

Department of Electrical Engineering

Research Group
Postbus 513, 5600 MB Eindhoven
The Netherlands
www.tue.nl

Author

Augustin Buzet (1960431)
Can Ak (1960431)
Merijn Verhaak (1979140)
Lelde Grike (1995049)
Soňa Hýblová (2005050)
Mick van Mastwijk (1976672)

Responsible Lecturer
Lorenzo Ceccarelli

Date
June 23, 2025

E-Track

Augustin Buzet (1960431)
a.j.j.m.buzet@student.tue.nl

Can Ak (1960431)
c.ak@student.tue.nl

Merijn Verhaak (1979140)
m.r.m.verhaak@student.tue.nl

Lelde Grike (1995049)
l.grike@student.tue.nl

Soňa Hýblová (2005050)
s.hyblova@student.tue.nl

Mick van Mastwijk (1976672)
m.m.v.mastwijk@student.tue.nl

Table of contents

Title		
E-Track	1 Introduction	1
	1.1 Background	1
	2 How we came up with this idea, design process, inspiration	2
	2.1 The current situation: How are electronics recycled in 2025? Where do they end up	2
	2.2 Inspiration	3
	2.2.1 Droppie	3
	2.2.2 Basel Action Network (BAN)	4
	2.3 Process	5
	2.3.1 First Diamond (Discovery and Definition phase)	5
	2.3.2 Second Diamond (Development and Delivery Phase)	7
	3 Recycling electronics: of our solution	10
	3.1 What is E-Track?	10
	3.1.1 The Software	10
	3.1.2 The Tracker Design	11
	3.2 Integration of different expertise	12
	3.2.1 Computer Science	12
	3.2.2 Electrical Engineering	12
	3.2.3 Industrial Design	12
	3.2.4 Industrial Engineering	12
	3.2.5 Mechanical Engineering	12
	4 Future directions	13
	4.1 The Plan of Action	13
	4.2 Limitations	13
	4.3 Possible improvements	13
	4.3.1 Reelables	13
	4.4 Reflection	14

Table of contents

Title		
E-Track		
	Appendix A Appendix 1	15
	A.1 Questionnaire	15
	Appendix B Code	18
	B.1 Flutter main class	18
	B.2 Flutter Map Widget	23
	B.3 Python Database Synchronisation Script	24
	B.4 ESP32 code for prototype	25
	Appendix C Smart labels details	30
	Appendix D CAD drawings	37

1 Introduction

1.1 Background

Electronics are being consumed more than ever before, creating a massive problem of electronic waste (e-waste). In 2022 66 million tonnes of e-waste were generated and less than one quarter (22.3%) of it was properly collected and recycled [unitar2024]. Despite the slowly increasing awareness of the problem and sustainability, there is still a lack of transparency and a proper system of handling e-waste. A study conducted by Basel Action Network (BAN) tracked 205 old electronics and found that 34% of them were illegally exported mainly to developing countries [ban2017], highlighting the need for a solution that reduces these illegal exports of e-waste and ensures that it gets to the recycling center and is properly recycled.

Several incentives are already being implemented to fight against this issue. For example, EU is implementing a directive that aims to prevent the creation of electrical and electronic equipment waste (WEEE) and contribute to the proper reuse and recycling of electronic waste [ec2012]. Furthermore, the Basel Convention seeks to control the movement of hazardous waste, including electronic waste, and also to restrict its dumping [basel2011].

These efforts are a step in the right direction, but the transparency process for recycling centers and users of electronic devices is not clear. This is where the E-track comes in. The goal is to develop an NGO that tracks e-waste in real time, revealing both to users and organizations whether or not the waste gets to the recycling centers.

2 How we came up with this idea, design process, inspiration

2.1 The current situation: How are electronics recycled in 2025? Where do they end up

E-waste generation hit an all-time high of 62 million metric tons in 2022, with an average generation of 7.8 kg per capita. Out of all this generated e-waste, only an estimated 22.3 % got formally collected and recycled in an environmentally sound manner. Under present trends, projection points to e-waste generation climbing to 82 million metric tons in 2030, while recycling may decrease to 20%. Across regions, recycling rates vary greatly. Africa lies at the lowest end with a recycling rate of less than 1%, whereas Europe stands as the leader with a national recycling rate of 42.8%.

