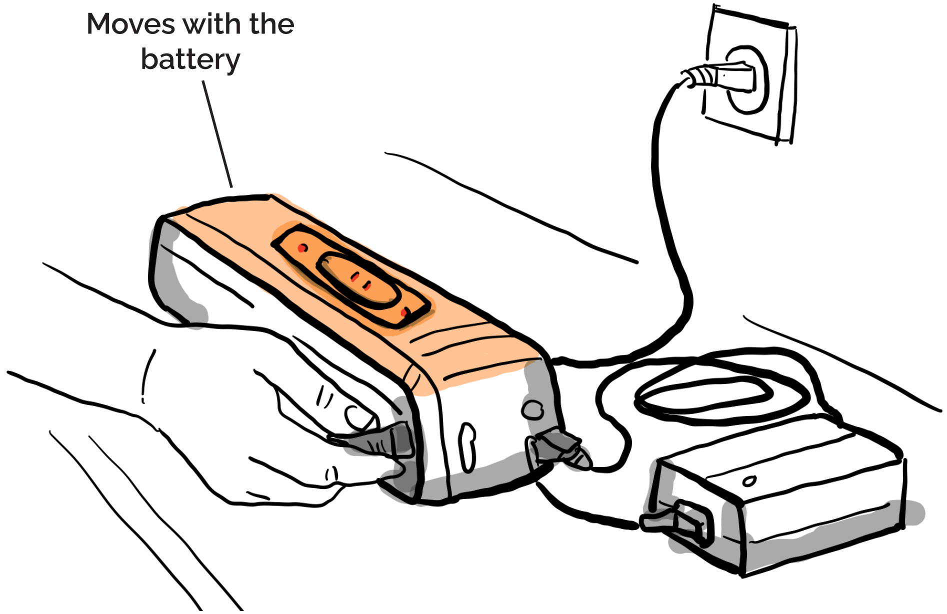
The sensor measures the temperature behaviour of the battery directly through contact, tracking rate of change close to the source. The system works over a network, that provides the resident with a feed of information together with push notifications when temperature increases or immediate risk forms. While only one device can be sensed per unit, the smaller size and lower production costs allow a system of multiple sensors.

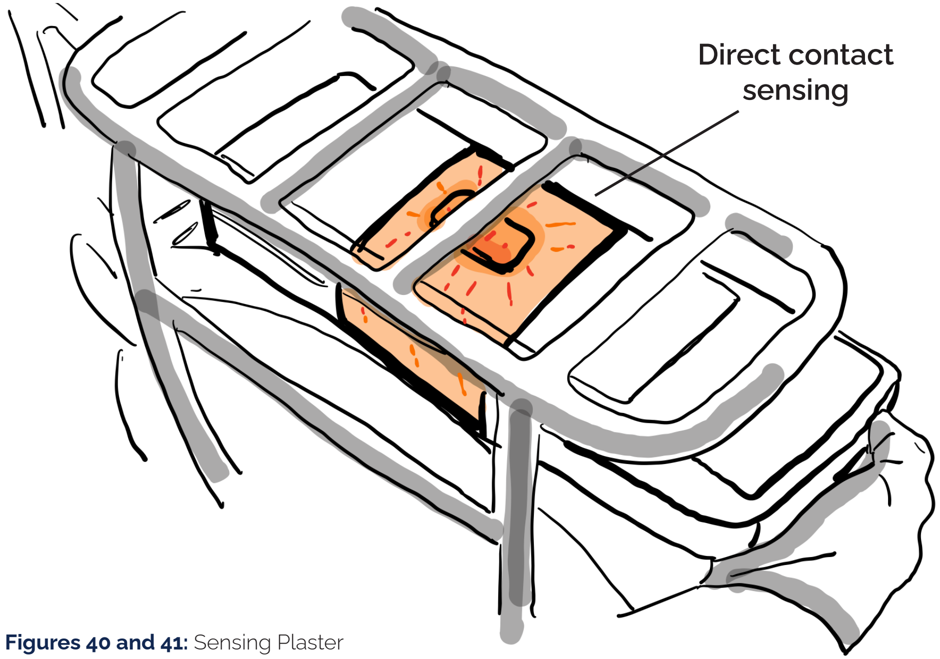
Advantages

- Direct contact sensing eliminates the viewing path dependency.
- The plug-and-play mechanic makes it easy to use for all residents.
- Levelled communication provides the resident with actionable information that gives clear guidelines on how and when to act.

Disadvantages

- No active prevention, it relies on an informed human response.
- One device per sensor, requiring multiple units for covering all devices.
- Correct placement on the battery is required, yet the battery location is not the same for each model, and battery sizes vary.





Figures 40 and 41: Sensing Plaster

5.4 The Socket Eye (3)

Description

The third concept, The Socket eye, as seen in Figures 42 and 43, creates a designated charging space that focusses on charging behaviour and placement awareness by limiting the charging locations. Rather than adapting the location of the sensor when the device is moved, it guides the resident to place their devices in a defined area. Distance, angle and placement are controlled by the design itself, actively changing the users charging pattern and making them think about the thermal risks. Using an aesthetic design, the solution blends in with the existing socket, so it does not create new clutter in the home.

How does it work?

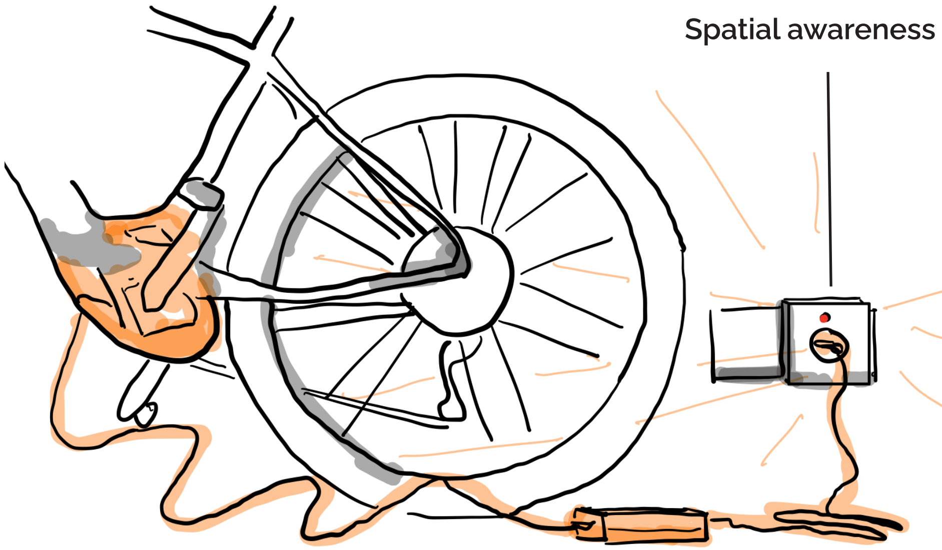
The resident places their device on or within the designated space. Thermal camera sensors monitor the temperature change to identify abnormal patterns, similair to Gekko Imaging. The system communicates actionably to the resident when risk develops. Because this system is also physically connected to the power, it can actively intervene by disconnecting when needed. It focusses on human charging behaviour patterns, and making the resident actively aware of the risks.

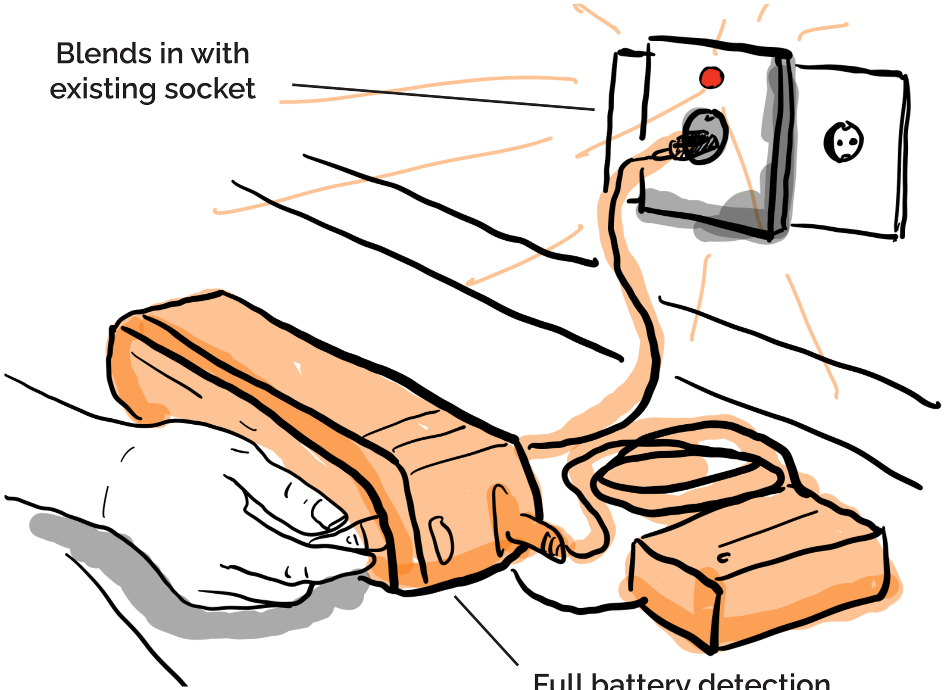
Advantages

- Controlled placement limits the user on device placement, these predefined variables allow for more reliable measurements.
- Active prevention through power disconnection upon thermal risk.
- The designated space creates a behavioural incentive, embedding safety awareness into the daily charging routine.

Disadvantages

- It requires the resident to change their charging behaviour entirely.
- It loses its protective function when the battery is placed elsewhere.
- The locations are limited to the locations of the sockets in the home.





Figures 42 and 43: The Socket Eye

5.5 Sensor selection

To make a well-informed decision on what solution direction to choose, I need to understand what type of sensor is best to use. In the domestic environment this could be different from an ideal laboratory setting where normal battery temperature tests are conducted. To properly structure and identify the best suited sensor I explored and mapped out two types of sensors: contact and non-contact sensors. Table 2 describes the comparison details of the selected sensors. The full table in more detail can be found in Appendix C.

The contact sensor methods rely on surface temperature, the temperature difference between material and surrounding air, resistance and voltage measurements. Non-contact sensors utilise the radiation and emissions of the heat source to detect heat patterns and map them using point values. Details of both methods describing the most common and relevant sensors used in the world of temperature sensing, can be found in Appendix C.

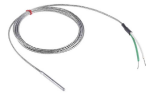
Contact sensors				
Sensor	**Image**	**How does it work?**	**Range & Accuracy**	**Pros & Cons**
Thermocouple	 [134]	Voltage from two different metals (Seebeck Effect) [47].	−200 °C to +1750 °C [17]. Moderate accuracy.	**Pros:** Cheap, wide range, fast response, low power usage. **Cons:** Less accurate than RTDs.
Resistance Temperature Detectors	 [135]	Predictable change in resistance proportional to the increasing temperature [85].	≈ −200 °C to +850 °C [42]. High accuracy.	**Pros:** Accurate, stable over time and a linear signal. **Cons:** Expensive, slow response.
Integrated Circuit temperature sensor	 [148]	Transistor voltage and temperature dependence. PCB-mounted [152, 154].	−55 °C to +130 °C [152, 154]. Moderate accuracy.	**Pros:** Small, accurate and cheap. **Cons:** Upper limit too low to cover thermal runaway escalation.
Negative Temperature Coefficient thermistor	 [83]	Resistance decreases as temperature rises [12].	−50 °C to +150 °C, up to +250 °C encapsulated [12]. High accuracy.	**Pros:** High sensitivity, cheap and small. **Cons:** Non-linear (requires linearisation).
Heat flux sensor	 [22]	Radiative or conductive heat transfer (Gardon and Schmidt-Boelter principles) [61].	−70 °C to +250 °C [79, 91]. Moderate accuracy.	**Pros:** Can measure all three forms of heat transfer. **Cons:** Needs calibration and measures flux, not absolute temperature.
Non-contact sensors				
Sensor	**Image**	**How does it work?**	**Range & Accuracy**	**Pros % Cons**
Thermal imaging camera	 [54]	2D thermal map of thousands of temperature points captured by infrared radiation [114, 118].	Setup- and emissivity-dependent.	**Pros:** Contactless, mobile use case, visualises hot-spots. **Cons:** Needs a wide FOV for domestic use, emissivity-sensitive, expensive.
IR temperature sensor	 [82]	Point measurement of emitted radiation [3, 41].	Emissivity- and angle-dependent [85, 124].	**Pros:** Contactless, fast, robust. **Cons:** Emissivity- and angle-dependent, single-point misses hot-spots.

Table 2: Temperature sensors comparison table

5.5.1 Which one to use

With the requirements of application, accuracy, and feasibility in mind, several sensors are feasible with their operating range; Thermocouples, Resistance Temperature Detector (RTDs), Negative Temperature Coefficient (NTC) sensors, heat flux sensors, Infra-Red (IR) sensors, and thermal imaging. Thermal runaway is typically detected from around 70˚C onwards, and after 150˚C the results are irreversible. Non-contact sensors, however, as seen in Figure 44, are dependent on emissivity and the position of the surface within the viewing angle. Taking this into account, in combination with the variables in human behaviour, the accuracy of these infrared sensors decreases, and the reliability is questionable. Additionally, the costs of these sensors when used for longer, continuous periods of time, is not yet interesting to the consumer market. This might change in the future, when a decrease of technology prices and innovation make it more suitable. Therefore, this cannot be seen as a realistic solution within the domestic context for this thesis.

Contact sensors like Thermocouples, IC and NTC are low-cost, support continuous monitoring with low power consumption, and can be compact and easily integrated with other sensors. By applying dual sensing methods [99], accuracy can be even higher. Moreover, these contact sensors, as seen in concept 2, The Sensing Plaster, can be placed directly onto the rechargeable battery shell. This removes the need for precise placement within the living space and only requiring the user to position the sensor correctly on the shell. Another benefit is the monitoring outside the domestic environment, as batteries can still overheat while not being charged. Even though this is not the focus of this thesis, it is still worth acknowledging as additional safety. This results in a simple, reliable, and user-friendly system that aligns with the criteria of Every Space Safe.

Following three interviews with an expert from the Research Center of Jülich on battery temperature measurements and battery management systems I identified the NTC resistor as the most suitable, best fit, sensor for this problem [127, 55]. The NTC produces a large change in resistance for every degree of temperature shift. This makes it easy to detect tiny fluctuations and calculate an accurate rate of change. It has a high accuracy at low temperatures from 0˚C to +150˚C, which is perfect for the required temperature limits, and it is inherently precise (often within +-0.1˚C). Moreover, an NTC does not require specialised amplifiers, it can read cleaner data using just a voltage divider circuit. NTC is also the best choice when comparing robustness of sensors, as these are more resilient to the electrical noise created by a charging field.

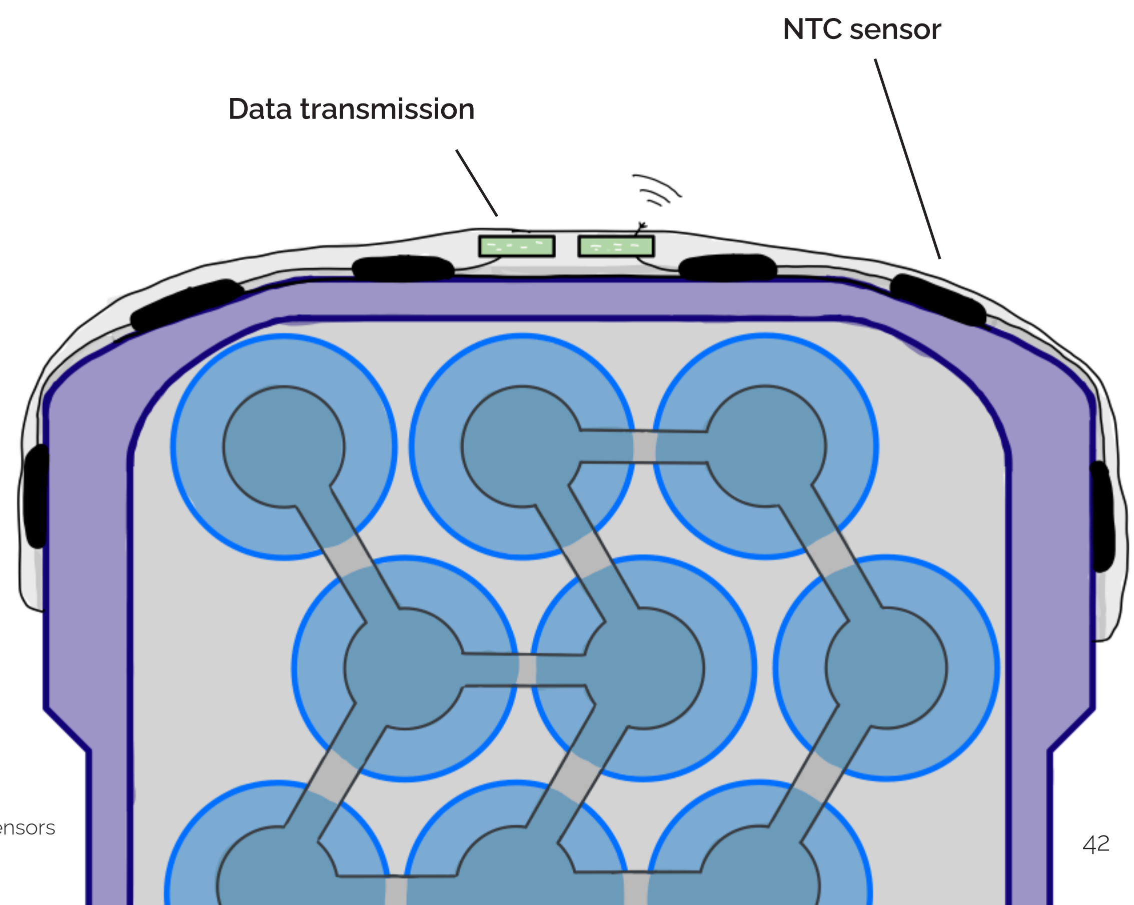


Figure 44: Battery cut through with NTC sensors

5.6 Selecting a concept

For the selection of the concept I used a Harris Profile. A Harris Profile is a graphic representation of the strengths and weaknesses of the design concepts with respect to predefined design requirements as described by the Delft Design Guide [165]. I will use the Harris Profile to evaluate the design concepts and facilitate decisions on which concept I choose to continue the design process with. I will weigh and score the solutions based on five requirements that I identified in Every Space Safe. These form a comprehensive solution space in which the ideal solution should live. The Harris Profile is shown in Figure 45.

As seen in Figure 45, based on the predefined design requirements, the second concept, the Sensing Plaster, emerges as the best concept. I will continue the design process using this concept.

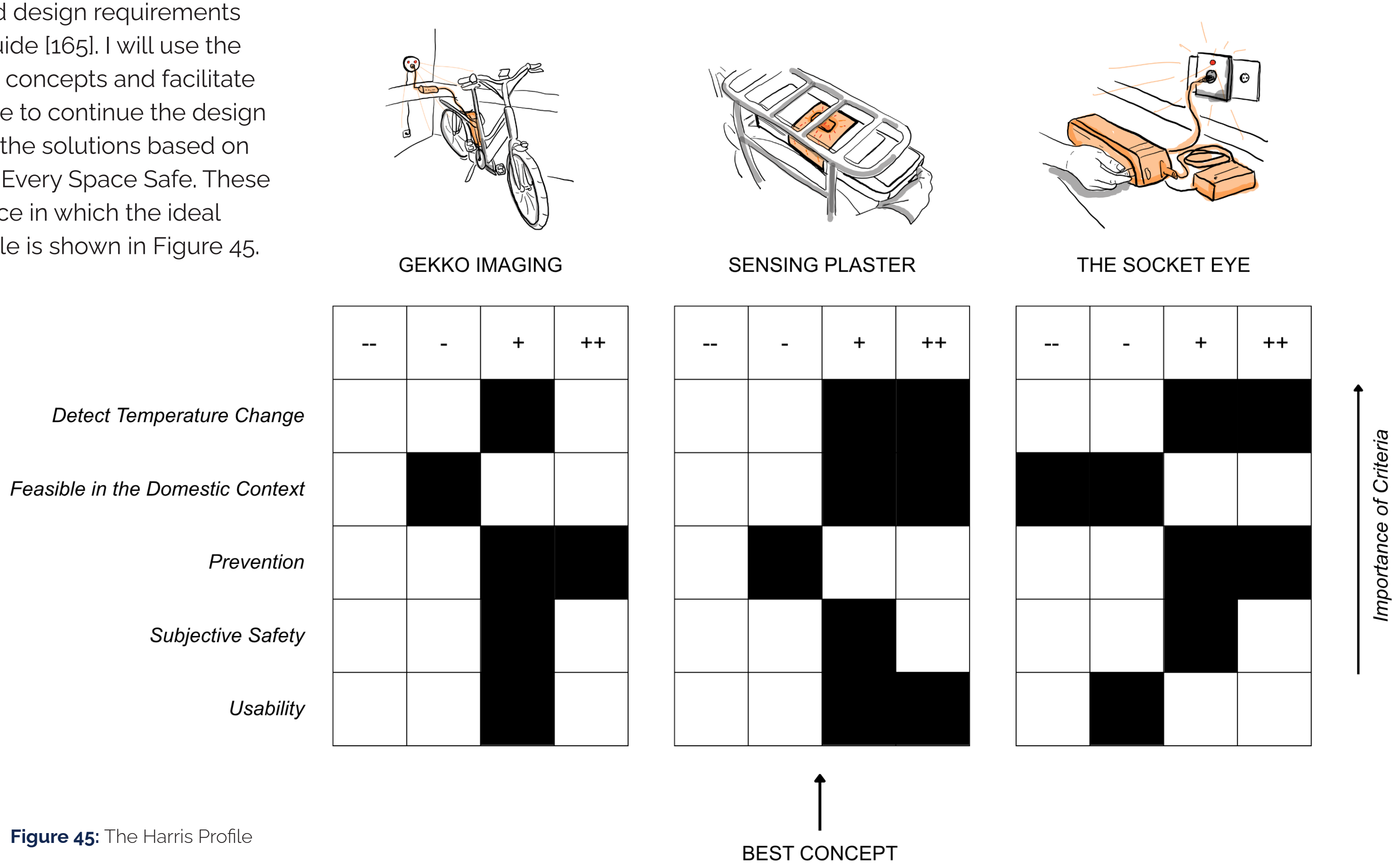


Figure 45: The Harris Profile

5.7 Evaluation

The Sensing Plaster

This concept had the best strengths and least weaknesses in comparison to the other concepts. Gekko Imaging and The Socket Eye had the best prevention, as they provide intervention using the connected cable. All three concepts use active communication using the resident's smartphone, to provide for subjective safety, a feeling of control, awareness, alert and reassurance, see Figure 46.

Gekko Imaging and The Socket eye use infrared measurements, yet this is dependent on emissivity and the position of the surface within the viewing angle. The Sensing Plaster detects temperature directly on the surface, which removes the human aspect in correct positioning, making it more reliable in detecting temperature change.

In a domestic context it assumes the resident has the discipline to charge their batteries in the same location, depended on the location of the concept. However, considering the human behaviour and routine patterns, this variability is too significant to assure reliable safety. Sensing directly on the battery shell removes this variability and that is why the Sensing Plaster is more usable and realistic in the domestic context. Ultimately, it was thus decided to continue with the Sensing Plaster.

Figure 46: Actionable communication to the user

The user scenario

The concept of the Sensing Plaster uses active communication to provide for effective prevention and control. Figure 47 shows the user scenario as described by the concept.

Steps 1, 2 and 3 show the installation of the sensor. It is first attached to the battery and using the home network it is connected to the user's smartphone. This communicates the temperature data directly, in real-time, to the user.
Step 4 illustrates the standard scenario of the battery while charged.
Step 5 displays a scenario in which the battery is charging normally under good conditions, the user is not notified but actively informed that the situation is ok and shown that the temperature change is within reasonable limits.
Steps 6 and 7 show the situation in which the battery has an abnormal, heightened temperature rate of change. The user is notified with an alert stating that the battery needs to be checked and is not behaving normally, it guides the user on what to do in this situation.
Steps 8, 9 and 10 display a scenario in which the battery is heating up to a dangerous extent. The user receives a push notification and alert to indicate with urgency that the battery has abnormal behaviour and that immediate action is required. The user is guided to the correct actions, unplugging the battery and removing it from the space to reduce the risk and danger. This user scenario is a sketch of what the resident experiences and does when using the concept. The user scenario will be further developed in the design process.

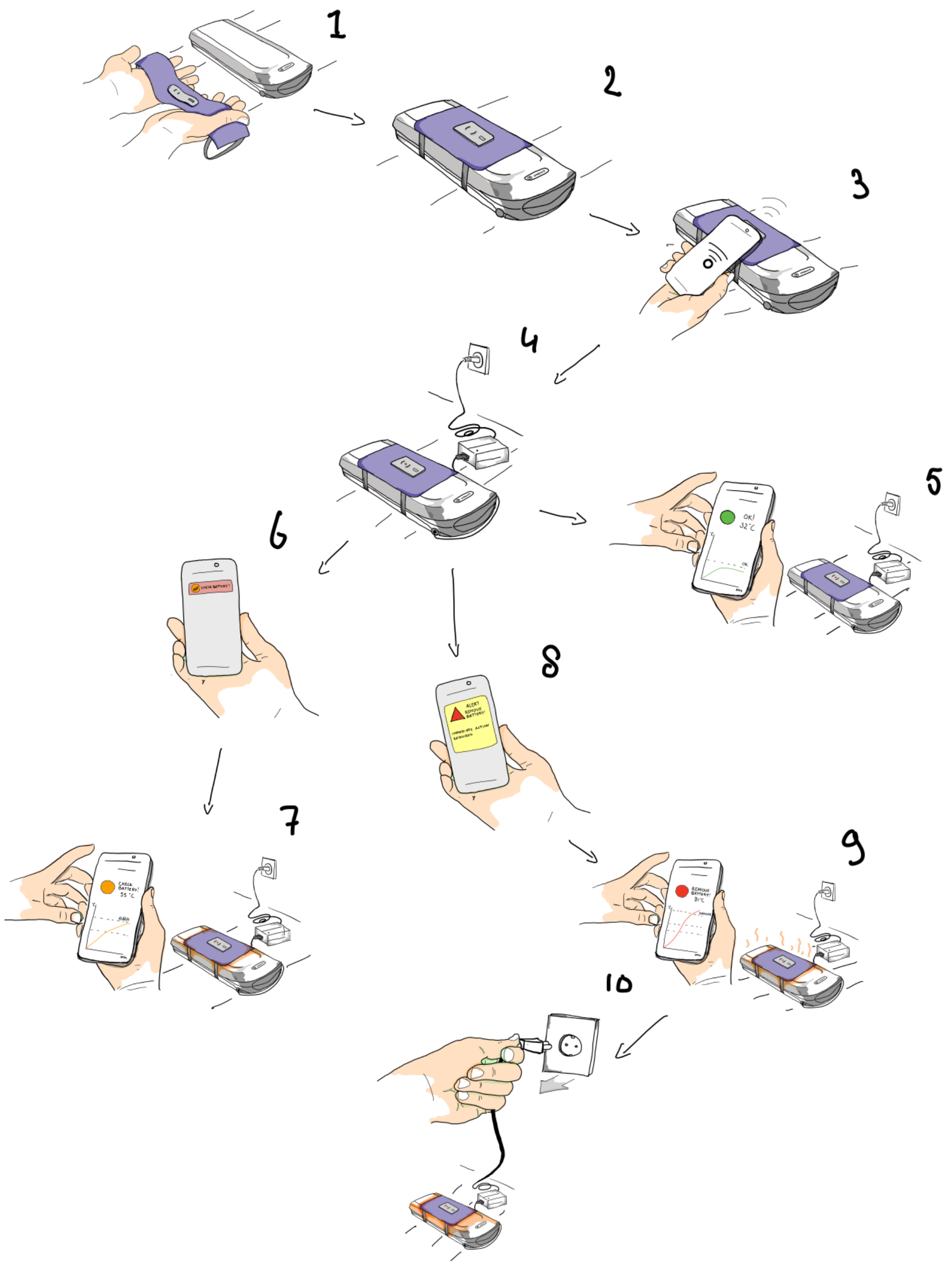


Figure 47: Concept version of the User Scenario

Chapter takeaways

Three concepts were developed using the Sprint methodology. Non-contact sensors depend on emissivity and line of sight and in a domestic context, that dependency makes them unreliable. Contact sensing removes this variability. The NTC thermistor is the best fit because of its high sensitivity, accuracy across the required temperature range, and resilience.

The Harris Profile confirmed the Sensing Plaster as the strongest concept, and attaching directly to the battery shell removes placement dependency. The next chapter demonstrates the technical plausibility and explores the best way to measure the temperature of the battery using the NTC sensor.

CHAPTER 6

TECHNICAL PLAUSIBILITY

To demonstrate the plausibility of the design within the scope of this thesis, it is important that the concept is grounded in theoretical literature, research, component specification and expert input. Each functionality is addressed with the provided reasoning. Further testing and research are needed to fully validate the concept and are recommended as follow-up work. The expert input follows from three interviews with an expert from the Research Center of Jülich on battery temperature measurements and battery management systems [127, 55].

For this chapter I assume a standard charging cycle of an e-bike battery in a representative domestic situation. There are many scenarios and exceptions to the standard use of an e-bike battery where it gets in contact with for example, extreme temperatures, abuse or rapid discharge. I acknowledge their existence but do not address them in this thesis.

The challenge is measuring the external surface of the battery shell instead of the cell itself, as internal sensors are not a practical solution for a consumer product. The thermal resistance, thermal conductivity, ambient temperature and air gap inside the housing all influence how fast heat reaches the surface and how the rate of change is detected. First it is important to know what I am measuring and how it is interpreted, and then to address the factors that shape what the sensor measures.

6.1 Measuring temperature change

Measuring the temperature change accurately is the foundation of the system. This section explains how this is done: which signal is measured, how much time is available to act, and how the system distinguishes a real thermal event from normal charging behaviour.

Rate of change

The shell's thermal resistance makes the external temperature lag behind the internal one and read lower, with the lag and offset varying per battery, shell and conditions. An absolute external reading is therefore unreliable. Instead, the system detects the temperature rate of change over time. An abnormally fast rise signals a developing fault, with the battery's normal charging pattern as the reference.

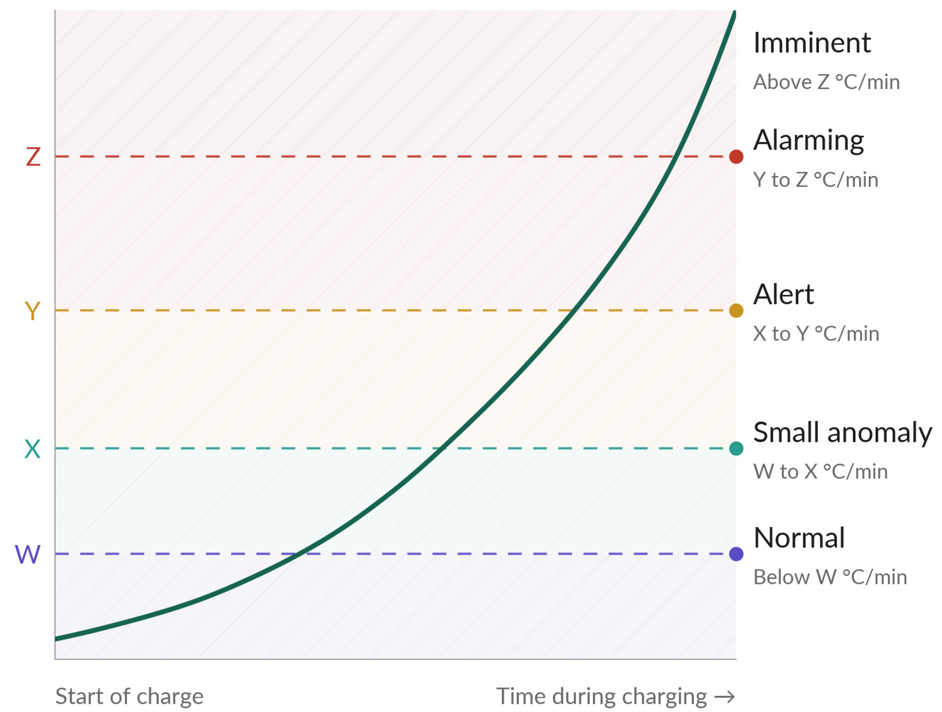
The rate of change is calculated as the difference in temperature over a defined time interval:

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{T_2 - T_1}{t_2 - t_1}$$

Where T_1 and T_2 are the temperature readings at times t_1 and t_2, expressed in ˚C/min.
To measure this rate accurately, the sensor must be precise enough to detect small changes on the surface. Chapter 5.5 discusses the NTC sensor and shows that its accuracy is sufficient for this purpose. The rate of change can therefore be measured directly on the surface.

The challenge is to determine which rates of change should trigger which response. Studies by Gu et al. gave me the 0.57 hour window until thermal runaway [58]. Translating these values from a lab setting to a real-life scenario is not simple, given the factors discussed above. For that reason, this thesis does not fix the thresholds to specific numbers. Instead, four thresholds are defined to separate five zones, see Graph 1. The actual values for W, X, Y and Z fall outside the scope of this design thesis and require further real-world testing on representative e-bike batteries.

The time that passes before the temperature reaches thermal runaway level in the five-stage model from Chapter 4.4 is called the prevention window. Defining this window helps to understand how much time there is for the system and the user to act.

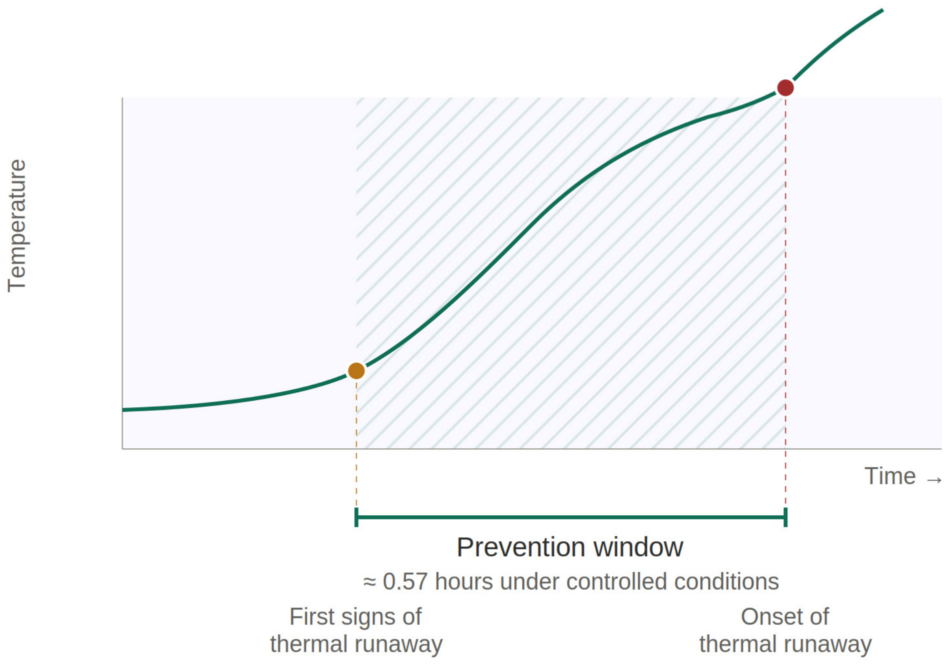


Graph 1: Rate of Change phases

The prevention window

The prevention window defines a time window that stretches from the first signs of a developing risk to the onset of thermal runaway, as described by Gu et al. [58]. Within this window, as shown in Graph 2, the system detects an anomaly in the temperature curve and alerts the user to act accordingly.

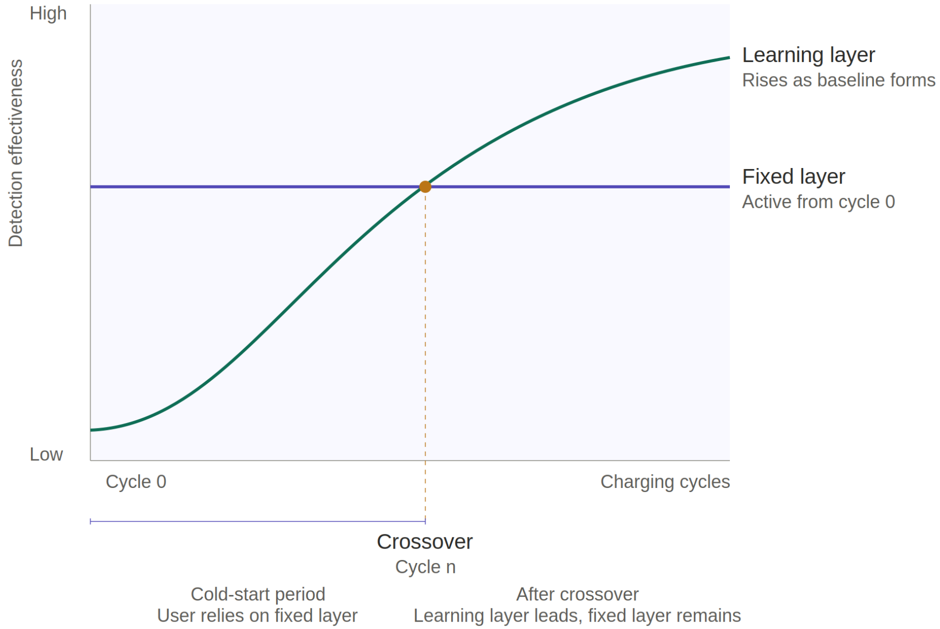
Gu et al. [58] measure this window as 0.57 hours under controlled and simulated conditions. For this thesis I use the 0.57 hours as the assumed time window, providing enough time for valuable action. This value may not directly translate to surface measurement on an e-bike battery, where a heat transfer delay from core to shell further affects the window. Elaborate testing under a wide variety of conditions is required to determine the realistic window.



Graph 2: The prevention window

How does it measure the temperature change accurately?

The system uses two measurement layers, see Graph 3.



Graph 3: Two measurement layer system

The first is a fixed safety layer with predefined limits. It is active immediately and works the same for all batteries. Looking at the rate of change of temperature during the use-charge cycle, an unusually fast increase can indicate a developing thermal runaway. When the measured value matches the threshold, the fixed layer, the system sends an immediate alert.

The second is a learning layer. It must first learn the normal use-charging pattern before it works. Over the first *n* charging cycles, the system measures the temperature curve and builds a data set of the mean curve and the spread. This is the healthy profile for this specific battery. Once this pattern is known, the system can detect subtle deviations and act on them earlier than the fixed layer can.

The fixed layer remains active at all times. During the cold-start period, the user relies entirely on it. A battery that is already degraded at purchase, or a first cycle that includes an abnormal event, can affect the quality of the baseline.

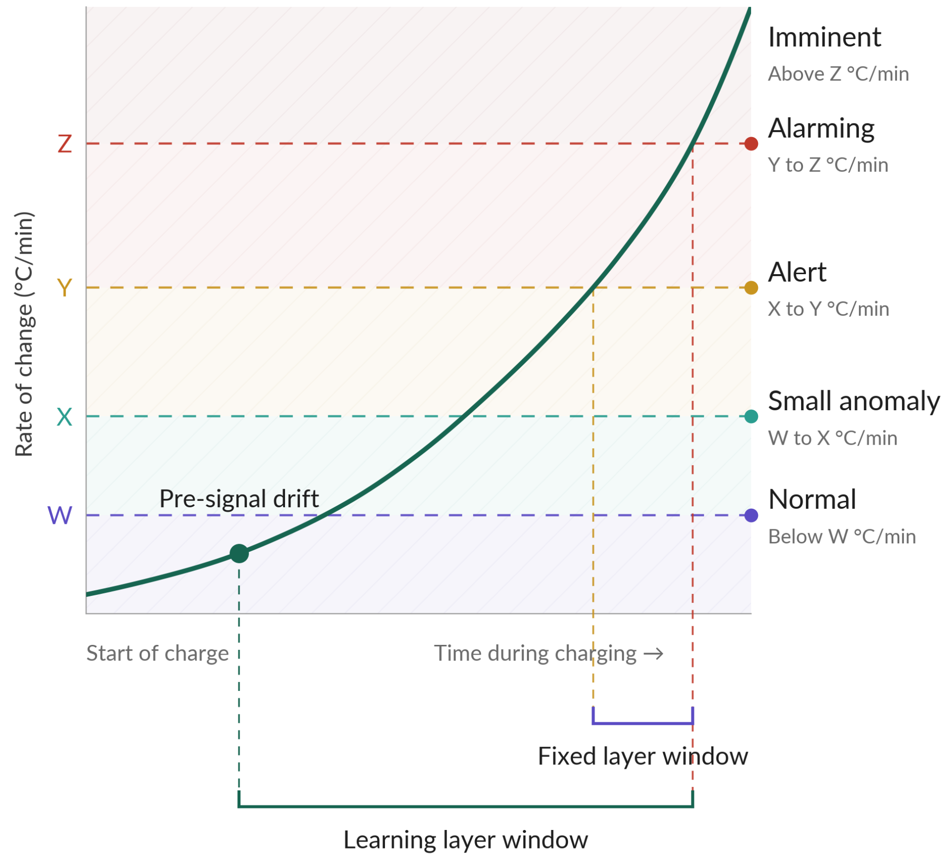
The combined effects of the internal variables are captured in the measured baseline. The limitation is that the baseline is trained under specific conditions, so its quality holds only within those conditions. Whether the baseline alone is enough to accurately measure anomalies is to be determined. The same is true for variables on cell level, such as ageing and degradation. When the sensors measure a rate of change pattern that differs from the baseline, this can still indicate cell ageing, degradation or other internal faults. Over time it is normal that a battery gets warmer when charging, but this indication can tell us it is time for a check or replacement.

Pre-signal drift as early warning

A deviation from the baseline does not only mean ageing or degradation. It can also be an early sign of thermal runaway. Because the system knows the healthy charging pattern for this specific battery, it notices when the live data starts to drift away from that pattern. This slow drifting is the pre-signal drift, detected before the rate of change crosses the fixed thresholds, see Graph 4.

The learning layer reacts to it because it looks for a deviation from what is normal, not a fixed limit. A detector without a learned pattern would only respond once the rate of change is high enough to cross a hard threshold.

This is why catching the early drift matters. The two-layer system can notice a developing risk earlier than a system that waits for a fixed threshold, and every minute counts.



Graph 4: Pre-signal drift detection with the learning layer

Values and thresholds

The predefined threshold for the fixed layer, the number of cycles *n* needed to establish a reliable baseline, and the tolerances for detecting deviations are all values that must be determined through further testing. Literature gives indications of ranges, but the exact values for this specific application have not been established. Defining them is recommended as follow-up research.

6.2 Temperature factors

This section addresses the physical factors that shape what the sensor actually measures on the outside of the battery: the thermal resistance and conductivity of the housing material, the air gap between cell and shell, the thermal interface between shell and sensor, and the ambient temperature.

Thermal resistance and conductivity of the material.

To understand the influence of the thermal resistance and conductivity of the material, I first need to know the material used for an e-bike battery. The primary, outer, shell is commonly made from plastic, more specifically ABS or polycarbonate as they are lightweight, durable and fire-resistant, see Figure 48 [78].
Other harder cases are made from aluminium or steel and softer cases can be made from nylon or neoprene [145]. However, for this thesis the focus is on the common e-bike battery and thus plastic.

Figure 48: ABS granules before used in the injection molding process to form the e-bike battery shell [121].

The secondary and internal materials are the nickel strips that connect the individual cells together and the cell spacers also made from ABS or polypropylene. Yet for heat dissipation and thermal resistance only the primary materials are considered as they are physically and significantly blocking the heat.

With the material known, the next question is whether the outside temperature can be linked to the inside temperature. Two properties matter here: thermal conductivity and thermal resistance.

Thermal conductivity (k) is a material property. It describes how well the material conducts heat, expressed in W/m·K. ABS has a thermal conductivity of around 0.14–0.21 W/m·K and polycarbonate around 0.19–0.22 W/m·K [40, 155]. Both are low, which means the shell insulates and a temperature difference will build up across it.
Thermal resistance (R) is a property of the specific shell. It depends on the material, the thickness and the surface area:

$$R = \frac{d}{k \cdot A}$$

A thicker shell of the same material has a higher resistance and thus a larger temperature drop across it for the same heat flow.
Both combine in Fourier's law for steady-state conduction through a flat wall:

$$q = \frac{k \cdot A \cdot (T_{\text{inside}} - T_{\text{outside}})}{d}$$

Where q is the heat flow (W), A the surface area (m^2), d the wall thickness (m) and T the temperatures on either side of the shell.
So yes, calculating the inside temperature from a contact measurement on the outside is possible. The conductivity of the material makes the principle work, the resistance of the specific shell determines how large the difference will be. The exact value falls outside the scope of this design thesis. What is important is that a measurable external signal reflects what happens internally, with a delay and an offset that depend on the shell.

Air gap between cell and shell

Inside the battery pack there is a layer of air between the cells and the outer shell, Figure 49. Air has a very low thermal conductivity of around 0.026 W/m·K [50], roughly eight times lower than ABS or polycarbonate. Even a thin air gap therefore adds a significant amount of thermal resistance to the path from cell to shell. This means the air layer, not the plastic, is often the dominant insulating element in the heat path. It is important to consider this insulation layer that is created by design of the e-bike battery. It influences the delay and reduced magnitude of the measurements, and it highlights the need for a thermal interface material on the outside of the shell to avoid adding yet another air gap between the shell and the sensor.

Combining the air gap and the shell

The air gap and the plastic shell are in series in the heat path from the battery cell to the outer surface. Their thermal resistances therefore add up to a total resistance:

$$R_{\text{total}} = \frac{d_{\text{air}}}{k_{\text{air}} \cdot A} + \frac{d_{\text{shell}}}{k_{\text{shell}} \cdot A}$$

And the total temperature drop from the cell to the outside of the shell is:

$$T_{\text{cell}} - T_{\text{outside}} = q \cdot R_{\text{total}}$$

This shows that both layers contribute to the difference between internal and external temperature, and that the layer with the higher resistance has the largest influence on the result.

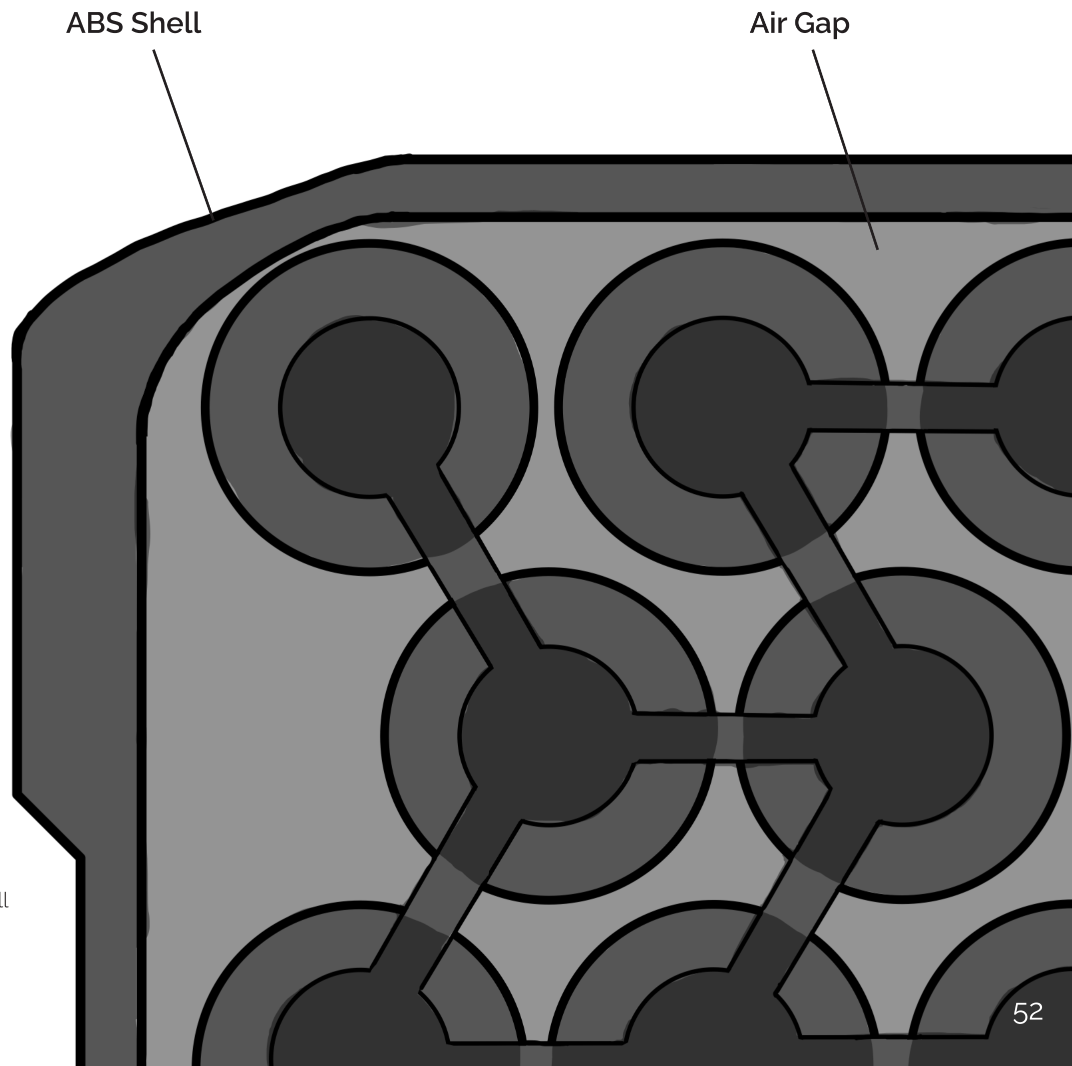


Figure 49: Representation of the air gap between cell and shell

Ambient temperature measurement

Measuring the rate of change accurately means accounting for external factors that influence the sensor reading. The e-bike battery is exposed to different temperatures and temperature changes. Colder and warmer temperatures in winter and summer, large increases due to direct sunlight, or small fluctuations due to air conditioning in the home, Figure 50. These changes impact the readings and can lead to incorrect results and false feedback.

The rate-of-change approach already handles most of this. If the battery rises gradually in temperature and drifts from the baseline curve, it will be detected. What this approach can not do on its own is tell the difference between a battery heating because of an internal fault and a battery heating because the room is heating. Both produce a real rate of change on the sensor.

To address this, a second NTC sensor is added to measure the ambient temperature. It allows the system to compare the two readings: if the battery and the ambient rise together, the change is environmental; if only the battery rises, the change is internal. A battery at 45 °C in a 40 °C room behaves differently than the same battery at 45 °C in a 20 °C room, and the second sensor makes that separation possible.

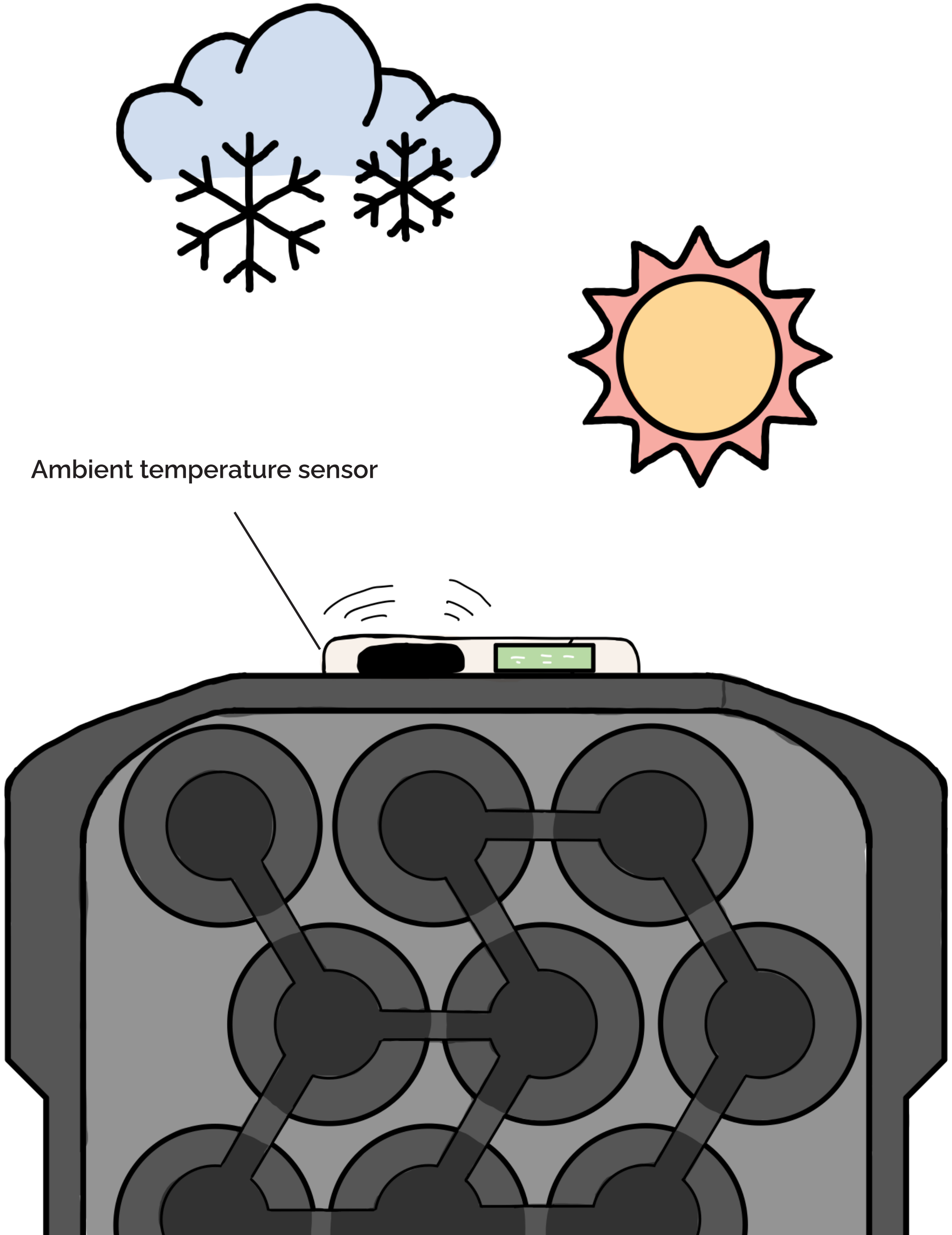


Figure 50: Ambient temperature compensation

6.3 Sensor placement

The previous section, *Temperature Factors,* addressed what influences the heat signal between the cell and the sensor. This section addresses where the sensors sit on the battery and how many are needed.

The structure of the e-bike battery uses battery cells over the full length of the shell, filling the entire shell, see Figure 24. Because the cells are uniformly spread, the sensors need to cover the full surface to detect changes anywhere on the battery. That is why multiple NTC sensors are placed systemically over the top and sides of the battery shell. The bottom surface is used for mounting in many common e-bike battery models and therefore not accessible foor measurement. Figure 51 shows the full surface of the shell that is covered by the sensors.

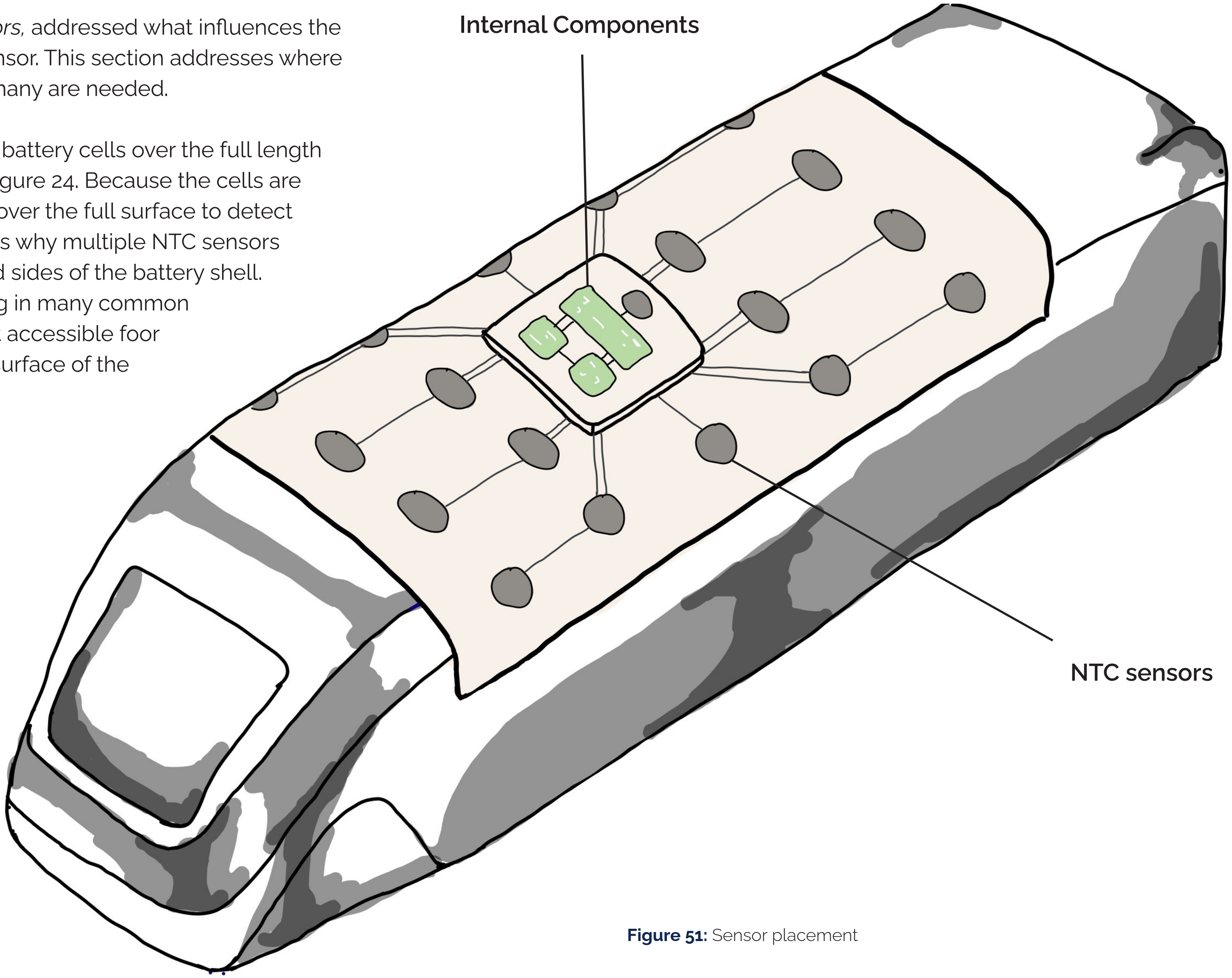


Figure 51: Sensor placement

Thermal simulation

The plastic shell does not spread heat evenly, see Figure 52, so a hot spot from one cell stays localised. A single sensor would miss hot spots elsewhere on the shell, which is why multiple sensors are needed.

This also allows for localised anomaly detection. If sensor 2 shows a rate of change above the baseline while sensors 1, 3 and 4 measure normally, the system has detected a local fault. This could mean a single cell or a group of cells going into early-stage thermal runaway. This information can inform the system on proportionate action and even faster and more sustainable repair. Multiple sensors also add redundancy: if one sensor fails, the others can compensate.

Ultimately, the decision to use multiple sensors is also a design decision. It tackles the “where do I stick it” problem that arises when only one sensor is used. Using a larger design that covers the entire length makes it easier and more straightforward to use, increasing the usability and user experience.

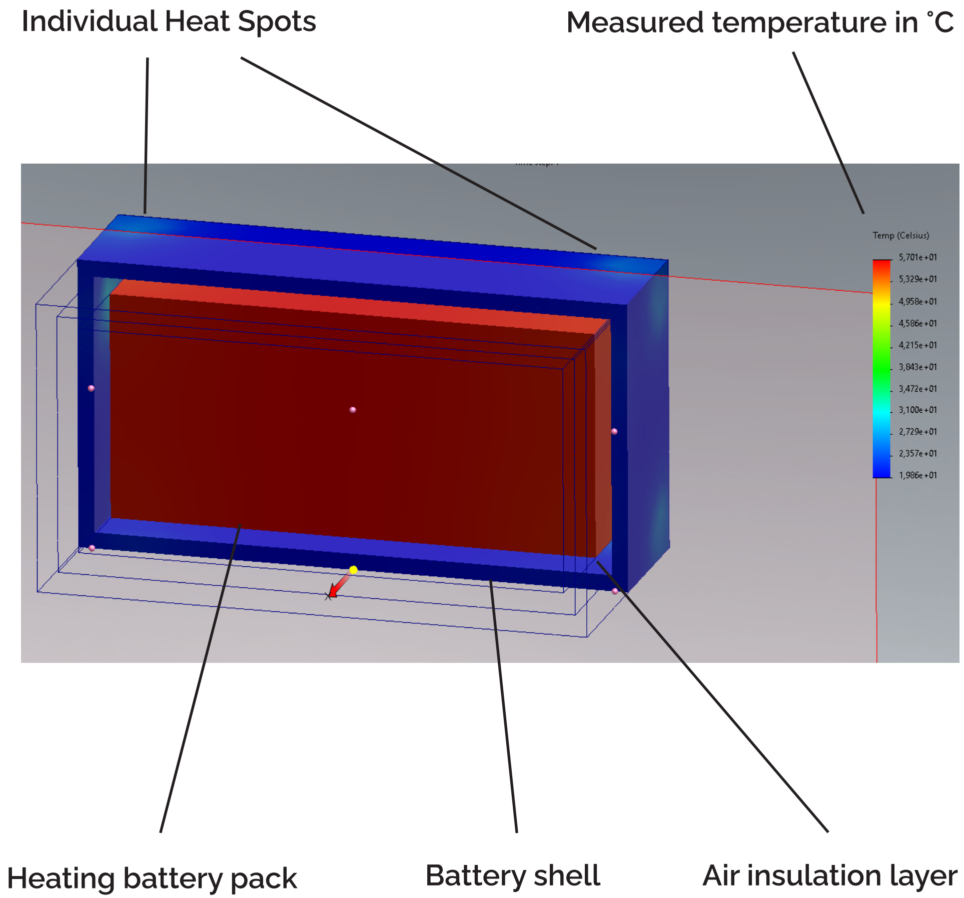


Figure 52: A thermal analysis in Solidworks Simulation of a uniform battery pack surrounded by an insulating air layer and a battery shell from ABS (Acrylonitrile Butadiene Styrene).

6.4 Communication

Correctly interpreting and reading the data is important, but without a functioning method of communication the user receives no information on the results in time. This section explains the chosen method of communication, when the data is sent and how this solution could function within the IoT space in the home.

Long Term Evolution for Machines (LTE-M) communication

The communication system needs to meet four requirements: it must be able to send data both during use and charging, it must send alerts with low latency, it must last several years on a single battery, and it must work in domestic spaces like basements and garages where signal can be poor.

LTE-M is a type of Low Power Wide Area (LPWA) cellular technology designed specifically for IoT communication, and currently used in devices like smart meters, shared e-scooters and agriculture [116]. It connects directly to the cellular network and towers, which means it does not depend on nearby devices, hubs or smartphones to relay data, Figure 53.

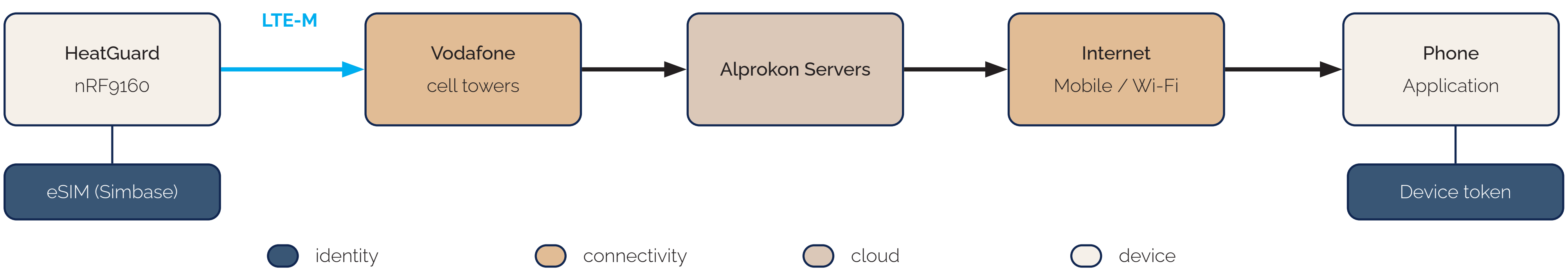
Thermal runaway often happens during charging, but battery damage and thermal runaway can also occur during use. A system that goes offline once the bike leaves the house cannot send an alert if this happens. LTE-M supports cell handover while the user rides, which keeps the sensor online across the full use-charge cycle.

LTE-M also allows devices to achieve several years on a single battery using Power-Saving Mode (PSM) and extended Discontinuous Reception (eDRX). This matches the requirement that the sensor must outlive the e-bike battery without manual recharging or replacement.
Another reason for choosing LTE-M is latency. Typical LTE-M latency is in the range of 50 to 100 milliseconds, which is fast enough to send a real-time alert.

LTE-M is based on the 4G network, but has better signal penetration and a more stable range even in hard to reach areas [1]. This matters in domestic spaces, where an e-bike can be charged in a basement, garage or shed. In deep basements or shielded spaces the signal can still drop, but penetration is significantly better than standard 4G or Wi-Fi. This is due to the lower frequency and smaller bandwidth that is used.

For this thesis, LTE-M coverage is assumed within the Netherlands, where Vodafone operates the network. The system requires a SIM and a data plan, which will be a one-time cost, see Chapter 9.

Figure 53: Use of LTE-M in HeatGuard



Data transmission

Continuous real-time data transmission would significantly increase power consumption and reduce the system's lifespan on one battery. The system uses LTE-M's Power-Saving Mode (PSM) to keep measurements passive. Data is stored and processed locally on the processor, with a rolling one-hour window saved on the local storage, keeping the data private until sent. This window covers the 0.57-hour prevention window plus an additional 0.43 hours of context. The extra time captures the learning layer's pre-signal drift detection, see Chapter 6.1, and provides diagnostic data on what happened before the alert was triggered. The system only transmits data when one of five conditions is met, see Table 3.

#	Condition	Trigger
1	Rate of change threshold	Rate of change exceeds W ˚C/min, see Chapter 6.1
2	Absolute temperature ceiling	Battery temperature exceeds a defined upper limit
3	Learning layer anomaly	A deviation from the baseline charging pattern is detected, see Chapter 6.1. This condition becomes active only after the learning phase is complete.
4	Scheduled heartbeat	A daily interval elapses without an alert
5	Sensor fault	A fault is detected in the sensor itself

Table 3: Conditions and triggers for data transmission

When conditions 1 to 3 trigger an alert, the stored data is pushed to the user. From that moment a real-time data stream is transmitted to keep the user informed of the current status. When nothing is wrong, no active data is sent and the application displays the e-bike battery as functioning normally. A weakness of this approach is when the device cannot transmit due to a bad or lost signal. The user does not receive alerts and may assume the system is working when it is not. The heartbeat is included to confirm that the system is still alive. The server will send for a "check-in" every 24 hours, this is called a Periodic Tracking Area Update (pTAU). The daily interval is introduced as a starting point and needs further definition through testing.

Integrated home network

In the future home, IoT and connectivity are becoming increasingly important. The Connectivity Standards Alliance has introduced Matter as an IP-based smart home connectivity standard [33]. Matter runs on common home networks like WiFi, Ethernet and Thread and is supported by major smart home platforms. This matters to this thesis because it points in a future direction where the system can connect to other smart home devices and provide a safer home.

One limitation of this solution as defined in Chapter 5.3 is that it does not support active prevention. However, in a connected home network, active prevention does not necessarily need to be integrated into the sensor itself. Instead, it could be provided by another connected device. For example, a smart socket switch can deliver the active prevention as described in the Gekko Imaging and the Socket Eye concepts, Chapters 5.2 and 5.4.

Ultimately, the solution will be able to extend beyond a single device. This could include communication through the Matter standard or through a new Alprokon home network, supporting the future vision of Every Space Safe, Figure 54.

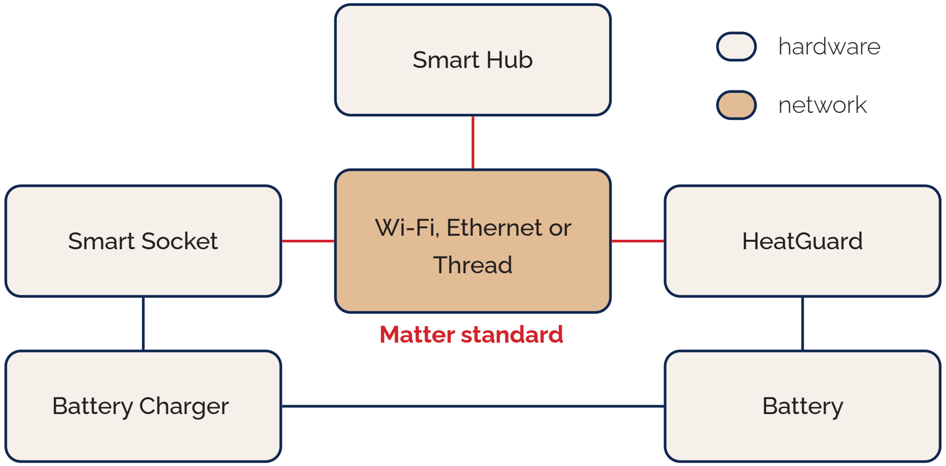


Figure 54: Illustration of the future of home network connections with HeatGuard

6.5 Components and power consumption

Chapters 6.1 to 6.4 address the principles that are required to understand to form the system. This section brings these principles to reality by defining the exact components that are required to make a functional system. Additionally, the power consumption is calculated along with the duration of the battery life.

Components

To approximate the power consumption of the system, I first define the components that perform its essential functions: sensing, processing, communication, storage, cellular positioning and power delivery. The components listed here are the parts planned for the final product, which requires custom PCB design in future steps. Real-world consumption depends on different variables such as duty cycle, operating modes and tolerances, so the figures derived here form an estimate, not a final specification.

The components have two separate purposes. The first set is the basis for the power consumption estimation. The second set is the experience prototype used for user testing, which simulates the user behaviour, experience and functionalities.

Components for the power consumption

The brain of the system, the Nordic nRF9160 [104], is a low-power chip that combines a processor and LTE-M modem in one package, see Figure 55. It can transmit the data over Vodafone's LTE-M network in the Netherlands

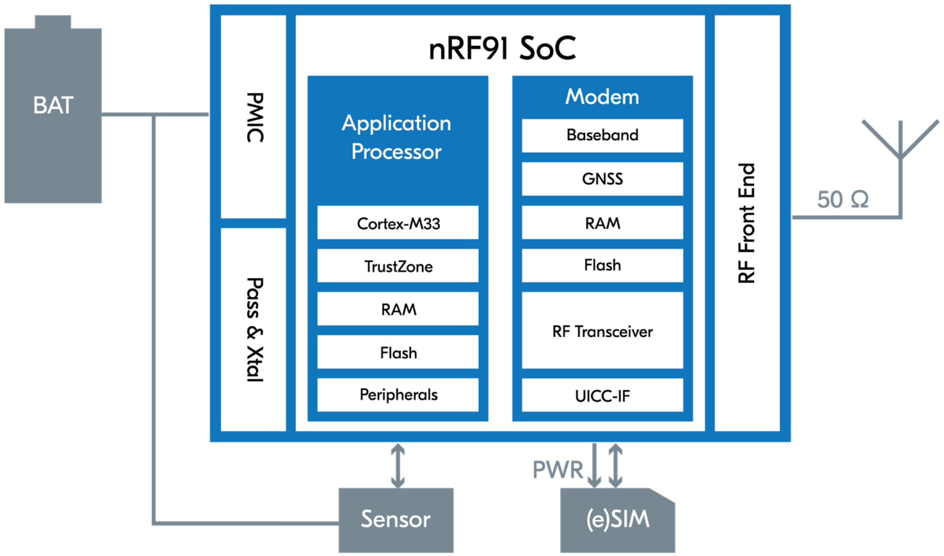


Figure 55: nRF91 SiP hardware setup [105]

using an embedded SIM (eSIM). The specifics of the eSIM, which one is used depends on the service package offered by Alprokon, for more details see Chapter 8.4.

The NTC temperature sensors are read through a simple voltage divider with a fixed reference resistor. Local data is stored on a small flash memory chip on the board itself, see Figure 55. The system is powered directly by a single-cell LiPo battery. Its nominal voltage of 3.7 V matches the chip's datasheet reference point and stays above the recommended 3.3 V threshold for almost its entire discharge curve [103]. Table 4 lists the components selected for each function.

Function	Component	Model
Processor and LTE-M modem	System-in-Package	Nordic nRF9160 [104]
Cellular subscription	eSIM	LTE-M
Temperature sensing	NTC thermistors	10 kΩ
Sensor reference	Fixed resistors	10 kΩ
Power source	Battery	3.7V 2500mAh

Table 4: HeatGuard components

Experience prototype for user testing

A prototype was built around an Arduino Nano ESP32 to simulate the user scenarios over the local Wi-Fi network. Its purpose is to convey the experience of the system during user testing, see Chapter 10.2. It is not used in the power consumption calculation and does not reflect the final electronics.
Six NTC sensors represent the individual measurement points on the battery shell, and one NTC sensor measures the ambient temperature. A DC-to-DC booster steps a 3.7 V LiPo battery up to the 5 V input required by the board.

Power consumption

Before the power consumption is calculated, I define a set of assumptions:

- The board sleeps in Power Saving Mode (PSM) between events and wakes only on the trigger conditions defined in Table 3.
- This calculation assumes 12 alert events per year and 1 heartbeat (pTAU) every 24 hours, with the device in continuous PSM sleep in between as described above in *Data Transmission*, see Graph 5.
- 80% of the rated battery capacity is treated as usable, to account for ageing and degradation.
- LiPo self-discharge is taken at 2% per month, a typical figure for healthy lithium polymer cells [21].

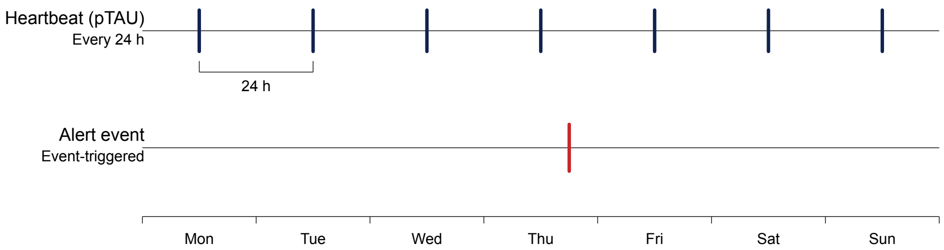
The full calculations of the current consumption and battery lifespan can be found in Appendix D.

When using a single-cell LiPo battery of 3.7 V and 2500 mAh, the usable capacity is 2000 mAh. Dividing this by 648 mAh per year gives a lifespan of approximately 3.1 years on a single charge, see Graph 6.

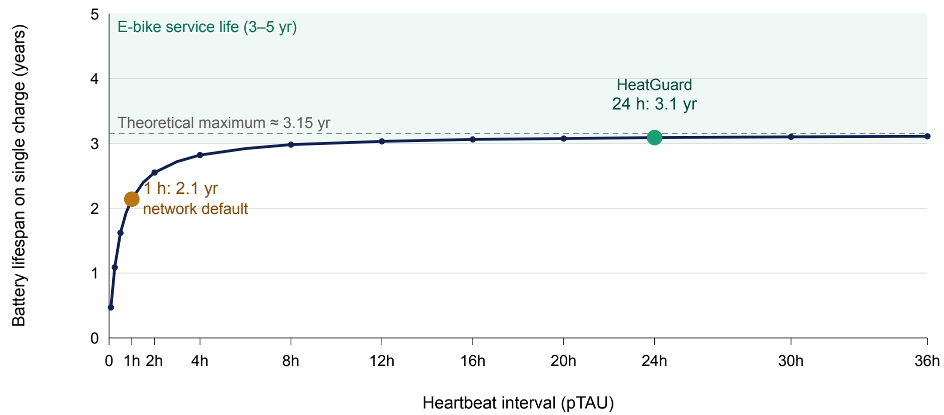
The expected service life of an e-bike battery is 3 to 5 years. The solution therefore reaches the lower end of that range on a single charge but needs at least one recharge for systems used towards the higher end. Recharging is preferred over replacement for sustainability reasons.

A useful observation from the calculation is that self-discharge has the most significant impact on the result. The transmission events themselves contribute less than 7% of the annual loss, the remaining ~93% is the battery degradation. Increasing battery size will not extend the device's lifespan as explained in Appendix D. Only using lithium polymer cells with lower self-discharge rates would meaningfully extend the time between recharges.

When looking at trends in cellular IoT and battery development, future iterations of this design are likely to combine more efficient processors with cells of lower self-discharge. This could close the gap toward a device lifespan that matches the e-bike battery without the need for charging.



Graph 5: Alert interval



Graph 6: Battery life

Chapter takeaways

This chapter establishes the technical foundation the system is built on and demonstrates the plausibility of the main technical choices. The tracked signal is the rate of change, measured by multiple NTC sensors across the top and sides of the shell, with an ambient sensor to filter external temperature. The two-layer detection method, fixed and learning, addresses both the alarming threshold and the over-time temperature curve that signals thermal runaway earlier than the fixed layer alone allows. LTE-M is the communication method, with data sent only on the five defined trigger conditions.

The power consumption calculation gives approximately 3.1 years on a single LiPo charge under the 24-hour transmission interval, with self-discharge as the most significant draw. This sits at the lower end of the e-bike battery lifespan and is the clearest constraint in the design.

The thresholds W, X, Y and Z, the number of cycles n, the heartbeat interval and the prevention window under domestic conditions require further testing and are set as assumed variables for this thesis. With these fundamentals, principles and values set, the next chapter translates them into a functional prototype for user testing.

CHAPTER 7

HeatGuard

In this chapter, the gathered insights and research are translated into a List of Requirements. Several design choices are then made using the Morphological Chart, a structured design method. Together with the technical requirements set out in the previous chapter, these form the foundation on which HeatGuard is designed. With this chapter I enter the Deliver phase of the Double Diamond, Figure 56. Through an iterative process, the sensing side of HeatGuard was designed and built. In the sections that follow, I elaborate on the steps taken and deliver HeatGuard.

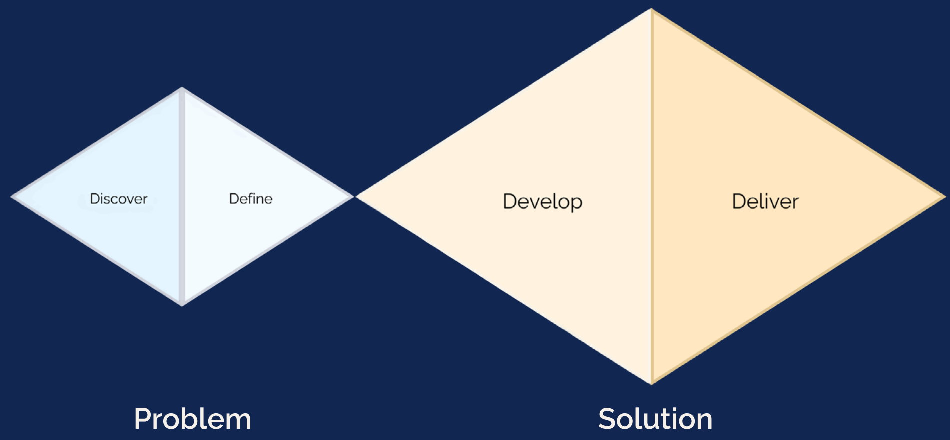


Figure 56: Deliver phase of the solution stage

7.1 List of Requirements

Based on the takeaways from Every Space Safe and the research and thermal runaway chapters, all gathered insights and focus areas were translated into a **List of Requirements,** Tables 5 and 6. Following the Delft Design Guide [165], a List of Requirements sets the mandatory conditions the design must satisfy. Each requirement is concrete and specific, stating an important characteristic the design must have to be considered successful. Together they form the basis from which the functions and aspects of the design are developed, and throughout the project they act as the directions that guide the design towards a complete product that meets all of them.

The List of Requirements is a document that lives throughout the entire process. It was updated at the end to reflect the status of the requirements.

Topic	Requirement	Status	Why?
General	The solution targets the consumer market as described in the mission of Alprokon.		Client's vision and design intention
Safety	The solution measures thermal activity with meaningful results.		Thermal runaway prevention
	The data describes and detects a prevention window.		Thermal runaway prevention
	The user feels safer and confident using the solution.		Subjective safety
Usability	The solution uses a do-it-yourself attachment method.		Usable by everyone, ease of use
	The solution is attachable to a variety of e-bike batteries, including different surface models and detachable batteries.		E-bike coverage
Feasibility	The solution compensates for atmospheric temperatures.		Accurate readings
	The solution is thermally sealed to the surface of the e-bike battery shell.		Accurate readings
	The thermal resistance of the shell material and the air gap beteween the battery and shell are acounted for.		Accurate readings
	Solution-to-application communication works over the lifetime of a general e-bike battery (3-5 years or 300-500 charging cycles).		Continuous prevention and safety
	The application visually instructs the user and displays the status of the sensor and battery.		Understandable and actionable communication
Durability	The solution and attachment material are water-resistant to IPX5 (low-pressure water jets).		Mechanical abusea and outdoor exposure of e-bikes
	The adhesive material must hold up across temperatures of -20°C (IEC 60068-2-1) up to +60°C (IEC 60068-2-2).		Attachment durability
	The adhesive material must withstand vibrations and shocks of daily bike use as tested with the EN 50604-1 standard for E-bike batteries.		Attachment durability
Sustainability	The solution has a rechargeable internal battery, allowing it to outlast multiple e-bike batteries.		One sensor serves one e-bike battery, recyclability

Table 5: List of Requirements

Status	Explanation
	Requirement met, integrated into the design.
	Requirement partially met and integrated, theoretical plausibility demonstrated, but further development is required.
	Requirement not met, further research required to meet the conditions.

Table 6: Legend List of Requirements

7.2 From sub-functions to a solution

After comparing the three concepts in Chapter 5 and defining the List of Requirements, six sub-functions were defined and compiled into a Morphological Chart. This is method from Delft Design Guide [165] used to find several solutions to a defined problem by deconstructing it into sub-functions.

The chart in Figure 57 shows the combinations:

- Insulation and attachment through tight adhesives.
- Transmission using ground-based towers.
- Power by rechargeable battery.
- Side and top placement of the sensor.
- Actionable push notifications for communication.

More combinations with other sub-solutions were done in the iterative
process, but this concept showed the most promising design directions. The upcoming sections will develop the chosen solution combination into a working prototype.

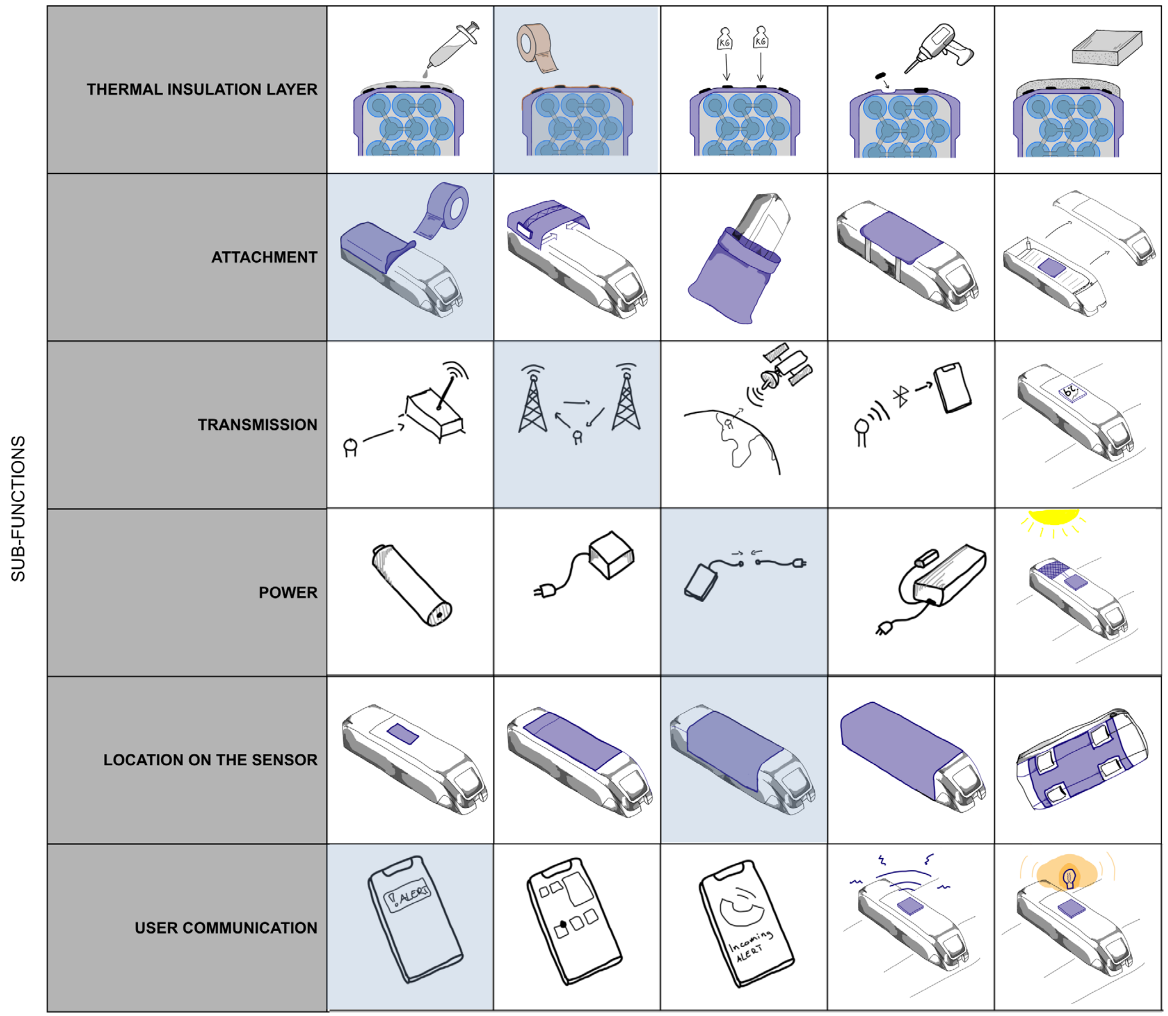


Figure 57: Morphological Chart

7.3 The birth of HeatGuard

A product needs a name. To find one, I had to think about what this solution actually does. It provides a new form of safety and ultimately guards the user from a developing fire. That called for a name which states its purpose, is strong and self-explanatory. And so HeatGuard was born.

I started by creating a rough prototype from a denim material on a 3D printed battery shell made from PLA, Figures 58 to 60. The printed battery shell can be seen in Chapter 3.1.2. This allowed me to test the attachment method and make quick iterative changes. After getting a rough idea of what HeatGuard was going to look like I continued with creating the electronics that form the technical foundation.

Figure 58: Cutting and sewing the denim patch

Figure 59: Denim patch

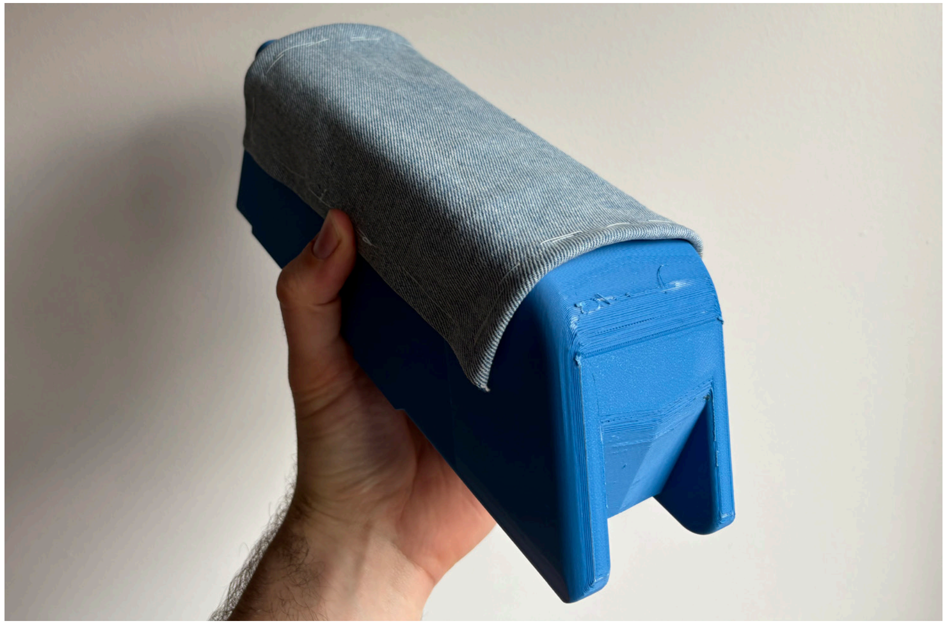


Figure 60: First HeatGuard prototype

7.3.1 Breadboarding

To make a functional prototype of HeatGuard, I had to use electronics that could simulate the final behaviour and the user experience. Therefore, I designed several prototypes that allowed me to test and explore the functionalities of HeatGuard. The first prototype contained one NTC sensor and LEDs for troubleshooting and communication, see Figures 61 to 63. It allowed me to test the fundamentals of the code before developing the final version. Whenever a signal was sent over Wi-Fi, an LED lit up according to the push notification: green, orange, or red. This way I could verify that the correct push notification was sent at the right time. Moreover, using the build-in serial monitor of the Arduino IDE, I could, in real-time, see the transmitted data. The notification also appeared on my phone via the NTFY application, which was ultimately used for the user tests [62].

The prototype worked as expected. I iterated on the design and built the next version using seven NTCs, still on a breadboard to allow for quick troubleshooting.

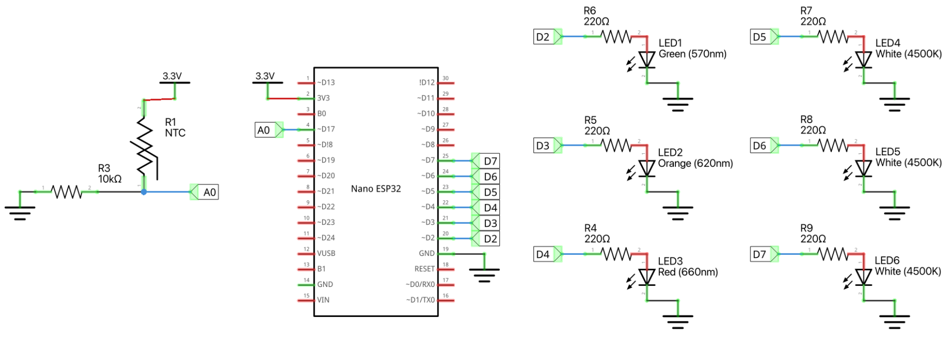


Figure 61: First prototype schematics created using Fritzing [56]

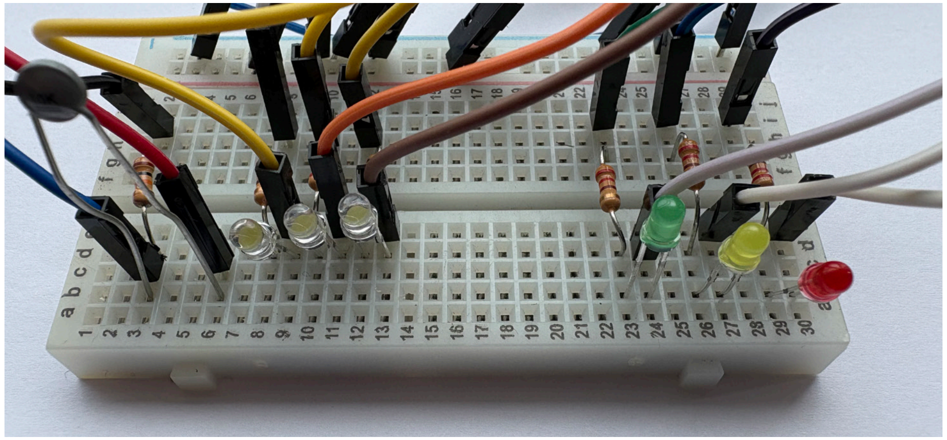


Figure 62: First prototype breadboard model (1)

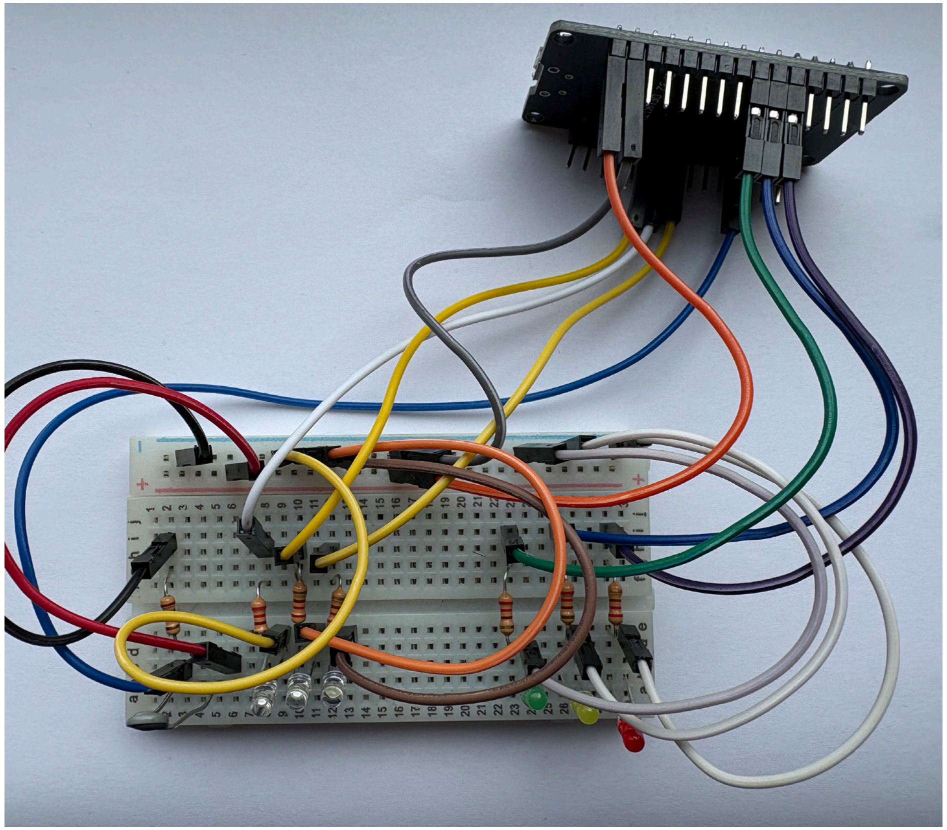


Figure 63: First prototype breadboard model (2)

7.3.2 Product integration

Designing the next prototype, I wanted to integrate the electronics into the denim patch to create the full HeatGuard experience. This allowed me to test the user interaction with the shape and the attachment process. Figure 64 shows the sketches I made for this design.

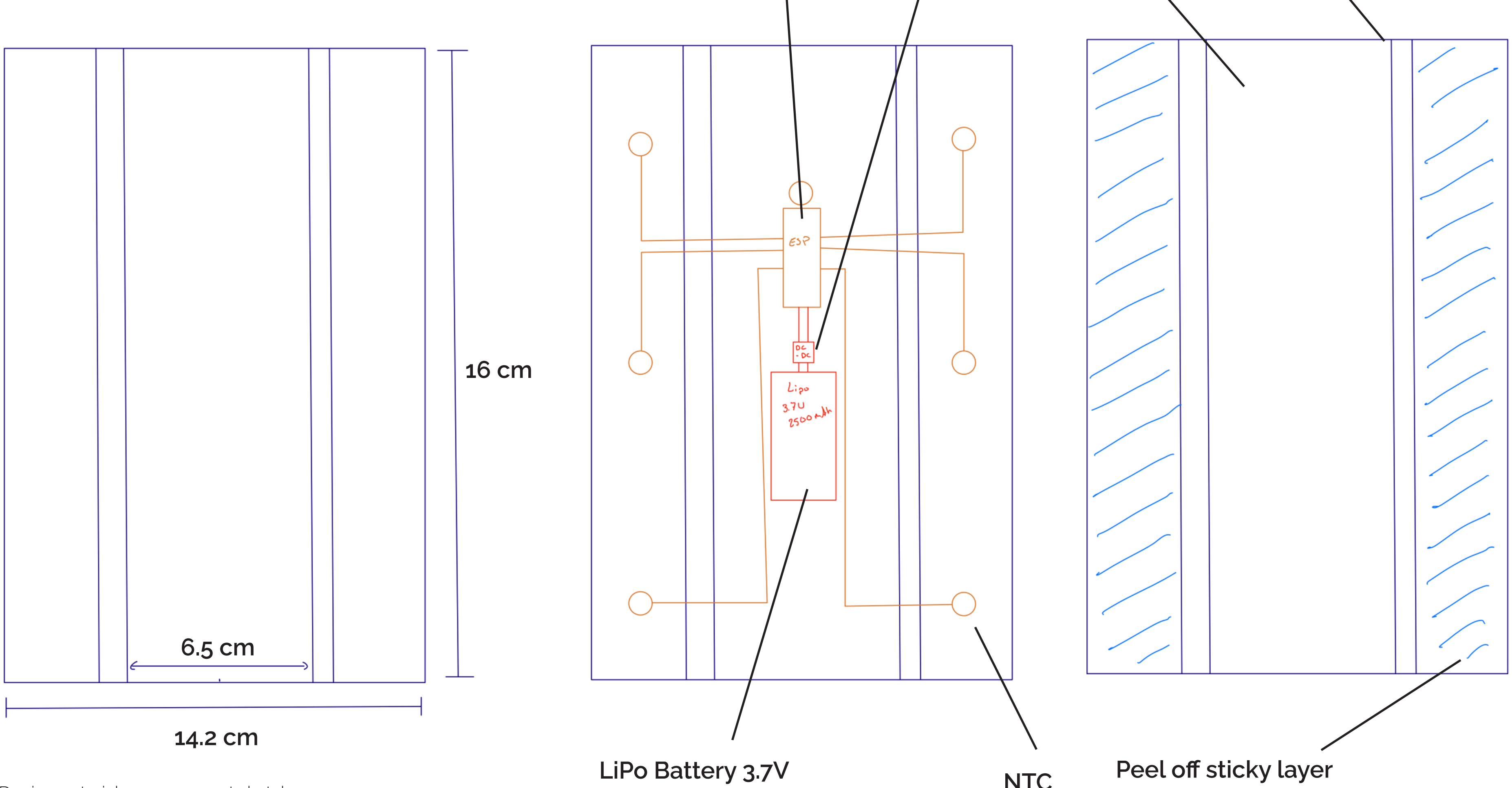


Figure 64: Denim material measurement sketches

This version of the breadboard prototype was used to test the final source code and the interaction between the NTC sensors, see Figure 65. The code is discussed in Chapter 7.3.3.