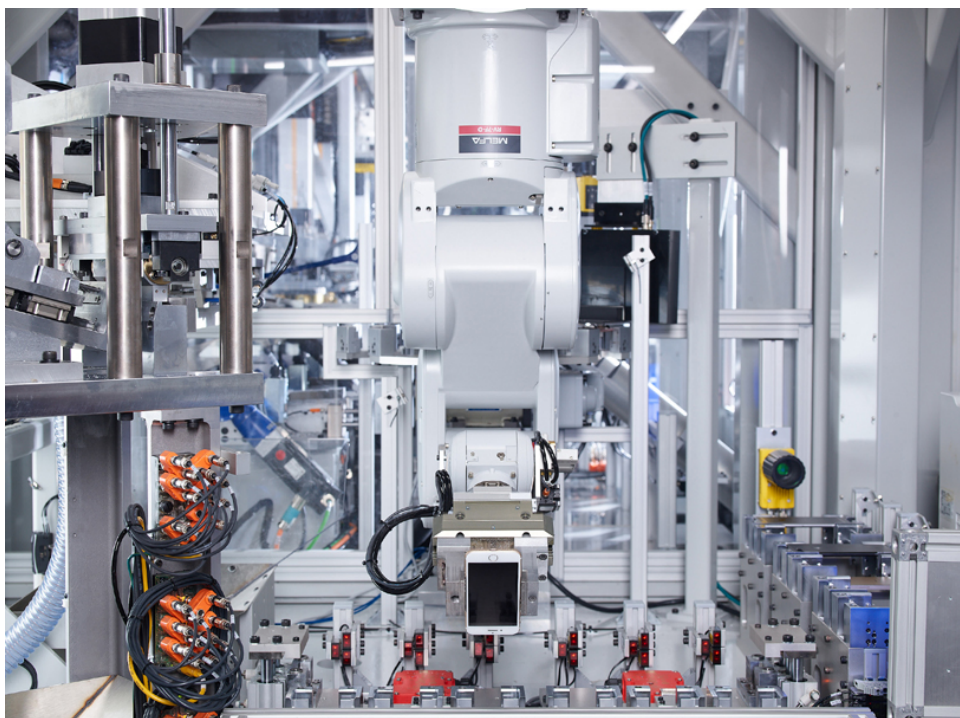


Figure 2.1: Apple recycling center

Some companies like Apple for example have a recycling program. iPhone users can give their broken or used phone to Apple in an Apple store and Apple will recycle it for free.

But other than that, most of the cheap electronics is not recycled. Some companies have also made it hard to recycle their products. It seems sometimes like companies chose on purpose a structure of the product to make it such that it is nearly impossible to recycle.

Disposable vapes is an example of electronic product that is really hard to recycle and the companies making them don't seem to make that much effort in order to recycle them better. Vapes have become increasingly more popular, especially among youth, leading to serious health impacts and environmental ramifications.

Popularity Among Youth Disposable vapes have emerged as the most popular e-cigarette product among youth throughout the United States, Canada, and England. For example, in 2023, disposables were the most commonly used e-cigarette product among vaping youth in all 3 countries (Canada = 58.5%; England = 83.2%; USA = 67.3%). There are a variety of reasons youth have taken to using disposable vapes:



Figure 2.2: e.g. vapes, an electronic product that is hard to recycle

Even though disposable vapes are made of plastics, metals, and lithium-ion batteries: theoretically recyclable materials, they are one of the most difficult materials to recycle. Disposable vapes are designed to be "one unit" making it difficult to disassemble, as they are not designed to be repaired or separated into recyclable materials. Each device is made of complex plastics, several metals (vehicle copper, aluminum, stainless steel), a lithium-ion battery, and electronic circuit boards, all made from specialized materials and then either require specialized equipment or a separate recycling process, which costs more than standard recycling programs can charge for. Additionally, spilled e-liquids often contain dangerous nicotine. These residual liquids can contaminate other materials, hindering their recycling. Usually, the most dangerous aspect of manners is the lithium-ion batteries built into them because of the potential to cause fires if damaged during collection or processing.