Instead of the LTE-M network, I connected it to my personal mobile hotspot. This allowed the system to function outside the home and across different spaces like the LTE-M network, but without complicating the prototype with a network chip and eSIM functionalities. It was still able to simulate real-life mobile behaviour.

The prototype demonstrated end-to-end signal flow, threshold triggering, and app notification. It conveyed the full user experience from start to end, covering the different scenarios, atmospheric temperature influences, and interaction with the mobile application.

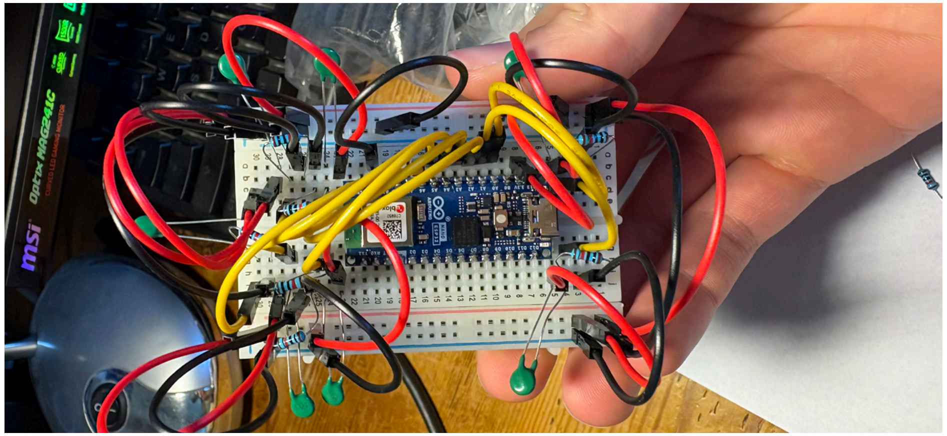


Figure 65: Seven NTCs breadboard prototype

Soldering

Knowing that the breadboard prototype was functional and worked as expected, I started to develop a custom, soldered electrical circuit that I could attach to the denim patch. I first created an iteration with two NTCs, see Figures 66 and 67.

After this proved functional, I iterated again on the design, making small adjustments to the length and type of the wires and adding the final seven NTCs.

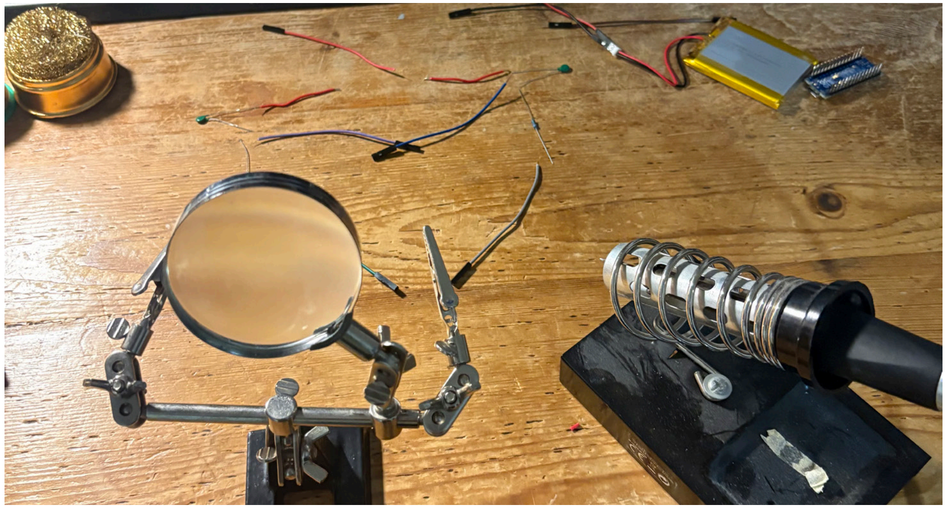


Figure 66: Soldering the two NTC prototype

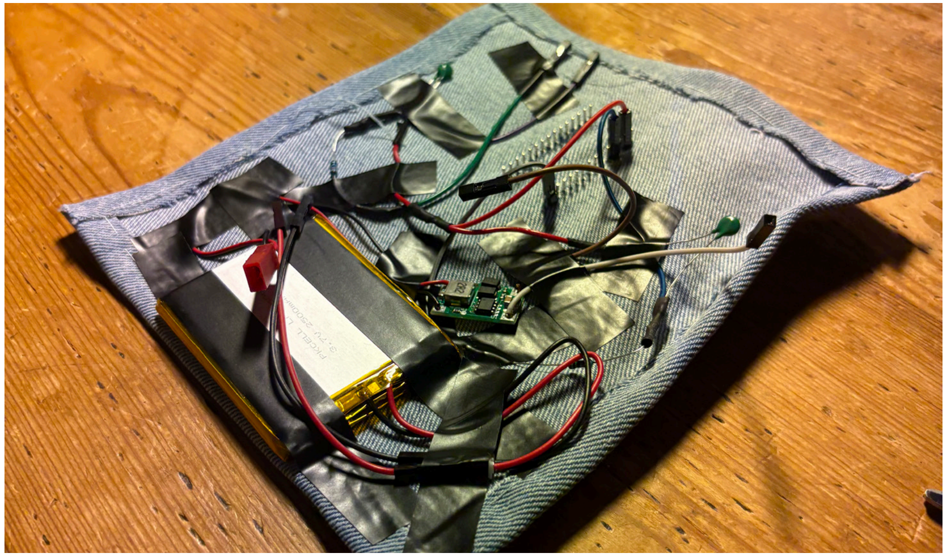


Figure 67: Integrating the two NTC electronics into the denim patch

Figures 68 to 72 show the soldering process. The final result is shown in Chapter 7.7.

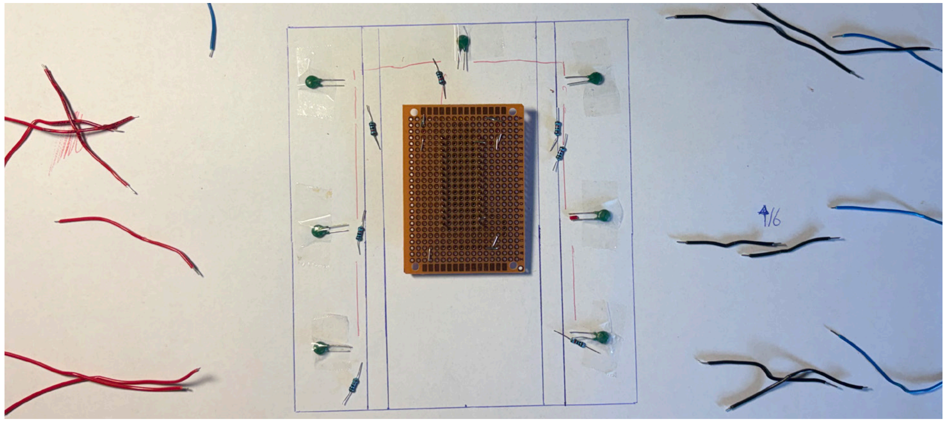


Figure 68: Based on the sketch in Figure 64, laying out all sensors for soldering

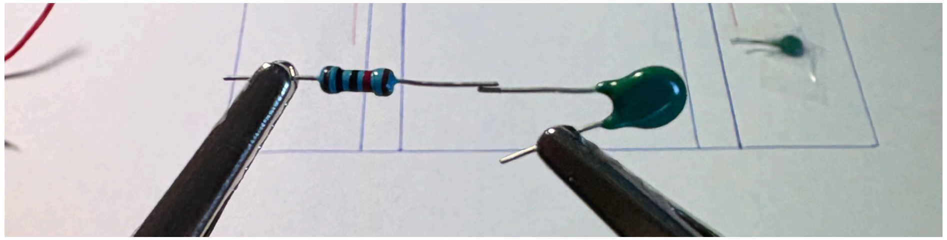


Figure 69: Soldering a resistor to a NTC sensor

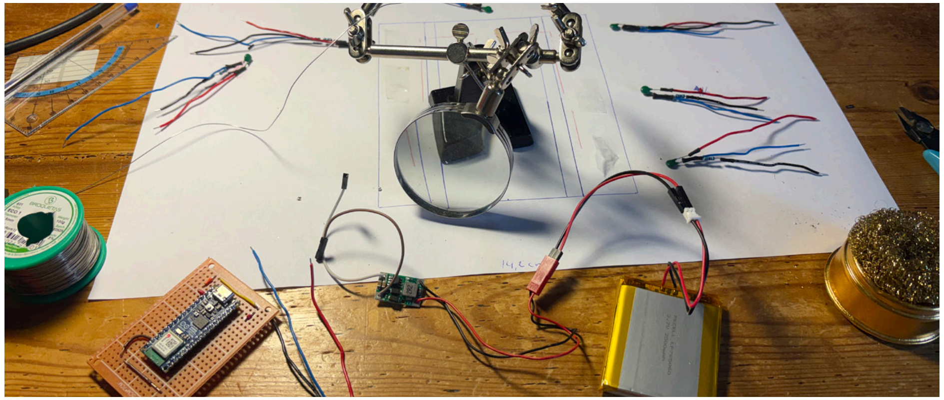


Figure 70: Gathering all components for the PCB

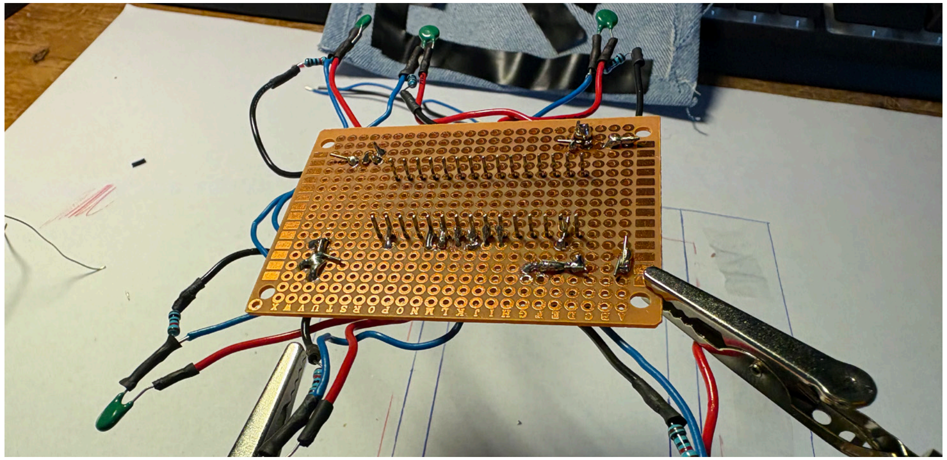


Figure 71: Soldering the wires to the underside of the PCB

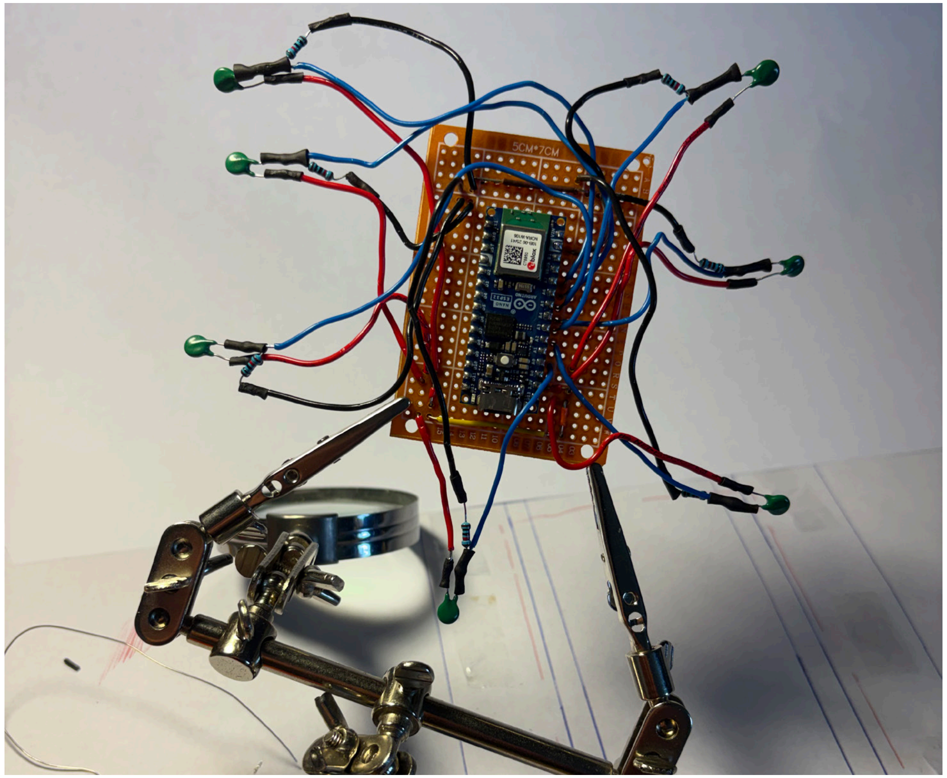


Figure 72: Electronics completely assembled

7.3.3 Coding

HeatGuard runs on an Arduino Nano ESP32, for which I used the Arduino IDE to write code in the C and C++ programming languages. For this part of the prototype I used vibe coding with Claude Code to support me in writing the algorithm for HeatGuard.

Using an iterative process, I developed several Arduino sketches, one for each prototype, that verify and test separate components and structures. I started with code that tested the communication to the NTFY app, followed by testing one NTC sensor, and eventually the seven NTC sensors discussed in the previous section.

For this prototype, the detection works with absolute temperature thresholds rather than the rate of change. The final system uses the rate of change (dT/dt), as described in Chapter 6.1. The rate of change functionality was tested on the prototype, but for the user tests and demonstration I decided to use absolute temperature thresholds. These are simpler to control and trigger in a test setting, which makes it easier to run and repeat the scenarios, while still demonstrating the full experience from sensor to notification.

Upon startup, the board loops while searching for a predefined hotspot network, Figure 73. A successful connection starts the measuring loop, which constantly checks the temperature of each sensor. Each NTC sensor returns a resistance value, which the code converts into a temperature using the Beta-parameter equation. When a temperature value passes a certain status threshold, Figure 74, a notification is sent to the NTFY app over the hotspot network, Figure 75.

The ambient NTC sensor adjusts the threshold according to its own temperature change. When that sensor measures a higher temperature, which could be due to direct sunlight, all other sensors have to reach a higher temperature before the next risk phase is triggered. This compensates for ambient temperature changes that may otherwise affect the reading.

The full source code can be found in Appendix E.

```
const char* WIFI_SSID     = "";
const char* WIFI_PASSWORD = "";

const char* NTFY_SERVER = "https://ntfy.sh";
const char* NTFY_TOPIC  = "Alprokon_HeatGuard";
const char* APP_URL     = "https://stijnboogie.github.io/Graduation/";
```

Figure 73: The personal hotspot network and NTFY server variables

```
if (anyRed) return STATUS_RED;

switch (current) {
  case STATUS_RED:
    if (!allBelowOrange) return STATUS_RED;
    return allBelowGreen ? STATUS_GREEN : STATUS_ORANGE;

  case STATUS_ORANGE:
    if (allBelowGreen) return STATUS_GREEN;
    return STATUS_ORANGE;

  case STATUS_GREEN:
  default:
    return anyOrange ? STATUS_ORANGE : STATUS_GREEN;
}
```

Figure 74: Status thresholds and change

```
void sendNtfy(const String& title,
              const String& message,
              const String& priority,
              const String& tags) {
```

Figure 75: Sending the correct message to the mobile application

7.3.4 Custom PCB assembly

With the final electronics selected and the power requirements of the Arduino Nano ESP32 understood, I developed the next version of the prototype, see Figures 76 to 79. I soldered the components together and sized them to match the e-bike battery, see Chapter 3.1.2. A custom PCB connected the sensors, power, and ESP32 in a compact form. The schematics in Figure 76 show how the components are wired.

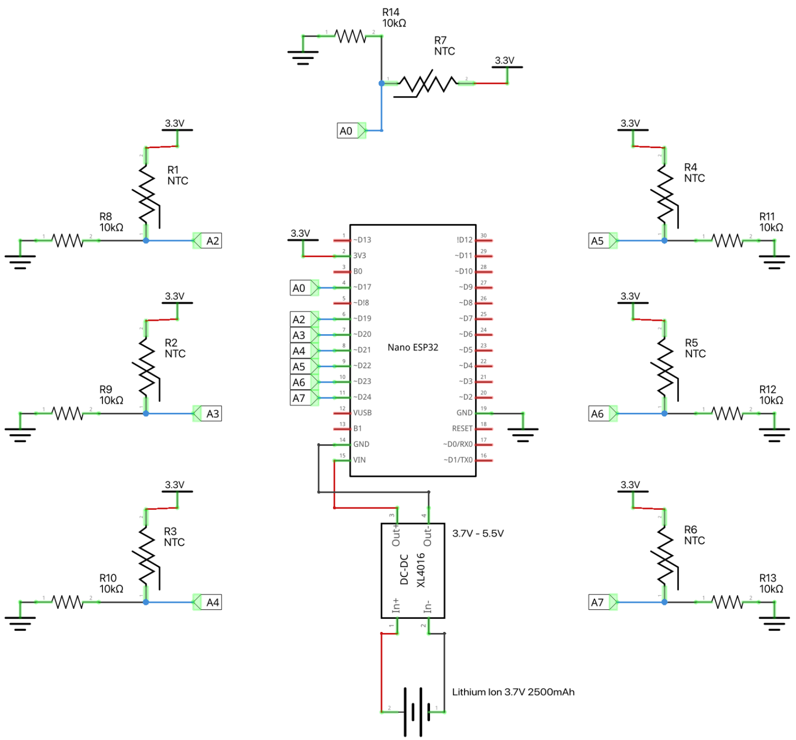
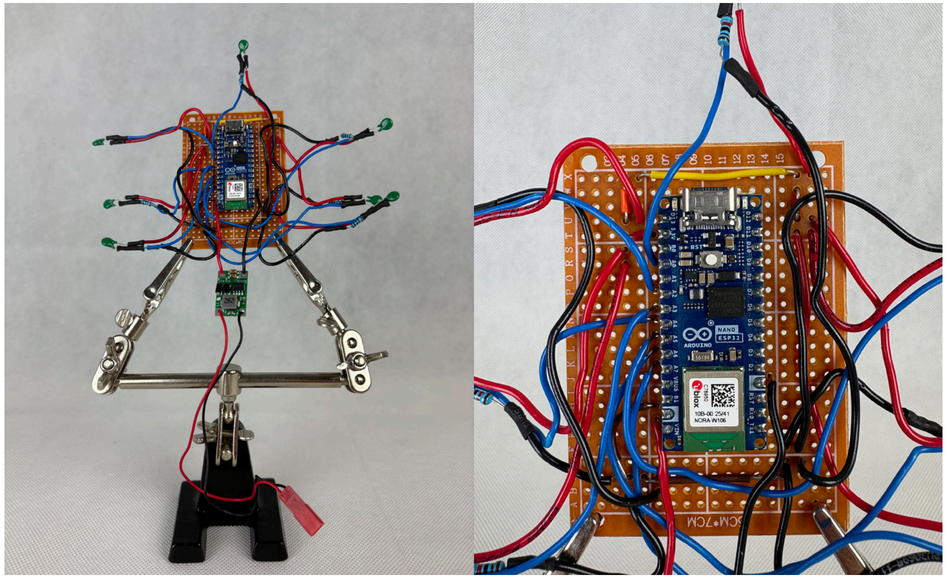


Figure 76: Custom PCB schematics created using Fritzing [56]

After assembling the electronics and powering them with a 3.7V LiPo battery, see Figures 77 to 79, the prototype still demonstrated the expected functionalities. This version forms the electronic foundation of HeatGuard. The materials and attachment method that turn it into a usable product are selected in the next section.



Figures 77 and 78: Prototype presentation with custom PCB

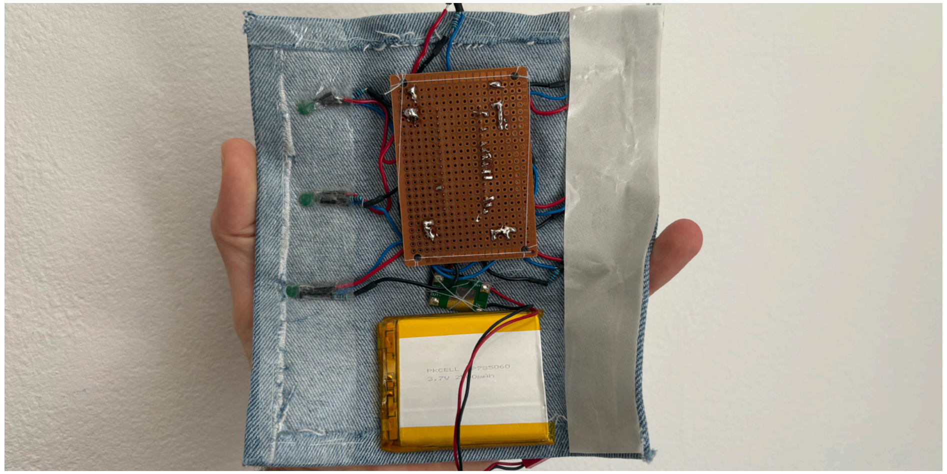


Figure 79: HeatGuard from below

7.4 Attachment method

The sensor is applied like a plaster, following one principle of using one application in one orientation. This builds on poka-yoke, the design principle for making the wrong action physically difficult through limitations and clear instructions [141].

The outer strips have the adhesive and the middle strip is non-stick, see Figure 80. The non-stick strip gives the resident something to hold on to during placement. And the layout guides them into the correct position. This reduces a large user-introduced variable in this system: placement. The strips align with the raised ridges on the side of the battery shell.

For the prototype, general hardware store double-sided tape is used. It simulates the final application experience well, without yet having the adhesive properties required in the List of Requirements, Chapter 7.1.

The strip cover also functions as a battery isolator. It breaks the power circuit until it is removed, the same principle used in children's toys and hearing aids. Pulling the strip removes the isolator, so the system receives power and turns on. This automatic turn-on during setup makes installation easier for the user.

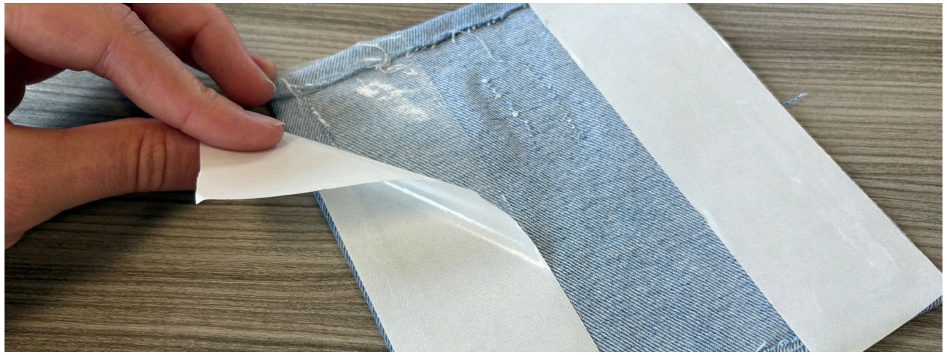


Figure 80: Adhesive peel

7.5 Material

Following contact with the Technical Sales Manager at HKO, I decided to make the prototype material from HKO's Silicatherm HS 650 AR, see Figure 81. See Appendix G for the full datasheet [66, 67]. This is a single strand silica fabric that is flexible, durable, non-combustible, and resistant to temperatures up to approximately 1,000 ˚C with low shrinkage.

These properties match the needs. The fabric is flexible, so it wraps around the curved battery shell, and it is a stable material with low shrinkage and high temperature resistance. This means that it does not soften or deform as the battery heats up, so the NTCs stay pressed against the shell. Moreover, because it is non-combustible, the fabric adds no fire risk to a solution whose purpose is fire prevention, and it is durable enough to travel with the e-bike through the full use-charge cycle.

In the prototype, the sensors are woven on the fabric and attached to the bottom side. These lie between the fabric and the battery shell, see Figure 84, shielding it from the surrounding air. This reduces heat loss, which improves the rate-of-change measurements. In the next iteration of the prototype, the battery shell is made from PLA in a matte charcoal colour, to resemble an e-bike battery and keep the full visual focus on HeatGuard.

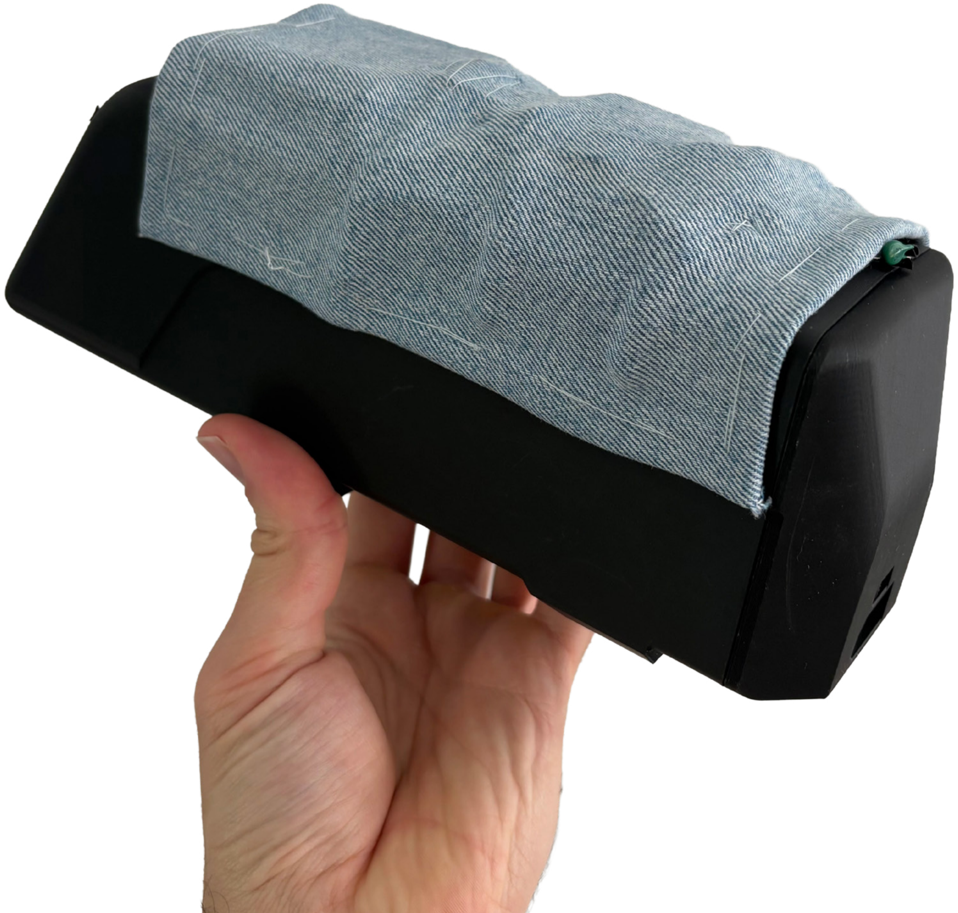
Alprokon and HKO have collaborated before on the development of fireproof roller doors. HKO is a familiar supplier, which simplifies sourcing and material qualification for the prototype. As part of Saint-Gobain, HKO can also finish and coat the fabric to specification.

Figure 81: Silicatherm HS 650 AR from HKO

Attaching HeatGuard

While still using the old denim material, but with the new 3D printed matte charcoal battery shell, a new iteration on HeatGuard was created, see Figure 82.

Figure 82: HeatGuard on a charcoal battery shell



7.6 Placement location

The e-bike battery consists of a series of connected cells running almost the full length of the shell. Each cell can develop thermal runaway individually, so the sensor must read across the entire length rather than at a single spot. This rules out the morphological chart options that cover only a small section of the shell and narrows the choice to solutions spanning the full length.

E-bike models vary in their attachment method [52], but all reserve one face for mounting. A full sleeve is therefore not usable with the frame interface. Some e-bike models allow the battery to be removed during charging, but a sleeve fitted only at that moment leaves the battery unmonitored while in use or located somewhere else, and thermal runaway can still develop even when not charging.

This leaves coverage of the top and sides, running the full length, see Figure 83. All cells are located beneath the sensor coverage, the mounting face stays clear, and the battery can still be charged or fitted to the bike with the sensor in place. The cell layout in Chapter 3.1.1 supports this choice and allows the rate of change to be read reliably from the top and side surfaces.

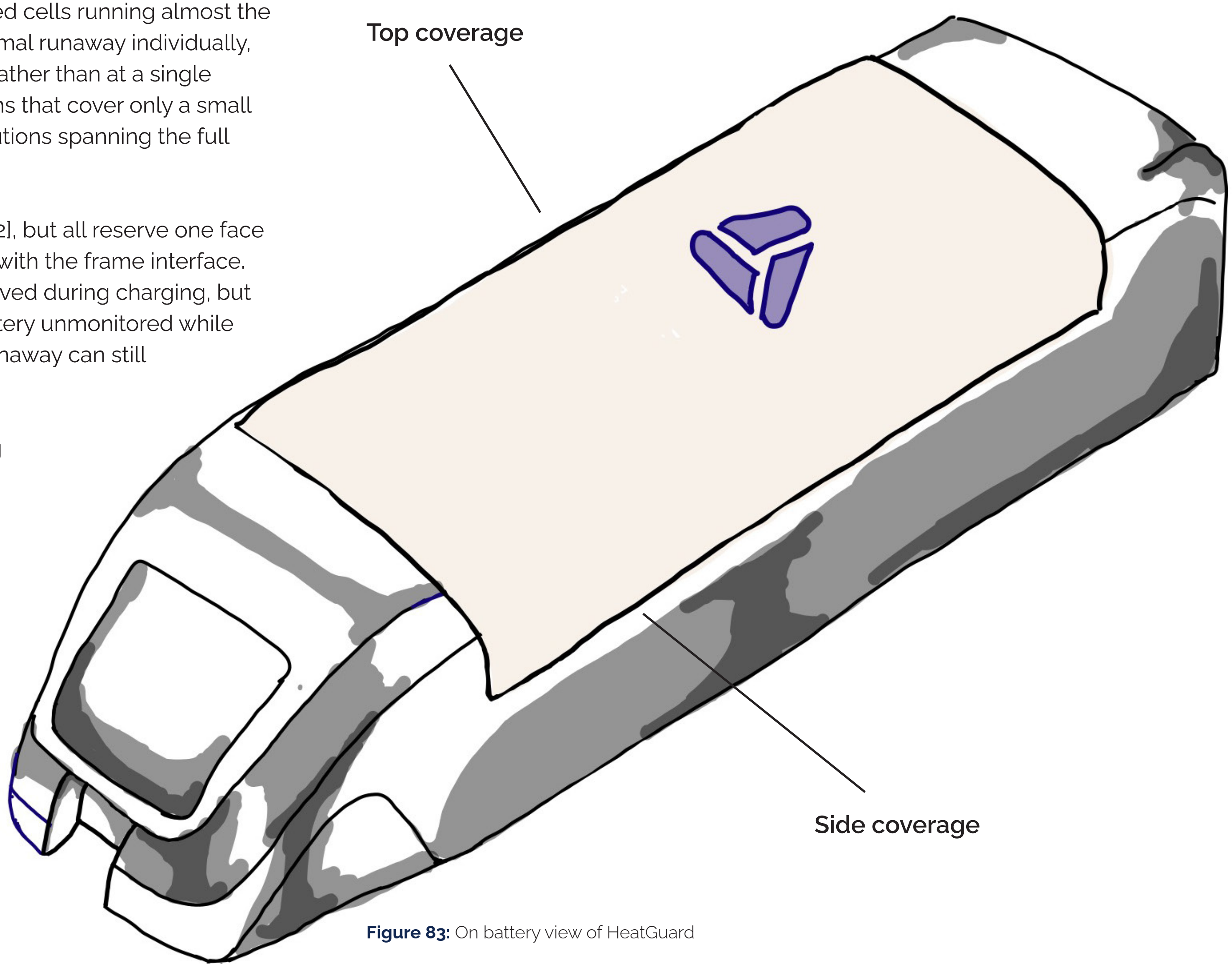


Figure 83: On battery view of HeatGuard

7.7 HeatGuard

Combining the material, electronic components, and adhesive strips creates the final prototype of HeatGuard. This sensing system demonstrates all the primary functions of HeatGuard in a simulated, ideal scenario. The prototype will be used as a visual reference for the mobile application presented in Chapter 8, and as a testing model during the user tests.

Figure 84 shows an exploded view of the general components used to make HeatGuard. All of these components hold smaller, more complex details, which have been discussed in this chapter.

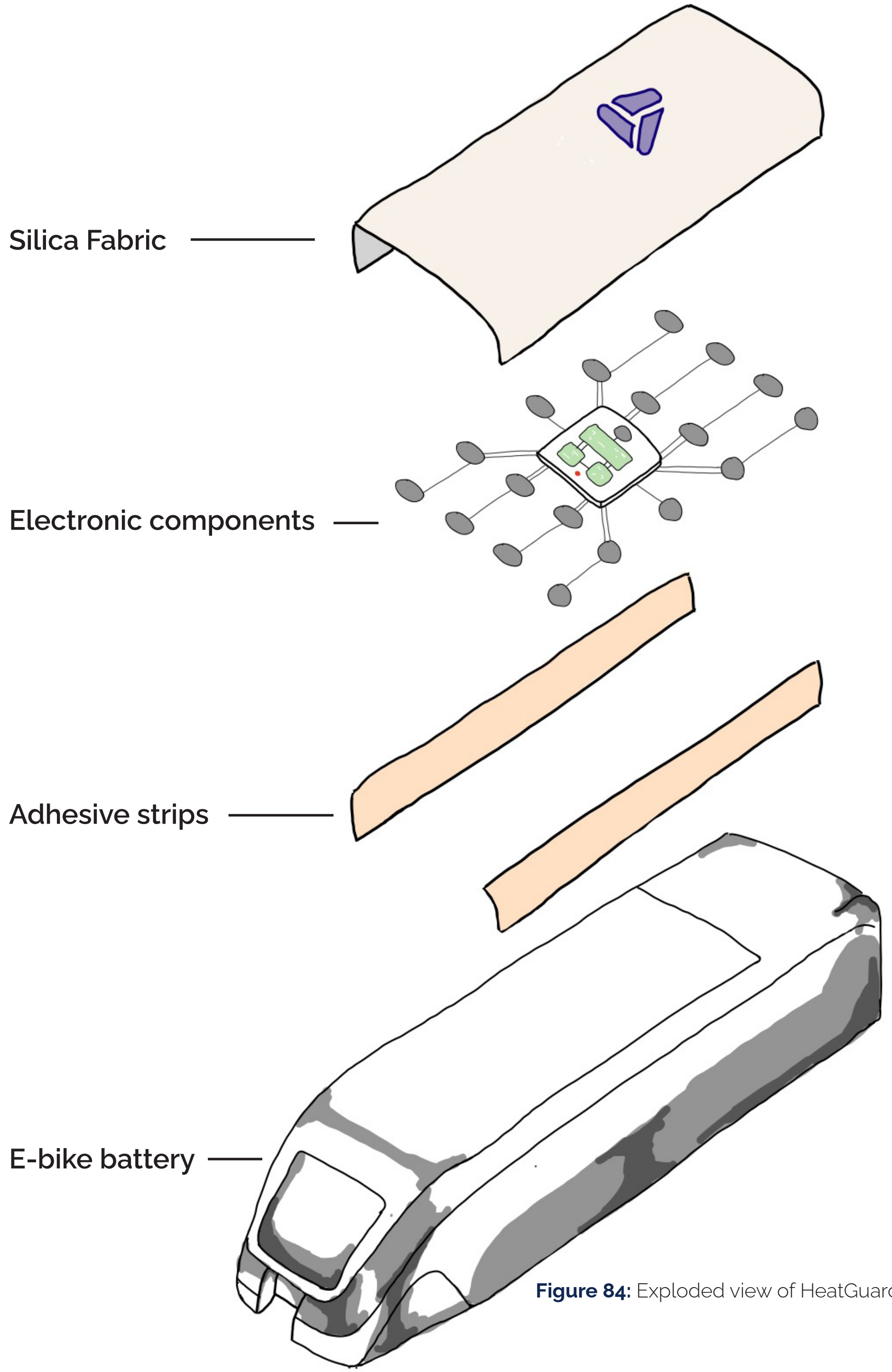


Figure 84: Exploded view of HeatGuard

The final prototype

The final iteration of HeatGuard displays the prototypes as they are used in the user test, see Figures 85 to 88. Two separate fabrics are created, one with the woven-on electronics and the other one without.

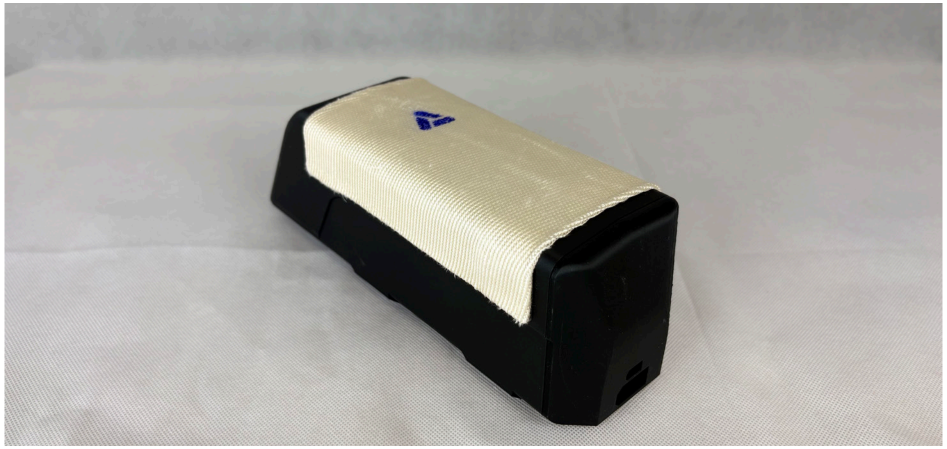


Figure 85: HeatGuard prototype

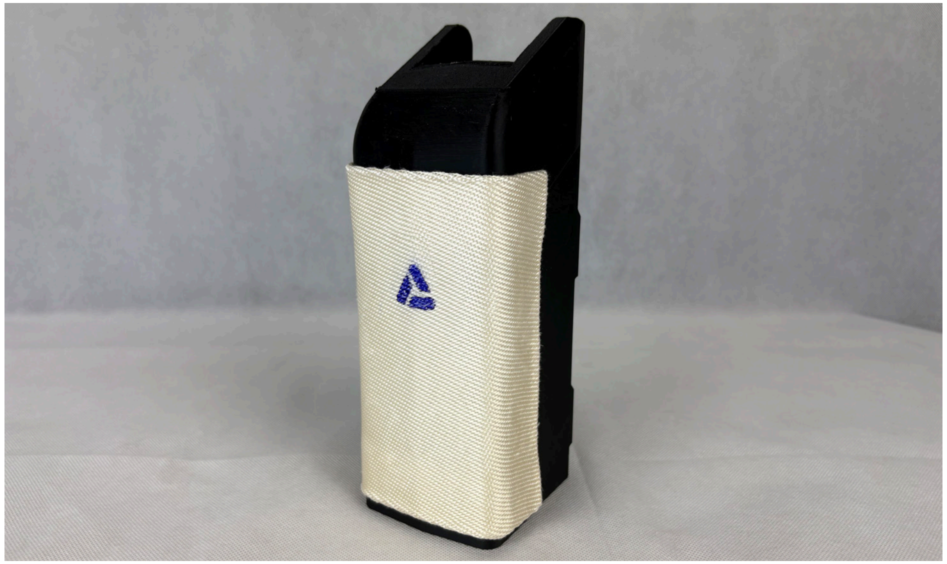


Figure 86: HeatGuard from the front

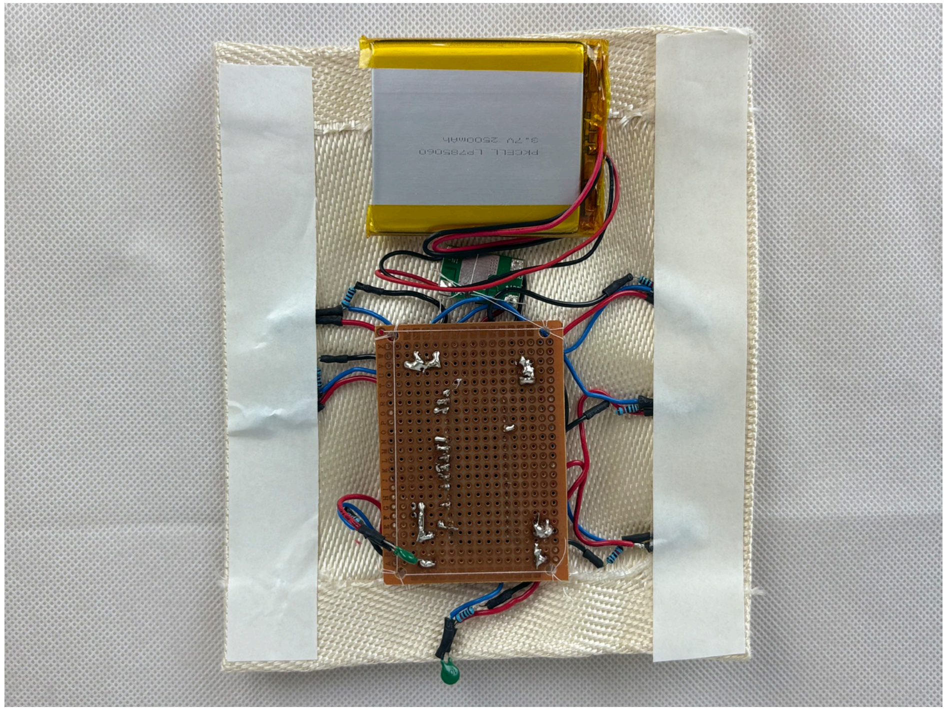


Figure 87: HeatGuard from below on the Silicatherm HS 650 AR

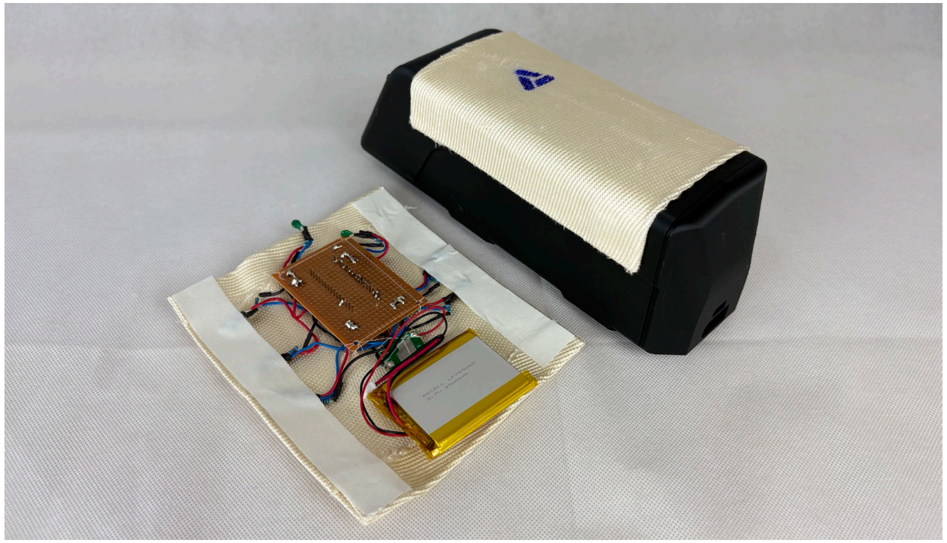


Figure 88: The full HeatGuard setup as used in the user tests

Chapter takeaways

The insights from Every Space Safe, the research and the thermal runaway chapters were translated into a List of Requirements. Six sub-functions were then defined and deconstructed into a Morphological Chart, and the most promising combination was selected to form the solution: adhesive attachment, transmission over ground-based towers, a rechargeable battery, side and top placement, and actionable push notifications. Since the solution needs a name, I wanted one that states its purpose and is self-explanatory, and so HeatGuard was born.

HeatGuard was built using an iterative process. The first prototype used one NTC sensor and some LEDs to verify the code and the notification to the NTFY app. The second one used seven NTCs on a breadboard to test the final source code and the interaction between the sensors. This one was connected to my mobile hotspot to simulate real-life mobile behaviour. On the third iteration I soldered the components onto a custom PCB, sized to fit the e-bike battery. The system is powered by a 3.7V LiPo.

The sensor is applied like a plaster, with adhesives on the side and a non-stick strip in the middle that helps the user when attaching HeatGuard, following the poka-yoke principles. The prototype material is HKO's Silicatherm HS 650 AR, which is a flexible, non-combustible silica fabric that holds its form under heat and keeps the NTCs pressed against the shell. To make sure every battery can be detected by a sensor, the coverage runs the full length across the top and sides.

This completes the physical prototype of HeatGuard, see Figure 89, which will be used as the testing model and the visual reference for the mobile application developed in the next chapter.

Figure 89: Render of HeatGuard, this image is created using ChatGPT [113]

CHAPTER 8

THE MOBILE APPLICATION

Still in the final phase of the Double Diamond, with HeatGuard defined and the physical prototype built, I continue by designing the mobile application, see Figure 90.

Figure 90: HeatGuard notification

8.1 Action matrix

A full-size version of the action matrix can be found in Appendix F.

Mapping out all the actions in one matrix is the bridge between understanding behaviour and implementing interactions. The action matrix lists all the standardised actions, see Table 7. These actions are relative to the prevention window. The battery's location is found using cellular tracking and the user's live location comes from the phone, the distance between the two is translated into a time distance. This makes sure the user receives the safest guidance based on how far they are from the battery and on what risk phase they are in. I make a distinction between five detection phases or scenarios: normal, small anomaly, elevated risk, developing danger and imminent risk.

The actions are determined based on Dutch Fire Department protocols and the researched indicators for recognising overheating batteries, as outlined by the Nederlands Instituut Publieke Veiligheid (NIPV). Actions build up as risk rises, but once the battery is too dangerous to touch, the user should not interact directly and the earlier instructions drop off [170].

Table 7: The action matrix

⚠ **If smoke, flames or gasses are present: DO NOT APPROACH the battery pack. Evacuate, close the door if safe, and call emergency services.**

Detection phase → Risk	**At the device** *physically present*	**In the home** *seconds to device*	**Within prevention window** *return ≤ 34 min*	**Beyond prevention window** *return > 34 min*
IMMINENT RISK $dT/dt \geq Z$ °C/min *thermal runaway*	**Evacuate space immediately** Close door behind you Call 112 *do not move the battery pack*	**Evacuate space immediately** Close door to device Call 112 *do not move the battery pack*	**Alert to evacuate space** Alert household to evacuate Call 112 *do not move the battery pack*	**Alert to evacuate space** Alert household to evacuate Call 112 *do not move the battery pack*
DEVELOPING DANGER $Y2 < dT/dt < Z$ *starting thermal runaway*	**Get out of the room** Cut power only if the plug is safely reachable *do not move the battery pack*	**Isolate the designated space** Cut power from the breaker cabinet *do not move the battery pack*	**Isolate the designated space** Alert household and ask for power cut-off only if safe *do not move the battery pack*	**Alert household** Alert household and ask for power cut-off only if safe *do not move the battery pack*
ELEVATED RISK $Y1 < dT/dt \leq Y2$ *abnormal behaviour*	**Unplug and isolate** Unplug the battery, move flammable objects away from the battery Arrange inspection	**Unplug and isolate** Unplug the battery, move flammable objects away from the battery Arrange inspection	**Alert household** Ask household / neighbour to unplug the battery Arrange inspection *monitor remotely en route*	**Alert household** Ask household / neighbour to unplug the battery Arrange inspection
SMALL ANOMALY $X < dT/dt \leq Y1$ *deviation in pattern*	**Observe the battery** Do not leave the battery unattended Stop charging	**Observe the battery** Do not leave the battery unattended Stop charging	**Note the alert** No intervention required Continue monitoring	**Note the alert** No intervention required Continue monitoring
NORMAL $dT/dt \leq X$ *charging as expected*	**No action**	**No action**	**No action**	**No action**

prevention window (≈ 34 min)
left of line: user can intervene, right of line: user must act remotely

Time for user to reach the device → relative to prevention window

8.2 User interface

Based on the action matrix, the HeatGuard application was developed, see Figures 91 and 92. The scenarios in the application represent a user at the device, creating the conditions for the user test. The mobile application lets the users set up their HeatGuard, view the data sent by the sensor, receive status push notifications, track the temperature change of their battery and get recommended actions.

The application was built using Claude Design, an AI-assisted design and coding tool [15]. I designed the interface myself by sketching out the layout and functions by hand. Using prompts and editing in Claude Design, I then built and developed the application. The tool helped me run quick iterations and develop ideas through vibe coding, accelerating the design process.

On first startup, the user is presented with a step-by-step guide on how to install the patch onto the e-bike battery, see Figure 91. The instructions in the app, combined with the strips on the patch itself, guide the user through correct placement. The user then enters HeatGuard's personal code for pairing, and is able to rename the patch to a personal label. This creates a personalised environment in which it is clear which sensor is which.

The application is built around the five scenarios presented by the action matrix. Each scenario presents the user with a different set of recommended actions on how to act. The instructions also adapt to the user's location and distance to the battery in relation to the prevention window. This allows the user to respond safely to the developing risk of thermal runaway.

The next section walks through three scenario's of the user interface; normal, elevated attention and immediate risk. The full application can be found in Appendix H or on the website: https://stijnboogie.github.io/Graduation/

Figure 91: Setup Guide

Figure 92: HeatGuard Application

8.3 Application walkthrough

The install guide animation, step by step

Every step of the installation is presented using an animation of 9 steps, see Figures 93 and 94. These steps are: **1**; The battery, **2**; Position HeatGuard, **3**; Flip HeatGuard over, **4**; Peel the first strip, **5**; Align over the battery, **6**; Stick the first side, **7**; Peel the second strip, **8**; Press the second side down, **9**; Done.

The steps can be paused and replayed to make sure everyone is able to install it correctly.

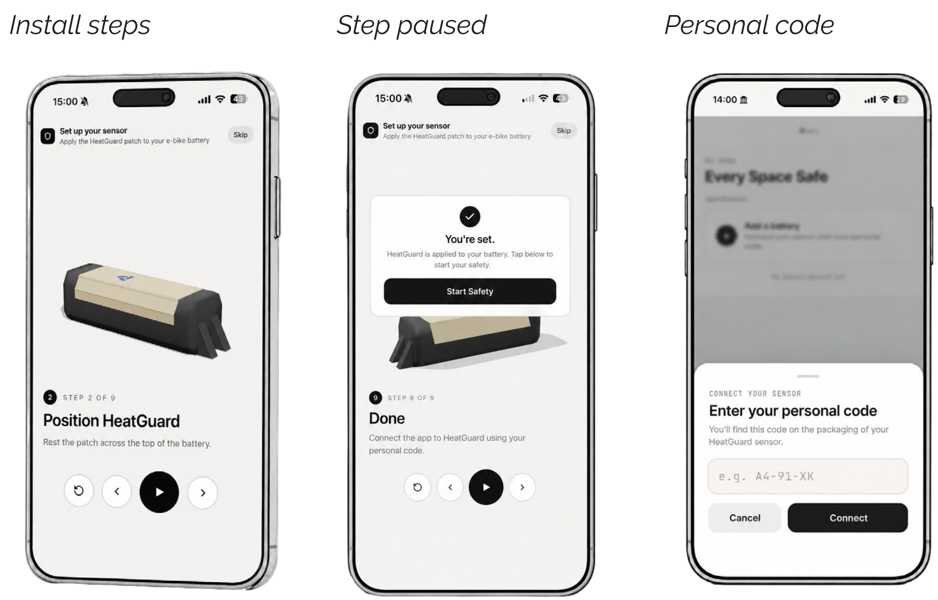
The full install guide animation steps can be found in Appendix H.1.

Personal code
After HeatGuard is installed, the application asks the user for the personal code that is supplied with the solution to connect and track the right sensor, see Figure 95. The personal code is a unique identifier that maps to the hardware identifier on the nRF9160 chip. It is supplied with each HeatGuard unit, tied to that one device.

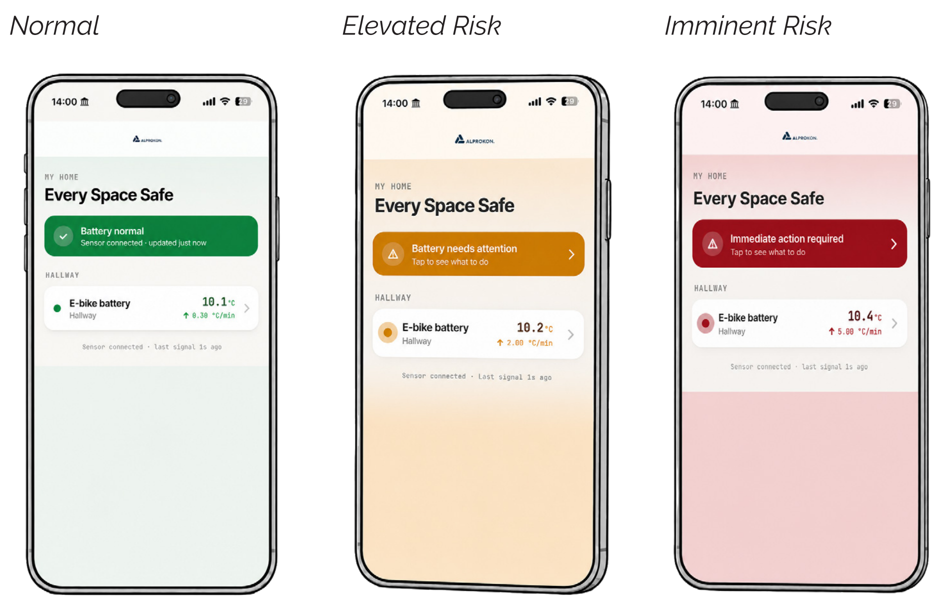
The HeatGuard overview

Once HeatGuard is properly connected, it is displayed in the overview screen, see Figures 96 to 98. This screen provides the user with the ability to customise the name, see the status of the battery using the indicative circular light and select the desired battery.

The full overview can be found in Appendix H.2.



Figures 93, 94 and 95 (left to right): Install Guide



Figures 96, 97 and 98 (left to right): Sensor overview

The notifications

Each scenario sends a different notification to the user according to the state of urgency, see Figures 99 to 101.

All the notifications can be found in Appendix H.3.

The scenario's

Each scenario displays and demonstrates a different behaviour and guideline based on the action matrix. The scenario screen visualises the temperature and temperature rate of change using numbers and a corresponding graph. This graph is colour coded to highlight when a certain change in temperature rise has occurred, see Figures 102 to 104.

Moreover, a set of instructions is presented that guides the user through each step on what to do in this exact scenario.

Lastly, additional functionalities allow the user to learn more on what is shown to them and check whether the system is active.

All the scenarioss can be found in Appendix H.2.

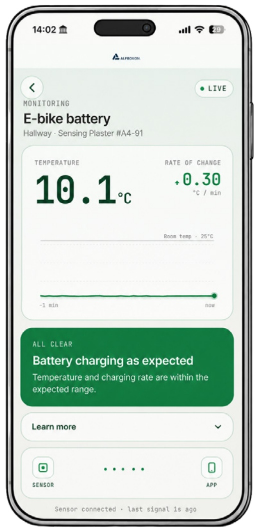
Small anomaly

Elevated risk

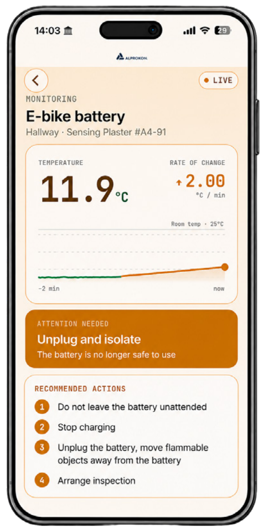
Imminent risk

Figures 99, 100 and 101 (left to right): Notifications

Normal



Elevated risk



Imminent risk

Figures 102, 103 and 104 (left to right): Scenarios

8.4 Data service

Communication from the sensors to the application runs through LTE-M, Chapter 6.4. Detection runs locally on the integrated chips and the data is transmitted only on the defined triggers and conditions. To provide a steady constant connection a reliable service is required. That is why the user is supplied with a one-time data bundle that covers up to 10 years of data transmission, which outlasts the full lifespan of HeatGuard. This is sufficient to ensure that all the data can always be sent.

An eSIM card in the chip set will use SIMBASE as the main provider [144]. Alprokon has had previous conversations with this company and these interactions were promising and allow me to suggest them as a potential partner. SIMBASE allows for eSIMs with coverage in the Netherlands, where Alprokon will buy their subscription, and provide the user with a full package for 10 years of data.

Currently the data runs over external public servers that share data with other parties, a future step will be an Alprokon cloud service. This will run internally, protect the user's privacy and create a more controlled and safe data environment with the potential for connecting future products to that same server.

Chapter takeaways

The action matrix maps out all the actions in one structured overview. It describes the safest and most responsible actions for handling the battery, in relation to the risk phase and the distance from the user to the battery. With this matrix as a basis, the mobile application was created.

Upon launching the application, the user is presented with a setup guide that uses a video and step-by-step walkthrough. This guides the user through installing HeatGuard. Once installed, the user adds the HeatGuard by entering the personal code tied to that HeatGuard.

In the application, the user is presented with an overview of the measurements and HeatGuards that are connected. Clicking on one shows the status of the battery, whether it is normal or at an elevated risk. Each scenario presents a new set of recommended actions and a user interface matching that risk. The user receives a push notification when a risk is developing, with an urgency that reflects it. The overview page visualises what is happening, and each battery screen shows more details using a temperature graph and the rate-of-change.

Communication runs through LTE-M on an external server. Future plans are to have an Alprokon cloud service that runs internally and protects the user's privacy in a safer and more controlled environment.

The next chapter sets out the total cost of HeatGuard, including what the data communication and mobile application add. It shows the predicted price the user will pay per unit, and how much it should eventually cost.

CHAPTER 9

COSTS

This section looks at what HeatGuard costs to make, what it costs to keep running, and what the user would pay when buying it from Alprokon. The goal is not an exact price to the cent, but an estimation based on assumed costs, volumes and components. Many values still depend on the final configuration, the supplier choices and the number of units produced.

9.1 Costs

The full cost build-up can be found in Appendix I.

What it costs to make
The cost to make one HeatGuard is described by the sum of its parts: the electronics, the data, the battery, the sensors, the silica fabric, the adhesive and the packaging, plus the work to make it. Assuming a prodcution of around 10,000 units this comes to roughly €37 per unit. The highest cost driver is the Nordic nRF9160 System in Package (SiP), on its own it is close to half of the parts cost. Everything else, the sensors, the battery and the fabric material, is comparatively cheap.

The one-time costs
Some costs are only paid once, no matter how many units are made. Before the first HeatGuard can be sold, the prototype electronics have to be turned into a finished product, the application has to be built, and the product has to be tested and approved before it is legally allowed on the European market. That approval is required for any product that communicates over a mobile network. For this thesis I assume they come to around €100,000 in total. If Alprokon makes and sells 10,000 units, that is €10 per unit. The more units are sold, the smaller this share becomes.

The running costs
HeatGuard needs a mobile connection to send its data. This costs very little as intended by design for power consumption and cost reduction. The system is designed to stay silent and only send data when something happens or once a day to confirm it is still alive, see Chapter 6.5. Because of this, it uses almost no data, and mobile data for this kind of device is sold per megabyte for a fraction of a cent. The same goes for the server data. Since the device only sends data when needed, the cost of receiving and storing that data on the server is almost negligible per unit.

This is because of the local processing choice that I made in Chapter 6.5, and that keeps the running costs low. Rather than charge the resident a monthly fee, the connection is bought once and included in the purchase price. The resident only pays one time for the full lifespan of the product.

What the user pays
For Alprokon to have a lucrative product, a product can not be sold for what it costs to make. The company needs to earn something on top to run the business and support the product. I assume to sell the product for twice its cost price, yet this can be decided otherwise by Alprokon. When I add the parts, the one-time costs, the connection and the shipping together, one HeatGuard costs Alprokon around €64. Selling it for about double, and adding the 21% Dutch VAT, gives a price for the resident of around €155, see Table 8. This is a one-time price, with no additional subscription.

Step	Value
Cost to make one unit (10,000 units)	€37
One-time cost per unit (at 10,000 units)	€10
Connection for the device life	€12
Shipping to the user	€5
Total cost to Alprokon per unit	≈ €64
Sold at about twice the cost price	≈ €128 before VAT
Plus 21% Dutch VAT	≈ €155 for the user

Table 8: The costs for the user

Cost reduction
This cost calculation was done using consumer-available products and components that I can buy in online stores. When producing HeatGuard directly via factories, through partnerships, and using custom components and electronics, of which the SiP is now the highest cost driver, the price would be reduced significantly. Moreover, producing at higher volumes would reduce the cost again. After conversations with Alprokon about future plans, a target to bring the price down to €12-15 was set for HeatGuard.

CHAPTER 10

USER EXPERIENCE

For the system to provide both safety and a sense of safety, users must understand how it works and how to act responsibly, see Figure 105. To explore how this understanding translates into behaviour, an ideal user scenario was developed. While many scenario's could happen in real life, this thesis only focusses on one ideal scenario, demonstrating the recommended actions of a user in the same home as the battery.

In this chapter the user scenario is sketched, the user interactions, and a user test was conducted and analysed to ultimately form the design recommendations.

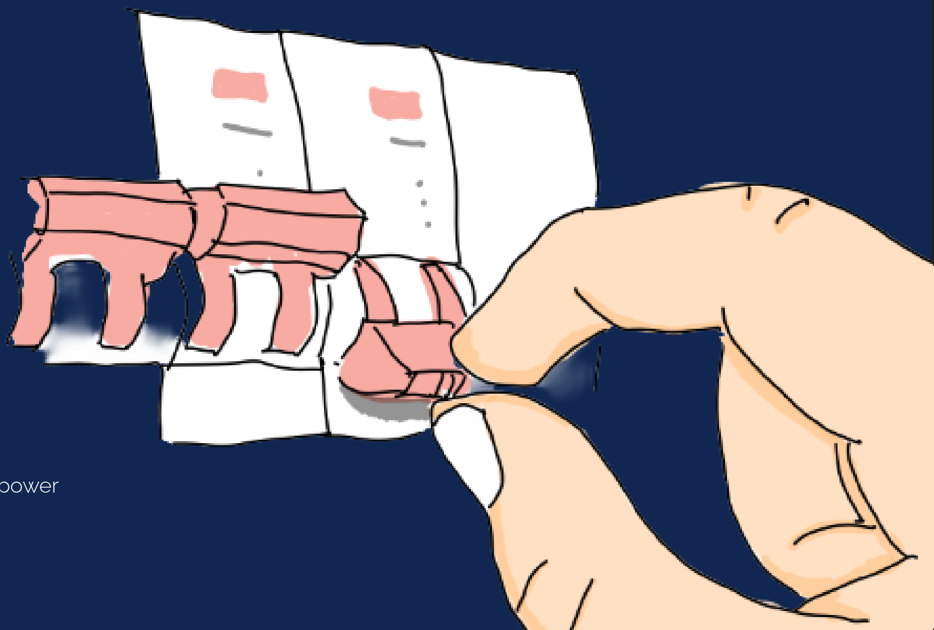


Figure 105: User action: safely switching off the power

10.1 User steps

Installation

Using the installation animation with the step-by-step guide in the HeatGuard app a user scenario for the Installation was created, Figure 106.

Testing requires a standardised set of interactions for each participant for efficient comparison and analysis of the results. The shown steps in Figure 106 show the ideal scenario that participants will follow when using HeatGuard.

Step 1 shows the unpacking of HeatGuard. **Step 2 and 3** describe the installation of the application and starting up the setup procedure on the phone, followed by **Step 4, 5, and 6** that highlight the attachment of HeatGuard. Lastly at **Step 7** the personal code is entered into the application and **Step 8** directly shows the working sensing patch that is ready for safety.

The full installation animation steps can be found in Appendix H.1.

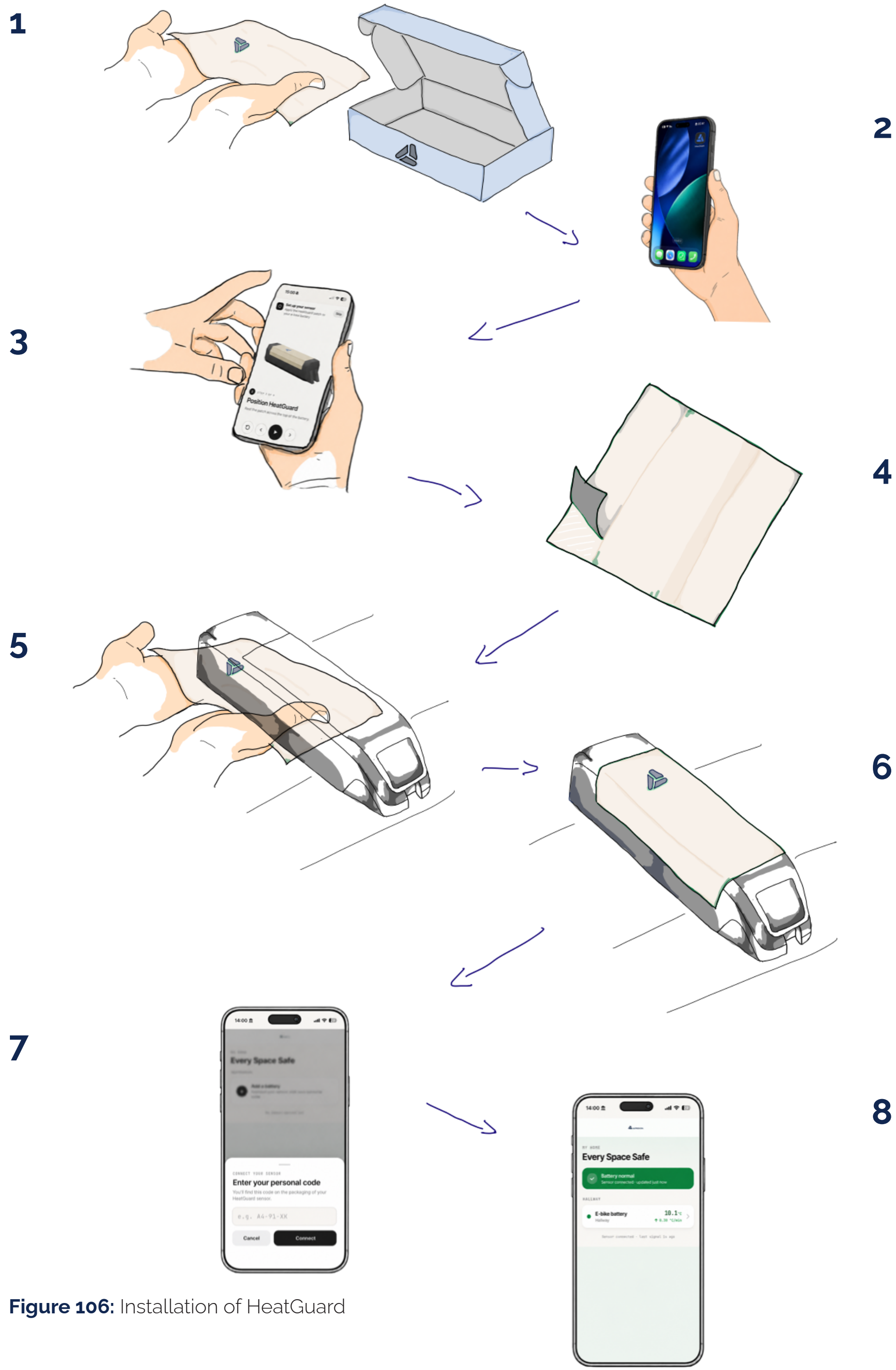
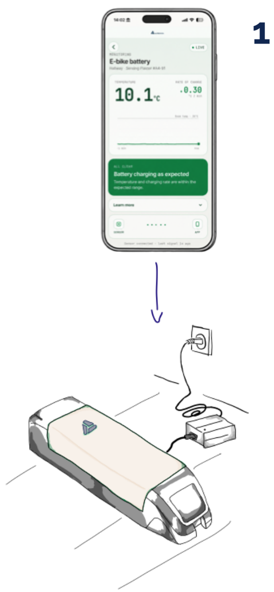
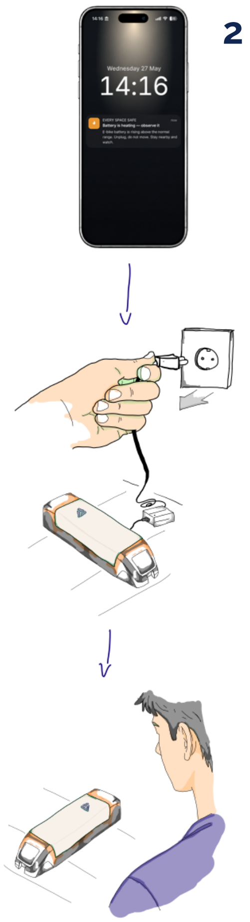


Figure 106: Installation of HeatGuard

Scenario's

Based on the action matrix, ideal user scenario steps were created following a user that is physically present with the battery, Figure 107. **Step 1** describes the Normal scenario, showing no unexpected behaviour. At **Step 2, 3 and 4**, a Small Anomaly, Elevated Risk and Developing Danger, the user is asked to observe the battery from a safe distance. However, **Step 4** highlights that the user can no longer approach the battery safely and is guided to disconnect it using the breaker cabinet. **Step 5** at last shows the Imminent Risk where the emergency services are contacted and the user is guided to isolate the room.





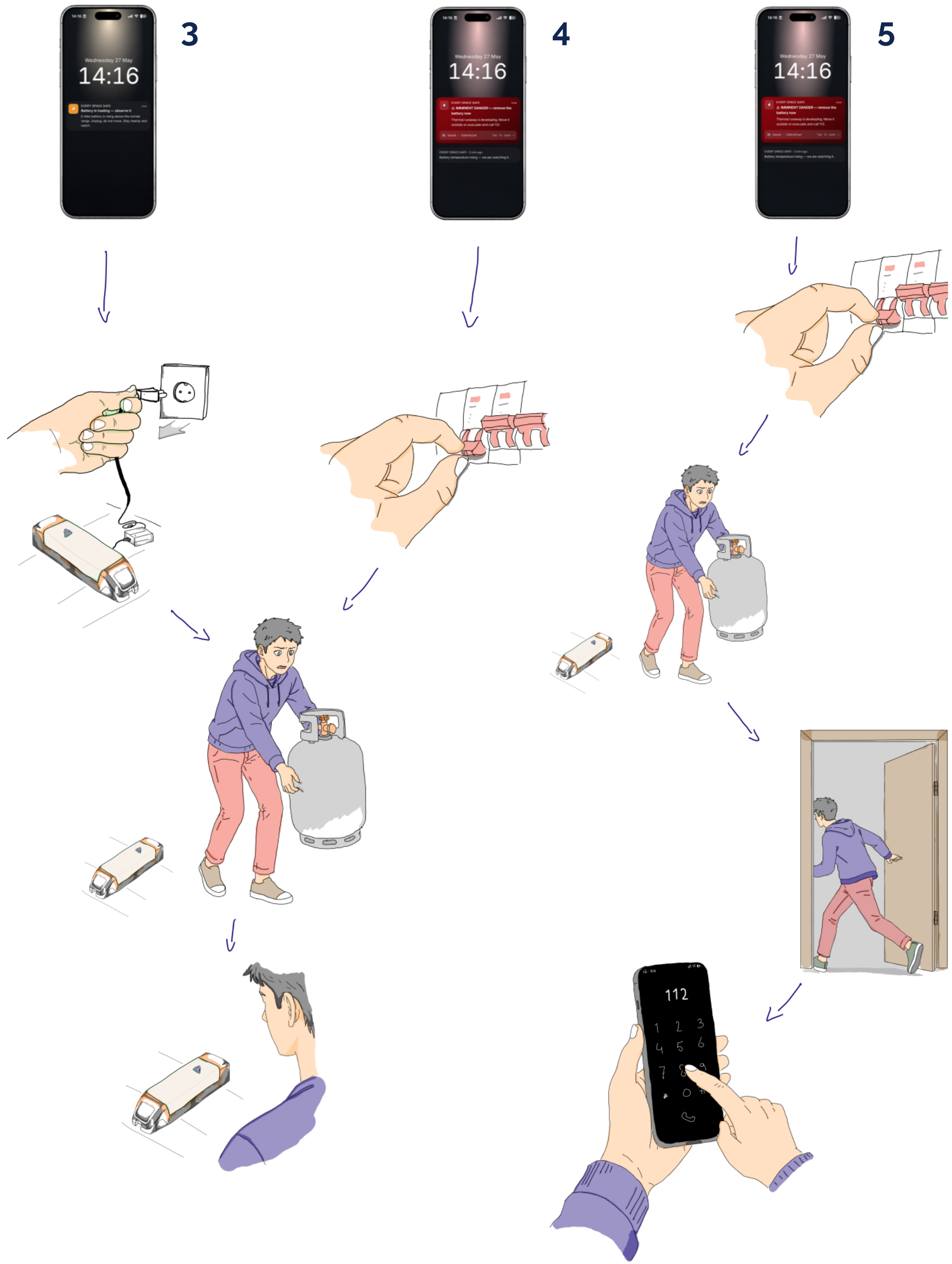


Figure 107: User scenario's

10.2 User test

Conducted tests

To test the user scenario described above, six user tests were conducted. Each test combined an observation and an interview. In the observation, the user is given a working prototype to interact with while the researcher observes what they think, feel and do. The interview questions are then asked to understand their behaviour and motivations, both as described by the Delft Design Guide [165].

The ultimate goal of this user test is to explore and evaluate the user's experience with the solution, from application to notification to action, and to see whether the user understands the system, can install and connect it, and knows how to respond in different scenarios.

The user is guided through the installation process and then experiences five scenarios, which I simulate using the Wizard of Oz method described in the Delft Design Guide, where the operator controls the prototype's behaviour [165]. I used a breadboard with an ESP32 that sends notifications via the NTFY app based on button input, so each button triggers a different scenario, Figures 108 and 109. This lets me control each scenario safely and repeatably, without exposing participants to a dangerously overheating battery. The full test setup can be found in Appendix J.1.

Participant group

The user test was conducted with six participants, recruited through personal contacts and selected via purposive sampling to ensure variation in age and prior familiarity with e-bikes. Sessions lasted 30 minutes, took place in a neutral setting, and were audio-recorded with informed consent, found in Appendix J.2. Participants were pseudonymised for analysis and publication as "Participant A," "Participant B," and so on.

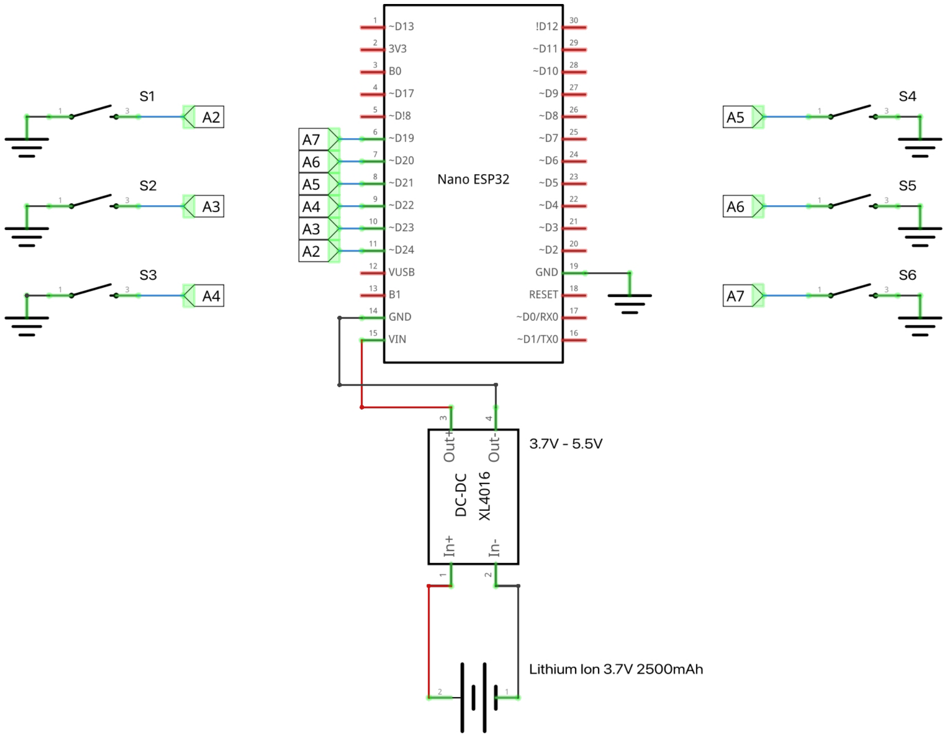


Figure 108: The 6 button Arduino Nano ESP32 configuration schematic created using Fritzing [56]

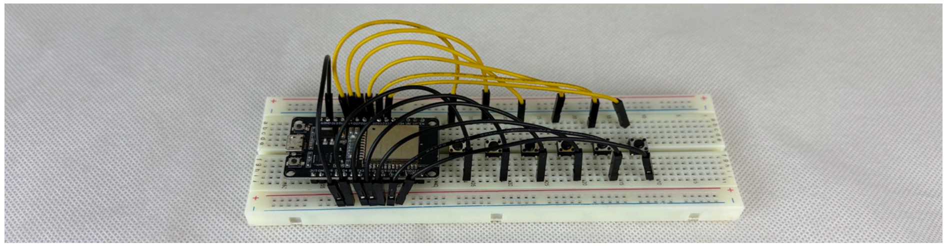


Figure 109: The Wizard of Oz device

While a sample of six does not create statistical generalisation, the intentional variation within the group allowed me to find recurring patterns and challenges across diverse profiles. Participants were selected within the age groups of 18-25, 40-65 and 65+, with half the participants having prior knowledge of e-bike usage. This provided a broader understanding of user interaction with the solution than a more homogeneous sample would allow.

10.3 Analysis and results

User test analysis

The full analysis can be found in Appendix K.

To analyse and evaluate the user tests I used an inductive thematic analysis to explore the data for emerging patterns in the functionality, design and user experience while using HeatGuard. An inductive thematic analysis is commonly used to derive theory from observations. This user test has an explorative function, so I believe this can bring me to conclusions that ultimately help me to form design recommendations.

The user test consisted of two stages, the Installation and the Scenarios. The participant was first asked to fill in the informed consent, Appendix J.2, and then read the instructions. Second, the participant was tasked to install HeatGuard using the in-app setup guide. And third, the participant was run through the five scenario's, using the device in Figure 111, all while speaking their thoughts and actions out loud. Participant quotes are kept in the original Dutch to preserve the original result and not change intonations, however, some parts are translated into english for evaluation. I analysed and evaluated the data based on the structure from the user test. I found four themes and several smaller insights that will inform the design recommendations. The four themes are presented here. The smaller insights can be found in Appendix K.2.

The Four themes

(1) Instinct before the safe response, and responsibility for others

Instinct is found as the most common reason for doing something different from the safest response. Participant A predicted: '*ik denk dat iedereen gewoon toch gaat kijken. Gelijk. Voordat zijn huis afbrandt.*'

Participant B knew she was wrong yet trusted her instincts: '*instinct zou zijn… ik gooi hem naar buiten. Maar dat moet ik niet doen*', and asked for a large '*blijf er vanaf*' text to prevent this. Participant E highlighted another behaviour that people want a visual confirmation, before they act: '*Met een brandalarm dan weet je. Hij gaat niet zomaar af… Als je niet de real life cues ziet. Dan wil ik toch wel zeker weten. Of het er is.*' And Participant C noted the same behaviour: '*Ik wil wel eerst zien of het echt in de fik staat en niet. Of de app wel gelijk heeft of niet, zeg maar.*'

Participant E's first reaction was more than just pure instincts, she would still carry the battery outside, out of responsibility for others: '*omdat wij met zoveel mensen in een gebouw wonen… je hebt geen verantwoordelijkheid voor één huishouden*.' This reflects another layer of responsibility feeling that confirms my findings in my research. People feel the need to protect others, responsibility, and that is a big motivator for safety.

(2) Meaningful numbers and graphs

The numbers and graph in the mobile application are hard to understand for users as Participant B highlights: '*voor mij zegt het niks, dus voor mij gaan er geen alarmbellen af*'. The flat information and numbers are described as meaningless by Participant C: '*dat grafiekje zegt natuurlijk niet heel veel*' and '*0,3 graden per minuut change, dat zegt in eerste instantie niet zoveel*'. The participants asked for a range or a reference frame, as this would be more comparable and ultimately understandable. Participant E described the need for this indication: '*deze grafiek, dat zegt jou niks als persoon*', and '*dit getal is het enige wat mij echt een normale indicatie geeft*'. Along with a better hierarchy of the text, Participant E: '*En als dit soort van echt zo dringend is, zou ik dit eigenlijk wel een stuk groter maken.*' and numbers, improving this issue would decrease the knowledge gap on what the information means.

(3) The step-by-step guide tempo, and confirmation of successful placement

There are two challenges that concern the setup guide, firstly the guide does not let the user lead, the video is paced too fast and makes the user lose control.

The animation ran too fast for Participant C: *'het ging een beetje snel, de animatie'*, and Participant E: *'hij ging dus wel al verder zonder dat ik verder wilde'*. Participant E predicted that other users would have even more struggles: *'En ik ben niet zon digibeet, in ieder geval. Ik weet dat ik dan gewoon terug kan klikken, maar ik kan begrijpen dat je dan helemaal een soort van verdwaald raakt in de instructie. Terwijl ik wil eerst gewoon kijken van, wat is het, wat staat daar, voordat ik pas naar de volgende stap ga..'* Participant B had the same issue because of the language barrier: *'Ja, het is moeilijker voor mij, maar ik snap dat alles in het Engels is. Maar dat is voor mij een drama.'* On the other side, Participant F was a fast reader and found it too slow.

Secondly, it never tells them if the placement is right, making them wonder instead of certain. Participant A, B, C, E and F all raised this issue. Participant E had the most clear case as she knew she had failed and the application could not tell her: *'dat is dus nu niet gelukt… ik eyeball nu eigenlijk hier erg op'*. She was eyeballing the placement, sure she was not centred but there was no real way of telling, Figure 110. Placement confidence is entirely with the user, but there should be one step that decides whether the sensor reads anything at all.

(4) The core value confirmed: knowledge and control make people feel safer

This theme validates the definition of Every Space Safe. Participant A called it reassuring: *'ik vind het echt super, ik denk dat er heel veel mensen gerust zijn'* and Participant C captured the knowledge value: *'het geeft me een fijn gevoel om te weten, want anders had ik een filmpje gekeken en gechilld en dan was het alsnog misschien tien minuten later in de fik gevlogen'*. HeatGuard also gave the users more control and insight, this matches the findings on subjective safety that note that people feel more safe when they are in control and have knowledge on what is happening. Participant C highlighted this: *'Het geeft veel meer een controle over. Of inzicht in wat er aan de hand is.'*

Participant E framed the value of HeatGuard as confirmation and awareness, *'bevestiging aan je ontwetendheid',* she valued that she was able to know which device is at risk and when, so she has more time to plan and act.

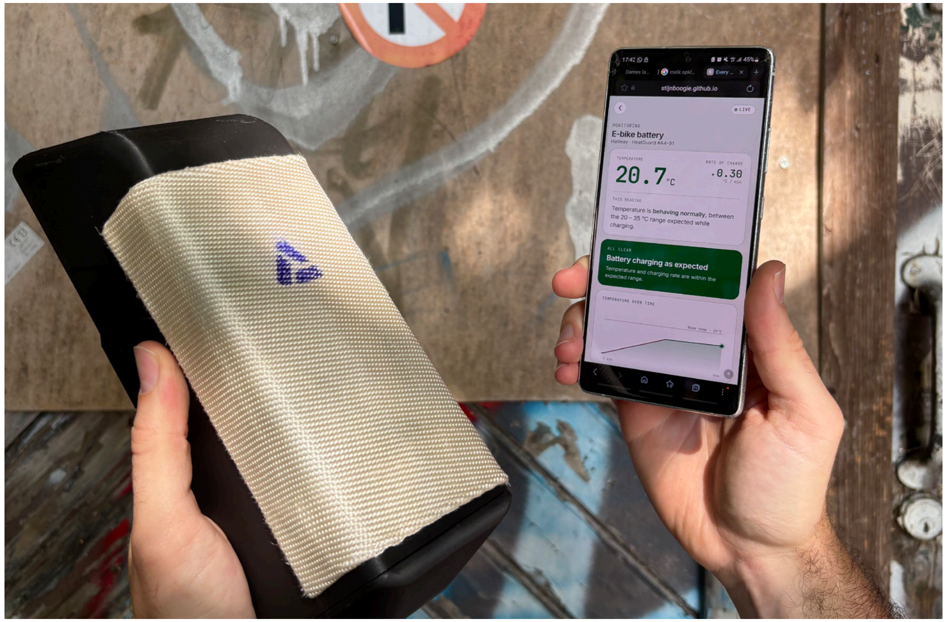


Figure 110: HeatGuard placed by a participant in a real life setting

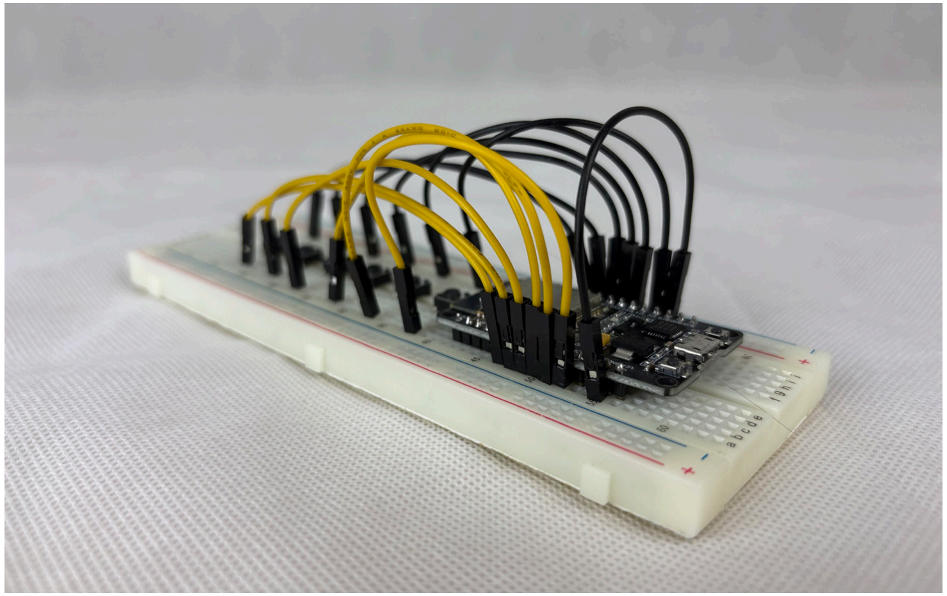


Figure 111: Switching scenario's using an ESP32 development board

Design iterations

Based on the findings from the user test analysis, three design iterations were performed on HeatGuard.

Self-paced click-through

The setup guide pace was addressed by making a self-paced click-through instead of a video as the primary navigation method. This option already existed, but the video played automatically upon start, which rattled participants. Now the click-through leads and the video is optional, see Figure 113.

Meaningful information

The information hierarchy was changed to show the most meaningful information first. The big temperature number now leads, followed by the recommended actions with the graph as support. As seen in Figure 114, the temperature number changes colour according to the severity level, and a temperature range describes what each reading means in relation to the expected behaviour. This creates a reference point for the user to compare it to. These values are indicative, based on Chapter 4.4, and require further testing and individual pattern learning per battery.

Peel-off indicator

The challenge with the adhesive strip that every participant faced was solved by adding an indicator and lip that show where to start peeling the white coverstrip from the adhesive. As shown in Figure 112, a dotted line lets users peel the strips off more easily.

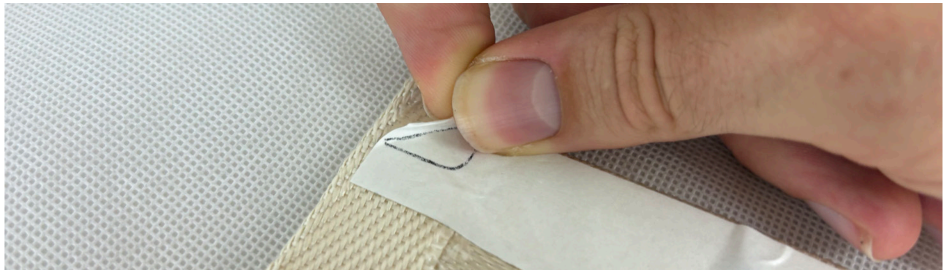


Figure 112: Peel-off indicator

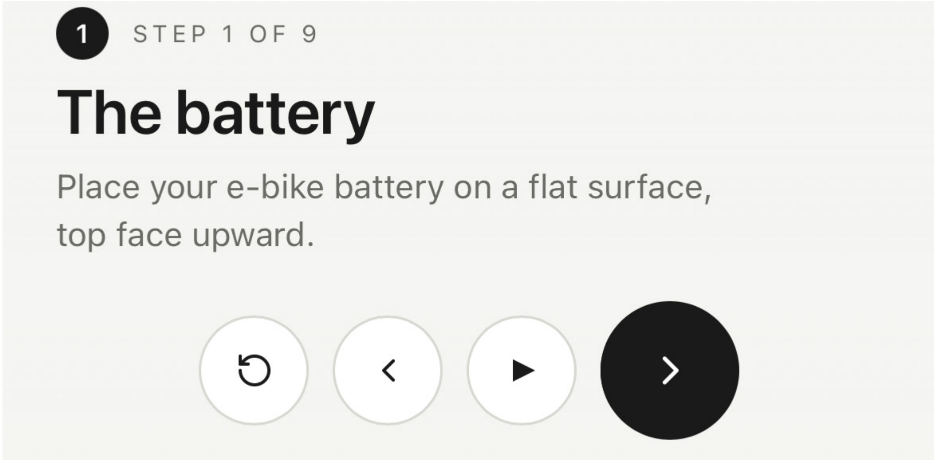


Figure 113: Self-paced click-through using the back and forward buttons highlighted in black.

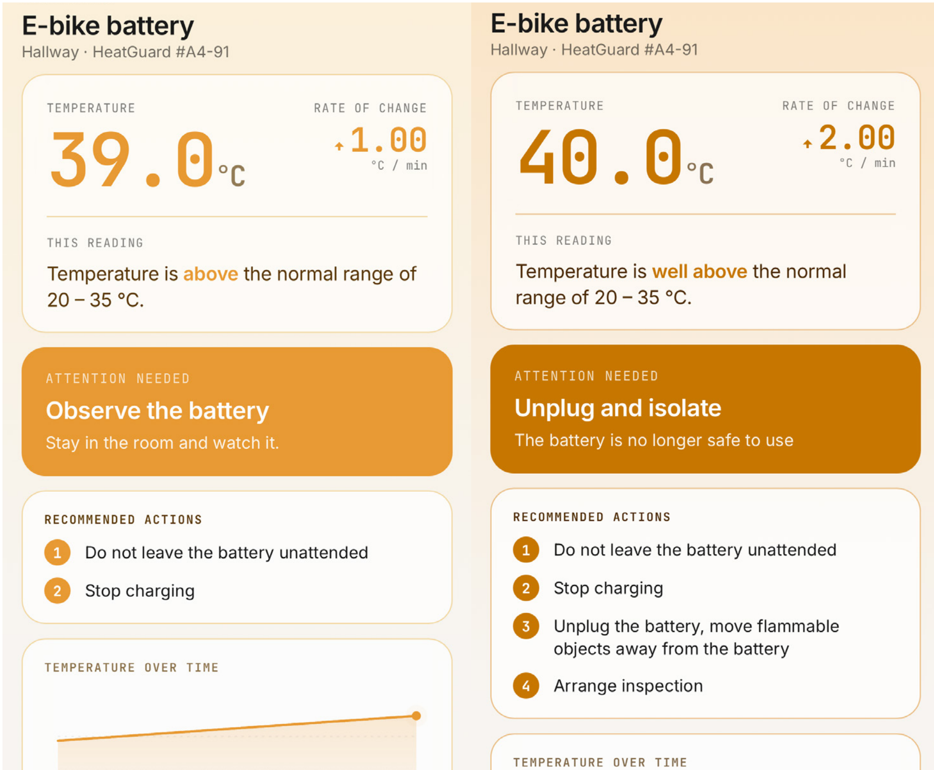


Figure 114: Changed the information hierarchy to place the meaningful information first

Chapter takeaways

From the user tests four themes emerged. Instinct is found to be the strongest behavioural driver for the initial actions, and it beats the safest, instructed response most of the time. Participants want to perceive the danger with their own senses, a visual confirmation, before they act on it. The safe action has to beat the instinctive response, so the 'do not move the battery' instruction must be dominant and shown first. Besides instinct, the initial drive is also a feeling of responsibility and safety for others, which reflects a large motivator for safety.

The numbers and graphs on their own did not mean a lot to the participants. The colour and the temperature number do most of the work, which calls for a new information hierarchy. The setup guide ran too fast and the application never confirmed correct placement.

Knowing what is happening with the battery and being more in control made the participants feel safer, validating the definition of Every Space Safe. Awareness followed from the insight into the battery temperature.

Three design iterations followed from these results: a self-paced click-through, a peel-off indicator, and more meaningful information through a changed hierarchy and temperature reference points. The next chapter interprets and evaluates the findings and limitations of this thesis, after which the design recommendations are presented for future work.

Discussion

Discussion

My goal for this thesis was to find a solution within the limits of 'Every Space Safe' that would be innovative, have a smart home integration and use technology to bridge the gap between the invisible risk and tangible safety. With HeatGuard I have created a solution that does both. Sensing and predicting the invisible risk of overheating within battery cells, and providing a new form of safety that is delivered through a tangible product with actionable communication. Where the user is still in control, both of its safety and its actions, but is informed about a risk that can otherwise not be perceived by humans before fire develops.

The main design solution proposed involves two parts, the physical HeatGuard sensor patch that is applied to the actual battery. And the HeatGuard mobile application that presents users with an overview of what is happening with the battery and what the responsible, safe actions are when risk develops.

Behind this solution are multiple aspects that need to work for HeatGuard to function: the algorithms deciding the risk, the electronics and components, location tracking, data transmission, production, maintenance, and the mobile application service. All of these are addressed, tested and demonstrated as plausible through theory, prototyping and user tests. What is challenging within this thesis scope is the human influence, which can create a wide variety of unexpected scenarios and risks.

The technical and theoretical work demonstrate that the approach is plausible. Measuring the rate of change against a learned baseline, rather than an absolute temperature, is the correct method when working with a sealed casing that has a thermal delay. The system has been developed on paper using theory and expert meetings, but requires further testing under real conditions.

The user tests then highlighted that detection is only half of the problem. The unexpected result was instinctive behaviour as a strong driver. Across the participants, instinct was the most common reason for doing something other than the safest response. People wanted to approach the battery, move it, or see the fire for themselves before acting. This provided me with the requirement that the safe action has to beat the instinct action.

That ties back to Every Space Safe. Safety was defined as both objective and subjective, and the user tests confirmed this. Unanimously, knowledge and control made people feel safer, which is exactly what subjective safety is about. The value of HeatGuard is not only that it can detect and predict risk before the fire, but that it makes an invisible risk visible and gives the user control over it.

The mobile application's strength depends on the data being readable and understandable, and here I misjudged the graphs and information. The numerical value of rate of change meant little to people. The colour did most of the work, the graph added almost nothing, and the big temperature number was the only figure most could reference to real life. Of course it made sense to me, as I am very well researched on this topic right now, so I misinterpreted what others would already know. Without a normal range to compare against, a reading like 0.3 °C per minute is meaningless.

Combining these findings, I found the biggest challenge with HeatGuard is communicating the risk to the user and correctly predicting and acting on their behaviour. As HeatGuard relies on the human response for safety, this is one of the key aspects that needs to work within the prevention window. What started as a question of sensing temperature turned into an interplay between the user's behaviour and the invisible risk of e-bike battery systems. This thesis establishes a set of design principles for thermal safety in e-bike and other rechargeable battery systems, which can form the basis for new designs and guide which risks and requirements to address.

Limitations

I identified multiple limitations for this thesis, most of which come back to the potential of the different aspects and the related time availability, and to the scoping within the design decisions.

Due to time constraints, I have proven the technical plausibility in theory and through expert meetings, but did not have the time to conduct the experiments and prove it through real-life tests with temperature changes, using the sensors and prototype to show that it works. The prototype does work, it measures temperature and rate of change to activate and send notifications based on the temperature. This, however, is based on assumptions of both the threshold values and the prevention window.

The prevention window value of 0.57 hours now comes from simulated lab environment tests. As the Action Matrix and the data package sent over LTE-M depend on this value, this is a limiting factor. Further research using real-life use-charge cycles and realistic tests should tell what this exact value is, or whether it is potentially a range in time.

The placement of the NTC sensors in HeatGuard is now assumed to be symmetrically placed over the full length at the top and sides of the battery. However, this could still depend on the type of battery and the exact arrangement of the battery cells. Limited time prevented me from testing these exact placements. Both this placement and the exact values of the temperature rate of change are also highly dependent on the new materials used in the final solution. So, taking into account these new variables like air gaps, adhesive material and the fabric, tests should conclude what those effects are.

The user tests are limited by the number of participants and the limited variety within the group. With a larger test group, more generalisable results could be found. The tests were also limited by a Wizard of Oz method that simulated the user experience as realistically as possible, however, for the best results a user test with a fully functional and tested prototype is required. I think that this would best create the user experience, as well as better responses from the participants. Right now some values in the application were not completely representative of reality, which created confusion and unexpected results.

HeatGuard depends on the human response for safety. It does not intervene in a dangerous scenario itself. During the user tests, five ideal scenarios were created and tested that put the users in a simulated reality where they had to imagine themselves as e-bike owners. The supervised tests did not account for any imperfections within the daily life of a user, such as phone on silent, asleep or away, notification fatigue or the changing mental state of the user that can influence both the response time and rational thinking. This limitation addresses the high deviations within human behaviour and the extensive amount of exceptions that exist when designing a product.

To fully explore and develop all the aspects of HeatGuard, it would take multiple extra months and research.

Finally, **this thesis is limited by its potential**. My personal struggle was making decisions on what could be done within the timeframe of 20 weeks, deciding which aspects required time and attention to benefit the thesis and which would be outside its scope. Proving the technical feasibility through real-life testing would require more time than available, and it would steer my thesis towards a more electrical and mechanical focus, which is not what I wanted for this design thesis. Ultimately I decided to focus on proving plausibility and creating a design layout for measuring temperature rate of change in e-bike battery systems and providing actionable communication to the user through a mobile application. Eventually, this can be adjusted to match multiple models and rechargeable battery systems, even ones that are not an e-bike battery.

Design recommendations

Based on the outcome of this thesis, a number of areas still need development before HeatGuard can be brought closer to a real-world implementation. The design recommendations are split into two sections, the physical product and the mobile application. They each highlight what actions could improve the solution.