2.2 Inspiration

2.2.1 Droppie

Droppie is a Dutch startup that launched in 2023, founded by Natascha Hermsen and Stef Traa. The idea is pretty straightforward: make recycling easier and actually worth people's time. They opened their first hub in Amsterdam in June 2024, and it works kind of like a modern recycling station. You bring in stuff you've sorted at home plastics, textiles, old electronics, cooking oil, ink cartridges, even weird things like tennis balls or wine corks and you get paid for it. The whole thing is managed through their mobile app, which tells you where to go, lets you scan your QR code when you arrive, and then tracks what you've dropped off and how much you've earned.

What makes it a bit different from your usual recycling point is the tech behind it. The Droppie collection spots they call them "Droppers" are fitted with smart sensors and sorting systems. That means they can recognize and handle materials more efficiently, without needing big manual sorting operations behind the scenes. They also run on renewable energy and don't need to be hooked up to the grid, so they can pop up in all kinds of places. You're not just throwing stuff into bins; the system logs the material type and weight, and then you get a small payout, usually around 15 cents per kilo, depending on what you bring.

They've already set up locations in cities like Amsterdam, Utrecht, The Hague, and Rotterdam, and they're working with city governments and other partners to expand. The idea is not just to make recycling more convenient but to shift people's mindset turning waste into something with value. And the app lets you either send your earnings straight to your bank account or donate them to charity if

that's your thing. It's a simple system, but it makes a difference, especially if more people start using it regularly.

At the core, Droppie is about changing habits. It doesn't try to guilt people into recycling; it just gives them a small push through convenience and a bit of cash. And honestly, it works it's easy to use, everything's clean and user-friendly, and it feels more like you're contributing to something that actually loops waste back into the system. The business model:

Droppie makes money by collecting clean, well-sorted recyclable materials from users and then reselling that material to recycling companies who actually want high-quality input, meaning stuff they don't have to sort or clean again. The users get a small payout per kilo through the Droppie app, and that reward basically comes from the margin Droppie makes when they sell the materials on. On top of that, they work with local governments and other partners like waste management companies or sustainability-focused brands who help support or subsidize the system, either financially or through infrastructure. The whole setup is fairly lean: the collection points are automated or semi-automated, often off-grid, so operating costs stay low, and the app handles most of the user interaction and tracking. Over time, all the user and material data they collect could also become a valuable asset for optimizing logistics or proving impact to partners. So clean waste in, small payout to users, higher payout from recyclers, and support from public/private partners to scale.

2.2.2 Basel Action Network (BAN)

The Basel Action Network (BAN) is a worldwide recognized nonprofit organization dedicated to confronting environmental injustice and preserving human health by promoting responsible and ethical management of hazardous waste, particularly electronic waste (e-waste). Founded in response to the concerning trend of wealthy countries disposing of toxic waste in developing countries, BAN has emerged as a prominent voice in support of environmental responsibility, traceability, and transparency in the global e-waste trade.

BAN's work serves as an inspiration for our project. Like BAN, our goal is to combat the electronics life cycle's hidden environmental and social costs by making the recycling process more transparent and trustworthy. BAN's emphasis on data-driven accountability and global ethical standards aligns closely with the vision of our app: to empower users with reliable information on where their electronic waste goes, ensure responsible handling, and build trust in the recycling ecosystem. By following in BAN's footsteps, we aim to foster a culture of conscious consumption and digital responsibility: bridging technology with sustainability for a more equitable future.

2.3 Process

Our project followed a double diamond design process [Design2004], which is conceptualized by two main characteristics: diverging and converging paths, that repeat twice, once for defining the research question, and one for the result/realization of that research question. Diverging is exploring the options, and converging is making decisions. Before truly getting started, we spent the first two weeks orienting ourselves into the topic through disassembling, creating system maps, meeting with stakeholders, and doing research ourselves in the form of SSA's. The first four weeks were characterized with these activities. What became clear to us is that this e-waste problem is a lot more of a social one than a purely engineering one.

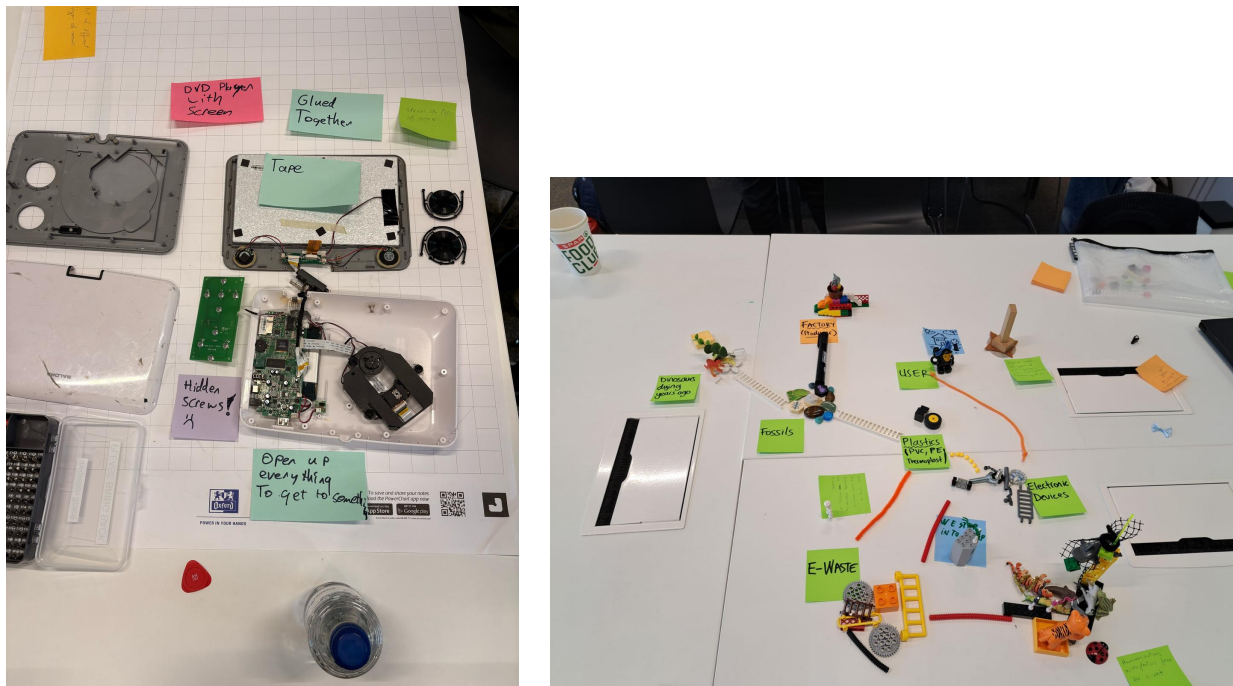


Figure 2.3: First picture: analysis of disassembled DVD player, Second Picture: System map created during the system map workshop