The physical product

DEFENSOR-Flex material

After meeting up with HKO in person and having a valuable conversation on potential fabrics and materials it was decided that the ML38 from the DEFENSOR-Flex range with synthetic MICA as finish was a more suitable material, see Figure 115 [65, 68]. This material is specifically designed for electrical vehicles and batteries to protect them and the bystanders from thermal runaway and the chemical effects and sharp projectiles that get released due to off-gassing and exploding battery parts [64]. It is resistant to high temperatures, it allows pressure relief and it protects the batteries during transportation. This material is tested on battery cells, within battery packs and as protective material between battery packs. This material can provide an extra layer of safety in case thermal runaway does occur and protect the user and bystanders from potential harm and danger.

Figure 115: DEFENSOR-Flex ML [68]

Adhesive material

To ensure a solid attachment and that HeatGuard will stay on during the use-charge cycles, a suitable adhesive material is required. The adhesive must hold up across temperatures of -20°C up to +50°C, withstand vibrations of daily e-bike usage and be resistant to mechanical abuse to account for normal use patterns, Chapter 7.1. I suggest an acrylic foam tape that is energy-absorbing, fatigue-resistand and weatherproof within these temperature boundaries, for example, this tape by 3M, VHB Tape 5952 [156].

Part of the attachment is the placement of HeatGuard onto the battery shell. An insight from the user tests was that Participant E struggled with the alignment of HeatGuard, Appendix K. As HeatGuard will ultimately be available for different battery models, a centring method on the solution itself would be best. I suggest indicative centre markings that allow the user to more easily find the centre and be sure it is aligned correctly.
This challenge should also be addressed in the application using a confirmation prompt that HeatGuard is installed correctly, but that is further discussed later in this chapter under *Sensor coverage per battery.*

Woven electronics

Recent studies have shown the move toward more compact and wearable electronics for measuring physiological conditions [45, 94]. These wearable electronics are used mainly in medical applications, where the main challenges are the dynamic shape of the body and a reliable energy solution. The same flexible electronics could allow HeatGuard to fit multiple battery models and hold up better through the use-charge cycle. A compact design woven into the DEFENSOR-Flex ML38 fabric could then reduce the dimensions of the design considerably.

Ultimately, a potential future step for HeatGuard could be the integration of the solution into the battery itself. By partnering with bicycle manufacturers, Alprokon could offer HeatGuard to new e-bike customers built into the battery, or onto the shell with a custom woven or 3D-printed attachment that fits the specific battery model.

Self-learning algorithm

Chapter 6 discussed and suggested future testing to determine the exact values for the temperature, rate of change and threshold variables. To further improve the algorithm, the reliability and accuracy of the measurements of HeatGuard, a self-learning algorithm and artificial intelligence is the suggested next step in HeatGuard's software.

Creating an algorithm that could learn from the use-charge cycles, when and where the battery is used, means it could better predict what the temperature changes mean for the battery's internal state. This design recommendation could give HeatGuard earlier detection and improve safety, especially in combination with the *Smart home integration* discussed later in this chapter. There, shared information and context recognition could better protect the user, and allow the system to provide more accurate and actionable communication based on where the battery sits in relation to the user.

Custom Printed Circuit Board

The next step in developing HeatGuard would be a custom printed circuit board. This opens up several opportunities: a smaller dimension and form, potential for flexible electronics, and a lower unit cost, since the main cost driver now is the Nordic nRF9160 SiP, Chapter 9.1. A custom board also leaves more room for future upgrades.

Sensor coverage per battery

User tests showed that the confirmation confidence is currently with the user and not the mobile application. Users get no confirmation of a correct placement. A confirmation prompt that says all sensors are working correctly, and that it is installed correctly, would improve setup confidence.

Ultimately, HeatGuard should work on every battery type. As discussed in Chapter 3.1.2, there are several e-bike battery models, so a recommendation is to create either a universal model or a model per battery. Figures 116 to 119 show the models found in Chapter 3.1.2 with HeatGuard attached, illustrating how HeatGuard could be applied to a wide variety of models.

Figure 116: The hidden in-frame tubing battery model [52]

Figure 117: The fixed in-frame battery model [52]

Figure 118: The rear rack battery model [52]

Figure 119: The behind the seat tube battery model [52]

Besides e-bike batteries, HeatGuard should be designed for other rechargeable batteries and systems carrying lithium-ion packs. Figures 120 to 123 show different devices using HeatGuard.

Figure 120: A growing number of household devices now run on rechargeable batteries

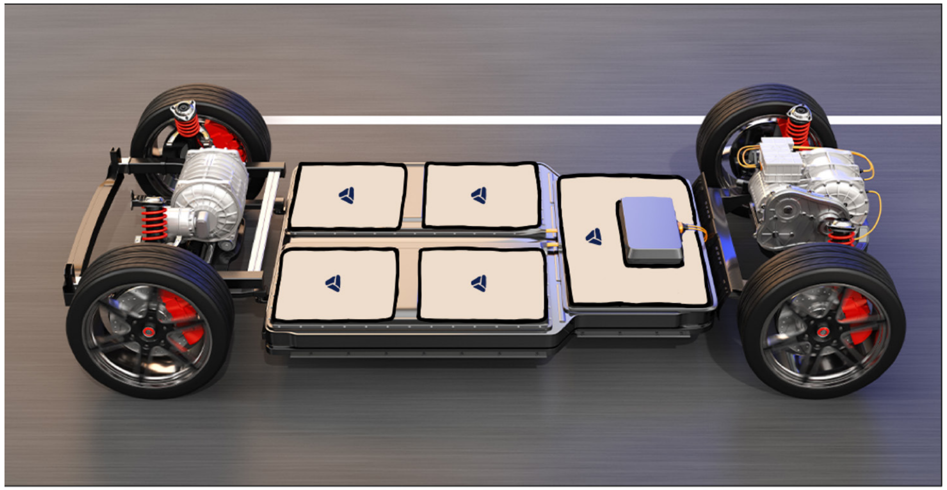


Figure 121: Electric cars are a growing market with the same underlying battery risk [13]

Figure 122: Shared e-bikes can be an interesting market, bringing new behavioural challenges

Figure 123: We carry our phones everywhere, a portable risk

A more compact model of HeatGuard, around the size of an AirTag, see Figure 123, could apply to all devices without the need for individual or custom design. I recommend exploring and testing this form factor to make HeatGuard completely universal in the future.

Smart home integration

In Chapter 6.4 I discussed an integrated home network potential and how trends indicate a future where all devices could be connected using the same communication standards. Here I mentioned the quickly developing Matter as a standard that could be used by Alprokon to extend HeatGuard's reach to other devices.

Integrating HeatGuard into the smart home could be a smart step towards more contextual and informed safety, where devices communicate with each other to both have more information on what is happening and better predict how this might affect safety.

As indicated during the user tests by Participant C and E, insight into what the battery is doing is valuable, see Appendix K. By using smart home integration, smart plugs for example, the user is able to start and stop charging based on whether the battery is empty or needs charging.

Moreover, HeatGuard could inform other devices about potential risks, upon which they can act or inform residents and emergency services. Through smart fire detectors, for example, they could alarm the resident earlier based on HeatGuard's detection, instead of only when fire develops.

Alprokon Cloud service

The largest next step in HeatGuard's data delivery is for Alprokon to provide its own cloud service, also see Chapter 6.4. A private network that stores and processes data just for Alprokon products improves privacy and security, as it removes the need for external overseas data centres or data storage by other countries such as America, see Figure 124.

Figure 124: Alprokon Cloud service

The mobile application

Effective communication

Research and user tests showed that every participant instinctively wanted to remove the battery from the home, to protect either others or their belongings. The application must anticipate this response and counter it through clear communication, making the safe action easier to follow than the instinctive one. At the dangerous states, the instruction to stay away and not touch the battery should be the most dominant element on the screen, so it is clear before the user acts on impulse.

Give the data a reference point. Participants found the graphs and numbers meaningless without something to compare against. Adding a range or reference value, alongside the exact threshold values, would close the gap between raw data and actionable communication, which would make the information more meaningful.

Multiple batteries and location based

The mobile application should support multiple batteries within one household, monitored under one clear overview. HeatGuard currently supports a single battery, so an add-on for registering multiple sensors would be a valuable step. User tests showed that customisable battery names add value, making it clear which battery is charging or at risk.

The Action Matrix bases its actions on the user's location relative to the battery. I recommend to build in accurate location tracking of both user and battery, so the system can create informed actions and show where the risk is forming, for both the user and emergency services. This same tracking could let public buildings monitor potential risk within their area, improving safety for others nearby.

Alprokon brand identity

A smaller design recommendation would be to redesign the graphical user interface (GUI) to match the brand identity of Alprokon. That creates a uniform message with aesthetics that matches the other Alprokon products.

Reflection

I want to end on a personal note. This thesis has developed me as a designer and as a person. With the broad design brief of 'Every Space Safe' I found both joy and struggle. I learned what I love to do most, creating technical solutions using electronics. My passion for integrated product design is growing, and I hope to develop it even further in the future.

Before starting this project I had written down one of the struggles I normally face in a design project which is making decisions and trusting my own design choices. It is a personal challenge that this thesis addressed directly from the beginning.

I started this thesis with a design brief from Alprokon for their new consumer platform, 'Every Space Safe', looking for innovative ideas that make every space safe. At first I thought a brief this broad was great, an opportunity to explore a new field, safety. But a topic that broad brought many challenges. I found it hard to make decisions and set boundaries. With the help of my mentors I learned to trust my own judgement. It took many convergent and divergent processes to scope down, and I learned that it is important to choose. Maybe it was not always the best choice, and I returned to some of them. But without choosing I got lost in the endless opportunities that such a broad topic presented. In the end I arrived at a current and interesting subject, scoped just broad enough to address a variety of design decisions.

In this thesis, by addressing many aspects of HeatGuard, I was able to explore and use the skills I have developed as a designer over the years. I also got to learn a couple of new skills. Firstly, I learned how to work better with AI in the design process. As it is a prevalent and unavoidable tool in the design industry, and in any industry for that matter, I am a firm believer that we should learn how to use it rather than ignoring that it is there. Yet I call it a tool deliberately, because it remains important that I am the lead designer, that I provide the input and control the output.

Working with Claude Design, an AI tool from Anthropic, let me generate fast prototypes of the mobile application interface and run rapid tests and iterations on them, speeding up the design process. This produced a more realistic, interactive prototype, which in turn allowed for better user tests and a more convincing user experience. It is one example of how AI can improve the design process, and I learned a lot about how to work with it in the future.

Secondly, I learned to work with network-integrated electronics that process, transmit and receive data. I have worked with electronics before, especially Arduino, but this was the first time I used my phone to receive alerts driven by the data the device collects from the NTC sensors. Learning how to send this data to my phone as notifications that automatically open other applications gave me knowledge for building better prototypes. I already used this approach in the user tests, and it gave much richer insights, because participants could imagine themselves using HeatGuard realistically.

Finally, I found it valuable to work with experts in the field of battery systems and to read on the physics behind thermal runaway. I believe that grounding my designs in physics and theory presents a much stronger case for plausibility. I learned a great deal on this topic and gained real knowledge of how to design for thermal risks. There is still a lot to explore and discover, but this is a great start, and I hope to learn more in the future.

Overall, this project has taught me valuable things, working through the design process from A to Z, from research to prototyping to user validation. I believe my passion and vision in design have come through clearly, and I got to do what I love, using physics, which I find fascinating, and working with electronics. I am very grateful for this experience and would not have wanted to miss it for anything.

Thank you for reading my thesis. I hope you enjoyed it as much as I enjoyed the project, the process and the writing.

Figure 125: Thank you

REFERENCES

[1] A1 Digital. (2024, August 20). LTE-M: The future of mobile technology for enterprises. https://www.a1.digital/knowledge-hub/lte-m-a-comprehensive-guide-for-enterprises/

[2] Abbing, J.-M., Biemans, M., Koolman, G., Seyfi, M., Van den Broek, B., Van den Broek Humphrey, G., & Bakker, T. (2023). Onderzoek veiligheid energie opslag systemen: Beoordeling veiligheidsaspecten van EOS en juridische context (BJ5136I&BRP001F02). Royal HaskoningDHV / Ministerie van Infrastructuur en Waterstaat. https://www.maatregelenwiki.nl/sites/default/files/2024-03/Onderzoek%20Veiligheid%20Energieopslagsystemen.pdf

[3] Acrel Energy. (n.d.). Exploring remote temperature measuring devices in healthcare. https://www.acrelenergy.com/exploring-remote-temperature-measuring-devices-in-healthcare.html

[4] ACT Power. (n.d.). How to measure electrical component temperatures. https://www.actpower.com/blog/how-to-measure-electrical-component-temperatures/

[5] AD. (2025, 27 september). Elektrische vouwfietsen van Windgoo per direct uit de verkoop vanwege brandgevaar accu. AD. https://www.ad.nl/binnenland/elektrische-vouwfietsen-van-windgoo-per-direct-uit-de-verkoop-vanwege-brandgevaar-accu~aa171629/

[6] Ajax Systems. (n.d.). Ajax MotionProtect: Draadloze bewegingsmelder (PIR). Inbraakpreventiewinkel. https://inbraakpreventiewinkel.nl/ajax-motionprotect-zwart-draadloze-bewegingsmelder-pir/

[7] Ali, K. (2025). The impact of temperature on battery lifetime for energy storage systems and performance. IOP Conference Series: Earth and Environmental Science, 1507, 012010. https://doi.org/10.1088/1755-1315/1507/1/012010

[8] AllRisk. (n.d.). De cijfers van valongelukken in Nederland. https://www.ar.nl/blog-cijfers-valongelukken-nederland

[9] Alprokon. (2026). Elke ruimte veilig. https://www.alprokon.com/

[10] Amazon Web Services. (n.d.). AWS IoT Core pricing. Retrieved June 2, 2026, from https://aws.amazon.com/iot-core/pricing/

[11] American Lung Association. (n.d.). Cleaning supplies and household chemicals. https://www.lung.org/clean-air/indoor-air/indoor-air-pollutants/cleaning-supplies-household-chem

[12] Ametherm. (n.d.). What is an NTC thermistor? https://www.ametherm.com/thermistor/what-is-an-ntc-thermistor

[13] Ampure. (2023, January 26). How electric vehicle battery technology works. Ampure. https://www.ampure.com/blog/how-electric-vehicle-battery-technology-works

[14] Anduril. (2025). Anduril's EagleEye puts mission command and AI directly into the warfighter's helmet. https://www.anduril.com/news/anduril-s-eagleeye-puts-mission-command-and-ai-directly-into-the-warfighter-s-helmet

[15] Anthropic. (2025). Claude [Large language model]. https://claude.ai/

[16] ANWB. (n.d.). Hoe veilig zijn fietsaccu's? https://www.anwb.nl/fiets/fietsaccu/fietsaccus-en-veiligheid

[17] Atlas Scientific. (n.d.). How do temperature sensors work? https://atlas-scientific.com/blog/how-do-temperature-sensors-work/

[18] Australian Government Department of Health and Aged Care. (n.d.). What are the effects of alcohol? https://www.health.gov.au/topics/alcohol/about-alcohol/what-are-the-effects-of-alcohol

[19] Autovisie. (2025). Meer dan 30.000 Volvo EX30's moeten terug naar dealer: dit kan leiden tot brand in de accu. Autovisie. https://www.autovisie.nl/nieuws/meer-dan-30-000-volvo-ex30s-moeten-terug-naar-dealer-dit-kan-leiden-tot-brand-in-de-accu/

[20] Ball, D. R., & Frerk, C. (2015). A new view of safety: Safety 2. British Journal of Anaesthesia, 115(5), 645–647. https://doi.org/10.1093/bja/aev216

[21] Battery University. (2021, November 2). BU-802b: What does elevated self-discharge do? https://www.batteryuniversity.com/article/bu-802b-what-does-elevated-self-discharge-do/

[22] Besomi. (n.d.). FHF05 Heat Flux Sensor 50x50mm Flexible. https://besomi.com/ae_en/fhf05-heat-flux-sensor-50x50mm-flexible.html

[23] Beveiligd Nederland. (n.d.). 12 beveiligingstips om inbraak thuis te voorkomen. https://beveiligdnederland.nl/12-beveiligingstips-inbraak-voorkomen/

[24] Bounce Imaging. (2025). World's first thermal 360 throwable camera revealed at NTOA. https://bounceimaging.com/worlds-first-thermal-360-throwable-camera-revealed-at-ntoa/

[25] BOVAG. (2025, 4 March). Fietsbranche laat lichte daling zien in 2024 – e-bikes ruggengraat van de markt. https://www.bovag.nl/pers/persberichten/fietsbranche-blijft-stabiel-in-2024-e-bikes-ruggengraat-van-de-markt

[26] Brandweer Nederland. (n.d.). Plug-and-play thuisbatterij. Brandweer Nederland. https://www.brandweer.nl/onderwerpen/plug-and-play-thuisbatterij/

[27] Bright.nl. (2025). AI kan het horen als de batterij van je e-bike bijna in brand vliegt. Bright.nl. https://www.bright.nl/nieuws/1238552/ai-kan-het-horen-als-de-batterij-van-je-e-bike-bijna-in-brand-vliegt.html

[28] butchja. (n.d.). MK2 e-bike battery pack for 40 cells and BMS [3D model]. Thingiverse. https://www.thingiverse.com/thing:3128457

[29] C-Parts. (n.d.). E-Bike accu heeft ook een onderhoudsbeurt nodig [An e-bike battery also needs a maintenance service]. Retrieved June 25, 2026, from https://www.c-parts.nl/vakhandel/e-bike-accu-onderhoudsbeurt/

[30] Centraal Bureau voor de Statistiek. (2026, 2 maart). Veiligheidsmonitor; kerncijfers, regio [Dataset 85146NED]. CBS StatLine. https://opendata.cbs.nl/#/CBS/nl/dataset/85146NED/table

[31] Centrum voor Criminaliteitspreventie en Veiligheid. (n.d.). Politiekeurmerk Veilig Wonen. https://politiekeurmerk.nl/over-pkvw/

[32] Charcoat. (n.d.). The future of passive fire protection: Trends to watch in 2026. https://www.charcoat.com/blog/the-future-of-passive-fire-protection-trends-to-watch/

[33] Connectivity Standards Alliance. (n.d.). Building the foundation and future of the IoT. https://csa-iot.org/

[34] Connectivity Standards Alliance. (2025). Matter: One protocol to connect compatible devices and systems with one another. https://csa-iot.org/all-solutions/matter/

[35] Consumer Reports. (n.d.). Best indoor motion-sensing lights. https://www.consumerreports.org/home-garden/best-indoor-motion-sensing-lights-a8544423852/

[36] De Jong, M., Van den Tol, S., & Mesu, S. (2015, 5 augustus). Inbrekers doen het liefst 's nachts hun werk. Of niet? Secondant. https://ccv-secondant.nl/platform/article/inbrekers-doen-het-liefst-s-nachts-hun-werk-of-niet

[37] Department of Homeland Security. (2023, 6 november). Picturing the future of firefighting. https://www.dhs.gov/science-and-technology/news/2023/11/06/feature-article-picturing-future-firefighting

[38] Design Council. (n.d.). The Double Diamond. https://www.designcouncil.org.uk/our-resources/the-double-diamond/

[39] DigiKey. (n.d.). NRF9160-SICA-B1A-R7 Nordic Semiconductor ASA [Product listing]. Retrieved June 2, 2026, from https://www.digikey.nl/en/products/detail/nordic-semiconductor-asa/NRF9160-SICA-B1A-R7/13533603

[40] Domer. (n.d.). All about polycarbonates. https://www.domer.co/all-about-polycarbonates/

[41] Dwyer Omega. (n.d.). Infrared thermometer: How does it work? https://www.dwyeromega.com/en-us/resources/infrared-thermometer-how-work

[42] DwyerOmega. (n.d.). RTD sensors. Retrieved 16 April 2026, from https://www.dwyeromega.com/en-us/resources/rtd-hub

[43] ECAM. (n.d.). Thermal camera monitoring: Spotting the spark of lithium-ion batteries and ensuring safe processing. https://ecam.com/security-blog/thermal-camera-monitoring-spotting-the-spark-of-lithium-ion-batteries-and-ensuring-safe-processing

[44] EcoComply. (2026, January 26). What does CE marking cost for your product? Retrieved June 2, 2026, from https://ecocomply.ai/blog/what-does-ce-marking-cost-for-your-product

[45] Eisenkraft, A., Goldstein, N., Fons, M., Tabi, M., Sherman, A. D., Ben Ishay, A., Merin, R., & Nachman, D. (2023). Comparing body temperature measurements using the double sensor method within a wearable device with oral and core body temperature measurements using medical grade thermometers — A short report. Frontiers in Physiology, 14. https://doi.org/10.3389/fphys.2023.1279314

[46] Electrical Safety First. (n.d.). RCDs explained. https://www.electricalsafetyfirst.org.uk/guidance/safety-around-the-home/rcds-explained/

[47] Electrical4U. (n.d.). Seebeck effect and Seebeck coefficient. https://www.electrical4u.com/seebeck-effect-and-seebeck-coefficient/

[48] Elektricienwijzer. (n.d.). Gevaren elektriciteit: Welke risico's & aandachtspunten? https://www.elektricienwijzer.nl/gevaren

[49] Ellsworth Adhesives. (n.d.). 3M VHB tape 5952 black 1 in x 36 yd roll. Retrieved June 2, 2026, from https://www.ellsworth.com/products/by-manufacturer/3m/tapes/double-coated/structural-vhb/3m-vhb-tape-5952-black-1-in-x-36-yd-roll/

[50] Engineering ToolBox. (n.d.). Thermal conductivity of selected materials and gases. https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html

[51] European Agency for Safety and Health at Work. (n.d.). Human error. OSHwiki. https://oshwiki.osha.europa.eu/en/themes/human-error

[52] Fietsersbond. (2024, 30 augustus). De plek van de accu, maakt het wat uit? https://www.fietsersbond.nl/de-fiets/fietssoorten/elektrische-fietsen/de-plek-van-de-accu-maakt-het-wat-uit/

[53] Finex Home. (n.d.). Slimme deurklink. https://finexhome.com/products/slimme-deurklink

[54] FLIR. (n.d.). FLIR E5 Pro Ex PRO WiFi Thermal Imaging Camera. RS Online. https://nl.rs-online.com/web/p/thermal-imaging-cameras/2732555

[55] Forschungszentrum Jülich. (n.d.). Forschungszentrum Jülich [Forschungszentrum Jülich research centre]. Retrieved June 25, 2026, from https://www.fz-juelich.de/de

[56] Fritzing. (2026). Fritzing (Version 1.0.7) [Computer software]. https://fritzing.org/

[57] Ghandily, N., Nakrani, P., Kisseler, N., Heimes, H., & Kampker, A. (2026). Overview of the current state of research on thermal runaway and thermal propagation testing of lithium-ion batteries. Cell Reports Physical Science, 7(2), 103111. https://doi.org/10.1016/j.xcrp.2026.103111

[58] Gu, X., Shang, Y., Li, J., Zhu, Y., Tao, X., Geng, H., Zhang, Z., & Zhang, C. (2025). Early warning of thermal runaway based on state of safety for lithium-ion batteries. Communications Engineering, 4(1), 106. https://doi.org/10.1038/s44172-025-00442-1

[59] Harasis, S., Khan, I., & Massoud, A. (2026). The impact of high ambient temperatures on lithium-ion batteries in electric vehicles: An in-depth review of thermal performance and chemistry-specific response. Renewable and Sustainable Energy Reviews, 229, 116623. https://doi.org/10.1016/j.rser.2025.116623

[60] Health and Safety Authority. (n.d.). Use chemicals safely at home and in the garden [Brochure]. https://www.hsa.ie/media/1nfngryi/103955_hsa-chemical-brochure_web_aw.pdf

[61] Heat flux sensor. (n.d.). In ScienceDirect Topics. Retrieved 26 March 2026, from https://www.sciencedirect.com/topics/engineering/heat-flux-sensor

[62] Heckel, P. (2026). ntfy [Computer software]. ntfy LLC. https://ntfy.sh/

[63] Hessels, T. (2022). Zakboek energietransitie voor incidentbestrijders. Nederlands Instituut Publieke Veiligheid. https://nipv.nl/wp-content/uploads/2022/10/20220920-NIPV-Zakboek-Energietransitie-voor-incidentbestrijders.pdf

[64] HKO. (n.d.). EV battery protection. https://www.hko.de/en/markets/automotive/ev-battery-protection

[65] HKO. (n.d.). Finishings. https://www.hko.de/en/technologies/our-technologies/finishing

[66] HKO. (n.d.). HKO: Trust the experts. Retrieved June 25, 2026, from https://www.hko.de/en

[67] HKO. (n.d.). Silica fabrics. https://www.hko.de/en/products/silica-fabrics

[68] HKO. (2023). DEFENSOR-Flex® ML-38 [Technical data sheet]. Saint-Gobain ADFORS. https://www.adfors.com/sites/hps-mac3-adfors-us/files/2024-02/DEFENSOR-Flex%C2%AE%20ML38.pdf

[69] Hollnagel, E. (2014). Is safety a subject for science? Safety Science, 67, 21–24. https://doi.org/10.1016/j.ssci.2013.07.025

[70] Honeywell. (n.d.). Li-ion Tamer: Battery off-gas detection. https://buildings.honeywell.com/us/en/brands/our-brands/li-ion-tamer

[71] Hornbach. (n.d.). Anaf poeder brandblusser 2 kg. https://www.hornbach.nl/p/anaf-poeder-brandblusser-2-kg/12010780/

[72] Hornbach. (n.d.). EZVIZ beveiligingscamera buiten H8C Pro 5MP WiFi. https://www.hornbach.nl/p/ezviz-beveiligingscamera-buiten-h8c-pro-5mp-wifi/12361483/

[73] Hornbach. (n.d.). FireAngel combinatie rook- en koolmonoxidemelder SCB10-INT. https://www.hornbach.nl/p/fireangel-combinatie-rook-en-koolmonoxidemelder-scb10-int/12043627/

[74] Hornbach. (n.d.). Kayoom antislipmat wit 110x160 cm. https://www.hornbach.nl/p/kayoom-antislipmat-wit-110x160-cm/5762873/

[75] Hornbach. (n.d.). Nemef cilinderslot 1269/4 dag-nacht PC55 wit. https://www.hornbach.nl/p/nemef-cilinderslot-1269-4-dag-nacht-pc55-wit/5086254/

[76] Hornbach. (n.d.). Philips WelcomeEye Link videodeurbel. https://www.hornbach.nl/p/philips-welcomeeye-link-videodeurbel/10307493/

[77] Hornbach. (n.d.). Q-Link tijdschakelaar mechanisch wit. https://www.hornbach.nl/p/q-link-tijdschakelaar-mechanisch-wit/10567475/

[78] HOVSCO. (2022, June 25). What's inside an e-bike battery? A 2025 deep dive. https://www.hovsco.com/blogs/blogs/whats-inside-an-e-bike-battery

[79] Hukseflux. (n.d.). FHF06 heat flux sensor. https://www.hukx.com/products/fhf06-heat-flux-sensor

[80] ICL Group. (2025). Top Industry 4.0 trends shaping the future of industry. https://www.icl-group.com/blog/top-industry4-0-trends-shaping-the-future-of-industry/

[81] IKEA. (n.d.). FORNUFTIG luchtreiniger. https://www.ikea.com/nl/nl/p/fornuftig-luchtreiniger-wit-50461937/

[82] IOThrifty. (2020, 20 January). Introduction to infrared temperature sensors. https://www.iothrifty.com/blogs/news/infrared-temperature-sensors

[83] JEC Capacitor. (n.d.). 100K Negative Temperature Coefficient Resistor. https://www.jeccapacitor.com/thermistor/100k-negative-temperature-coefficient-resistor.html

[84] Karemaker, M., Ten Hoor, G. A., Hagen, R. R., Van Schie, C. H. M., & Ruiter, R. A. C. (2025). The effects of the Fire Safety at Home programme on four fire safety behaviours among older adults. Fire Safety Journal, 152, 104337. https://doi.org/10.1016/j.firesaf.2025.104337

[85] Keyence. (n.d.). Temperature sensors. https://www.keyence.com/products/process/temperature/

[86] Kim, J., Bae, D., Park, C., & Park, H. (2025). Pre-detection of thermal runaway in Li-ion 18650 batteries via temperature and voltage: The importance of temperature measurement location. Applied Thermal Engineering, 269, 125991. https://doi.org/10.1016/j.applthermaleng.2025.125991

[87] Kim, J., Oh, J., & Lee, H. (2019). Review on battery thermal management system for electric vehicles. Applied Thermal Engineering, 149, 192–212. https://doi.org/10.1016/j.applthermaleng.2018.12.020

[88] Knapp, J., Zeratsky, J., & Kowitz, B. (2016). Sprint: How to solve big problems and test new ideas in just five days. Simon & Schuster.

[89] Kumar, R. (2021). Design sprint: Theory vs reality. Prototypr. https://blog.prototypr.io/design-sprint-theory-vs-reality-4cb3f48a00fd

[90] Lv, S., Wang, X., Lu, W., Zhang, J., & Ni, H. (2022). The influence of temperature on the capacity of lithium ion batteries with different anodes. Energies, 15(1), 60. https://doi.org/10.3390/en15010060

[91] Masè, M., Werner, A., Putzer, G., Avancini, G., Falla, M., Brugger, H., Micarelli, A., & Strapazzon, G. (2022). Low ambient temperature exposition impairs the accuracy of a non-invasive heat-flux thermometer. Frontiers in Physiology, 13. https://doi.org/10.3389/fphys.2022.830059

[92] Maslow, A. H. (1970). Motivation and personality (2nd ed.). Harper & Row.

[93] Metsch, T. (2025, 24 december). Dit zijn dé 5 technologietrends voor de beveiligingssector in 2026. Security Management. https://www.securitymanagement.nl/dit-zijn-de-5-technologietrends-voor-de-beveiligingssector-in-2026/

[94] Moon, S., Oh, S., & Chung, S. (2026). Hybrid thermoelectric–battery architectures for self-powered wearable electronics. Wearable Electronics, 3, 11–29. https://doi.org/10.1016/j.wees.2025.10.003

[95] Nederlands Instituut Publieke Veiligheid. (n.d.). Batterijen. https://nipv.nl/onderzoek/batterijen/

[96] Nederlands Instituut Publieke Veiligheid. (n.d.). Brandveiligheid woonomgeving. https://nipv.nl/onderzoek/brandveiligheid-woonomgeving/

[97] Nederlands Instituut Publieke Veiligheid. (n.d.). CO2 kooldioxide. https://nipv.nl/onderzoek/co2-kooldioxide/

[98] Nederlandse Voedsel- en Warenautoriteit. (n.d.). Risico's huishoudchemicaliën. https://www.nvwa.nl/onderwerpen/huishoudchemicalien/risico-s-huishoudchemicalien

[99] Netbeheer Nederland. (n.d.). Energieleveren.nl. https://www.energieleveren.nl

[100] Netbeheer Nederland. (2024). Huishoudelijke elektriciteitsongevallen achter de meter: Jaaroverzicht 2023 (Version 1.0) [PDF]. Netbeheer Nederland. https://www.netbeheernederland.nl/sites/default/files/2024-07/e-ongevallen_achter_de_meter_2023_v1.0_2024-06-07.pdf

[101] Nexans. (2025). Electrical fire safety solutions: Protecting lives and assets. https://www.nexans.com/perspective/electrical-fire-safety-solutions-protecting-lives-and-assets/

[102] Nguyen, V., Paredes, D., & Blankstein, A. (2023, February 7). An exploding problem: Fires sparked by lithium batteries are confounding firefighters. NBC News. https://www.nbcnews.com/news/exploding-problem-fires-sparked-lithium-batteries-are-confounding-fire-rcna65739

[103] Nordic Semiconductor. (n.d.). nRF9160 product specification. https://docs.nordicsemi.com/r/bundle/ps_nrf9160/page/nrf9160_html5_keyfeatures.html

[104] Nordic Semiconductor. (n.d.). nRF9160 SiP product brief (Version 2.1). https://www.nordicsemi.com/-/media/Software-and-other-downloads/Product-Briefs/nRF9160-SiP-PB-v2.1.pdf

[105] Nordic Semiconductor. (n.d.). nRF9160 system-in-package. https://www.nordicsemi.com/Products/nRF9160

[106] NOS. (2021, 15 September). E-bike in brand na ontploffing accu [Video]. NOS. https://nos.nl/video/2397930-e-bike-in-brand-na-ontploffing-accu

[107] NOS. (2025, 30 september). Honderden gebouwbranden per jaar door fietsaccu's, 'mensen onderschatten gevaar'. NOS Nieuws. https://nos.nl/artikel/2584663-honderden-gebouwbranden-per-jaar-door-fietsaccu-s-mensen-onderschatten-gevaar

[108] NOS Nieuws. (2025, September 25). Brandweer waarschuwt voor 'levensgevaarlijke' accu's van vouwfiets Windgoo. NOS. https://nos.nl/artikel/2584008-brandweer-waarschuwt-voor-levensgevaarlijke-accu-s-van-vouwfiets-windgoo

[109] Novieto, D. T., Kulor, F., Markus, E. D., & Apprey, M. W. (2023). Safety precautions in the usage of extension cords by students in halls and hostels. TELKOMNIKA (Telecommunication Computing Electronics and Control), 21(2), 468–476. https://doi.org/10.12928/telkomnika.v21i2.24743

[110] Obasi, I. C., Benson, C., & Akinwande, D. V. (2026). Smart systems and safety 4.0: A systematic review of technologies enhancing safety decision-making in industry 4.0. Results in Engineering, 29, 109331. https://doi.org/10.1016/j.rineng.2026.109331

[111] Onderzoeksraad voor Veiligheid. (2015). Koolmonoxide: Onderschat en onbegrepen gevaar. https://onderzoeksraad.nl/wp-content/uploads/2023/11/b4a6d08bb6f4rapport_koolmonoxide_nl_interactief.pdf

[112] 1NCE. (n.d.). 1NCE IoT Lifetime Flat – pricing. Retrieved June 2, 2026, from https://www.1nce.com/en-eu/1nce-connect/pricing

[113] OpenAI. (2026). ChatGPT [Large language model]. https://chatgpt.com

[114] Optris. (n.d.). Preventing fire hazards and early detection of thermal runaway in lithium-ion batteries. https://optris.com/application/battery-monitoring/preventing-fire-hazards-and-early-detection-of-thermal-runaway-in-lithium-ion-batteries/

[115] Otten, T., Karemaker, M., & De Witte, L. (2024). 15 jaar fatale woningbranden. Nederlands Instituut Publieke Veiligheid. https://nipv.nl/wp-content/uploads/2024/12/20241212-NIPV-15-jaar-fatale-winingbranden.pdf

[116] Papanikolaou, K. (2021, April 13). What is LTE-M? Long term evolution for machines explained. emnify. https://www.emnify.com/blog/lte-m

[117] Pelco. (n.d.). Future of security technology: Industry trends of 2026. https://www.pelco.com/blog/security-technology-trends

[118] Pelco. (n.d.). How do thermal cameras work? https://www.pelco.com/blog/how-do-thermal-cameras-work

[119] Pesaran, A. A. (2002). Battery thermal models for hybrid vehicle simulations. Journal of Power Sources, 110(2), 377–382. https://doi.org/10.1016/S0378-7753(02)00200-8

[120] Piepers, N., Van Soomeren, P., & Pluijm, M. (2021). Wat kunnen we leren over de preventie van woninginbraken? WODC. https://repository.wodc.nl/bitstream/handle/20.500.12832/3138/3213-wat-kunnen-we-leren-over-preventie-woninginbraken-volledige-tekst.pdf

[121] Plastic4trade. (2026, April 15). ABS granuls [Product listing]. https://plastic4trade.com/supplier/abs-granuls-abs-reprocess-granule-injection-molding-kolkata-west-bengal-india-2

[122] Pleysier, S. (2011). Over objectieve en subjectieve onveiligheid: En de (on)zin van het rationaliteitdebat. Tijdschrift voor Veiligheid, 10(4), 24–40. https://doi.org/10.5553/TvV/2011010004003

[123] Pluralsight. (2025). Tech in 2030. https://www.pluralsight.com/resources/blog/tech-operations/tech-in-2030

[124] POWER Magazine. (n.d.). How thermal imaging improves early warning fire detection for battery storage and handling. https://www.powermag.com/how-thermal-imaging-improves-early-warning-fire-detection-for-battery-storage-and-handling/

[125] Raheemy, Y., Sherratt, F., & Hallowell, M. R. (2025). What is safety? Contemporary definitions and interpretations across North America. Safety Science, 185, 106798. https://doi.org/10.1016/j.ssci.2025.106798

[126] RAI Vereniging. (2025). Mobiliteit in Cijfers Tweewielers 2025–2026. https://www.raivereniging.nl/mobiliteit-in-cijfers-tweewielers

[127] Raijmakers, L. H. J., Danilov, D. L., Eichel, R.-A., & Notten, P. H. L. (2019). A review on various temperature-indication methods for Li-ion batteries. Applied Energy, 240, 918–945. https://doi.org/10.1016/j.apenergy.2019.02.078

[128] Ramaker, R. (2026, April 7). Brandweer bezorgd over onveilig gebruik van steeds populairdere stekkerbatterij. NOS. https://nos.nl/collectie/13871/artikel/2609352-brandweer-bezorgd-over-onveilig-gebruik-van-steeds-populairdere-stekkerbatterij

[129] Ramaker, R. (2026, 7 April). Stekkerbatterij steeds populairder: 'Ik heb er echt lol in.' NOS. https://nos.nl/artikel/2609361-stekkerbatterij-steeds-populairder-ik-heb-er-echt-lol-in

[130] Rijksoverheid. (n.d.). Salderingsregeling stopt in 2027. https://www.rijksoverheid.nl/onderwerpen/energie-thuis/salderingsregeling

[131] Riley, R. (n.d.). The Lotus Blossom creative technique. Thought Egg. https://thoughtegg.com/lotus-blossom-creative-technique/

[132] Ring. (n.d.). All products. https://ring.com/nl/nl/collections/all-products/

[133] Roels, J. M., Walhout, A. M., Westra, J., Kloosterboer, H. E., & Wezenbeek, J. M. (2018). Bewust omgaan met veiligheid: Doelen en effectmaten in het risico- en veiligheidsbeleid. RIVM. https://www.rivm.nl/bibliotheek/rapporten/2018-0029.pdf

[134] RS PRO. (n.d.). RS PRO Type K Grounded Thermocouple 40 mm Length, 4 mm Diameter, −60 °C 350 °C Max. RS Online. https://nl.rs-online.com/web/p/thermocouples/8722534

[135] RS PRO. (n.d.). RS PRO Type K RTD Sensor, 4 mm Diameter. RS Online. https://nl.rs-online.com/web/p/rtd-sensors/4554056

[136] RTL Nieuws. (2026, 16 januari). Gaslek kan enorme gevolgen hebben: hier moet je thuis op letten. RTL Nieuws. https://www.rtl.nl/nieuws/binnenland/artikel/5555362/gaslek-gasexplosie-huis

[137] RTV Utrecht. (2025). Brandweer rukt steeds vaker uit voor brand door fietsaccu: 20 branden per jaar. RTV Utrecht. https://www.rtvutrecht.nl/nieuws/3949298/brandweer-rukt-steeds-vaker-uit-voor-brand-door-fietsaccu-20-branden-per-jaar

[138] Salomons, H. (2024). Huishoudelijke gasinstallatieongevallen: Jaaroverzicht 2023 (VGI/1603/Sal). Kiwa Technology / Netbeheer Nederland. https://www.netbeheernederland.nl/sites/default/files/2024-11/kiwa_technology_-_registratie_gasinstallatieongevallen_jaaroverzicht_2023_-_vgi_1603_sal.pdf

[139] Scheunis & Co. (n.d.). Dit zijn de 10 meest voorkomende ongevallen thuis. https://www.scheunis.be/blog/de-10-meest-voorkomende-ongevallen-thuis

[140] Second Layer. (2026). Napkin AI [Computer software]. https://www.napkin.ai/

[141] Shingo, S. (1986). Zero quality control: Source inspection and the poka-yoke system (A. P. Dillon, Trans.). Productivity Press.

[142] Siemens. (2025). Cerberus ECO: Connected system for fire detection. https://www.siemens.com/en-us/products/cerberus/eco/

[143] Simbase. (n.d.). Global IoT coverage. Retrieved June 2, 2026, from https://simbase.com/global-iot-coverage

[144] Simbase. (n.d.). Simbase. Retrieved June 11, 2026, from https://simbase.com/nl

[145] Skya Power. (2025, October 23). E-bike battery cases. https://skyapower.com/e-bike-battery-cases/

[146] Slachtofferwijzer. (n.d.). Waarom brandveiligheid in huis zo belangrijk is. https://slachtofferwijzer.nl/artikelen/brandveilig-wonen-praktische-tips

[147] Smart Home World. (2025). AI-powered homes: The new era of predictive, context-aware living. Smart Home World. https://www.smarthomeworld.in/ai-powered-homes-the-new-era-of-predictive-context-aware-living/

[148] SmartQat. (n.d.). LM35DZ Temperature Sensor IC. https://smartqat.com/products/lm35dz-temperature-sensor-ic

[149] Smit, M. (2024). Veiligheid in de wijk: De invloed van sociale cohesie, individuele kwetsbaarheid en objectieve veiligheid op het inschatten van de wijkveiligheid door inwoners van de Gemeente Groningen [Master's thesis, University of Groningen]. University of Groningen Student Theses. https://gmwpublic.studenttheses.ub.rug.nl/3110/

[150] Stam, C. (2025). Letsels 2024: Tabellen kerncijfers LIS (Rapport 1058). VeiligheidNL. https://www.veiligheid.nl/sites/default/files/2025-09/kerncijfers_tabellen_2024_20250911.pdf

[151] StartUs Insights. (2025). Technology trends to watch. https://www.startus-insights.com/innovators-guide/technology-trends-to-watch/

[152] STMicroelectronics. (n.d.). Temperature sensors. https://www.st.com/en/mems-and-sensors/temperature-sensors.html

[153] Suricat. (2025). The future of fire detection technology in industrial plants. https://suricat.app/the-future-of-fire-detection-technology-in-industrial-plants/

[154] Tempsens. (n.d.). Temperature sensing solutions. https://tempsens.com/ct/temperature-sensing-solutions/

[155] Thermtest. (n.d.). Thermal conductivity of acrylonitrile butadiene styrene (ABS). https://thermtest.com/thermal-conductivity-of-acrylonitrile-butadiene-styrene-abs

[156] 3M. (n.d.). 3M™ VHB™ Tape 5952. https://www.3m.com/3M/en_US/p/d/b40065688/

[157] Ting. (n.d.). How it works: The technology protecting your home. https://www.tingfire.com/how-it-works-technology/

[158] TinyTronics. (n.d.). 10kΩ weerstand (standaard pull-up of pull-down weerstand). Retrieved June 2, 2026, from https://www.tinytronics.nl/nl/componenten/weerstanden/weerstanden/10k%CF%89-weerstand-(standaard-pull-up-of-pull-down-weerstand)

[159] TinyTronics. (n.d.). PKCell Li-Po Batterij 3.7V 2500mAh JST-PH (LP785060). Retrieved June 2, 2026, from https://www.tinytronics.nl/nl/power/batterijen/li-po/pkcell-li-po-batterij-3.7v-2500mah-jst-ph-lp785060

[160] TinyTronics. (n.d.). SR Passives NTC 10kΩ 4000K (NTCC-10K). Retrieved June 2, 2026, from https://www.tinytronics.nl/nl/sensoren/temperatuur/sr-passives-ntc-10k%CF%89-4000k-ntcc-10k

[161] TW.nl. (2025). Deze nieuwe batterij blust zichzelf voordat hij in brand vliegt. TW.nl. https://tw.nl/deze-nieuwe-batterij-blust-zichzelf-voordat-hij-in-brand-vliegt-batterij-van-de-toekomst-is-veiliger-dan-ooit/

[162] Tweakers. (2025). Anker roept in Amerika meer dan een miljoen powerbanks terug om brandgevaar. Tweakers. https://tweakers.net/nieuws/236216/anker-roept-in-amerika-meer-dan-een-miljoen-powerbanks-terug-om-brandgevaar.html

[163] University of Georgia College of Agricultural and Environmental Sciences. (n.d.). Hazardous household products: What's in your house? (Publication C1051). CAES Field Report. https://fieldreport.caes.uga.edu/publications/C1051/hazardous-household-products/

[164] US Air Force. (2025). Laser-focused innovation lets firefighters see through smoke. https://www.af.mil/News/Article-Display/Article/4183737/laser-focused-innovation-lets-firefighters-see-through-smoke/

[165] van Boeijen, A., Daalhuizen, J. J., van der Schoor, R., & Zijlstra, J. (2013). Delft Design Guide: Design strategies and methods. BIS Publishers.

[166] Van den Eijkel, E. (2025, 25 juli). Top 3 oorzaken voor woningbrand. Vulkon. https://www.vulkon.nl/blogs/top-3-oorzaken-voor-woningbrand

[167] Van den Handel, C., Nauta, O., Van Soomeren, P., & Van Amersfoort, P. (2009). Hoe doen ze het toch? Modus operandi woninginbraak: Eindrapportage. DSP-groep. https://www.dsp-groep.nl/wp-content/uploads/2025/04/11pvmodop_Eindrapport_Modus_Operandi_woninginbraank.pdf

[168] Van der Voort, G. (2016). Safety science and the George dilemma: Towards structural safety management [Doctoral dissertation, Delft University of Technology]. https://doi.org/10.4233/uuid:3dec02ac-c659-4741-980f-85619f2c4da6

[169] Van Harn, T., Brans, H., & Reinders, J. (2024). Explosieveiligheid f-ion energieopslagsystemen. Nederlands Instituut Publieke Veiligheid. https://nipv.nl/wp-content/uploads/2025/01/20241120-NIPV-Explosieveiligheid-lithium-ion-energieopslagsystemen.pdf

[170] van Harn, T., Brans, H., & Zweverink, B. (2026). Incidentbestrijding lithium-ion thuisbatterijen [Incident response for lithium-ion home batteries]. Nederlands Instituut Publieke Veiligheid (NIPV). https://nipv.nl/wp-content/uploads/2026/03/20260326-NIPV-Rapport-Incidentbestrijding-Thuisbatterijen.pdf

[171] Van Harn, T., & Reinders, J. (2025). Batterijmanagementsysteem en thermal runaway. Nederlands Instituut Publieke Veiligheid. https://nipv.nl/wp-content/uploads/2025/05/20250423-NIPV-Batterijmanagementsysteem-en-thermal-runaway.pdf

[172] Veiligheidsregio Midden- en West-Brabant. (n.d.). De energietransitie: Veiligheid in een veranderende wereld. https://www.vrmwb.nl/actueel/energietransitie-veiligheid-in-een-veranderende-wereld

[173] Vos, J., Brans, H., & Reinders, J. (2024). Literatuuronderzoek naar de brandeffecten van lithium-ion batterijbranden. Nederlands Instituut Publieke Veiligheid. https://nipv.nl/wp-content/uploads/2024/04/20240402-NIPV-Literatuuronderzoek-naar-brandeffecten-van-li-ionbatterijbranden.pdf

[174] Wijlhuizen, G. J., & Van Rooij, E. H. C. (1997). Prioriteiten in preventie van privé-ongevallen (in en om huis) (TNO-rapport PG 97.022). TNO Preventie en Gezondheid. https://publications.tno.nl/publication/34612161/hp7Qwj/wijlhuizen-1997-prioriteiten.pdf

[175] Wolfs, L., & Van Liempd, R. (2025). Brandexperimenten (elektrische) fietsen en (elektrische) scooters. Nederlands Instituut Publieke Veiligheid. https://nipv.nl/wp-content/uploads/2025/05/20250107-NIPV-Brandexperimenten-elektrische-fietsen-en-elektrische-scooters.pdf

[176] World Economic Forum. (2025). Top 10 emerging technologies of 2025. https://reports.weforum.org/docs/WEF_Top_10_Emerging_Technologies_of_2025.pdf

[177] Yale Home. (2025). Yale Home: Securing the smart home through reliable connectivity. CSA-IoT. https://csa-iot.org/newsroom/yale-home-securing-the-smart-home-through-reliable-connectivity/

[178] Zandvliet, M. (2020, 26 juli). De top 10 brandoorzaken. KluisStore.nl. https://www.kluisstore.nl/blog/top-10-brandoorzaken/

[179] Zhang, X., Chen, S., Zhu, J., & Gao, Y. (2023). A critical review of thermal runaway prediction and early-warning methods for lithium-ion batteries. Energy Material Advances, 4, 0008. https://doi.org/10.34133/energymatadv.0008

[180] Zou, B., Zhang, L., Xue, X., Tan, R., Jiang, P., Ma, B., Song, Z., & Hua, W. (2023). A review on the fault and defect diagnosis of lithium-ion battery for electric vehicles. Energies, 16(14), 5507. https://doi.org/10.3390/en16145507

APPENDIX A: Research

A.1 5 Safety types research analysis

Burglary
Space, Risk and Need
Burglary is the illegal entry into a building or home without permission, it remains a structural safety issue within the domestic environment [23]. Contrary to the common understanding, most incidents occur during the afternoon and evening (60%), rather than at night (13%) [36]. This is in direct parallel to the assumption that darkness alone is the primary threat factor. Moreover, burglars typically operate within approximately 800 metres of their own residence, creating a geographical overlap between where the offender might live and the crime locations [120]. Safety in this context is therefore not random, but spatially patterned and predictable, when you know someone is actively breaking in near you.

Entry methods reveal that burglary is rarely planned, it is opportunistic [36, 167]. Windows and doors are pried open using basic tools such as screwdrivers or crowbars, applying pressure between frame and lock until it fails. Open or tilted windows are particularly vulnerable. Nearly fifty percent of the interviewed burglars report accessing homes through upper floors, often by climbing rainpipes. This indicates that perceived inaccessibility, and the idea that you are sure you are safe does not equal actual security [167]. Burglars often find a way you have not thought of to break in. The weakest point in the house defines the overall safety. Your house is as vulnerable as your weakest spot. As stated: a good lock in a bad door is as ineffective as installing lighting where no one can see it.

Risk factors are more then pure hardware issues. Poor closure behaviour, forgotten locks and poor window frame quality demonstrate that safety often fails at the level of resident behaviour rather than technology. Additionally, the lack of social control plays a significant role [36, 120]. In neighbourhoods with weak social cohesion, people passing by rarely intervene or take action. Environmental characteristics like badly eluminated back alleys, overgrown vegetation, older buildings and proximity to major roads increase exposure [120, 167]. Lower economic neighbourhoods face higher targeting rates, partly due to reduced collective vigilance.

Solutions
Prevention therefore requires multiple layers of measurements rather than isolated solutions, as one good isolated solution might highlight another point that is weaker. Mechanical reinforcement (anti-burglary strips, three-point locking systems, door reinforcement, certified hardware according to the Keurmerk Veilig Wonen standard requiring three minutes of burglary resistance) forms the objective safety baseline [31]. However, mechanical resistance alone does not guarantee perceived, objective safety. Lighting, removal of climbing opportunities and visible surveillance increase the scare factor. Alarm systems and smart detection technologies improve detection and response, though some can be disabled if poorly installed.
The technological landscape is increasingly fed with more compact and embedded systems. Smart cameras, biometric locks, PIR motion sensors and cloud-based alarm systems create interconnected ecosystems [6, 53, 132]. Current industry trends focus on prevention, deterrence, detection and response as their fundamentals. AI-driven video analytics and edge computing allow faster identification of anomalies, while cloud-based management enables remote control and detection [93, 117]. However, this introduces cybersecurity vulnerabilities and risks: a compromised IoT network might be more dangerous for physical safety, increasing its vulnerability.

Fire
Space, Risk and Need
Home fires remain one of the most dangerous domestic safety threats. Approximately 50% of residential fires are caused by human action, indicating that behavioural factors are structurally involved in fire risk [115]. Fire safety therefore cannot be reduced to technical malfunction alone, it is equally shaped by everyday routines, human errors and misunderstanding of hazard development.
Risk distribution across the house is uneven. The living room accounts for 38% of incidents, often involving couches and chairs or other textiles, followed by the kitchen (20%) and bedroom (17%) [115]. Furniture, textiles and electronic devices frequently act as ignition objects, with couches and chairs (16%), clothing and textiles (14%), and electronic devices (13%) representing the most common starting points. Chimneys, garages and spaces with battery storage introduce additional vulnerability, particularly in the context of home energy systems and lithium-ion batteries [96, 166].

Primary causes show a combination of technical and human triggers. Smoking remains a dominant factor (26%), followed by electrical-related causes (16%) such as defective wiring, overloaded sockets, faulty appliances and overheated devices [115, 178]. Cooking accounts for 15%, mostly through unattended pans and overheated oil. Open flames, heating equipment and chimney fires contribute additional ignition sources. A concerning trend is the increase in fatal fires caused by faulty devices or installations, indicating that technological density in homes is a raising risk [178].

A critical insight is the role of smoke and rapid fire development. Poorly ventilated areas can lead to unpredictable growth, and smoke remains one of the primary causes of death in residential fires. Early detection is therefore not optional but really important, yet many homes still do not have enough smoke detector coverage, revealing a persistent gap between known risk and actually implementing protection [146].

Solutions

Technological solutions are increasingly shifting towards automation and early intervention [32, 70]. Automatic suppression devices such as extinguishing stickers activating on temperature operate without electricity and require minimal maintenance, they offer protection in bad to reach technical spaces. In relation to lithium-ion battery risks, off-gas detection technologies can identify early warning signs of thermal runaway minutes before ignition, which enables proactive intervention [70]. However, in the thermal runaway prevention, there is still a lot of opportunity. Cooking safety technologies introduce intelligent heat monitoring and automatic disabling mechanisms, these adress the unattended cooking behaviour dangers.

At the same time, fire protection is evolving and developing through digital integration from IoT-enabled monitoring, predictive analytics and simulation modelling. However, this increase in connectivity also introduces a dependency on digital infrastructure, potentially shifting failure points from physical to systemic.

Personal Safety

Space, Risk and Need

Personal safety is the individual's ability to move around the domestic environment without the fear of risks and dangers. It is highly dependent on the human behaviour and primarily solved through mechanical, systemic and behavioural design.
Personal accidents, however, within the domestic environment, represent a large, underestimated safety issue. Unlike burglary or fire, these incidents are rarely perceived as external threats as they arise from everyday interaction with the space itself. Stairs, furniture, small level differences and routine objects become risk agents, particularly when familiarity leads to reduced attention. The domestic environment is therefore not neutral and passive, yet it continuously interacts with the resident's behaviour.

Falls and trips form the dominant accident category [30, 150, 174]. Stairs remain the most frequent location, followed by small step-ups, beds and temporary climbing solutions such as ladders or stools used during cleaning [8]. Slipping occurs across various surfaces and becomes particularly critical when unstable supports are used [150]. Bumping incidents, for example, against tables, sharp corners, open cabinet doors, represent another recurring injury factor. Cuts and door or window injuries further illustrate that everyday objects carry serious risks.

Age significantly influences vulnerability. Children experience falls from stairs, beds and furniture, as well as poisoning incidents and bump injuries. Adults face stairs related falls, tripping hazards and kitchen-related cuts. Elderly residents show heightened susceptibility to slipping and bed related falls, with more severe consequences due to reduced balance, reaction speed and bone density. The risk exposure may be similar across age groups, but the severity of impact differs substantially.

Solutions

Prevention measures currently rely heavily on behavioural and mechanical solutions. Anti-slip mats, grip foils and anti-slip socks provide low-cost risk mitigation [139]. Stair gates and child rails offer physical barriers, while motion-sensing lighting improves visibility [35]. Protective corner foam reduces injury severity rather than preventing collision. Safety checklists, educational programmes and community-based awareness (e.g. neighbourhood applications) support behavioural adaptation. However, most interventions are reactive and generic rather than predictive and personalised.
A behavioural phenomenon worth noting is perceived invulnerability. Many residents do not install safety measures because they do not expect an accident to happen to them personally. This indicates that subjective safety perception does not always align with objective risk exposure. Routine familiarity with the home reduces alertness, meaning accidents often occur when something in the environment changes unexpectedly like an open cabinet, misplaced object or changed lighting condition.

Night-time movement introduces an interesting vulnerability. Fatigue, reduced visibility and messy hallways increase falling odds. For individuals with night blindness or reduced visual adaptation, orientation becomes more complex. Smart nightlights with motion detection provide a trending response, offering guidance, yet their function remains limited to lighting rather than actual hazard awareness.

Chemical and Gas hazards

Space, Risk and Need

Household chemical and gas hazards represent a category of risk that is largely invisible, slow in development and potentially fatal. Unlike burglary or falls, these dangers often lack immediate sensory feedback. Gas leaks, carbon monoxide (CO) exposure and chemical vapours accumulate silently, meaning detection frequently occurs too late [63, 97]. Safety within this category therefore depends strongly on monitoring and infrastructure integrity rather than behavioural awareness and safety alone.

Recent statistics (2024) indicate 132 accidents involving gas leaks, 11 CO poisonings, 6 explosions and 1 suffocation [136]. Gas installations and boilers form additional high-risk systems. Flue gas discharge pipes that come loose, ageing piping and improper installation increase the likelihood of CO leakage or explosion [138]. Leaving gas on for one hour can fill an entire house, highlighting how rapidly an invisible threat can escalate.

Detection remains the most critical vulnerability. Only 5% of households possess CO detectors, as they are not mandatory [111]. While 58% have some form of detector, incidents are often identified either by activated detectors (44%) or by health symptoms (39%). Detection through physical symptoms indicates that exposure has already reached harmful levels. The statement that "without the right equipment it is difficult to detect any leaks or issues until it is too late" summarises the structural detection gap. CO poisoning is particularly dangerous due to its odourless and colourless nature, leading to slow and unexpected fatalities.

Children and younger residents are particularly vulnerable due to limited awareness of chemical risks [98]. Hobbyists handling chemicals represent another exposure group. Chemical storage practices therefore play a critical role, including separation, childproof access and clear labelling. However, many of these measures rely on consistent behavioural actions.

Solutions

Current solutions focus primarily on detection devices and storage practices. Gas, CO and CO_2 detectors provide direct monitoring [81], while boiler safety depends heavily on professional installation and periodic inspection of piping [60]. Air quality sensors and purifiers are increasingly integrated into consumer products, where monitoring humidity, dust, gas concentration and particles matter [163, 11]. Companies such as IKEA and Dyson offer air filtration systems that combine monitoring with purification, contributing to improved indoor environmental quality [81]. However, these systems often operate independently rather than as part of a holistic safety system.

A key challenge lies in the fragmented nature of chemical safety management. Boiler leakage, battery off-gassing and household chemical storage are typically addressed separately. Yet they share characteristics: invisibility, delayed detection and a systemic infrastructural dependency.

Electrical Hazards

Space, Risk and Need

Electrical hazards are identified by the dangers that arise from electronically connected devices, domestic wiring and other faults that occur due to electrical failure [95]. This category is heavily linked to fire hazards, as a big cause of fires is electrical hazard. However, I have decided to treat this category separately as this danger proposes a rising trend in the increasing energy density of the domestic environment. As this becomes more relevant, I believe it is worth exploring on its own.
Electrical hazards thus remain an increasing risk within domestic environments. In 2023, 770 electrical accidents were recorded, with a notable rise in battery-related and fuse box cabinet incidents [9]. Battery accidents alone accounted for 161 cases, a development closely aligned with the growth in e-bike ownership in the Netherlands (453,000 units sold in 2023). Of the incidents where charging status was known, 72% occurred during charging, while 28% happened spontaneously. This indicates that charging behaviour and faults is a dominant risk moment, but not the only one. Incidents and ignition tend to happen during charging, however a significant portion also occurs elsewhere [48, 172, 175].

Most electrical accidents (65%) have an unknown origin, which highlights a gap within diagnostics in the domestic energy system. Identified causes include short circuits (24%), charger-related failures (21%) and fuse box cabinet overload or overheating (19%) [100, 109]. These numbers suggest that while device faults are relevant, system level strain within the home's electrical infrastructure is equally significant.
Lithium-ion batteries introduce a distinct risk profile. Thermal runaway can lead to rapid fire development, explosion potential and release of toxic gases [169, 171, 173]. Damage through dropping, improper storage or the use of non-certified chargers increases instability. The shift towards electrically powered mobility, particularly e-bikes and similar vehicles, means that high-energy batteries are now stored and charged inside garages, sheds, hallways and living spaces [107]. These areas were not historically designed for high-density energy storage.

Fuse box cabinets represent another critical area of interest. Overload occurs when multiple devices use power simultaneously like washing machines, dryers, dishwashers and electric heaters particularly in combination with solar panel backfeed into the grid. Data shows dryers (56 incidents), ovens and microwaves (47), armatures (34), washing machines (25) and solar panels (24) as recurring contributors.

The integration of renewable systems therefore adds complexity to domestic load management [2].

Solutions

Current prevention strategies focus on both behavioural and infrastructural measures. Battery safety recommendations include ventilated storage, charging supervision, automatic charge management devices and gas detection for early signs of thermal runaway. Electrical system improvements involve installing additional circuit groups, overload protection, smarter fuse configurations and monitoring systems that activate only during abnormal current behaviour. Increased awareness regarding extension cord misuse is also emphasised.

Existing protection mechanisms mostly begin at the circuit breaker level. Residual Current Devices (RCDs), surge protectors and smart switches disconnect circuits during irregularities [46]. More localised solutions, such as socket-based smart switches, monitor individual devices. However, diagnostics of the entire home wiring system remain limited. Services such as Ting offer subscription-based electrical fault detection, analysing grid behaviour and reporting potential fire risks [157]. Such systems rely on connectivity and continuous monitoring, introducing dependency on internet infrastructure.

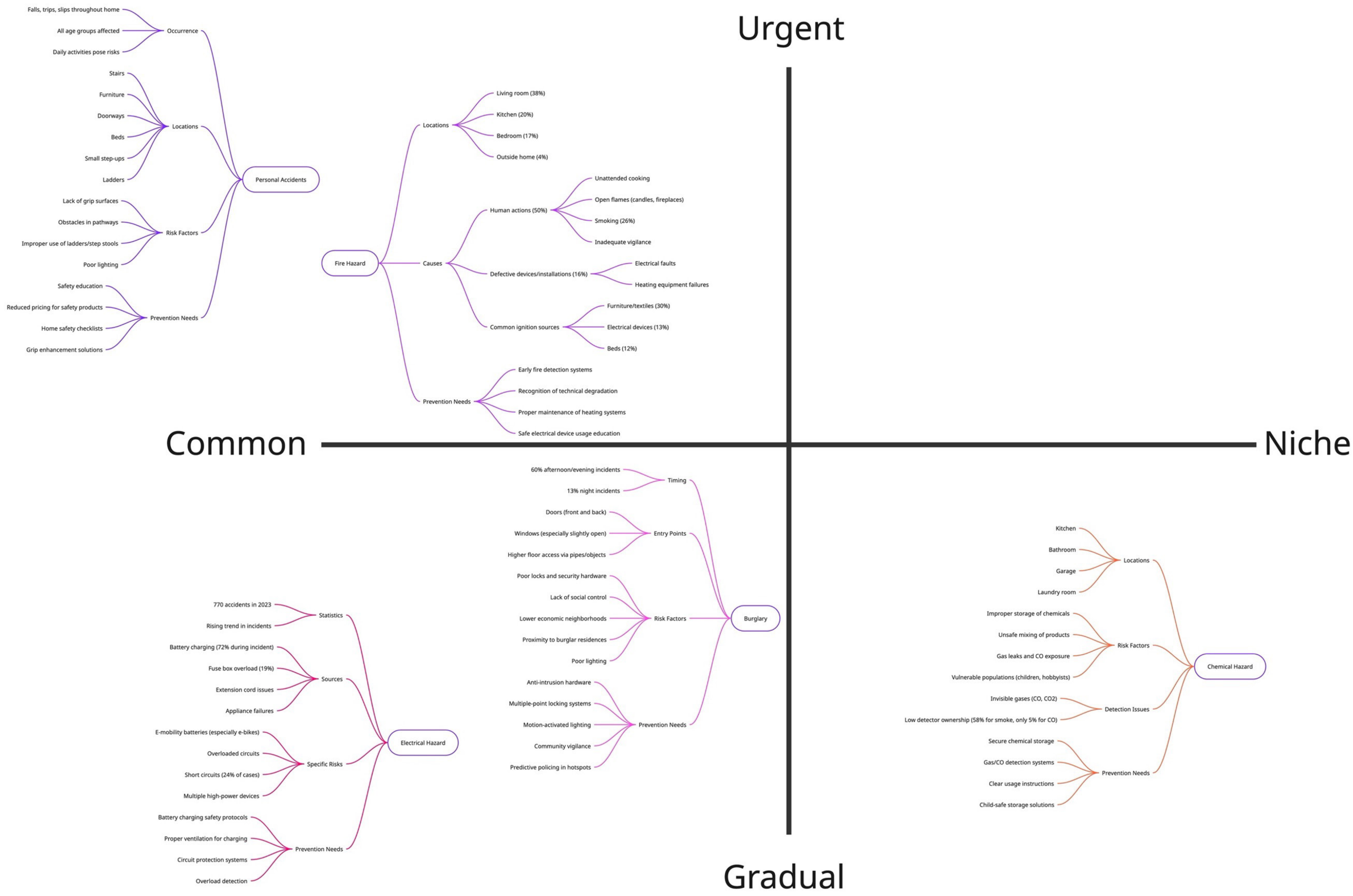


Figure 126: Map of the Five types of safety, left to right: Common vs. Niche, bottom to top: Gradual vs. Urgent

A.2 Sketching the domestic space

Figure 127: Map - Alex

Alex
30 y/o single father with wife, Comes home after work, often mentally tired, attention split (phone, bags, conversation), wants to "switch off"

I come home from work, daily routine until bedtime

Journey Step	Come home from work	Makes comfortable at home	Uses the bathroom	Cooking dinner	Cleaning the house	Relaxing on the couch	Gets ready for bed	Goes to bed	Wake up in the middle of the night to pee	Wake up in the morning
Experience	*Steps out of the car, Walks along the driveway, needs to find keys, enters the house, Might greet wife,* ***might be on the phone, might be carrying laptop bag + groceries.*** "I'm home, I can relax." Slight uncertainty if the house feels "off", lower **situational awareness,** more autopilot	*Takes off shoes and coat in the hallway, puts his key on the cabinet,* ***places his bag near the staircase,*** *puts on flipflops* Wants the home to feel organised and "under control". **If clutter builds up, it creates mild stress and a vague feeling of unsafety**	*Opens the bathroom door, turns on the light, uses the bathroom, tries to find new toilet paper, flushes the toilet*	*In kitchen, gathers ingredients, uses the fridge, cuts the food, cooks the food,* ***takes a call while cooking, uses boiling water,*** *serves food* **Kitchen feels familiar and routine, risks are "normalised".** He may feel confident ("I know how to cook"), even when distracted.	*Kitchen cleans the food, pots and pan, living room uses vacuum cleaner, goes for small spots, uses chair to reach the ceiling, uses a big bucket of water, starts laundry,* ***charges all devices like e bikes,***	*Walks to the living room, walks over the carpet, lies on the couch,* ***turns on the tv, plugs in phone for charging, lights fireplace and candles for vibes,*** *talks to wife, comfort, low awareness*	*Turns off tv, fireplace and candles,* ***walks upstairs, takes of clothes in the hallway,*** *showers in bathroom, brushes teeth* ***and takes off lenses, turns of the lights of the bathroom***	*Walks to the bedroom, closes the blinds,* ***turns off the lights, puts away flipflops,*** *goes to bed,* ***leaves phone in the charger for the night,*** *checks windows and doors, one last kitchen check* Wants closure: "everything is safe; I can sleep." If unsure, he either checks repeatedly (anxious) or avoids checking (false certainty).	*Wake up,* ***find the flipflops, walk in the dark to the bathroom,*** *pee,* ***walk back in the dark,*** *go back to bed*	*Wake up, open the blinds, put on flip flops, go to the bathroom, morning routine, shower, go downstairs ready for the day*
Risk agent	*Slippery driveway, bumping into the driveway,* ***losing keys, curling doormat,*** *rain,* ***entry obstruction,*** *gas smell, fast entry leads to tripping, wet floor,* ***low light, carrying objects block the view,***	*Fall when taking off shoes, losing balance, bumping head into the wall,* ***dropping the coat and tripping, losing the keys behind the cabinet, tripping over the bag later,*** *slipping or tripping over doormat inside or carpet,* ***time pressure, trip hazards***	*Finger stuck between door, bumping knee against toilet, slipping on bathroom floor, cant find new toilet paper, scratch hand or arm against toilet paper holder*	*Bumping against kitchen cabinets, slipping on the kitchen floor, sharp cutlery / knifes cut wound,* ***boiling water, unattended kitchen fires and overflowing water, leaving the hot pans unattended, charging devices near food / water, dangerous boiling water, hot materials,*** *dropping glass,* ***electrical overload or danger from water near socket,*** *poor ventilation, distractions, fatigue*	*Sharp knifes,* ***hot pots and pans, hot water,*** *unstable chair, falling danger, bumping against vacuum cleaner,* ***tripping over wires, vacuum cleaner getting to hot, damaging devices,*** *water damage, slipping danger, time pressure, dryer lint, washing machine leaks,* ***exploding or burning batteries, damaged cables, overnight use***	*Tripping hazard from carpet or cables, bumping into tv stand,* ***fire from defective tv or charging phone, leaving fire unattended, too close to textile, hot tip of lighter left somewhere it can burn other things, leave the tv on, hot tea burns, hot fireplace, forgetting the fireplace or candles*** **"quiet hazards" build (chargers overheating, candle left burning).**	*Still hot fireplace,* ***leaving phone or devices plugged in,*** *slippery stairs, falling from stairs,* ***falling over clothes,*** *slippery bathroom floor, wet bathroom floor, too moist, shower slip, dropping things,* ***not seeing anything without lenses, no lights, darkness, dangerous stair hole***	*Slippery bedroom floor,* ***darkness cant see anything, trip over flip flops, leave phone in charger over night,*** *sharp bed edges, unattended human in case something happens, fireplace left on low, candles still smouldering, did not close the windows or doors, dryer running,* ***overloaded chargers, relying on memory "Im sure its fine"***	***Darkness, fall over flip flops, trip over mess, slippery,*** *cant find toilet paper, sit next to toilet, miss the seat*	*Slippery,* ***exploded phone*** *or bad air circulation, danger to health,* ***slip over stairs, trip down, drop something on the stairs to later fall over***
Preventive system *What systems are used or acted on to prevent the risk*	• Using salt in the winter • Gravel for grip • Recognisable hanger on keychain • Nailing the doormat to the floor • Heavy doormat • Canopy • Habits of locking door, turning on light, smart lights • Smart door lock • Hallway is transition zone where attention is low and mess / clutter is high	• Shoe rack • Shoe horn • Designated bowl for keys or hanging place • Keeping the walkway clear • Putting the bag on the stairs • Anti slip doormat / carpet • Remove carpet • Tape down carpet • General house rules; "keep clear"	• Slow closing doors • Automatic lights, motion detected • Anti slip or with a lot of grip flip flops • Clean bathroom • No sharp edges	• Reminding other the cabinet door is left open • Keeping sharp knifes stored separately • Good ventilation • Heat proof mits • Fire, smoke and heat detectors • Use special tools for boiling water and handeling hot pans, heat proof • Careful approach • Routine behaviour • Fire blanket	• Use dishwashing brush with a long stick • Stable stool for getting to higher places • cleaning tools with long stick for reaching higher places • Wireless vacuum cleaners • Appliance safety feature • Fuses • Lint cleaner	• Anti slip or sticky carpet • Fire smoke and heat detectors • Put the hot lucifer on the box to cool down • Good ventilation for fireplace • Safe wood, good wood •	• Phones automatically stop charging when full • Anti slip strips on stairs • Use carpet on stairs • Good flip flops with grip • Handles for stairs • Moisture detection in bathroom for better ventilation • Good lighting • Automatic lights • Clean hallway with nightlights • A gate before the hallway to prevent accidental slipping.	• Nightlight motion detected • Use smartwatch to detect and alarm in case of cardiac arrest • Smart home to turn off lights or lock doors	• Guiding lights or railings to know where to be and sit	• Fire alarms • Ventilation

Figure 128: Map - Domestic environment

	Hallway	Living Room	Kitchen	Garage	Stairwell and corridor	Bathroom	Bedroom	Study	Cleaning room
The house A two bedroom semi-detached house that is semi modern. I am a house, all my rooms / spaces have separate and unique functions, which means each room has it's own risks.									
Journey Step	**Hallway**	**Living Room**	**Kitchen**	**Garage**	**Stairwell and corridor**	**Bathroom**	**Bedroom**	**Study**	**Cleaning room**
Experience	People enter through the door, **fatigued,** dirty and wet, slippery shoes. Lay they keys in the key bowl, hang their coat, take of their shoes. I have a fuse box with the water pipes and all the electricity, also a fire alarm, there is a bathroom as well. **This is the room where people come home and make a mess,**	People are relaxed, comfortable and have low energy. I have a tv, carpet, tv stand, candles that can be lit, plants, a couch, a fireplace, usually some speakers, **a lot of wallplugs where people charge their phones or lights, a** place for books, drinks, food, guests, busy area	Dangerous place filled with sharp objects, **knifes, hot pans, water boilers, hot water,** cabinets that expand be left open while cooking oor taking out a glass, people make food, eat, **converse, have a laugh, routine behaviour while cooking or simply drinking**, the room next to the outdoors, dinner table, lots of chemicals and medicine are stored.	**Big mess, a lot of random objects, bikes,** workbench, fridge, freezer, **people make stuff here,** store items they dont need anymore, have plants, **scooters or cars stored,** garden equipment, **place to repair items, storage of chemicals, lots of burnable equipment, use it in a hurry or frustrated they cant find anything**	Stairs to go up and down, handbars to keep a hold, sometimes wood, carpet or metal with anti slip, **messy place with many items, place to store things to go upstairs,** place to have a chat, shout things, fire alarm, **leave things to pick up later,** vacuum cleaner, steep drop, **carrying items**	Used for morning and evening routines, showering, taking a bath, brushing teeth, doing make up, weighing, has carpet, toilet, sinks, mirror, **small stool, storage rack, heater,** very moist room, high humidity, very wet, **electrical applications used in wet environment**	Has a bed, clothing storage , nightstand, **nightlights, a chair for clothes**, big curtains, heater, some art, a desk or chair with computer, **place to charge your devices at night, go to pee in the middle of the night, people sleep here are sleepy, vulnerable, change clothes, routine behaviour, just awake, not fully aware.**	A **messy place** with lots of papers, books, a computer, pencils, chair, printer, a carpet, heater. People come here to work, read or study, mostly full alert and ready to focus, are here for a longer period alone, focussed.	A moist, high humidity room with wet clothes and dry clothes, very warm room, chemicals for cleaning, **a dryer and washer that are running for longer periods of times unattended,** i have the boiler and warm water reservoir, sometimes a closet and a basket for dirty clothes. People are here shortly, **but leave unattended**
Risk agent	**Fatigue, carpet edge up high, falling,** fuse box, overheating, water damage, **tripping due to mess, wall plugs,** fire alarm, break in, doorway not secure, cant find the keyhole, cant find keys, **poor lighting**	carpet trip hazard, bumping into couch or tv stand, **lots of wall plugs and charging devices,** fire hazards, lit candles, smouldering lighters, fireplace, textile couches and curtains, hot food or drinks, people peaking inside, break in, **multi plug overload, low lighting**	Sharp objects, **fire hazards open fire, flame in pans, devices charged near water,** bad ventilation, lit candles, break in through back door, sharp cabinets, pointy objects, tripping hazard over chairs or mats, bumping into cabinets or fridge, **oven or microwave malfunction,** ventilation, **high electrical load**	**Tripping hazard due to mess,** sharp dangerous objects, **gasses from vehicles, charging batteries or big vehicles dangerous,** break in, door not locked, falling objects, **chemical dangers,**	Slipping, **falling,** bumping to the walls, losing keys, **tripping over mess, wall sockets things plugged in,** fire alarm, falling down stairs, burning vacuum cleaner, **fast movement, hurry, running**	Slipping, tripping and sliding, bad ventilation, very humid air, **electrocution from wet devices,** falling in shower, wet floor, dropping shower head, drowning, peaking from others, **burning to heater,** soap residu	Dying in bed during sleep with nobody noticing, **tripping or slipping to carpet,** bumping, falling while grabbing the top clothes or cleaning, **exploding devices, fire hazard from charging, not seeing at night, bumping, overload on charging, night time fire** **Overnight risk build-up unnoticed** **Reassurance depends on memory**	**wall sockets, charging devices near burnable materials, heater burns, poor cable management**	**Dryer lint fire hazard, overheating devices,** water damage, gas poisoning, **chemical dangers,** exploding boiler, slipping in water leak, water leak, **burning dryer.**
Preventive system What systems are used or acted on to prevent the risk	• Good lightning • anti slip carpets, tape • smart fuse boxes switches, earth switches • Fire alarm • Anti theft strips or better locks • key bowl, key lights up	• Fire alarms • Place lighters on different spot • surge protecting power strips • dimmers	• First aid kit • Mits • Heat alarms • Anti theft strips, locks • cooker hood • auto turn off	• Fire alarm, • organisation binders, • dedicated storage spaces for parts for easy find • locks for vehicles • Air filters / ventilation system • First aid • Storage cabinets • Special place to store chemicals • Circuit breaker • Concrete floor	• anti slip steps, or tape • sturdy handbars • Protective gate at top of stairs • Nightlights	• Anti slip mats • Humidity control • Ventilation • Good blinds • Devices that handle water well • Bars in shower to hold on to •	• Nightlights • Stable stool to pick up things • Grippy slippers • Good curtains • Big light, automatic • automatic night mode to put devices to sleep • Phone alarm	• Be organised • Fire alarm • power strip • desk lamp	• Dryer lint automatic cleaner • Automated stop when overheating or water leakage • Gas detector • separate storage for chemicals • water proof flooring, anti slip tiles

A.3 Field research

Available Products

The primary products available focus on the five categories defined in Chapter 2. However, analysing the products presents an uneven list of available safety measures. Fire safety is by far the most developed and saturated category, with a wide range of products like extinguishers, fire blankets, and detection devices including smoke, heat, optical and combined carbon monoxide detectors. As well as detectors that can detect multiple hazards at once. This saturation in the market likely reflects both the big demand for these products, the awareness that that brings and the pressure from regulatory parties since most of these products are mandatory by law.

Security and smart systems are a growing section, however still fragmented into both traditional products like cylinders, locks, and window security. And connected smart home alternatives such as smart doorbells, cameras, sirens and smart hubs. These two product lines remain largely separate, you do not see any integrated packages available. To prevent electrical hazards, products like fuse boxes, voltage dimmers and socket protectors are available. Additionally air quality sensors and moisture detection devices are present, yet very limited.

The most interesting category is personal safety, with the available products preventing and protecting falling and slipping with anti-slip sheets, handrails, bathroom grips and bump protection being very mechanical and standard. There is no smart or connected solution there, in contrast to the fire and safety categories.

What strikes me the most is the fragmentation in the setup of the available products, it is very difficult to find exactly where everything is and it is a puzzle to collect all necessary items. It lacks a clear guidance on what is needed and where everything is located. It is missing an Ikea like structure, presenting the full home safety setup for people to understand. Secondly, many items are delivering symptom management after the fact instead of preventing the risk from developing. This is where this design could fill the gap for the available products in the consumer market, putting focus on prevention of development instead of alarming after development.

Symptom Management

Symptom management, as described by George van der Voort [168], refers to the urge within safety design to address observable problems or vulnerabilities without first questioning the systemic conditions that make these issues vital. In section 1.4.5 of his doctoral dissertation, he formulates four fundamental questions that can guide system design: "(1) why is this (part of the) system vital, (2) what can be done to protect the system or diminish its vital position, (3) how can this be achieved, and (4) with what means can it be implemented." However, design often begins with the last questions, selecting the technology and materials that will be used before establishing the critical reasoning. When the first question is not structurally answered, safety measures risk being suboptimal or even dismissive for the longer term [168].

For product design, this perspective from system design is very relevant. Designers often respond to incidents or identified hazards by adding features, warnings, or technological safety, reinforcing the existing system rather than critically looking at and reconsidering the underlying issues. Within the context of domestic IoT systems, additional sensors or alarms may be introduced to mitigate risks, yet the underlying dependency on a single component, behavioural pattern, or spatial configuration may remain unchanged. Structural safety in product design therefore requires moving beyond simply adding sensors towards a reconfiguration of the product–environment interaction.

A.4 Fire department interview analysis

An interview was conducted with the fire department in the Netherlands to gain practical insight into the most worrying and common domestic fire causes and emerging risk trends. Moreover, it was used to explore fire risks, and find interesting design gaps. The interview was conducted over the phone and serves complementary to the desk research findings. Thematic analysis was done to analyse the interview. The following themes emerged as the most relevant insights.

Theme 1: “Roken, Koken en Stoken”

The fire department summarises the three dominant causes of domestic fire as” roken, koken en stoken”, which means smoking, cooking, and heating. They described fires related to cooking through a specific behavioural pattern: residents arriving home, starting a deep fryer or airfryer, and then falling asleep or becoming distracted before the cooking is complete. This results in unattended heat sources escalating into fire. This aligns with the desk research finding that unattended cooking accounts for a substantial portion of domestic fire incidents, but the interview frames it more precisely as a sequence of fatigue, routine, and reduced attention.

Theme 2: Chimney Fires

Chimney fires were highlighted as a big cause to domestic fire incidents, which can be a result of the use of incorrect fuels like painted wood, treated timber, or materials that are not intended for indoor burning, and insufficient cleaning of flue passages. Blockages in the airway caused by soot accumulation create conditions for ignition within the chimney itself, which can then spread to the surrounding structure. These are, according to the fire department, most of the time textile furnitures.

Theme 3: The use of Smoke Detectors

The fire department noted that approximately 85% of households now report having a smoke detector installed, following the 2023 legislation making them mandatory. However, they immediately qualified this by stating that the fire department has no means of verifying what happens behind closed doors. Whether these detectors are correctly installed, still functional, or maintained is entirely unknown. This exposes a gap between what is legally demanded and what is actually covered in the household.

Theme 4: Home Battery Systems

A trend the fire department already foresees as a growing problem is the rise of home battery storage systems. As the electricity grid reaches capacity and residents must pay to feed surplus solar energy back into the grid, more households are choosing to store that energy domestically. They indicated that the fire department anticipates risks in the installation, usage, and increasing density of these battery systems. Battery cells can ignite or explode without warning, and the domestic environment is not designed to contain and handle such events.

Theme 5: Biobased Construction

The development towards sustainable building materials, including straw-based construction as given as example, is growing across new housing developments. The fire department expressed concerns that while these materials meet fire safety requirements on paper, the fire department lacks sufficient real-world data on how biobased structures behave during an actual fire. The materials are combustible by nature, and current firefighting strategies may not be enough and up to date. This introduces a future oriented risk category that is not yet researched a lot in the domestic safety literature.

A.5 General practitioner interview analysis

Interview with a General Practitioner

In understanding the most common personal accidents in the household when it comes to personal safety, an interview was conducted with a general practitioner (GP). When people experience an unsafe situation and have injuries from domestic hazards, the first professional they typically consult is their GP. This positions the general practitioner as a valuable source of information in domestic accidents. Unlike emergency departments, which primarily encounter more severe cases, the GP has a continuous and varied flow of domestic injuries that are significant indicators of recurring risk within the home. The purpose of this interview was to verify and explore the desk research findings on personal accidents, to identify and understand whether certain accidents aree typical or rare compared to reality. The interview was analysed using a thematic analysis, from which four themes were derived. Moreover, a word cloud was created to find the most common topics, in this case kitchen, and thing where very prominent, highlighting the cluttering, messy spaces and kitchen accidents.

From the thematic analysis four themes were derived that together describe the structure of personal safety as observed from practice. Theme 1: Falling is the most common domestic risk. Theme 2: Vulnerability is a major factor for the increase of domestic risks. Theme 3: Cluttering and the home layout are fundamental risk factors. Theme 4: Existing prevention is behavioural and about creating awareness. Each theme is discussed below in relation to the desk research and journey mapping findings.

Theme 1: Falling is the most common domestic risk

The GP described falling as the most frequent, most common, and most urgent domestic risk encountered in the general practice: "Vallen is voor ons de grootste." During periods of illness falls would increase and thus this vulnerability is directly associated with health consequences, including hip fractures and reduced life expectancy. Across multiple spaces falls were noted as the most common, including the bedroom and living room. These spaces align closely with the desk research, which found that falls and trips are the dominant accident category, with stairs as the most frequent location, followed by step-ups, beds, and temporary climbing solutions such as ladders or stools. The first thing the GP associated domestic danger with was falling rather than burns, electrocution or cutting injuries. This told me that fall prevention is the most common and clinically relevant safety domain in the home.

The research further identified that night-time movement introduces additional vulnerability due to fatigue, reduced visibility, and messy hallways [51]. The interview confirmed that injuries sustained during night-time, particularly falls between bedroom and bathroom, are a recurring pattern, especially among older adults and individuals with night blindness.

Theme 2: Vulnerability as a major risk factor

The second theme describes the relationship between risk and vulnerability through illness. The GP described that risk is not only linked to age but equally to physical conditions and physical and mental vulnerability. Examples included residents with ALS, pneumonia, post-cardiac events, and chronic illness, as well as older adults above 80. Moreover, young individuals were also described as vulnerable when chronically ill or medicated. Vulnerability reduces reflexes, balance recovery and injury resistance. This redefines safety from an age-based category towards safety that factors in human conditions and physical resilience, which aligns with the desk research finding that risk exposure may be similar across different age groups, but th e impact differs greatly. Especially for elderly residents, a single fall can have long-term consequences, but the GP made clear that vulnerability, not only age itself, is the biggest variable.

Theme 3: Spatial Layout as a Structural Risk Factor

The GP repeatedly talked about "volle ruimtes" and obstacles in walking routes as directly contributing to fall incidents. Smaller homes, too much furniture, loose rugs, coffee tables with sharp corners, objects blocking graspable surfaces, and unstable step stools were all identified as structural risk factors. Important to highlight, clutter was not described as negligence but as normal domestic behaviour. Residents store items in places that may not be the smartest from a safety perspective, but they do not actively think about the accident potential of their spatial choices. When space is scarce, there is often literally nowhere else to put things. Comfort and practicality therefore conflict with safety optimisation.

This highlights a fundamental tension between realistically living in home and safety logic. The desk research supports this: a space is characterised by behaviour, and residents move, act and do routines within it. Journey mapping showed that risks emerge from behavioural patterns, repetition of actions, and interactions between residents and the physical characteristics of the space. A chair used as a step, a wet floor after showering, a cluttered hallway walked by in the dark, these are not unique activities but predictable outcomes of normal human behaviour in familiar environments.

Theme 4: Current prevention methods are about Behaviour and Awareness

The GP talked about and confirmed that the current preventive measures rely heavily on ergotherapy, behavioural advice and the creation of awareness. The primary prevention method is ergotherapy, of which three hours are reimbursed annually, only this happens after the incident. Ergotherapists visit the home, assess spatial risks, and advise on interventions: removing rugs, replacing wheeled chairs with stable dining chairs, adjusting rollators, and clearing walking routes. The GP also identified vision as the most common cause of personal accidents. People do not see how dangerous it can be when their vision is insufficient to judge distances and obstacles accurately. Vision checks were therefore described as the first assessment made when accidents occur.

The desk research and field study to the hardware stores backs this idea up. Anti-slip mats, grip foils, stair gates, motion-sensing lighting, and protective corner foam represent the landscape of safety products, alongside safety checklists and awareness initiatives. These solutions share two main factors, they are general and mechanical, changing and viewing the environment through passive modification without adapting to individual conditions. And they are reactive, most responses often occurs after a fall has already happened, aimed at preventing repetition rather than the initial incident. The thematic analysis further revealed that awareness campaigns alone are not enough; repeated government campaigns do not completely eliminate injuries, there is still the human behaviour.

Behavioural theme

A clear thread running through all four themes is that the vast majority of domestic personal accidents are caused by human behaviour. Human influence research shows that fatigue, distraction, and routine behaviour increase the likelihood of domestic accidents [51]. The effects of alcohol further compound this, impairing balance, coordination, vision and reflexes [18]. The GP confirmed this from the clinical side, the injuries she treats are mostly the result of routine actions gone wrong. People trip over objects they placed themselves and fall on stairs they have walked thousands of times. The common factor is not a dangerous space, but a dangerous moment within a familiar space, where attention or coordination temporarily is not in line with the activity. The domestic environment, exactly because it is familiar, is one in which people systematically and unaware underestimate risk.

A.6 Lotus diagram

The eight explored directions and their key outcomes are summarised below.

Messy Garages, or Working in the Garage

The garage presented itself as a space where residents are less cautious, where e-bikes and scooters are charged unattended, and where the direct connection to the house creates a pathway of escalation into the living environment. This direction highlighted all three themes: devices are placed in varying positions (yellow), charging occurs without oversight (blue), and thermal risks from batteries are invisible (red). The convergence makes the garage one of the strongest spatial contexts identified.

Kitchen Fires

Fires related to the Kitchen area brings ideas centred on appliances left running without supervision like airfryers or deep fryers. Moreover, alongside pan fires, hot liquid spills and poor ventilation. The blue and red theme were strong on this area, while yellow was less dominant. Kitchen appliances generally operate from fixed positions, but the timing of overheating is unpredictable. This suggests that relevant monitoring in the kitchen is very time based rather than spatial, it is more about tracking rate of thermal change over time rather than scanning for the location of a heat source.

Houses Built from Bio-Based and New Materials

This direction explored the unknown fire behaviour of new building materials. Ideas were largely framed as uncertainties instead of documented risks, making it the most exploratory cluster. Its results are not a specific risk that I can address, but more a principle: if material compositions are changing and their fire behaviour is not yet fully characterised, a system that monitors thermal conditions independently of material assumptions becomes more relevant. It supports the argument for a material or spatial focussed detection approach.

Battery and Accumulator Ignition

The most data focussed direction. Ideas in this topic addressed thermal runaway, gradual temperature rise before ignition, pressure build-up, production faults and non-ideal storage environments. This direction covered all three themes really well, batteries are charged in varying locations (yellow), charging is routinely unsupervised (blue), and the thermal trajectory preceding ignition is invisible (red). The pattern that is identified here is a gradual, detectable thermal signature that happens before failure. It points strongly towards continuous, real-time sensing that tracks rate of change as a viable intervention method.

Fireplace and Chimney Fires

Ideas included dirty chimneys, invisible fire development inside chimneys, sparks, flammable materials nearby and leaving it unattended overnight. The blue and red theme are well covered by chimney fires, yet the yellow them less, given the fixed position of fireplaces. A relevant finding that needs addressing is that fireplaces involve intentional high temperatures. This means that any monitoring system would need to distinguish between normal heat generation and abnormal escalation. This would require a detailed contextual interpretation rather than simple threshold detection.

Smoking and Smoke Hazards

Smouldering cigarette buds on textiles, ashes, cigarettes in waste bins, vape and e-cigarette charging, and air quality. While smoking is statistically a dominant fire cause, the heat signature of a smouldering cigarette is small and very local, which leads me to wonder about detection feasibility at room scale. Especially in a busy, cluttered and covered room. However, the vape charging idea connects back to battery ignition (direction 4), reinforcing the approach to thermal runaway as a more holistic idea.

Feedback to the User

This direction described human interaction requirements rather than a risk category. Colour-coded status, simple nudging, direct alerts when risk is forming, phone-based accessibility from anywhere, and motivating behavioural awareness were emerging ideas. This direction formed because every other direction raised the same underlying question: how does the resident know what is happening? The ideas point towards a more actionable communication built around proportional feedback, it needs to be calibrated to risk level and accessible regardless of whether the resident is at home or away.

Charger and Charging Fires

Different from direction 4 by focusing on the charging infrastructure rather than the battery itself. This area addressed non-certified chargers, invisible wiring faults, unsafe charging environments, devices left connected for extended periods, and the spatial mobility that wire-based charging brings. A device can be charged anywhere within cable reach, creating a new challenge of where the phone at the time of charging in proportion to the sensor is. This direction touched on all three themes and reinforces the argument for spatial thermal monitoring

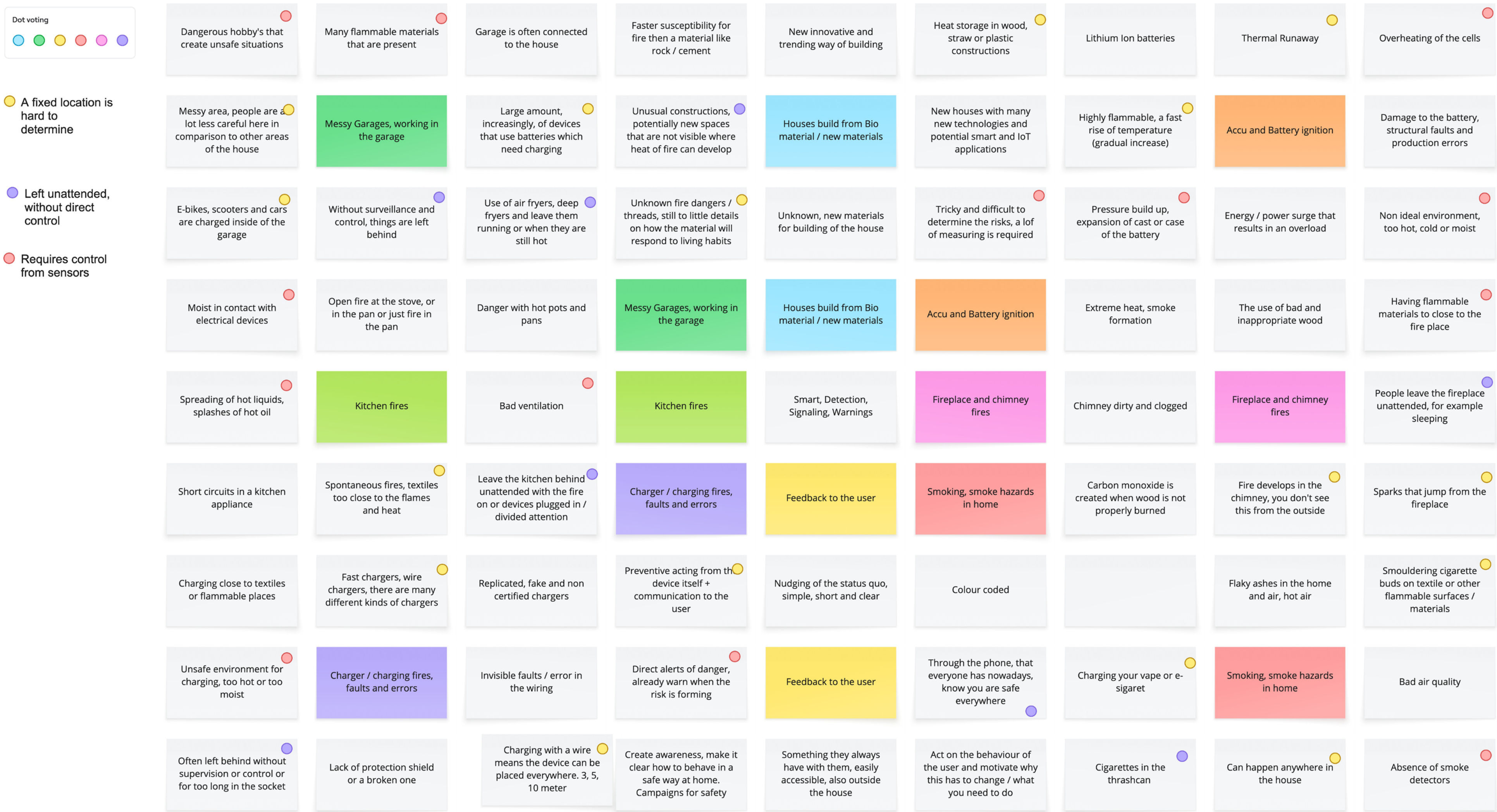


Figure 129: Lotus Diagram with dot voting full screen

A.7 Trend analysis

The identified trends are structured across three sections of relevance. Trends that are in direct connection with the technological and behavioural needs for these directions. Supporting trends that provide contextual benefits and information that strengthen the direction's feasibility or expand its potential. Adjacent developments create interesting ideas and technologies from related domains, but are not explicitly connected to the domestic context.

Directly Enabling Trends

AI-Driven Adaptive Systems

The most significant trend that I identified is the transformation of the home from a passive space with added technology towards an adaptive, context-aware system. Instead of responding to simple commands, AI-powered domestic systems increasingly learn from the residents behaviour patterns, interpret activities and anticipate needs. This indicates a shift from rule-based automation, where predefined static commands produce predefined responses, to learning-driven adaptation, where the system develops an understanding of normal conditions and responds to deviations from those conditions [147]. This shift is directly relevant to the proposed directions and definition of Safety, which depends on contextual interpretation of data and understanding behavioural anomalies.

The trends show a pattern that emerges beyond convenience and comfert, AI-powered systems can intelligently analyse energy consumption to predict peak usage and optimise electrical loads in advance [147]. Within the context of domestic fire prevention, this predictive ability is essential. The interpretation layer, which distinguishes between a normal conditions and a device approaching a critical threshold, is exactly what requires this type of pattern recognition. A system that learns that an airfryer typically reaches 180°C during a 20-minute cycle can differentiate that from an abnormal rise that deviates from the usual pattern. Pluralsight [123] introduces the broader framework of Adaptive Predictive Artificial Intelligence (APAI), describing systems that autonomously manage energy grids and predict failures through specific interventions. While the term comes from industrial and healthcare contexts, the underlying logic, predicting problems before they manifest and intervening proactively, connects directly to the detection, interpretation, communication, intervention order that defines these directions.

Additionally, transparency and trust are important when talking new technologies. The integration of conversational AI interfaces enables residents to ask why something happened within their home, receive a clear actionablee explanation and control the behaviour when needed [147]. This transparency and clear language, understandable by the resident, is essential for the communication layer. A system that alerts a resident to a developing anomaly must be able to explain what it detected, why it considers the pattern abnormal and what action it is taking. Without this explanatory capacity, the system risks being perceived as unreliable, which would undermine the subjective safety.

Collaborative Sensing and Data Sharing

The World Economic Forum's Top 10 Emerging Technologies of 2025 report identifies collaborative sensing as a major development [176]. Connected systems strong enough to make context-aware decisions by sharing data across devices. Instead of sensors operating individually, where each monitors a single parameter within a single confined space. Collaborative sensing enables a network of inputs to produce a shared situational understanding.

Applied to the domestic context, this means that a lighting sensor's occupancy data can inform whether a space is supervised, a smart plug can determine whether a device genuinely needs power, and a thermal sensor's readings can be interpreted against the behavioural context of the household. The implications for the proposed directions are of great significance, as this spatial awareness can create a difference in understanding between an empty dark room and an occupied light room. A charging e-bike in a garage where no one is present represents a different risk profile than a laptop charging on a desk where someone is working. Collaborative sensing provides the contextual layer that enables this differentiation.