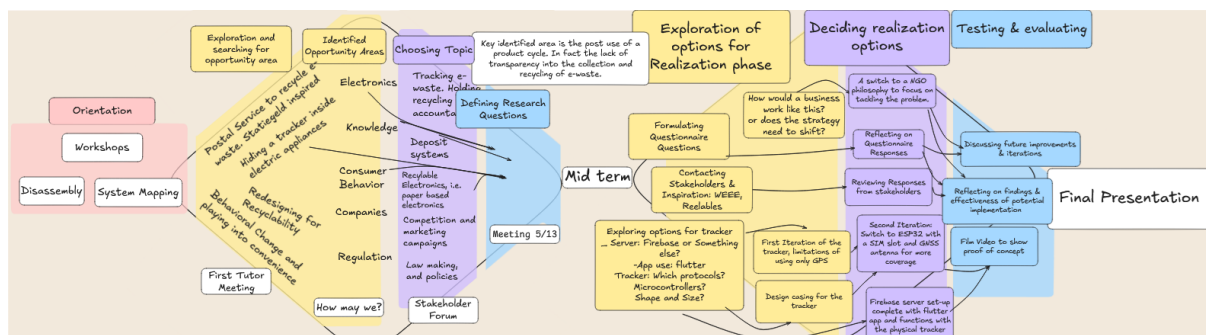


Figure 2.4: The overview of design process

2.3.1 First Diamond (Discovery and Definition phase)

In our first meeting, we discussed areas of interest like Greenwashing, Behavioral Change, making it easier to recycle electronics for consumers, Consumer Rights (Think Right to Repair), and designing

a recyclable, repairable, and cost-effective solutions. Each group member brought their own strengths and expertise, and we tried to find an area where our collective expertise could shine by using the R-strategies. Mainly Rethinking in this case. Then, after the first meeting we had a couple of ideas:

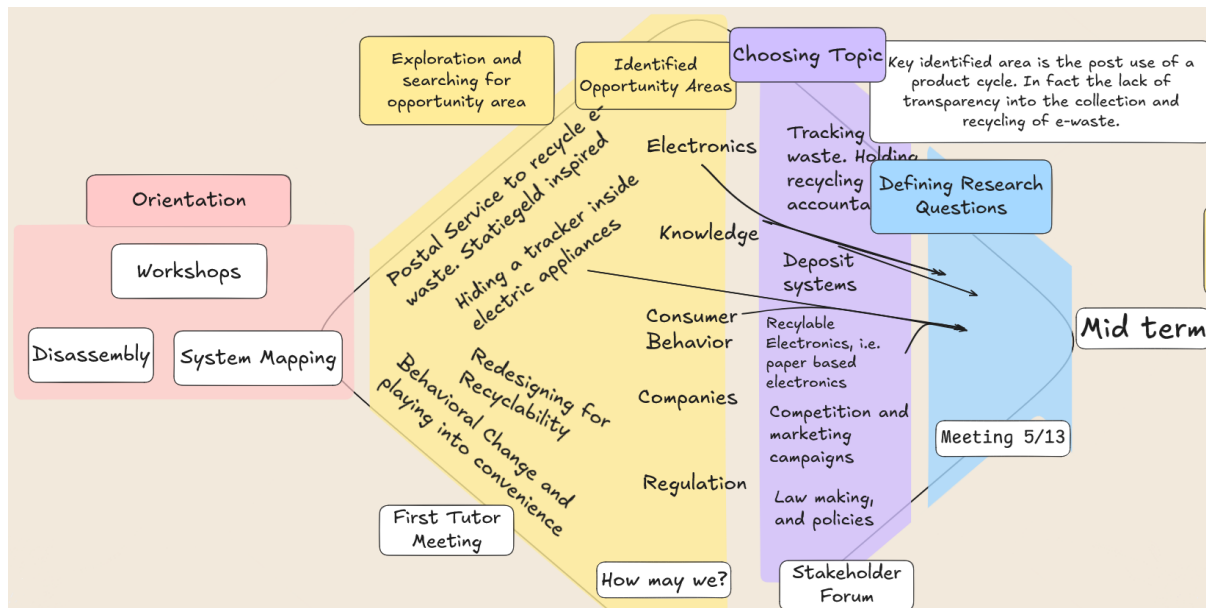


Figure 2.5: The first diamond

- Postal service to collect, track, repair and recycle e-waste.
- *Statiegeld* incentive for electronics.
- Changing the perspective and playing into the consumers convenience.
 - Behavioral Change: Designing Rethinking
 - Redesigning for recyclability
 - * Modularity
 - * Circularity
 - * Right to Repair

The next meeting, after doing more research, some new things came up: A tracker and post box service, where the tracker would be fitted during manufacturing. Inspired from the work by BAN[ban2017]. This raised a lot of ethical concerns. But the overall idea is interesting, since it is a problem that is overlooked. And the idea is a little crazy, but manageable to work out during our project. Another idea is conducting workshops with children or adults about repairing electronics or extended producer responsibility policy, which was too law-focused and out of everyone's expertise to be a good idea.