This trend also strenghtens the spatial logic, which follows the device rather than the room. If sensors throughout the home share context, the system can track where unsafe scenarios are present and where human presence is absent, dynamically adjusting its risk assessment as conditions change. A single nightlight motion sensor, that was originally installed for convenience, can thus contribute to safety by informing the broader system about movement patterns and room occupancy.

Escalating Battery Risk

The lithium-ion batteries in consumer products has introduced a rapidly growing category of domestic thermal risk. Data from Netbeheer Nederland [100] records 161 battery-related accidents in 2023, which is likely correlated with the rise in e-bike ownership (453,000 units sold that year). Of the incidents where the charging status could be determined, 72% occurred during charging. This positions charging behaviour as a dominant risk moment within the domestic environment.
This trend is supportedd by a pattern of product recalls across the industry. In recent years, recalls have affected vehicles [19], folding e-bikes [5], and portable power banks [162]. Fire brigade data from Utrecht indicates approximately 20 callouts per year specifically for e-bike battery fires, with a rising trend [137]. These are not individual manufacturing defects, moreover, they reflect a systemic increase in domestic energy density without a corresponding increase in domestic safety infrastructure.

An interesting reason for this is the shift in how chargers are handled. Manufacturers increasingly ship devices without chargers for sustainability objectives. This makes consumers turn towards aftermarket chargers, many of which are uncertified, badly tested for the current loads required by fast-charging protocols. These are sold through discount retailers or directly from overseas suppliers. These chargers may lack the safety mechanisms required to prevent overheating, short-circuiting or thermal runaway, especially when they are connected to multiple devices simultaneously. The common assumption that safety is guaranteed by default is increasingly unreliable and undermined by falsely certified technology. This behavioural and market related risk arguments for the need of a system in the domestic environment that monitors thermal conditions independently of safety claims.

Emerging research also focus on new detection methods, for example Bright.nl [27] reports on AI-based acoustic detection that can identify the sound signature of a lithium-ion battery approaching thermal runaway, while TW.nl [161] describes self-extinguishing battery technology that suppresses thermal events before external ignition. Both developments adress that the window for intervention before ignition is not only detectable but actively being researched over multiple sensing methods like thermal, acoustic and chemical.

Supporting Trends

Devices Working Together

The Matter protocol, developed by the Connectivity Standards Alliance, establishes a unified communication standard that enables devices from different manufacturers to connect within a single system [34]. Products such as Yale's smart home security range already operate on this standard [177]. For this study, interoperability is very interesting, lets say a thermal sensor from one manufacturer must be able to instruct a smart plug from another to disconnect power. Interoperability is then essential for its functionality, Matter addresses this extra layer of connectivity. However, connectivity and intelligence are separate things that should both be adressed equally, Matter enables devices to communicate, yet it does not determine what they should do. This study therefore depends on both a unified protocol and an AI-driven interpretation layer operating above it.

Predictive Maintenance

Predictive maintenance, using real-time sensor data and AI to predict equipment failure, is an important industrial practice [142]. The ICL Group describes continuous AI-driven monitoring that minimises disruptions and enhances reliability [80]. StartUs Insights [151] identifies it as a primary IoT use case, while Suricat [153] captures the shift as moving from passive monitoring to active management. The logic transfers directly to the proposed directions: monitoring the standard situation, detecting deviations and intervening before failure or accidents. However, the domestic environment lacks that it is a controlled context like in industrial settings where standardised equipment and professional oversight is used. The system therefore demands that the product is self-calibrating, easy to use and low-maintenance.

Adjacent Developments

Two adjacent developments offer valuable principles that can be used in the domestic context, without being directly applicable. In emergency response, thermal 360-degree throwable cameras [24], HUD systems that enable firefighters to see through smoke [37, 164], and sensor-based threat detection through walls [14] demonstrate that thermal sensing can be made compact, real-time and spatially aware. The framing of such systems as teammates rather than tools [14] resonates with the direction's ambition to create a system that assists rather than controls.
Separately, Nexans [101] highlights the hidden risk of the electrical infrastructure, he notes that cable density continues to increase with new energy usages while remaining invisible to residents. As domestic loads grow through e-bike charging, solar panel backfeed and high-consumption appliances, the strain on wiring that was not designed for these demands intensifies. This reinforces the argument that domestic fire risk extends beyond visible devices to the hidden infrastructure that connects and powers them.

APPENDIX B: 11 Problem directions

I created 11 opportunity directions that each describe the space, target group and what kind of risk is predicted within this context. Moreover, I briefly describe what kind of safety is provided.

11 Directions

1. Biobased material housing, fire safety.

Newer homes constructed with biobased materials introduce a new fire risk due to the unpredictable thermal and combustion behaviour of these materials. Residents are typically younger adults or starters, sustainability-oriented, and more likely to have solar panel installations with home battery storage, which adds electrical and thermal risk to an already uncertain and new material environment. The space is the structural interior of the home itself. Safety requires both predictive monitoring of material behaviour under thermal stress and awareness of the risks introduced by high density energy systems within these new bio-based constructions.

2. Home battery for solar energy storage, fire safety.

Homes with solar panel installations use battery systems to store energy. These batteries bring big thermal and electrical risk when improperly installed, overcharged or degraded over time. The space concerns areas where these home batteries are stored and charged, this could be in garages, utility rooms and sheds, and is often without continuous supervision. Residents are homeowners investing in energy independence. Safety in this direction addresses both risk through detection of abnormal thermal and electrical behaviour, and subjective safety through awareness of an invisible danger.

3. Night routine, personal safety.

The spaces in and around the bedroom, like the hallway, stairs and bathrooms, become high-risk environments during night and early morning routines. Residents are barely awake, fatigued or suffering from reduced visual adaptation, which can result in a decreased spatial awareness and slower reaction times. Falls, trips and collisions with furniture, open doors or misplaced objects are common in these conditions, with poor lighting consistently identified as a contributing factor. The target group is adults living together, where nightly movement patterns vary and one person's actions may introduce hazards for another. Safety in this direction is about the prediction and detection of spatial irregularities like misplaced objects, open cabinets and cluttered pathways. Combining this with adaptive guidance that illuminates risks as they become relevant, directing the resident through the space rather than simply lighting it.

4. Kitchen fires, fire safety.

The kitchen remains one of the most dangerous spaces in the home. Cooking introduces open flames, hot surfaces, overheated oil and appliances working at high temperatures. Moreover, it is the risks that escalate when attention is divided. Conversations with others, fatigue or multitasking reduce active awareness of what is happening in the kitchen, allowing unattended risks to develop. The target group is adults sharing the domestic environment, where social interaction in and around the kitchen diverts attention from risk sources. Safety in this direction concerns the detection of developing thermal risk during cooking due to rising temperatures, unattended appliances or proximity of combustible materials. Besides it is about timely communication to the resident before the situation escalates.

5. Tripping, falling and tripping in the entrance hall, personal safety.

The entrance hall is a transitional space where residents arrive and leave, often in a rush, carrying bags, packages or other objects. Items are dropped, stacked or placed temporarily, this creates an accumulating mess that introduces tripping and falling hazards for the next person passing through. The target group is adults living together, where one person's behaviour directly creates risk for another. In this direction, safety is about the recognition of behavioural patterns and spatial clutter that develop into these hazards, about predicting when objects obstruct pathways or when routines create risk. And communicating this to the resident in the way a housemate would, using a timely, natural prompt to watch out or be careful before something goes wrong.

6. General safety in the garage due to spatial clutter, personal and fire safety.

The garage is another one of the most high risk spaces in the domestic environment. It is used as a workspace for hobbies and maintenance activities that produce dust, chemical vapours and heat, which are all potential fire contributors. Flammable materials, solvents, paints and fuels are often stored nearby, which makes this space even more dangerous. Additionally, vehicles, e-bikes, power tools and other battery-powered devices are charged and stored here, introducing an even higher thermal and electrical risk in a space that typically lacks supervision, ventilation and adequate detection. The mess and chaos common to garages further adds to the hazard.

The target group is adults who use the garage for storage, charging and manual work, often without awareness of the growing risk their behaviour introduces. Safety concerns the identification of fire risks, thermal and spatial hazards within a single messy space, detecting conditions as they develop rather than responding after ignition or injury.

7. Chimney fires due to improper cleaning / usage, fire safety.

The highest percentage of domestic fire incidents happen in the living room, with the chimney as a major cause. Soot buildup from poor maintenance, the use of unsuitable or wet firewood and leaving fires unattended are the most common causes. Residents underestimate the effect of neglected cleaning and improper fuel, allowing conditions to develop that lead to chimney fires. The target group is adults with wood-burning fireplaces or stoves, where the routine of lighting a fire becomes so natural and normal that the risks aren't even considered. The detection of decreasing chimney conditions like soot accumulation, abnormal flue temperatures, poor combustion patterns from inadequate firewood are important in understanding how to make it safer. And communicating this to the resident before a chimney fire develops. The primary challenge is the environment itself in which the risk forms, extreme heat and open flames make sensing and intervention technically challenging.

8. Electrical vehicles, batteries or electrically charged devices, electrical / fire safety.

Garages, hallways, sheds and utility rooms, all spaces where batteries are stored and charged. These form domestic spaces that were never designed for this type of high-density energy storage and safety. E-bikes, scooters, power tools and portable devices are increasingly charged in these areas, often simultaneously and without supervision. The target group is urban households with light electric vehicles and multiple battery-powered devices, particularly adults living together with combined charging behaviour that stress the electrical load. This risk increases further in homes with solar panel installations and battery storage systems, where backfeed and peak consumption place additional strain on domestic infrastructure not built for these demands. Safety is firstly addressed by the risk of electrical fires, thermal runaway and toxic gas release from battery failure, and secondly by the systemic overload of fuse boxes and wiring when multiple high-consumption devices operate at once. Even more dangerous is that the hazard is largely invisible: batteries degrade silently, overload builds incrementally, and failure develops without humans being able to perceive it.

9. Indoor microclimate control, chemical / personal safety.

The living room and bedroom are continuously exposed to bad air as these are environments where residents spend majority of their time. In these spaces, risks build slowly rather than appear instantly. Poor ventilation, humidity imbalance, particulate matter and invisible pollutants gradually affect health and sleep quality, that is a problem that is increasingly occuring in well-insulated modern homes where air exchange is deliberately minimised. The target group is adults, particularly in newer or renovated housing with high insulation standards. Safety is about the detection of deteriorating air quality over time like CO_2 buildup, humidity fluctuation, volatile organic compounds, and making that invisible exposure visible to the resident, improving both objective environmental safety and the subjective feeling of breathing safely within their own home.

10. Smoking risks, fire safety.

Fire incidents caused by smoking are still, despite the decrease in smoking in the Netherlands, a common cause for fires. Hot cigarette ends in contact with textiles like couches, curtains, cushions, or smouldering butts left on wooden surfaces or near other combustible materials create conditions for slow-developing fires that often go undetected until escalation. Even though fire can develop rapidly, the smoker will not notice a small scent of smoke amongst the already existing smoke. The target group is adults who smoke indoors, where a smouldering cigarette may be left unattended when attention shifts or the smoker falls asleep. In this direction it is important to detect the smouldering heat sources early on or near combustible surfaces and provide active intervention before ignition develops.

11. The entry of the house as a HUB for safety, safety check, home network control, fire, personal and electrical safety.

The hallway is the transitional hub of the home, the last space before departure, the first space upon return. It is where residents instinctively perform a final check: keys, wallet, weather, windows closed, doors locked. But this check is limited to what is visible and remembered. Unseen risks; appliances left on, devices still charging, an airfryer running in an empty kitchen or batteries connected overnight, fall outside that routine assessment. The target group is adults living together, where shared responsibility for the home creates uncertainty about what the other person did or did not switch off. Safety in this direction does not target a single hazard category but addresses the moment of transition itself. Upon departure, the system provides a spatial summary, a house check that confirms whether conditions across all rooms are safe. Or it flags a space that requires attention. Upon return, it communicates how the home has been in the resident's absence. This direction connects with the increasing density of electrical appliances, the human error and the need for certainty and control that the home is safe when no one is watching or home.

APPENDIX C: Sensor analysis

There are two main type of sensor methods when it comes to temperature sensing: contact and non-contact. The contact sensor methods rely heavily on surface temperature, the temperature difference between material and surrounding air, resistance and voltage measurements. Non-contact sensors utilise the radiation and emissions of the heat source to detect heat patterns and map them using point values. I will go into detail of both methods describing the most common and relevant sensors used in the world of temperature sensing.

Contact sensors

This type of sensing derives temperature by achieving thermal equilibrium with the medium, it has a direct conduction from the heat source. In this case that would be the surface of the device or direct contact too the battery casing. The surface and the sensor seek equilibrium, and through measurable physical properties; voltage, resistance, expansion or wavelength shift, it converts it into temperature.

Thermocouple

These types of sensors rely on the Seebeck Effect basics, named after the discoverer Thomas Johann Seebeck [47]. The difference between two surfaces or metals generates an electrical current (Voltage), which is used for a thermocouple [4, 154]. The device can then interpret the voltage change to derive the according temperature change [86]. Thermocouples may not be as accurate as resistive temperature detectors (RTDs), however, they are much more cost-effective and have an extensive temperature range (-200°C – 1750°C) [17]. For the application purpose of the domestic environment and the fact that the detectable temperature range would like to be between 0°C and 300°C before total ignition, this is more than sufficient. Moreover, thermocouple sensors have a fast response speed, the ability to measure small targets and can be used for easy processing and analysis of temperature information [85].

Resistant Temperature Detectors (RTDs)

Resistant Temperature Detectors operate on the basis that electrical resistance of a conductor increases consistently and proportionally to the increasing temperature [42, 85]. A change in each can accurately detect temperature.

It works by measuring the predictable change in resistance of metals like platinum. They are more accurate and stable over time than NTCs, and much more linear, which simplifies signal processing. However, they are more expensive, slower to respond, and less sensitive to small temperature changes compared to NTC thermistors, especially in the narrow range relevant to battery monitoring.

Fibre Optic Sensors

Fibre optic sensors operate by measuring temperature using principles of wavelength shift, scattering or fluorescent decay [154]. Their advantage is that they show to be immune to lightning and high-voltage interference, making them more suitable for environments where the metal sensors cannot be used due to electrical sensitivity.

IC Temperature Sensors

It is a semiconductor based electronic device that measures temperature using the physical properties of transistors, especially the dependence of voltage on temperature. This sensor typically measures within a range of -55°C to 130°C [152, 154]. The most common applications are on circuit boards, computers and consumer electronics [17]. They are small and accurate, but have a smaller, less suitable range for this application.

Negative Temperature Coefficient (NTC) Thermistor

A sensitive temperature sensor that reacts to very small temperature changes, providing high accuracy. The range is -50°C to 150°C, with a maximum of 250°C for encapsulated thermistors, which is just enough for the domestic environment with the application for rechargeable batteries, beyond that point it is irreversible, so measuring does not matter, alarming does [12]. It does require linearization.

A thermistor is a temperature sensing device made of semiconductor materials that have been sintered to display large changes in resistance, in proportion to small changes in temperature. Using a small and measured direct current, send through the thermistor and measuring the voltage drop, the resistance can be measured. The NTC thermistor specifically is a non-linear resistor, which change their resistive characteristics with temperature change. The resistance of the NTC decreases as the temperature increases [12].

Heat Flux Sensor

These sensors measure radiative and/or conductive heat transfer based on Gardon and Schmidt-Boelter principles, normally used for aerospace testing and fire-safety analysis. A heat flux sensor is an instrument used to measure the rate of heat energy transfer per unit area [61]. It is a transducer which generates electrical signal (output voltage) which will be proportional to this measure of heat rate. The sensor can measure all three forms of heat transfer, conductive, convective, and radiative heat transfer, on the surface or from the surface of a body [91].

A heat flux or thermal flux is the amount of heat energy passing through a certain surface. In a clothing system a heat flux sensor can provide information on the heat exchange between the body and the environment and thus give direct input to improve the thermal comfort of the garment [45]. This can also be useful when measuring the heat exchange between the battery and the battery casing. Heat Flux sensors come with different materials, each having their own typical operation range [91]. The most interesting for this application would be Polyimide foil heat flux sensors, with an operating temperature range between -70°C and 250°C continuous use [79].

Non-Contact Temperature Sensing

These non-contact sensors derive temperature by analysing emitted infrared radiation. These contactless sensors provide the benefit of being able to measure from a distant. With moving objects this can be a benefit, especially in the domestic environment where people move things around, are in a hurry or things get left in new places. This can be very susceptible to human behaviour and human errors. There are two main sensing techniques when it comes to non-contact sensing, thermal imaging and infrared. These two principles cover most of the sensors that are relevant for this application.

Thermal Imaging Cameras

Thermal cameras create a two-dimensional thermal map that have thousands of temperature points. These points change in value at the same time, creating a 2D representation of the space with the according temperature values [118]. This can be used to predict energy spots, detect hot-spots and monitor devices in real time [114]. It captures infrared radiation (energy also known as heat) emitted by objects and converts it into a visible image. It visualises thermal energy, and more interestingly, everything we know radiates thermal energy.

In industrial applications, thermal cameras can help scan equipment and these heat maps can help identify whether the machinery needs repairs or is approaching failure. Linking this to the domestic environment, it can be used to detect battery failure, which is what I want to detect before it starts the thermal runaway. The display of the camera can, with the right software, show overheating scenario's and detect irregular patterns and hot spots [43, 114]. A wide-angle field of view camera is required to accurately detect the required area as the accuracy of the device is dependent on the setup. A reading is only accurate when the resident properly fills the sensor's field of view under stable conditions, which, in a messy household, can be a challenge.

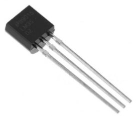
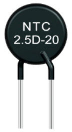
Infrared (IR) Temperature sensors

IR sensors detect radiation emitted by light, outlining objects based on the intensity of the radiation [3, 41]. They measure the strength of the radiant heat to determine the temperature. They can be grouped into three radiation sensors; total radiation sensors, which integrate energy across a broad wavelength range; wide- or narrow-band sensors, which focus on selected wavelength ranges for improved stability; and single-wavelength (one-color) pyrometers, which estimate temperature from radiation at a specific wavelength assuming emissivity is known [3]. Their accuracy depends heavily on surface emissivity and measurement conditions, which makes them sensitive to material, angle, and environmental changes [85, 124]. This is why wide-band IR sensors are the most used in practical applications, as they provide a good balance between cost, robustness, and reliability.

Both Thermal imaging and IR sensors are heavily dependent on the emissivity of the surface, the angle of the surface, and the position of the measurable surface in the sensors field of view. Shiny, reflective, textured, dirty or changing battery housings can disrupt the readings, making it less accurate and reliable.

Table 9: Sensor comparison Table

Contact sensors

Sensor	Image	How does it work?	Range & Accuracy	Pros & Cons
Thermocouple	 [134]	Voltage from two different metals (Seebeck Effect) [47].	−200 °C to +1750 °C [17]. Moderate accuracy.	**Pros:** Cheap, wide range, fast response, low power usage. **Cons:** Less accurate than RTDs.
Resistance Temperature Detectors	 [135]	Predictable change in resistance proportional to the increasing temperature [85].	≈ −200 °C to +850 °C [42]. High accuracy.	**Pros:** Accurate, stable over time and a linear signal. **Cons:** Expensive, slow response.
Integrated Circuit temperature sensor	 [148]	Transistor voltage and temperature dependence. PCB-mounted [152, 154].	−55 °C to +130 °C [152, 154]. Moderate accuracy.	**Pros:** Small, accurate and cheap. **Cons:** Upper limit too low to cover thermal runaway escalation.
Negative Temperature Coefficient thermistor	 [83]	Resistance decreases as temperature rises [12].	−50 °C to +150 °C, up to +250 °C encapsulated [12]. High accuracy.	**Pros:** High sensitivity, cheap and small. **Cons:** Non-linear (requires linearisation).
Heat flux sensor	 [22]	Radiative or conductive heat transfer (Gardon and Schmidt-Boelter principles) [61].	−70 °C to +250 °C [79, 91]. Moderate accuracy.	**Pros:** Can measure all three forms of heat transfer. **Cons:** Needs calibration and measures flux, not absolute temperature.

Non-contact sensors

Sensor	Image	How does it work?	Range & Accuracy	Pros % Cons
Thermal imaging camera	 [54]	2D thermal map of thousands of temperature points captured by infrared radiation [114, 118].	Setup- and emissivity-dependent.	**Pros:** Contactless, mobile use case, visualises hot-spots. **Cons:** Needs a wide FOV for domestic use, emissivity-sensitive, expensive.
IR temperature sensor	 [82]	Point measurement of emitted radiation [3, 41].	Emissivity- and angle-dependent [85, 124].	**Pros:** Contactless, fast, robust. **Cons:** Emissivity- and angle-dependent, single-point misses hot-spots.

APPENDIX D: Power consumption

The power consumption of the system was estimated using Nordic's Online Power Profiler (OPP) for LTE [*]. Two simulations were run, one for the daily heartbeat event of 24 hours and one for a TAU of 1 hour. The settings and results are listed in Table 10.

Table 10: OPP simulation settings and results.

Parameter	24 Hour TAU	1 Hour TAU
General		
Chip	nRF9160 rev1	nRF9160 rev1
Supply voltage	3.7 V	3.7 V
PSM		
Periodic TAU	24 hours	60 min
Periodic TAU timer element	"00000110"	"00000110"
Active time timer element	"00000000"	"00000000"
RRC connected mode		
Data upload interval	24 hours	5 hours
Data upload charge	1.97 mC	1.97 mC
cDRX average current	6.32 mA	6.32 mA
cDRX charge	30.32 mC	30.32 mC
Connection management charge	28.08 mC	28.08 mC
Total event charge (radio cycle)	30.05 mC	30.29 mC
Output		
LTE event total charge	123.07 mC	121.50 mC
PSM floor current	4.0 µA	4.0 µA
Total average current	5.42 µA	37.75 µA

The two simulations represent two different intervals for the network configuration. The 60-minute case shows the standard interval that operators normally give, the 24-hour case shows a longer PSM, which the network can grant under a custom IoT subscription that could be offered by Alprokon. The 60-minute case returns a total average current of 37.75 µA, the 24-hour case returns 5.42 µA, this is a factor of seven difference.

For the headline calculation I take the 24-hour TAU scenario as the operation target. The 60-minute case is used as a control check.

The data upload itself adds only ~2 mC per event, which is negligible against the ~123 mC LTE event total. For the rest of the calculation the heartbeat and alert events are therefore treated as a single LTE event type, with 12 alerts per year added on top of the daily heartbeat already captured in the OPP's average.

Energy per event (C to Ah):

123 mC ÷ 3.6 = 34.2 µAh per event

Annual energy draw, assuming 12 events per year with the device in continuous PSM sleep in between:

Table 11: Anual draw per component

Component	Calculation	Annual draw
Total average current	5.42 µA × 8 760 h	≈ 47.5 mAh/yr
Alerts (12 events)	12 × 34.2 µAh	≈ 0.4 mAh/yr
Active total		≈ 48 mAh/yr
Self-discharge	2% × 2500 mAh × 12 months	≈ 600 mAh/yr
Grand total		≈ 648 mAh/yr

Lifespan on a single charge:

Usable capacity ÷ annual draw = (0.8 × 2500 mAh) ÷ 648 mAh/yr ≈ 3.1 years

Sensitivity to the TAU interval. Under the control 60-minute TAU, the OPP returns a total average current of 37.75 µA. Substituted into the same calculation, this gives an active draw of ~331 mAh/yr, a total annual draw of ~931 mAh/yr, and a lifespan of approximately 2.1 years on the same 2500 mAh cell. The lifespan therefore varies between ~2.1 and ~3.1 years depending on what the network grants.

Battery's uneven lifespan as a function of battery capacity

The lifespan calculation above uses a 2500 mAh cell, but to know if I need a bigger battery it is worth checking whether a larger battery would meaningfully extend the runtime. The annual draw consists of two terms: the active draw (≈ 48 mAh/year), which is fixed regardless of battery size, and the self-discharge, which scales linearly with capacity at 2% per month [21]. With C as the battery capacity in mAh, the lifespan in years is:

Lifespan(C) = 0.8C ÷ (48 + 0.24C)

[*] Nordic Semiconductor. (n.d.). Online power profiler for LTE [Online tool]. Nordic DevZone. Retrieved June 20, 2026, from https://devzone.nordicsemi.com/power/w/opp/3/online-power-profiler-for-lte

As C grows, the fixed 48 mAh/year becomes negligible against the self-discharge term, and the lifespan approaches a limit of:

$$\text{Lifespan}(C) = 0.8 \div 0.24 \approx 3.3 \text{ years}$$

This means the system cannot exceed approximately 3.3 years on a single charge by increasing the battery size alone. As the cell grows, its self-discharge grows in proportion, leaving the ratio fixed. The 2500 mAh design choice is already close to this limit at 3.1 years. Extending the lifespan beyond this point requires a cell with lower self-discharge, not a larger one.

APPENDIX E: HeatGuard source code

```
/*
 Arduino Nano ESP32 - 6x NTC Temperature Monitor + ntfy push
 ------------------------------------------------------------
 - Reads 6 NTC thermistors on A0..A5
 - Status escalates if ANY sensor crosses a threshold up
 - Status de-escalates only when ALL sensors drop below the threshold
 - Notifications include all temperatures
*/

#include <WiFi.h>
#include <HTTPClient.h>

const char* WIFI_SSID     = "";
const char* WIFI_PASSWORD = "";

const char* NTFY_SERVER = "https://ntfy.sh";
const char* NTFY_TOPIC  = "Alprokon_HeatGuard";
const char* APP_URL     = "https://stijnboogie.github.io/Graduation/";

// ---------- Pins ----------
const int NUM_SENSORS = 7;
const int NTC_PINS[NUM_SENSORS] = {A0, A2, A4, A3, A5, A6, A7 };
const int AMBIENT_PIN = A0;

// ---------- NTC parameters ----------
const float SERIES_RESISTOR    = 10000.0;
const float NOMINAL_RESISTANCE = 10000.0;
const float NOMINAL_TEMP_C     = 25.0;
const float B_COEFFICIENT      = 3950.0;
const float ADC_MAX            = 4095.0;
const float VCC                = 3.3;

// ---------- Thresholds (deg C) ----------
// Base thresholds at AMBIENT_BASELINE. Effective thresholds shift by
// (T_ambient - AMBIENT_BASELINE), so when the room/sun is warmer the alert
// points move up by the same amount. Sensor temps themselves are NOT shifted.
const float GREEN_MAX_BASE   = 22.0;
const float ORANGE_MAX_BASE  = 25.0;
const float AMBIENT_BASELINE = 20.0;

// ---------- State ----------
enum Status { STATUS_UNKNOWN, STATUS_GREEN, STATUS_ORANGE, STATUS_
RED };
Status currentStatus           = STATUS_UNKNOWN;
unsigned long lastAlertSentMs  = 0;
const unsigned long ALERT_REPEAT_MS = 60000;

float lastTemp[NUM_SENSORS];
float lastAmbient = NAN;

// ---------- Setup ----------
void setup() {
 Serial.begin(115200);
 delay(200);

 analogReadResolution(12);

 for (int i = 0; i < NUM_SENSORS; i++) lastTemp[i] = NAN;

 Serial.println("[Boot] Powered on.");

 connectWiFi();
 if (WiFi.status() == WL_CONNECTED) {
  Serial.println("[Boot] Wi-Fi connected.");
 }

 for (int i = 0; i < NUM_SENSORS; i++) {
  lastTemp[i] = readTemperatureC(NTC_PINS[i]);
 }
 lastAmbient = readTemperatureC(AMBIENT_PIN);

 Status firstStatus = decideStatus(lastTemp, lastAmbient, STATUS_GREEN);
 Serial.print("[Boot] First readings: ");
 for (int i = 0; i < NUM_SENSORS; i++) {
  Serial.printf("T%d=%.2f ", i, lastTemp[i]);
 }
 Serial.printf("Tamb=%.2f -> %s\n", lastAmbient, statusName(firstStatus));
```

```
  currentStatus = firstStatus;
  sendForStatus(firstStatus);
  if (firstStatus == STATUS_ORANGE || firstStatus == STATUS_RED) {
    lastAlertSentMs = millis();
  }
}

// ---------- Main loop ----------
void loop() {
  if (WiFi.status() != WL_CONNECTED) {
    connectWiFi();
  }

  for (int i = 0; i < NUM_SENSORS; i++) {
    lastTemp[i] = readTemperatureC(NTC_PINS[i]);
  }
  lastAmbient = readTemperatureC(AMBIENT_PIN);
  Status newStatus = decideStatus(lastTemp, lastAmbient, currentStatus);

  float shift = isnan(lastAmbient) ? 0.0 : (lastAmbient - AMBIENT_BASELINE);
  for (int i = 0; i < NUM_SENSORS; i++) {
    Serial.printf("T%d=%.2f C   ", i, lastTemp[i]);
  }
  Serial.printf("Tamb=%.2f  thresholds=[%.1f/%.1f]  -> %s\n",
              lastAmbient,
              GREEN_MAX_BASE + shift, ORANGE_MAX_BASE + shift,
              statusName(newStatus));

  handleNotifications(newStatus);

  delay(2000);
}

// ---------- Wi-Fi ----------
void connectWiFi() {
  if (strlen(WIFI_SSID) == 0) {
    Serial.println("WIFI_SSID is empty - fill in credentials at top of sketch.");
    return;
  }
  Serial.printf("Connecting to Wi-Fi \"%s\"", WIFI_SSID);
  WiFi.mode(WIFI_STA);
  WiFi.begin(WIFI_SSID, WIFI_PASSWORD);
```

```
  unsigned long start = millis();
  while (WiFi.status() != WL_CONNECTED && millis() - start < 20000) {
    delay(500);
    Serial.print(".");
  }
  Serial.println();
  if (WiFi.status() == WL_CONNECTED) {
    Serial.print("Connected. IP: ");
    Serial.println(WiFi.localIP());
  } else {
    Serial.println("Wi-Fi connect FAILED. Will retry on next loop.");
  }
}

// ---------- NTC reading ----------
float readTemperatureC(int pin) {
  const int samples = 16;
  long sum = 0;
  for (int i = 0; i < samples; i++) {
    sum += analogRead(pin);
    delay(2);
  }
  float adc = sum / (float)samples;

  float vPin = (adc / ADC_MAX) * VCC;
  if (vPin <= 0.0001) vPin = 0.0001;
  if (vPin >= VCC - 0.0001) vPin = VCC - 0.0001;

  float rNtc = SERIES_RESISTOR * (VCC / vPin - 1.0);

  float steinhart;
  steinhart  = rNtc / NOMINAL_RESISTANCE;
  steinhart  = log(steinhart);
  steinhart /= B_COEFFICIENT;
  steinhart += 1.0 / (NOMINAL_TEMP_C + 273.15);
  steinhart  = 1.0 / steinhart;
  steinhart -= 273.15;
  return steinhart;
}
```

```
// ---------- Decision logic with hysteresis ----------
// Effective thresholds shift with ambient: T_amb - AMBIENT_BASELINE is added
// to GREEN_MAX_BASE / ORANGE_MAX_BASE. If ambient is NaN (disconnected),
the
// shift is 0 (i.e. the original fixed thresholds are used).
Status decideStatus(const float* temps, float ambient, Status current) {
  for (int i = 0; i < NUM_SENSORS; i++) {
    if (isnan(temps[i])) return current;
  }

  float shift = isnan(ambient) ? 0.0 : (ambient - AMBIENT_BASELINE);
  float greenMax  = GREEN_MAX_BASE  + shift;
  float orangeMax = ORANGE_MAX_BASE + shift;

  bool anyRed         = false;
  bool anyOrange      = false;
  bool allBelowOrange = true;
  bool allBelowGreen  = true;
  for (int i = 0; i < NUM_SENSORS; i++) {
    float t = temps[i];
    if (t >  orangeMax) anyRed = true;
    if (t >= greenMax)  anyOrange = true;
    if (t >  orangeMax) allBelowOrange = false;
    if (t >= greenMax)  allBelowGreen  = false;
  }

  if (anyRed) return STATUS_RED;

  switch (current) {
    case STATUS_RED:
      if (!allBelowOrange) return STATUS_RED;
      return allBelowGreen ? STATUS_GREEN : STATUS_ORANGE;

    case STATUS_ORANGE:
      if (allBelowGreen) return STATUS_GREEN;
      return STATUS_ORANGE;

    case STATUS_GREEN:
    default:
      return anyOrange ? STATUS_ORANGE : STATUS_GREEN;
  }
}
```

```
const char* statusName(Status s) {
  switch (s) {
    case STATUS_GREEN:  return "GREEN";
    case STATUS_ORANGE: return "ORANGE";
    case STATUS_RED:    return "RED";
    default:            return "UNKNOWN";
  }
}

// ---------- Notification logic ----------
void handleNotifications(Status newStatus) {
  unsigned long now = millis();
  bool transitioned = (newStatus != currentStatus);

  if (transitioned) {
    currentStatus = newStatus;
    sendForStatus(newStatus);
    if (newStatus == STATUS_ORANGE || newStatus == STATUS_RED) {
      lastAlertSentMs = now;
    }
    return;
  }

  if (newStatus == STATUS_ORANGE || newStatus == STATUS_RED) {
    if (now - lastAlertSentMs >= ALERT_REPEAT_MS) {
      sendForStatus(newStatus);
      lastAlertSentMs = now;
    }
  }
}

String tempLine() {
  char buf[200];
  int n = 0;
  for (int i = 0; i < NUM_SENSORS && n < (int)sizeof(buf); i++) {
    n += snprintf(buf + n, sizeof(buf) - n, "T%d=%.1fC  ", i, lastTemp[i]);
  }
  float shift = isnan(lastAmbient) ? 0.0 : (lastAmbient - AMBIENT_BASELINE);
  if (n < (int)sizeof(buf)) {
    snprintf(buf + n, sizeof(buf) - n, "amb=%.1fC (thr %.1f/%.1f)",
             lastAmbient,
             GREEN_MAX_BASE + shift, ORANGE_MAX_BASE + shift);
  }
  return String(buf);
}
```

```
void sendForStatus(Status s) {
  switch (s) {
    case STATUS_GREEN:
      sendNtfy("Status: Normal",
               "There is nothing abnormal detected. " + tempLine(),
               "default", "white_check_mark");
      break;
    case STATUS_ORANGE:
      sendNtfy("Alert",
               "You have to check. " + tempLine(),
               "high", "warning");
      break;
    case STATUS_RED:
      sendNtfy("Warning",
               "Go check now fast and remove the device! " + tempLine(),
               "urgent", "rotating_light");
      break;
    default:
      break;
  }
}

// ---------- ntfy.sh ----------
void sendNtfy(const String& title,
              const String& message,
              const String& priority,
              const String& tags) {
  if (WiFi.status() != WL_CONNECTED) {
    Serial.println("ntfy: skipped, no Wi-Fi.");
    return;
  }
  if (strlen(NTFY_TOPIC) == 0) {
    Serial.println("ntfy: skipped, NTFY_TOPIC is empty.");
    return;
  }

  HTTPClient http;
  String url = String(NTFY_SERVER) + "/" + NTFY_TOPIC;
  http.begin(url);
  http.addHeader("Content-Type", "text/plain; charset=utf-8");
  http.addHeader("Title",    title);
  http.addHeader("Priority", priority);
  http.addHeader("Tags",     tags);
  http.addHeader("Click",    APP_URL);
  int code = http.POST(message);
  Serial.printf("ntfy POST %s -> %d\n", url.c_str(), code);
  http.end();
}
```

APPENDIX F: Action matrix

If smoke, flames or gasses are present: DO NOT APPROACH the battery pack. Evacuate, close the door if safe, and call emergency services.

Detection phase → Risk

	At the device *physically present*	**In the home** *seconds to device*	**Within prevention window** *return ≤ 34 min*	**Beyond prevention window** *return > 34 min*
IMMINENT RISK $dT/dt \geq Z$ °C/min *thermal runaway*	**Evacuate space immediately** Close door behind you Call 112 *do not move the battery pack*	**Evacuate space immediately** Close door to device Call 112 *do not move the battery pack*	**Alert to evacuate space** Alert household to evacuate Call 112 *do not move the battery pack*	**Alert to evacuate space** Alert household to evacuate Call 112 *do not move the battery pack*
DEVELOPING DANGER $Y2 < dT/dt < Z$ *starting thermal runaway*	**Get out of the room** Cut power only if the plug is safely reachable *do not move the battery pack*	**Isolate the designated space** Cut power from the breaker cabinet *do not move the battery pack*	**Isolate the designated space** Alert household and ask for power cut-off only if safe *do not move the battery pack*	**Alert household** Alert household and ask for power cut-off only if safe *do not move the battery pack*
ELEVATED RISK $Y1 < dT/dt \leq Y2$ *abnormal behaviour*	**Unplug and isolate** Unplug the battery, move flammable objects away from the battery Arrange inspection	**Unplug and isolate** Unplug the battery, move flammable objects away from the battery Arrange inspection	**Alert household** Ask household / neighbour to unplug the battery Arrange inspection *monitor remotely en route*	**Alert household** Ask household / neighbour to unplug the battery Arrange inspection
SMALL ANOMALY $X < dT/dt \leq Y1$ *deviation in pattern*	**Observe the battery** Do not leave the battery unattended Stop charging	**Observe the battery** Do not leave the battery unattended Stop charging	**Note the alert** No intervention required Continue monitoring	**Note the alert** No intervention required Continue monitoring
NORMAL $dT/dt \leq X$ *charging as expected*	**No action**	**No action**	**No action**	**No action**

prevention window (≈ 34 min)
left of line: user can intervene, right of line: user must act remotely

Figure 130: Action matrix

APPENDIX G: Datasheet Silicatherm HS 650 AR

Retrieved from HKO through personal contact.

TECHNISCHES DATENBLATT
TECHNICAL DATA SHEET
FICHE TECHNIQUE DONNÉES

HKO
TRUST THE EXPERTS

Var: 06

SILICATHERM®-GEWEBE HS 650

SILICATHERM®-FABRIC/TISSU SILICATHERM®

	Prüfung Test/Test	**Prüfnorm*** **Standard*** / Norme*	**Stuhlroh** **Loomstate** / écru	**AR**	**AR, + eins. Alufix** **AR, + one side Alufix** AR, + une face Alufix
	Art.-Nr. **Art-No.** / N° d'article		620 0650 4..	620 0650 360	401 1406 010
1.	**Bindung** **Weave** / Armure	DIN 61 101-1	**Atlas 1/7** **Satin 1/7** /satin 1/7		
2.	**Breite [mm]** **Width** / Largeur	DIN EN 1773	≥ 900		
3.	**Dicke [mm]** **Thickness** / Épaisseur	DIN EN ISO 5084 DIN EN ISO 2286-3	0,6	0,75	0,75
4.	**Gewicht [g/m²]** **Weight** / Poids	DIN EN 12127	600	615	660
5.	**Fadenzahl [Fd/cm] Kette / Schuß** **Number of threads/cm warp/weft** Nombre de fils chaîne /trame	DIN EN 1049-2	19 / 13		
6.	**Garnfeinheit [tex] Kette / Schuß** **Yarn count warp/weft** Titre de fils chaîne /trame	DIN EN ISO 2060	200 / 200		
7.	**Filamentfeinheit [µm] Kette / Schuß** **Filament diameter warp/weft** Diamétre de filament chaîne/trame	DIN EN ISO 137	6 / 6		
8.	**Höchstzugkraft [N/5cm] Kette / Schuß** **Tensile strength warp/weft** Force de rupture chaîne/trame	ISO 4606	> 2000 / > 1500	> 3200 / > 2200	> 2800 / > 1500

*** z.T. an die Norm angelehnt** / partly according to the standard / s'appuyant à la norme
Toleranzen und technische Änderungen vorbehalten / Subjects to tolerances and technical changes / Sous réserve de tolérances et modifications techniques!

SAINT-GOBAIN

Stand/issued/etat: CW09/2023
Seite/page/page: 01/02

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TECHNISCHES DATENBLATT
TECHNICAL DATA SHEET
FICHE TECHNIQUE DONNÉES

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Var: 06

BESCHICHTUNGEN/AUSRÜSTUNGEN/KASCHIERUNGEN – HS 650

COATING/TREATMENT/LAMINATION - ENDUCTION/TRAITEMENT/ CONTRECOLLAGE

AR	**Goldbraune nicht brennbare, rein anorganische Imprägnierung.** • **Dauertemperaturbeständigkeit (Verbund): bis ca. 1000°C** • **hohe Schiebe- und Schnittfestigkeit** • **Minimierung der Rauchentwicklung**	**Goldbrown non-combustible, pure inorganic impregnation.** • **continuous temperature resistance (composite): up to approx. 1000°C** • **good antislip properties and frayproofness** • **minimization of smoke development**	Traitement non inflammable, pure inorganique en couleur mordorée. • résistance à la température permanente (composite): jusqu' à env. 1000°C • ferme, approprié au dècoupage • minimisation du développement de la fumée
Alufix	**Graue, schwerentflammbare PU- Beschichtung mit Aluminiumpigmentierung, wahlweise einseitig oder beidseitig.** • **lösungsmittel- und halogenfrei** • **keine thermische Zersetzung bis ca. 200 °C** • **max. Anwendungstemperatur ca. 500°C, kurzzeitig bis ca. 600°C** • **zur Erhöhung der Schiebe- und Schnittfestigkeit**	**Grey, flame retardant PU- coating with aluminium pigments, alternatively one-sided or double-sided.** • **free from solvents and halogen** • **no thermal decomposition up to 200°C** • **maximum application temperature 500°C, shortly up to approx. 600°C** • **increase of antislip properties and frayproofness**	Enduction grise avec polyuréthane (PU) aluminisée, difficilement inflammable, sur une ou deux faces au choix. • sans dissolvants et sans halogènes • aucune décomposition thermique jusqu' à env. 200°C • température d'utilisation: max. env. 500°C, pour courte durée jusqu' à env. 600°C • augmentation de la stabilité antiglissante et de la fermeté à la coupe

Toleranzen und technische Änderungen vorbehalten/Subjects to tolerances and technical changes/Sous réserve de tolérances et modifications techniques!
Die angegebenen Beständigkeiten sind abhängig vom jeweiligen Anwendungsfall wie Grundgewebe, Art und Menge der Beschichtung/Ausrüstung. Die angegebenen Werte sind nur annähernd und nicht verbindlich/The stated resistances depend on the particular case of application such as basic fabric, type and quantity of coating/finish etc. The stated values only are approximate and not binding/Les durabilités données dépendent de l'application respective comme tissu de base, type et quantité d'enduction/de finissage etc. Les valeurs données sont seulement approximatif et pas sûr.

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APPENDIX H: Step-by-step setup guide

H.1 Setup guide screenshots

From left to right, top to bottom, the setup guide runs through steps 1 to 9, finishing by adding the battery to the application.

The full application can be seen online via:

https://stijnboogie.github.io/Graduation/

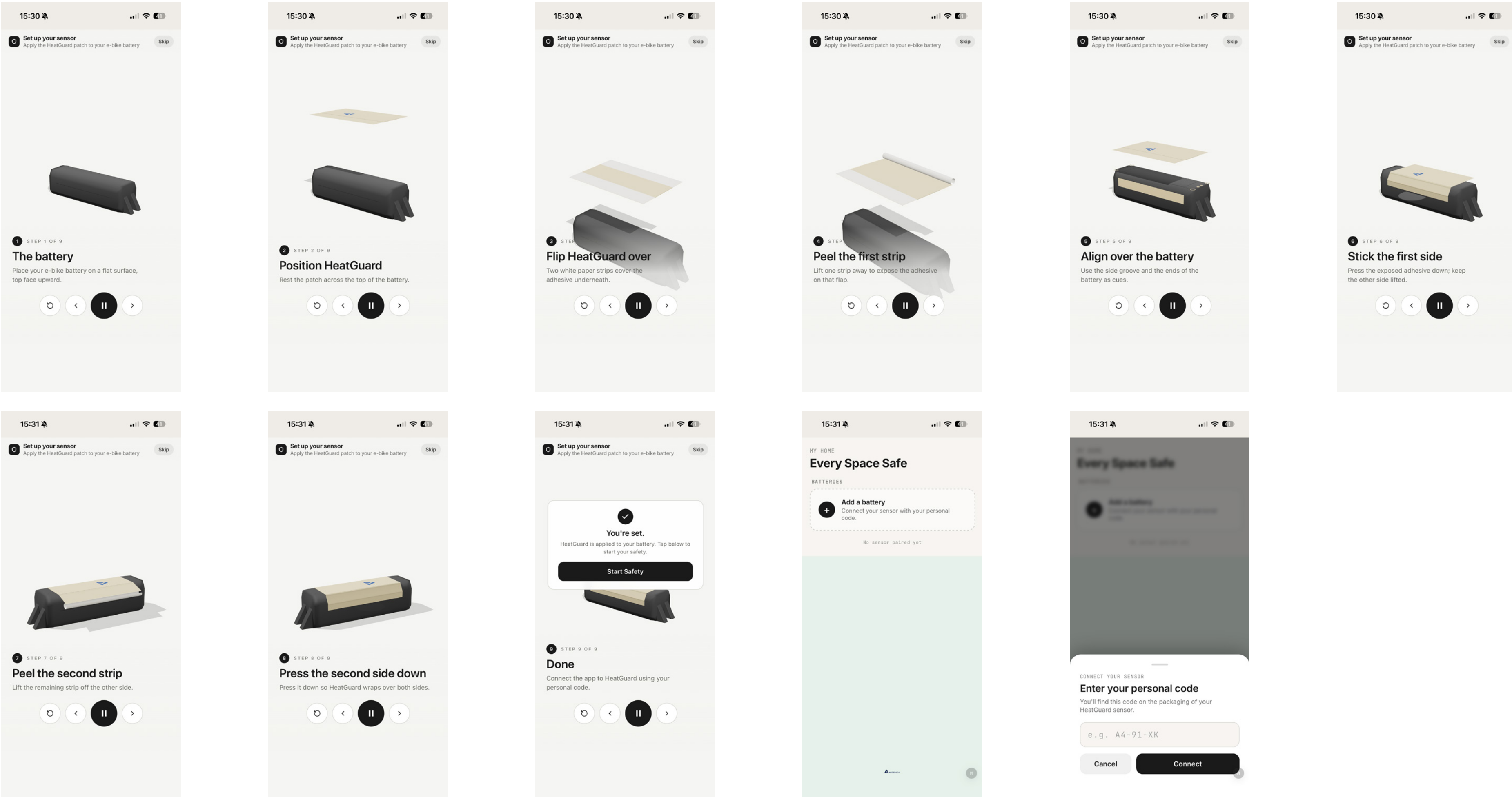


Figure 131: Setup guide screenshots

H.2 Battery status screenshots

From left to right, top to bottom, the screenshots run over the five scenario's and the information that is displayed in the application accordingly.

Normal | Small anomaly | Elevated risk | Developing danger | Imminent risk

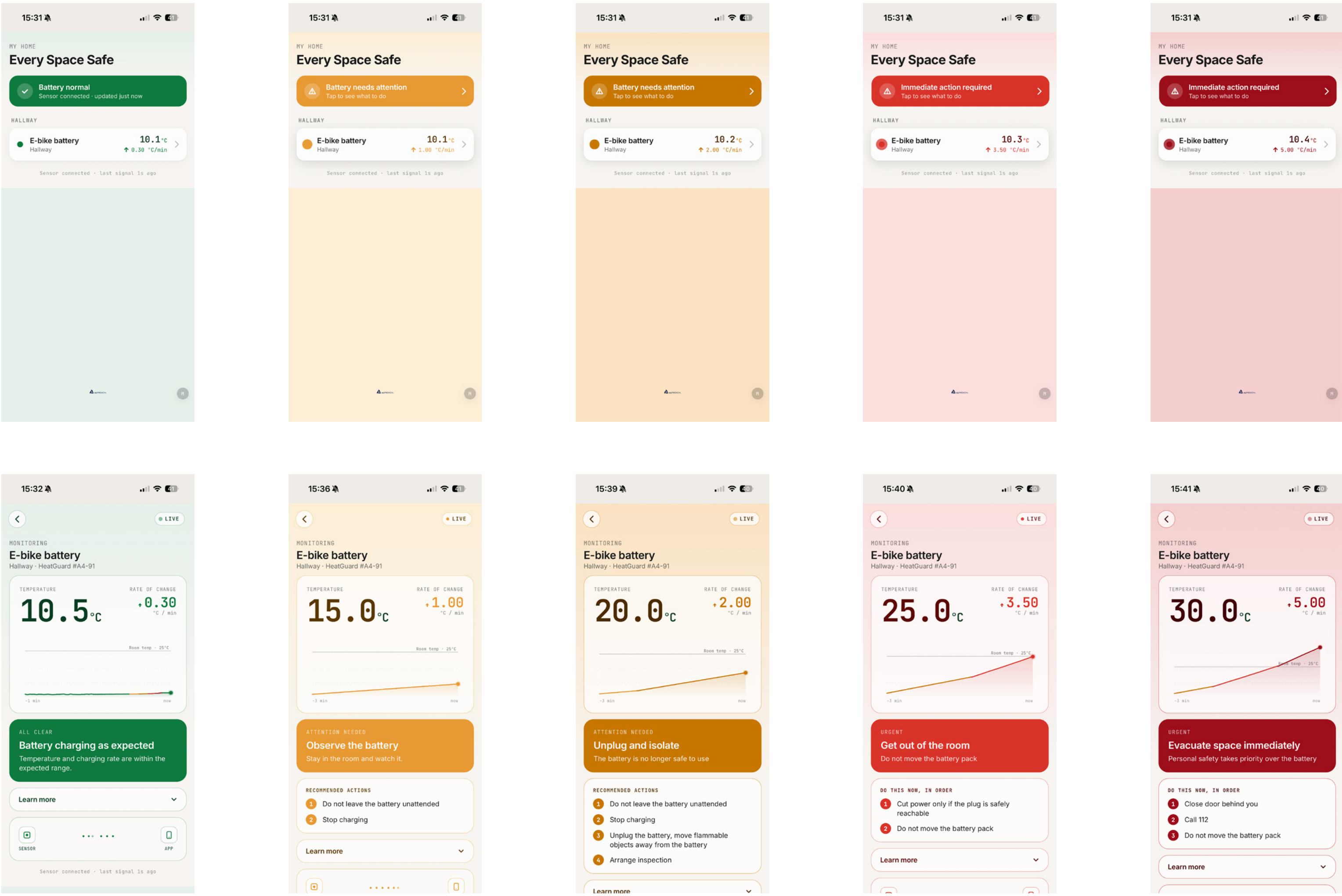
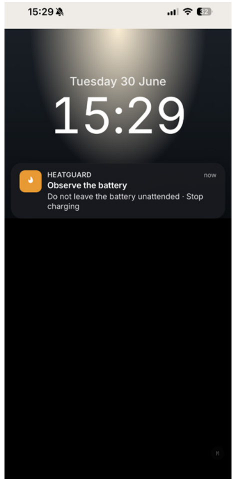


Figure 132: Battery status screenshots

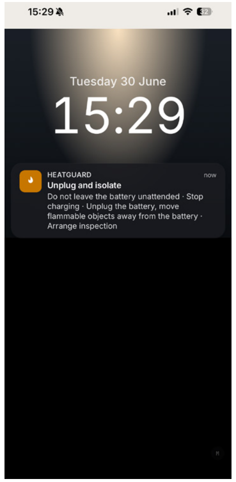
H.3 Push notification screenshots

From left to right, the screenshots show the four push notifications the user receives when a risk is developing. Normal requires no push notification as a normal status assumes the battery is charging as expected.

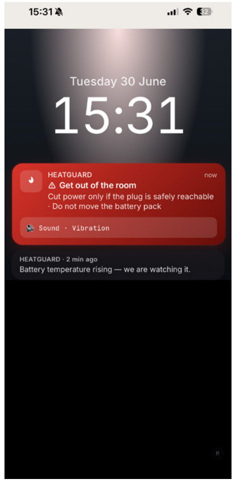
Small anomaly



Elevated risk



Developing danger



Imminent risk

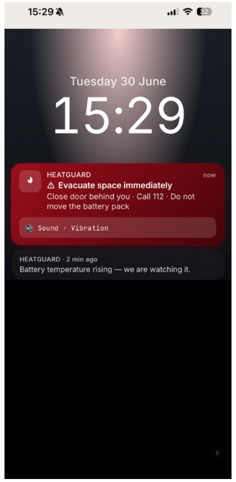


Figure 133: Push notifications screenshots

APPENDIX I: Costs calculations

This appendix holds the detailed sums behind the Costs section. All values are estimates for the Dutch market in euros. Where a real price was found it is referenced; where no public price exists, the value is marked as an estimate.

I.1 Cost to make one unit

Part	~100 units	~10,000 units	Note
Nordic nRF9160 (processor + modem)	€26.82	€17.00	€26.82 single-unit at DigiKey, lower at volume [39]
LiPo battery 3.7V 2500mAh (PKCell)	€8.50	€4.00	€8.50 at TinyTronics; ~€4 at volume (estimate) [159]
Silica fabric patch (HKO)	€6.00	€3.00	estimate
7× NTC sensor (10kΩ)	€2.80	€1.75	€0.40 each single, €0.25 each at 100+ (TinyTronics) [160]
7× reference resistor (10kΩ)	€0.35	€0.14	€0.05 each single, €0.02 each at 1000+ (TinyTronics) [158]
eSIM chip (soldered)	€2.50	€1.50	estimate
PCB + small parts + antenna	€8.00	€2.80	estimate
Adhesive (3M VHB 5952 + glue)	€1.00	€0.55	VHB roll ~€20–40, few cm per unit [49]
Assembly and test	€12.00	€5.00	estimate
Packaging	€3.00	€1.50	estimate
Cost to make one unit	≈ €71	≈ €37	

Table 12: Cost to make one HeatGuard unit.

I.2 One-time costs

One-time cost	Estimate	Note
Turning the prototype into a finished product (electronics + firmware)	€25,000–60,000	estimate
Building the application (iOS + Android + server)	€20,000–50,000	estimate
Testing and European approval (CE/RED, EMC, battery and transport tests)	€10,000–20,000	wireless approval; pre-certified chip avoids the most costly cellular tests [44]
Tooling for the patch	€2,000–8,000	estimate
Total one-time cost (assumption)	≈ €100,000	midpoint used in the Costs section

Table 13: One-time costs, paid once before any unit is sold.

Divided over the number of units sold:

Units sold	One-time cost per unit
1,000	€100
10,000	€10
50,000	€2

Table 14: One-time cost per unit at different production volumes.

I.3 Running costs per unit per year

Running cost	Per unit per year	Note
Mobile data	under €0.10	device sends a tiny amount; ~€0.005 per MB in Europe [143]
Server (receiving and storing data)	under €0.05	~€0.04 per device per year for a constant connection [10]
Connection (SIM), bought once for the device life	≈ €12 one-time	lifetime data plan, ~€12 for 500 MB over 10 years [112]

Table 15: Running costs per unit.

Because the connection is bought once and included in the price, the user pays no monthly fee. The server currently used for cost estimation is the AWS Amazon server, however, Alprokon can in the future use its own servers or any other Dutch server supplier instead of an external American server.

I.4 Price for the user

Step	Value
Cost to make one unit (10,000 units)	€37
One-time cost per unit (at 10,000 units)	€10
Connection for the device life	€12
Shipping to the user	€5
Total cost to Alprokon per unit	≈ €64
Sold at about twice the cost price	≈ €128 before VAT
Plus 21% Dutch VAT	≈ €155 for the user

Table 16: Build-up of the price for the user.

APPENDIX J: User test

J.1 User test setup

Introduction

Thank you for participating in my user test today. This will take about 30 minutes, and there is no need to prepare anything beforehand.

We are used to charging things at home all the time, phones, tools and bikes, without giving it much thought. We suspect it to be fine and do not assume something can go wrong. Most of the time that is perfectly fine, however, with the increasing amount of batteries in the home, battery fires increase accordingly. In 2024, around 300 home fires in the Netherlands were linked to batteries, and e-bike batteries are a growing part of that total. The internal structure of a battery can create a chemical reaction that starts an exothermic process, this overheating of the battery is what we call thermal runaway. Most devices detect symptoms, smoke or fire, but that is too late, damage is already done. This idea behind this project, HeatGuard, is to be one step ahead, and detect the risk before the smoke.

HeatGuard is a project made for my client Alprokon. The device is a patch that sticks to the top of your e-bike battery and senses the battery for temperature changes. An unusual temperature pattern? You get notified immediately through the app, with a step by step guide so you know what to do in each situation anywhere you are.

Today you will go through the full HeatGuard experience, from the setup to an immediate risk scenario. I will see how you manage and respond, along the way I will ask you a few short questions on your experience. I will ask you to think out loud, speak your mind, every thought is interesting to me! There are no wrong answers or thoughts.

Nothing in the experience is a real danger or risk, the battery and patch do not contain any live elements or batteries that can hurt you. Everything is simulated as part of the test setup, controlled by me. You can respond to the scenario's exactly as you would if you were at home. You are a user that has just purchased the HeatGuard product. You are now using it for the first time at home for your e-bike battery. Throughout the scenario's you and your e-bike battery are at home.

Step-by-step (9) installation using the HeatGuard application.

After unpacking HeatGuard you see the product next to your e-bike battery. You have just downloaded the application: "HeatGuard" from the app store and are ready to install HeatGuard to the battery. You follow the step-by-step guide:

#	Step	What to do
1	The battery	Place your e-bike battery on a flat surface, top face upward.
2	Position HeatGuard	Rest the patch across the top of the battery.
3	Flip HeatGuard over	Two white paper strips cover the adhesive underneath.
4	Peel the first strip	Lift one strip away to expose the adhesive on that flap.
5	Align over the battery	Use the side groove and the ends of the battery as cues.
6	Stick the first side	Press the exposed adhesive down; keep the other side lifted.
7	Peel the second strip	Lift the remaining strip off the other side.
8	Press the second side down	Press it down so HeatGuard wraps over both sides.
9	Done	Connect the app to HeatGuard using your personal serial number.

Questions

- What do you think this device does?
- Were the instructions clear? 1 - 10
- Did you feel confident you placed it correctly? 1 – 10

Scenarios (5)

Now that HeatGuard is installed and active we are going to simulate scenario's that can happen when the battery is increasing in temperature. Remember to speak your mind out loud and respond as you would, no wrong answers. There are 5 scenarios which are described below, we will go in order from 1 to 5.

#	Scenario	What it means
1	Normal	The battery is behaving as expected; no anomalies are detected.
2	Small anomaly	A small deviation appears in the expected temperature curve.
3	Elevated risk	The battery shows abnormal temperature behaviour; the risk is increased.
4	Developing danger	The temperature increase is alarming; thermal runaway has likely started.
5	Imminent risk	Thermal runaway is in progress; the temperature is climbing at an alarming rate and danger is imminent.

Questions

- Does this make you feel safer and more in control?
- Were the instructions clear, what do you think needs more definition? 1 – 10
- Was anything missing in the information you received?
- Would you buy or use this device? Why or why not?

Feedback and takeaways

Thank you for participating in this user test, I hope everything was clear. In case there are still questions, remarks or feedback, now is the time. Please feel free to mention anything that comes to mind.

J.2 Consent form

Delft University of Technology
HUMAN RESEARCH ETHICS
INFORMED CONSENT

You are being invited to participate in a research study titled HeatGuard: Sensing Risk before Fire. This study is being done by Stijn S.J. van den Boogaart from the TU Delft, for a Master thesis in Integrated Product Design with Alprokon Aluminium Bv. as the client.

The purpose of this research study is to understand the premise of safety in home, what does safety mean and where are the needs and opportunities for safety, and will take you approximately 30 minutes to complete. The data will be used for this research, creating an understanding and forming results, and in the publication of the Master's thesis. We will be asking you to answer several semi-structured questions and have a discussion following these questions in an audio recorded interview.

As with any online activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimize any risks by collecting and storing as little Personal Data as possible. Any Personal Data collected will be stored safely on the TU Delft drive, pseudonymised for publication using terms as; "Participant A" and all stored Personal Data will be deleted 2 months after completion of the study.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions. Any Personal Data can be removed within 1 week of conducting the interview on request and will otherwise be removed 2 months after the completion of the study.

Stijn S.J. van den Boogaart

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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 [../06/2026], 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: • An audio-recorded semi-structed interview with written notes to collect useful information. • The information is recorded using an audio recorder application on the phone, additional information is recorded using written notes. • The audio recordings will be transcribed as text and used to collect data and results after the interview. The recordings will be destroyed once the transcription is completed. • The collection of Personal Data (name, email, age, occupation, living situation and gender), stored in the TU Delft one drive.	☐	☐
4. I understand that I will not be compensated for my participation.	☐	☐
5. I understand that the study will end at the start of July 2026.		
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
6. I understand that taking part in the study involves the following risks of describing personal discomforts and experiences. I understand that these will be mitigated by the ability to stop the experiment at any point.	☐	☐
7. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) [email] and associated personally identifiable research data (PIRD) [gender, age, occupation, living situation] with the potential risk of my identity being revealed.	☐	☐
9. 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 [anonymous data collection after transcription, secure data storage on the TU Delft one drive with limited access to the researchers.]	☐	☐
10. I understand that personal information collected about me that can identify me, such as [email], will not be shared beyond the study team.	☐	☐
11. I understand that the (identifiable) personal data I provide will be destroyed [email, gender, age, occupation, living situation] 2 months after the end of the study.	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
12. I understand that after the research study the de-identified information I provide will be used for the Master Thesis publication in the TU Delft repository.	☐	☐
13. I agree that my responses, views or other input can be quoted anonymously in research outputs	☐	☐
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE		

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PLEASE TICK THE APPROPRIATE BOXES	Yes	No
14. I give permission for the de-identified interview transcript, living situation, age and gender that I provide to be archived in the TU Delft repository so it can be used for future research and learning.	☐	☐
15. I understand that access to this repository is open to public.	☐	☐

Signatures

____________________ ____________________ ________

Name of participant 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.

____________________ ____________________ ________

Researcher name. Signature Date

Study contact details for further information:

Stijn S.J. van den Boogaart

+31 6 37193214

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APPENDIX K: User test analysis

K.1 Evaluation Participant A

Step-by-step (9) installation using the HeatGuard application

Participant A directly understood the product, how it works and how it was supposed to be installed following the steps. He described it as a way to watch over the battery temperature and read the risk before anything goes wrong. The steps were very clear and understandable for Participant A

The only friction point was the adhesive strips and the white cooveres. He wanted a corner or lip to lift the white strip away from the glue, marked with an 'open here' cue. The peel works, but the start of the peel is not clear or indicated, this took him more time and he almost ripped of the entire glue layer. This is a small poka-yoke gap: the device does not show where the action begins.

Were the instructions clear? (1–10) Participant A give the instructions a solid 8. The only usability issue he raised was the missing peel corner or line, which suggests the written steps themselves are clear and read well.

Did you feel confident you placed it correctly? (1–10) Participant A was confident it was placed correctly, he didn't see anything that would make him think otherwise, so he gave it a 7 score. He only indicated that to know for sure it aws placed correctly the app would have to show that it is correct. Right now, there is no indication of whether it is actually placed correctly with all the sensors.

Scenarios (5)

The colours are difficult to differentiate. Participant A was unable to tell the different scenario severities apart based on the colour. It was difficult to see why the first orange was less urgent then the second one as the oranges appeared the same to him. He said that he did not see the difference and would make the serious state red. This is a clear mistake in the application and the graph, the colour differences are supposed to show the differences in severity, however now it does not. In the graph too it is the same to him. He flagged himself that it is not colour-blind friendly.

States four and five show the same and are one. He found Developing danger and Imminent risk overlapping heavily and was unsure what each one meant. He treated Developing danger as if this was the final stage. That if you do nothing right now it is going to flames any second. He suggested cutting the five scenarios back to three, because he lost track of what scenario four stood for.

Clear Instruction. The concrete instructions like, stop charging, unplug the battery, move flammable objects were clear immediately. He called them urgent and unavoidable, an alert you cannot ignore.

Instinct fights the safe response. At Imminent risk he predicted that everyone would run to the battery to look before their house burns down. That is the opposite of the safe action. So the top state must say, in simple terms, do not approach, cut the central fuses from the meter cupboard, and call 112. Without that instruction the natural instinct goes first and above the safe one. This is the most critical and important finding.

The urgency is not conveyed, it is not true to what it should be. Participant A suggested the final state should be the darkest red with a flame icon, to convey real alarm. Colour alone, and especially the orange colour, does not signal urgency enough.

'Normal' means nothing on its own. Participant A noted that the word normal in the temperature reading does not tell the user a lot. Between which temperatures is normal, and which step is critical? He suggested showing the battery reference values on screen.

The charger instruction misses duration. He asked how long he should keep the charger out of chargiing, what does that mean, briefly, ten minutes, or for good.

Does this make you feel safer and more in control? Yes. Participant A found it a reassuring thought that you can watch over your own battery temperature. He expected many people would feel calmer because of it.

Were the instructions clear, what needs more definition? (1–10) Participant A gave the clearity a 7. The general and core idea are very clear and usefull. What needs more definition: the difference between states four and five, the meaning and reference values of 'normal', the charger-removal duration, and the do-not-approach and central-fuses instruction at the top state.

Was anything missing in the information you received? Yes. Something that was missing was the meter-cupboard and central-fuses instruction with an explicit no-approach warning at Imminent risk. Reference temperature values behind 'normal'. The charger-removal duration. Stronger urgency cues, a true red and a flame icon, at the final state.

Would you buy or use this device? Why or why not? Participant A was very positive on the safety value, repeatedly calling it super and reassuring, and expecting many people to feel safer with it.

Evaluation Participant B

Step-by-step (9) installation using the HeatGuard application

Participant B did not directly understand the product. She first understood install as if an app had to be installed, it was unclear that this was already done, plus that the sensor would work directly. Once it was clear that HeatGuard is a patch you stick onto the battery for safety, she described it as something that watches the battery and warns you, which matches the intention.

The dominant challenge was language for Participant B. The animation and the app are in English, and Participant B was not good at reading English, calling it a 'drama'. This slowed down the process, which in turn meant that the animation was going too fast for Participant B, and made several screens unreadable without help. The animation itself was described as calm and clear even though the language barrier, so the visual guidance is good on its own. The English-only text is a hard barrier for a Dutch user.

The adhesive strips were the next issue, raised by other participants too. Participant B wants a corner or a visible mark, even a pen line would be fine, showing where the white strip lifts from the glue. Without it the peel start is invisible and you risk pulling the whole adhesive layer off. This is the same poka-yoke gap: the device does not show where the action begins. She also briefly missed that one side must stay open at Step 6, but this was recovered and she found this out herself..

Pairing the sensor to the application was the last challenge. At Step 9 Participant B could not find where to enter the personal code. The '+' to add the sensor was not obvious, and the difference between the sensor and the code was unclear. This is a clear usability gap in the connection steps.

Were the instructions clear? (1–10) Participant B gave the instructions a 7. The animation was clear and perceived as well structured, but the English text and the hidden button for entering the code on step 9 meant she could not finish the install without my help.

Did you feel confident you placed it correctly? (1–10) Participant B felt quiet confident she placed it correctly, a 7 as well. She placed it with guidance and some help of me, but raised no doubt about the position itself. As with Participant A, the app gives no confirmation that the patch is placed correctly, so confidence in placement is with the user.

Scenarios (5)

Green communicates the meaning, the numbers do not mean anything. At Normal, Participant B read green as good and was confident at once. She saw the temperature rising but did not know whether to act, and said the numbers meant nothing to hear without any context. The colour did the work, the figures added little.

The alarm sound must be impossible to miss. This was Participant B's strongest attention point. The sound did not work as expected during the test. Participant B was structural in stating that users are not always near their phone and do not carry it through the house, so a soft ping reads as 'a message came in', not a fire alarm. They compared it to hospital alarms that can be very loud to your ears, and felt it should grow with the severity. An actual loud alarm, not a notification ping, is needed for the dangerous states.

Instinct is to move the battery, the app must prevent that from happening. At the red states the instinct was to grab the battery and throw it outside. The screen says do not move the battery pack, and they read it, but the instinct came before actually performing the read safests response. Participant B said that the 'stay away and do not touch' message must be large and clear, because people freeze or act on impulse. As with Participant A, this is the most critical finding: the safe action has to beat the instinct.

Urgency through hierarchy, not clutter. Participant B wanted more urgency and hierarchy in the bold text, but warned against too much decoration, 'poppenkast', because it distracts.

Plug versus breaker is not clearly seperated in the text. Participant B missed the change from unplugging the charger yourself in the early steps to cutting the power at the breaker cabinet once the battery is too hot. It was unclear when this changed and didn't see this. She asked where that was stated and said she probably skipped past it. This not clear and landing properly.

The system should say whether the battery is charging or not. Participant B noted the app should recognise and say whether a charger is connected, so 'stop charging' still makes sense when there is nothing to unplug.

Read-a-loud and larger text for accessibility. Participant B needs reading glasses and mentioned text-to-speech and enlargeable text for elderly or poorly sighted users, comparing it to audiobooks. She also stated again that the application was in English and that this was a problem. The final Imminent state was clear and simple: door closed, call 112, shown in red, this worked.

Does this make you feel safer and more in control? Yes, but it was still confusing what all the information inside the application meant. Participant B was reassured by the green state and trusted the app provide the safest guidance. She was positive about using this in the future to have more control about what is actually happening. Howerever, the control was undercut by the silent alarm and the English text, so the feeling of safety depends on fixing both.

Were the instructions clear, what needs more definition? (1–10) Participant B gave a 6 on the clearity of the instructions, but when I explained it all this became an 8, so the language barrier was real. The red, final states were clear and simple. What needs more definition is the language (Dutch), the plug-versus-breaker transition, where to enter the pairing code, the meaning of the numbers, and an explicit stay-away instruction at the dangerous states.

Was anything missing in the information you received? Yes. Dutch text. An alarm that escalates with severity. A large, explicit 'stay away and do not touch' at the dangerous states. The plug-versus-breaker distinction. A clear place to enter the code. Whether a charger is present. Read-aloud and larger text.

Would you buy or use this device? Why or why not? Participant B was not clear in this, but was positive on the safety value and that it would help in feeling more in control.

Evaluation Participant C

Step-by-step (9) installation using the HeatGuard application

Participant C was fast in understanding how the product worked and what the general idea was. She read it as a way to keep insight into the battery and be warned when something goes wrong, and described the value the solution gives as control over what is happening. The steps spoke for themselves and she moved through them without my help.

The animation ran a bit too fast for her, but the pause was easy to use. She would have preferred to step through it herself, swiping one step at a time, instead of watching it play through. She was clear this is a preference, not a make-or-break point.

The one challenge in the installation was the adhesive strip. Participant C would have liked a small fold-over tab to separate the strip from the glue, the kind you can pinch and pull apart. The start of the peel is the hard part. She liked the material itself, calling it solid and sturdy, though that firmness is part of what makes the strip awkward to lift.

Participant C raised a good question. This battery has side grooves that the patch clicks into, but other batteries do not. She liked that you do not have to specify your bike or battery in advance, and expected a general patch that wraps around the middle. That way you do not have to set up or indicate what battery you specifically have beforehand.

At connecting the HeatGuard to the application she followed the personal-code idea easily. Participant C asked three useful questions about this Step 9 of the installation: can you put multiple sensors in one app, can you add a battery, and can you give each battery a name, 'my battery and my partner's battery'. The prototype did not show the add-battery and naming option cleanly, which is worth adding.

Were the instructions clear? (1–10) Participant C gave it a solid 9. The steps were self-explanatory and she completed them without help. Her only challenges were the fast animation, with the wish to have it self directed with steps instead of a video, and the peel tab.

Did you feel confident you placed it correctly? (1–10) Participant C mentioned she was confident it was placed correctly when comparing it to the animation, giving it an 8. She placed it quickly, the patch fit the grooves, and she raised no doubt about her own placement. The feedback was that the app gives no confirmation that the placement is correct.

Scenarios (5)

Green gives the correct vibe. At Normal the flat graph and the figures did not tell Participant C much, and said the 0.3 °C per minute reading meant nothing at first. She compared it to her father reading out solar-panel output, where you cannot tell a lot from the numbers until you have watched it for a while. She suggested showing a normal range at the start, or in a manual, so the early readings carry meaning.

The sensor to app is confusing. The live-data indicator confused her. She was unsure whether the app was connecting, loading, or waiting on her, and it looked as though the battery was still charging in the sensor to app live indication.

Observe and isolate are not specific enough. At the orange states the instructions to observe the battery and to isolate it were unclear to Participant C, making it more confusing as to what this exactly meant. She did not know what she was watching for, or whether isolate meant putting it outside or just setting it aside to keep an eye on.

A warm charger is normal, so the warning gets taken less serious. Participant C kept mentioning the low temperature reading and felt it did not matter much. That is because a charger of 20 degrees doesn't seem a lot and that she is used to chargers running warm, even using a hot laptop adapter as a foot-warmer in winter. And her sense was that it usually turns out fine. The low displayed temperature reinforced this and worked against the colour. This is a discussion and improvement point, the low temperature indication in the app undermined the realistic scenario.

Orange is interpreted as still fine and not alerting per se. From a design view she wanted a darker orange. The current orange told her that things were still alright, not very alarming, and did not move her to act.

She trusts her own eyes and senses over the app, and that undermines the safe action. At the red state Participant C's instinct was to walk over to the battery, look for fire or smoke, and unplug, rather than follow the on-screen steps. She compared the app to a rain forecast that can be wrong in the moment but right minutes later, and said she would want to see flames before evacuating. This verification instinct is the most critical finding: it places observing before evacuating. A trust in the users own senses and seeking verfication by looking for visual or sensory cues can undermine the safety and preventive nature of HeatGuard.

Instinct is to move the battery out of the house, the app must make sure it counters this. Participant C's first reaction was to get the battery outside, instinctively. After the explosion and gas risk was explained she understood, and compared it to carrying a burning pan out of the kitchen and spreading the fire. She suggested that the app should clearly and primarily state not to move it, with the reason, because that is exactly what she would otherwise do. So make sure this is clearly stated at the start to prevent instinctive behaviour.

The foreknowledge itself is valuable. Even while Participant C distrusted the app, she valued knowing the state of the battery and the potential risk early. She said it felt good to have had the chance to act, rather than finding out minutes later when it is actually too late. It also changed her behaviour over the states, she would charge in the living room where she sits rather than the bedroom, and would watch more closely once a battery had gone red. It made Participant C more aware of the risks and more alert on potential danger.

Does this make you feel safer and more in control? (1–10) An 8. Participant C felt safer because the system gives insight and control. She valued being able to check the state while out doing groceries, knowing things were fine and potentially whether it is actually charging or not.

Were the instructions clear, what needs more definition? (1–10) Participant C indicated a clear instruction, a 7. What needs more definition is the meaning of observe and isolate, a normal range for the numbers, and an explicit do-not-move warning at the dangerous states.

Was anything missing in the information you received? Yes. A normal range or reference for the readings, early on. A clearer observe and isolate instruction. A darker orange and an explicit do-not-move, explosion-risk warning at the red states to indicate how dangerous it is to actually do so. A multi-battery overview with charging status and the ability to name each battery.

Would you buy or use this device? Why or why not? Participant C was positive. She valued the insight and control, and even continued imaging this at other devices, wanting it for other appliances she does not trust like an old laptop charger, an old microwave, an old dryer. She also saw value at a distance, citing grandparents who charge in a separate shed with no smoke alarm for who this could be a good insight to know what the battery is doin while they are inside the house. Information is key.

Evaluation Participant D

Note: Participant D is in the 65+ group and was not familiar with smartphone applications.

Step-by-step (9) installation using the HeatGuard application

Participant D is not technically inclined and did not know exactly what was happening inside the sensor. She is not familiar with technology, but drives an ebike, making her an interesting user group to test with. What she did realise was the benefit, just not the mechanism: a device that watches the battery and gives more control over it. That partial understanding was enough for her to feel safer using it.

The animation was good to follow, but it was too fast. Participant D struggled to navigate it and became a little stressed when it skipped to the next step before she had done that step in real life. This points guide that can be self paced, the user moves forward and back themselves, rather than a video that plays through on its own.

Two usability barriers stood out for this participant and age group. The font size was too small to read comfortably, and the English text made the app hard to understand. A larger font and a Dutch translation would both be needed.

Were the instructions clear? (1–10) Participant D gave the instructions a 7. The animation was followable and the install was easy overall, but the pace, the small font and the English text made it hard for the participant to keep up. However, the instructions were followed using my help, so this was a limitation, but necessary to succesfully complete all the steps.

Did you feel confident you placed it correctly? (1–10) An 8, Participant D found the device easy to use and install, and was sure it was placed correctly. She didn't see anything that would make her question otherwise. This could be because she was not fully aware of what technology is inside HeatGuard.

Scenarios (5)

Colour and the big temperature number are the biggest tells, the graph is not.
The numbers and the graph did not mean a lot to Participant D. She mostly looked at and understood the colour and the large temperature number, these were the main indicators of what each scenario meant. She talked about those two when giving her understanding of what was happening. Participant D believed and trusted what was shown.

The scenario actionable information is too vague. The wording in the app, the way it is phrased and the information given during the scenarios was confusing for Participant D. She was not really sure what to do exactly, it was all a bit too vague. She suggested icons along with the text, for older users or anyone who does not know the terms.

The data and information needs to be simpler. The graph and the numbers should be more simple and straightforward, so the screen instantly conveys the right message rather than asking the user to interpret figures.

Does this make you feel safer and more in control? (1–10) A 7. Participant D felt safer and more in control of the battery and the temperatures. The score is a 7, because she did not know what was exactly happening inside the sensor itself, was unable to read the english instructions, so relied only on the given information and self interpretation.

Were the instructions clear, what needs more definition? (1–10) Participant D found my instructions as a researcher very clear and gave that an 8. However, over the scenario's and the instruction it was difficult to pin an exact number as the user was unable to read english. A limitation of the study.

Was anything missing in the information you received? Yes. A larger font and Dutch text. A simpler graph and clearer numbers. Icons next to the scenario instructions. A self-paced installation guide. A tab on the adhesive strips.

Would you buy or use this device? Why or why not? Participant D was positive. She found it easy to use and install and it gave a better feeling of safety, even without understanding the technical detail behind it.

Evaluation Participant E

Step-by-step (9) installation using the HeatGuard application

Participant E was able to understand HeatGuard without trouble, and figured out what it does quickly. She understood the value as being confirmation and awareness: a way to challenge the unknown, so you find out early when a device is heating up rather than discovering it too late.

As the animation is a video and continues on its own, Participant E was caught off guard and said out loud how it went too fast. It moved to the next step before she had finished the previous one in real life. Participant E wanted to read and do each step at her own pace.

Centring the patch was a real challenge for Participant E. The side groove was not enough of a cue, and she could not get it straight, eyeballing it which ended in a slight angle. Participant E wanted it to be perfectly centered with the argument that it would otherwise not work correctly according to her, so without me telling her. This also adresses a way of confirming and knowing the sensor is installed correctly through the sensor itself or the application.

Moreover, she wanted visual alignment marks on the patch, lines or even small centimetre ticks, so you can line the patch up against the battery. She expected the patch to be universal, however, when I explained that each modeel would be different she reinforced her cue statement and how clear placement cues more important, not less.

The adhesive strips were a friction point too. They found the white strip awkward to peel and expected most people would, even though she was quiet fast with it. A lip or tab to start the peel would help.

Were the instructions clear? (1–10) Participant E said the video read clearly, but the automatic continuation was too fast and made it hard to follow, however, she still gave it an 8. She could see how someone would get lost when the guide moves on before they are ready.

Did you feel confident you placed it correctly? (1–10) A 7. Participant E was openly not confident. She knew the patch was not centred and were eyeballing the position. Without alignment cues, and with no in-app confirmation of correct placement, she could not be completely sure it sat right.

Stop charging is interpreted as the battery being written off, it was not clear when she could start charging again. At the first alert, small anomaly, the instruction to stop charging and not leave the battery unattended made her think the battery was finished and that she would have to buy a new one. She wanted to know whether it is recoverable: can I charge again later, do I have to wait 10 minutes, or is it done? She compared it to a phone water-damage warning that never tells you when it is clear. A recovery or cue that it is all good is missing.

Isolate is vague. The instruction to isolate the battery was unclear to Participant E, where do I have to isolate it, in the fridge? She has worked with batteries in the past and thought of a fireproof box, but also noted that most people do not own one. She also questioned why the screen asks you to move objects away from the battery, when the more simple and straightforward move feels like taking the battery itself outside. That is also the most instinctive move according to Participant E.

The temperature number should have the colour, not the graph. The graph and the figures did not mean a lot to her, since she does not know what is normal for a battery and what is not. For example her own phone runs hot too and this is viewed as normal. The large temperature number was the one intuitive indicator, she knew what this meant and that 10 degrees Celcius was not hot. She suggested the big number itself should change colour with urgency.

Put Do not move the battery as the first instruction. Participant E's instinct on stop charging is to grab the battery, so the do-not-move warning needs to be the first instruction, not hidden under a learn-more tap. At the dangerous states she suggested to enlarge the instructions and move it above the number and graph, so the actions are simple and read more simple like I have to do this, this and this.

The silver lining is that the user wants to verify with the senses. Across the orange and red states Participant E's instinctive and consistent response was to go and look first, for fire, smoke or a sound, before following the screen or evacuating. She would not wake or warn neighbours based on the app alone without a real-life cue. She cited the fire brigade's message of first look and then act. The early warning is seen as a reason to go and check, but not yet as a reason to act blind.

The instinct to move it outside is driven by the motivation of protecting others. Even knowing the battery is unstable and should not be moved, Participant E would still take it outside. The reason was responsibility for others. She lives in a large shared building where a fire spreads fast and is dangerous for neighbours. People are asleep upstairs, and other people's belongings are in danger too. In here own home alone she would be less direct to move the battery, so the duty to others is what overrides the safe instruction.

Does this make you feel safer and more in control? (1–10) An 8. She first contemplated on the word safety, as she did not know what it meant for her. She knew it being different from certainty and control, but once that was seen as safety too she knew what it meant. The value of HeatGuard is in the pre knowledge of knowing which device is at fault and when, so you do not have to search every room, and you keep time to plan and act.

Were the instructions clear, what needs more definition? (1–10) A 7. Participant E found that the instructions could use a better hierachy in order, more definition and take into account intuition moree.

Was anything missing in the information you received? Yes. A recovery or it is all clear cue after an alert. The do not move the battery instruction placed first, with the reason, and a note that water does not work and special foam is needed. Alignment marks for placement. A reference range for the numbers. A view of whether a device is currently charging.

Would you buy or use this device? Why or why not? Yes. Participant E would use it, provided it is easy and quick to apply and not bulky, with all sensed devices in one app and overview. She priced it at around €20 for a larger patch and roughly €10 for a small one, and suggested a customisable starter pack at a reduced price as a business model, with good pricing each time a new device is added.

Evaluation Participant F

Step-by-step (9) installation using the HeatGuard application

English was no barrier to Participant F and he did not have a lot of trouble unnderstanding the purpose of HeatGuard. He moved through the steps quickly, faster than the guide intended. He did not read each step completely, but did a quick scan and using his intuition he completed the installation. This turned out to be the correct way.

So in his case the animation was a little too slow, he was fast and wanted to move on quickly, some steps like Step 1 and 2 were a little too slow while Step 6 was too fast or he skipped ahead and missed that one. A self-paced guide helps here too, but bigger issue here was that he did not want to wait that long for the next step. He was a confident user, the main takeaway here is that each user will have their own pre knowledge and pace, which requires a different speed for everyone.

The adhesive strip was, again, a point of struggle, although he was still rather fast. He placed the HeatGuard within second and assumed it was rightly placed, he mentioned that he did not have any way of telling for sure but was confident in his actions. This is the same placement gap the others raised. Participant E knew she had failed and the app could not tell her, Participant F assumed he had succeeded and the app could not confirm it.

Were the instructions clear? (1–10) Participant F gave the instructions an 7. For him they read clearly and the English was easy. The point he made was about his own pace, that he rushed the instructions, and that a potential skipped step which resulted in wrong placement would not be noticed.

Did you feel confident you placed it correctly? (1–10) Participant F gave an 8. Even though he had no confirmation and he did not check the placement, he was internally confident that it was placed correctly. But again, there was no way of knowing for sure.

Scenarios (5)

The numbers do not mean anything. At Normal, Participant F was reading the green screen and moved on. He understood the green colour and associated it with okay directly. He had no trouble reading the text and figures on the graph, but he noted that it didn't mean anything deeper to him, it was just numbers but without a reference for what a battery should do. The colour did the work.

A low temperature reads as nothing to worry about. Like Participant C and E, Participant F dismissed the early readings because the number was low. His own phone and laptop run warm and nothing happens. A reading that does not look hot worked counter effective.

First thoughts are; This will not happen to me. One of the most interesting findings is one that was an insight from my research. Participant F says he has seen fat-bike and e-bike fires on the news and is aware of the risks and dangers. Yet, he does not see it happening to him. He says he keeps his bike safe and charges it only when it needs to be charged. However, this is half of the potential abuse and even when all that is safe, thermal runaway can still happen. After some explaining he saw the risk more, but was still confident it would not be him.

His instinct is to save the bike. At the dangerous states Participant F's first move was to grab the bike and get it outside, however, the motivation was different. For Participant E it was responsibility for others, for Participant F it is the bike itself, which cost him a lot and means a lot to him. He would carry the battery through the house to protect his own bike, and thus material value.

Phone on silent. His phone is always on him, but his notifications are muted and he ignores most of them, knowing he can respond to it later. This normalised behaviour, standard reaction, is what can be a problem when working through notifications. While Participant B's point was that the alarm must be loud, she indicated it because she can be far removed from the phones location, and Participant F silences his. The alarm has to bypass Do Not Disturb and a sleeping user.

Does this make you feel safer and more in control? Partly. Participant F would not say he feels unsafe to begin with, so convincing or making him aware of the danger was difficult in the beginning. But he eventually saw the value in when he was not there. When he was away, sleeping or gone, he would be able to see what is happening, gain insights, and warn others.

Were the instructions clear, what needs more definition? (1–10) A 7. Participant F thought that the phrasing was clear, so it did not matter that it was in english. What needs more definition is the meaning behind the numbers, a do-not-move instruction strong enough to beat the instinct, and an alarm that reaches a sleeping user.

Was anything missing in the information you received? Yes. A reference for what the numbers mean. A do-not-move warning. An alarm that bypasses past silent mode and wakes you.

Would you buy or use this device? Why or why not? Not directly, Participant F believed that it would not happen to him, so it was hard to make him believe that he needs it. However, he wuold use it when given to him to protect others and gain valuable insight in what is happening to the bike.

K.2 Deductive thematic analysis results

This section combines the six participant evaluations and analyses the patterns that are found across the user tests. I document the four most interesting and common patterns first, then the smaller findings, several of which was only dicussed by one participant. That is why these are less important then the ones that are mentioned by all or multiple participants. Participant quotes are kept in the original Dutch to preserve the original result and not change intonations, however, some parts are translated to english for the evaluation.

The four themes

1. Instinct before the safe response, and responsibility for others.

Across Participant A, B, C, E and F this is the most critical finding. Instinct is found as the most common reason for doing something different from the safest response. Their acts reflected a response that was formed by instinct and self trust. Participant A predicted everyone would approach the battery rather than retreat: 'ik denk dat iedereen gewoon toch gaat kijken. Gelijk. Voordat zijn huis afbrandt'. He suggested to cut power from the central fuses from the meter cupboard instead of going to the device. Participant B went straight to the battery and moved it immediately, even though she knew that would be wrong: 'instinct zou zijn... ik gooi hem naar buiten. Maar dat moet ik niet doen', and asked for a large 'blijf er vanaf' text to preven this. Participant C trusted her own eyes over the application: 'ik zou denk ik echt eerst de vlammen willen zien voordat ik echt weg ga'. Trusting her own senses and requiring a visual confirmation of the risk before taking actual actions. Her own first reaction was 'het huis uit met dat ding', and she then suggested the application itself should cleary state 'beweeg hem niet, er is kans op ontploffingsgevaar' So that people will directly know that that is not the right move. Moving the battery out of the house could suggest a motivator that is protecting your belonings and your nearest and dearest that run a potential danger with a house fire. Participant E did both. She would verify herself first by looking at the battery, citing the fire brigade, 'neem je het waar en dan act', but then she would still carry the battery outside out of responsibility for others: 'omdat wij met zoveel mensen in een gebouw wonen... je hebt geen verantwoordelijkheid voor één huishouden'.

This reflects another layer of responsibility feeling that confirms my findings in my research. People feel the need to protect others, responsibility, and that is a big motivator for safety. She wanted the instruction on not moving the battery placed first instead of evacuating the room first :" Dan zou nummer drie eigenlijk op nummer één moeten. Do not move the battery pack. Ja. En dan... Close the door behind you. Call 112 ". This would make more sense to her as you would not move the battery out of the room anyway when you already left: 'nummer drie eigenlijk op nummer één'. The safe action has to beat the instinct action. This can be done by making the 'do not move the battery' and 'watch out explosive danger' the first and largest instruction, with the reason attached. Another common challenge regarding this theme is that pepole want to see the fire for themselves first, with their own senses, a visual confirmation, before they act, as described by Participant E: " Met een brandalarm dan weet je. Hij gaat niet zomaar af. En hier ook. Wel een beetje. Maar het is toch. Als je niet de real life cues ziet. Dan wil ik toch wel zeker weten. Of het er is." And participant C: "Ik wil wel eerst zien of het echt in de fik staat en niet. Of de app wel gelijk heeft of niet, zeg maar."

2. Meaningful numbers and graphs.

This is unanimous across all six participants. Participant B knows that green is good and sees the numbers, but they don't mean anything: 'voor mij zegt het niks, dus voor mij gaan er geen alarmbellen af'. Same goes for Participant F. The colour did most of the work, and the figures added little meaningful information. Participant C found the graph flat and the rate meaningless at first, 'dat grafiekje zegt natuurlijk niet heel veel' and '0,3 graden per minuut change, dat zegt in eerste instantie niet zoveel', and asked for the normal range. She wanted to know between what temperatures is normal, to have a reference frame for the information. Participant D, looked only at the colour and the big temperature number, 'De grafiek en de nummers zeggen mij niet zo veel, het is te lastig voor mij.' Participant E stated: 'deze grafiek, dat zegt jou niks als persoon', and 'dit getal is het enige wat mij echt een normale indicatie geeft' talking about the big temperature number. She discussed that a temperature of 10 degrees says more to her, as she can reference this to other things in real life. Her fix is the pattern dominated by the big temperature number and better references: the temperature number should have the colour, not the graph. Participant A's point about 'normal' belongs here too, 'dat zegt mensen niks', with the battery reference values on screen.

3. The step-by-step setup guide tempo, and a confirmation of successful placement.

There are two challenges that consern the setup guide, firstly the guide does not let the user lead, the video is paced too fast and makes the user lose control. Secondly, it never tells them they placed it right, making them wonder instead of certain. The animation plays on its own and runs too fast for Participant C, 'het ging een beetje snel, de animatie', Participant D, who became stressed when it skipped ahead before she had done the step, and Participant E, 'hij ging dus wel al verder zonder dat ik verder wilde' and 'Dus dan ben je helemaal van, en ik ben niet zon digibeet, in ieder geval. Ik weet dat ik dan gewoon terug kan klikken, maar ik kan begrijpen dat je dan helemaal een soort van verdwaald raakt in de instructie. Terwijl ik wil eerst gewoon kijken van, wat is het, wat staat daar, voordat ik pas naar de volgende stap ga..' Participant B had the same issue because of the language barrier: "Ja, het is moeilijker voor mij, maar ik snap dat alles in het Engels is. Maar dat is voor mij een drama.". All of them want a self-paced guide, stepping forward and back themselves rather than watching a video play through. This is already the case, the user is able to skip through the setup on their own pace, however, upon opening the app the video plays instantly and this is the main feature. This could be redesigned to start with a step based setup, and make the video optional.

On completion of the setup, the app never confirms that HeatGuard is placed correctly. Participant A, B, C, E and F all raised this. Participant F was a confident user and sure that it was correct, but the app could not confirm: 'Ik denk dat het goed is, daar ga ik gewoon van uit'. Participant E had the most clear case as she knew she had failed and the app could not tell her, 'dat is dus nu niet gelukt... ik eyeball nu eigenlijk hier erg op'. She was eyeballing the placement, sure she was not centered but there was no real way of telling. Placement confidence is entirely with the user, but there should be one step that decides whether the sensor reads anything at all.

4. The core value confirmed: knowledge and control make people feel safer.

This is unanimous and it validates the definition of Every Space Safe. Participant A called it reassuring, 'ik vind het echt super, ik denk dat er heel veel mensen gerust zijn', and described it as a way to watch over your own battery temperature. Participant C scored it an 8, 'omdat het inzicht geeft', and captured the knowledge value: 'het geeft me een fijn gevoel om te weten, want anders had ik een filmpje gekeken en gechilld en dan was het alsnog misschien tien minuten later in de fik gevlogen'.

Participant D felt safer and more in control even without fully understanding the mechanism behind it.

Participant E framed it as confirmation and awareness, 'bevestiging aan je ontwetendheid', she valued that she was able to know which device is at risk and when, so she has more time to plan and act. The value can be described as control and insight, and even though Participant C distrusts the use of apps: ' Ja. Zeker. Het geeft veel meer een controle over. Of inzicht in wat er aan de hand is.', this value still provides enough confindence in its use.

Smaller findings

The following findings were found too, but smaller, several from a single participant.

- **The adhesive strip has no visible start to peel from.** This was unanimous, but it is the smallest fix and one I had flagged while doing the user tests: a corner, lip, tab or pen line marked 'open here'.
- **Orange reads as still fine, not colour blind friendly.** Participant A could not tell the oranges apart, and said that is was not colour blind friendly: "Nee, dat verschil zie ik niet. Dan zou ik hem hier rood maken of zo. Oké, oké. Dus het lijkt mij gewoon dezelfde lijn. Dus daarom vroeg ik. Dan denk ik nou... Snap je?". Participant C wanted a darker orange.
- **A warm charger or hot phone is normal, so a not too hot reading is often dismissed.** Participant C is used to a laptop adapter running warm, 'in de winter gebruik ik die als voetenwarmer'. Participant E reads her own phone at 60 degrees as normal. The low displayed temperature works counter intuitive.
- **Observe and isolate are too vague.** Participant C did not know what to watch for and what isolate exactly meant, where and for how long? Participant E asked 'isolate waar dan, in de koelkast of zo?'.
- **Stop charging can be read as the battery being written off, with no recovery cue.** Participant E asked 'zou ik hem dan nooit meer kunnen opladen, moet ik dan gelijk een nieuwe gaan kopen?', she was not aware of what this meant and whether a slightly heating battery means that it is fully broken or not. Her first thoughts were to buy a new one directly, which works agains the sustainability. Also, like a phone water-damage warning, there was no cue that showed when the battery was fine again. Participant E also asked how long the charger should stay out: "Maar ja, kan ik dan wel weer gaan chargen uiteindelijk? Of niet? Of is hij afgeschreven? Of moet ik iets nieuws komen? Of is de instructie soort van, oh wacht tien minuten. Doen we dan weer erin."

- **English-only is a barrier and the application needs Dutch language (or others).** Participant B called it 'Ja, het is moeilijker voor mij, maar ik snap dat alles in het Engels is. Maar dat is voor mij een drama', addressing the fact that she had to do so much effort to translate it herself. Participant D stated that she found the English text hard "Ja engels kan ik eigenlijk niet echt, alleen de simpele woordjes", and in her age group (65+) this would be a common challenge. Participant E noted the average Dutch user will not know a word like anomaly: "Ja, en ik denk dat de gemiddelde Nederlander ook niet weet wat anomaly is." However, the animation was clear to Participant B: "Het filmpje is duidelijk. Ondanks dat ik slecht in Engels ben".

- **Have the overview show multiple batteries with charging status and customisable naming.** Participant C asked for multiple sensors in one app, a customisable battery name, and whether each one is charging or not to have a clear overview and maybe even more information on the status: "Ja, en het zou inderdaad leuk zijn als je meerdere apps of meerdere batterijen… meerdere batterijen kan zien. En ook misschien of ze op dit moment aan het opladen zijn of niet. Dat als ik aan mijn dochter vraag van, hey, kan je mijn e-bike even in de batterij?… En dan vraagt, kan je even mijn batterij aan de oplader stoppen? En dan doet ze dat niet. Dan heb ik s'avonds een probleem of zo.".

- **Read-aloud and larger text for accessibility.** Participant B adressed the urgency for text-to-speech and enlargeable text, like audiobooks, especially with older users: "Ik heb dus een leesbril nodig. Maar stel dat ik de nu bij me heb, dan moet ik het groter kunnen maken. Als ik deze lezen, dan denk ik aan de mensen die het slecht zien. Dan denk ik aan de slechtzienden mensen, dat die het ook gebruik van kunnen maken. Dat die het op gehoor, ja, dat die daarop kunnen klikken. Als ze dat willen. Hoe horen ze het?". Participant D found the font too small as well.

- **The alarm must be a real, escalating alarm, not a ping.** Participant B said this very well: 'het moet echt een alarmsignaal zijn, niet klein piep piep', growing with the severity, like her alarms in the hospital.

- **Alignment marks for centring.** Participant E wanted lines or centimetre marks on the HeatGuard or battery to line it up, which ties back to the placement-confirmation gap: "Maar als je hier bijvoorbeeld al iets meer streepjes ziet van wat nou het midden is. Een soort van dit is het midden, dat weet je. Maar je weet niet hoe ver dit is en hoe ver dit is. Dus je kan misschien wat van die centimeterstreepjes of zo doen. Misschien aan de zijkant zo pop pop of vooral hier eigenlijk. Dat je een beetje kan zien van oh het is dat streepje en het is dat streepje en dan kan je hem beter eye ballen".

- **This would not happen to me.** Participant F had an interesting motivator agains the use of HeatGuard, one that was an insight from my research. Participant F noted that: 'Ik zie het wel eens op het nieuws, maar goed er gebeurt zo veel en ja ik ga er niet van uit dat dit bij mij gebeurt… Ik ben best voorzichtig.' He was confident he was carefull enough and that a fire like that would never happen to him. This could mean insufficient or bad information, or a case of false security.

APPENDIX L: Use of AI

In this thesis I used Artificial Intelligence (AI) tools to support my design process. This appendix presents an overview of the specific tools I have used and to what purpose. For all AI tools used the input is supplied by me and the output critically assessed. AI was not used to generate any data or draw any conclusions for this thesis. All data is original and I, as the author, remain responsible for all outcomes.

For each rendered image and graph, it is noted whether and which AI was used. Except for my sketched art, that is noted here: to place the screenshots into my sketched drawings, ChatGPT was used to match the perspective. Both my screenshot and sketch served as reference and final material. ChatGPT only combined the two in the correct perspective by generating a new image. Table 17 gives an overview of which AI was used for what purpose.

Artificial Intelligence	Use
ChatGPT [113]	Image rendering and generation
Claude [15]	Grammar checks and rephrasing, brainstorming, clarifying source material, reference ordering and formatting, vibe coding, help in creating the mobile application interface
Napkin [140]	Graph generation

Table 17: The use of AI