The main decision on the area of interest was made just before the stakeholder forum, where we could pitch our concept. We landed on the tracker idea again, only we took the postal service and the statiegeld idea, this meant that we would pick up the e-waste, give a tiny compensation towards the user, and mount a tracker into the e-waste in batches. Then sent this out, and have an app where the user and companies alike can see the progress. We drafted up a system map which is seen in figure 2.6. We pitched this to various stakeholders, the overall feedback was positive. PreZero mentioned Droppie as a similar project and raised a key technological flaw: How do you prevent generating e-waste yourself while trying to track that very same thing?

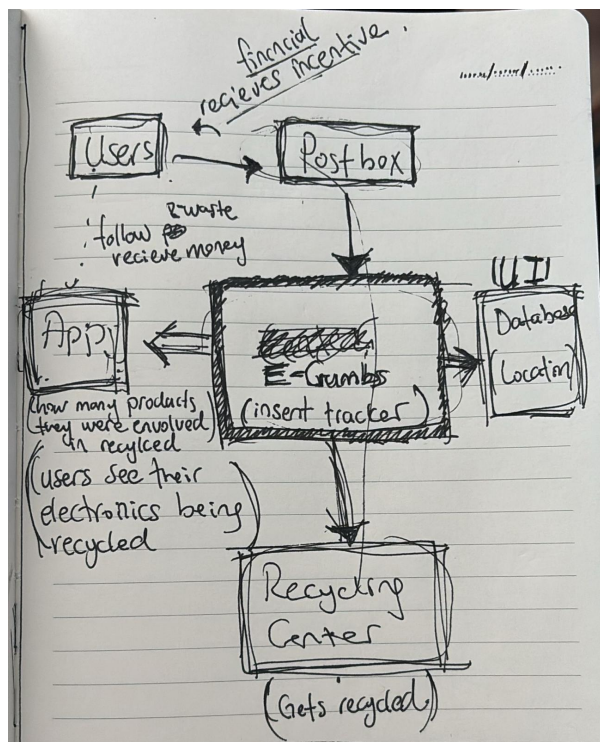


Figure 2.6: System map used for the pitch during the stakeholder forum

The concept is this: We are a business / NGO that collects e-waste from consumers and companies, and adds a tracker to the e-waste per batch, ships it to recycling organizations and see what happens to the e-waste. This can all be followed in an app that the tracker connects to by sending data to the database.

It was time to formulate our research questions, our identified area of interest became the post-use and recycling process of electronics. The goal is to look and try to create more transparency, especially since Western Europe is such a major contributor to these illegal shipments.

The main research question we reached was:

How can we create more transparency in the recycling process, so that both consumers and organizations alike can see the faulty parts of the system?

This is what we presented during the midterm and got overall positive feedback, the main concerns were ethical risks, and how to avoid tampering with the tracker. Additionally, remove the word faulty from the research question, since it assumes a negative/hostile viewpoint towards waste management companies.

We had one last shift in direction while deep in the development phase. It doesn't make economic sense to have a company that buys e-waste, adds a tracker to have that tracker just be destroyed potentially. It bleeds money from all sides. And since you are a business, making a profit is necessary which removes the focus on the core idea. So we shifted to an NGO minded approach, where it allows us to fully try to take on this problem.

2.3.2 Second Diamond (Development and Delivery Phase)

After the mid-term presentation, we got to work on creating a proof of concept for our idea. We had three main things we were working on at the same time:

- Creating a Questionnaire to get a better understanding of the public's perception.

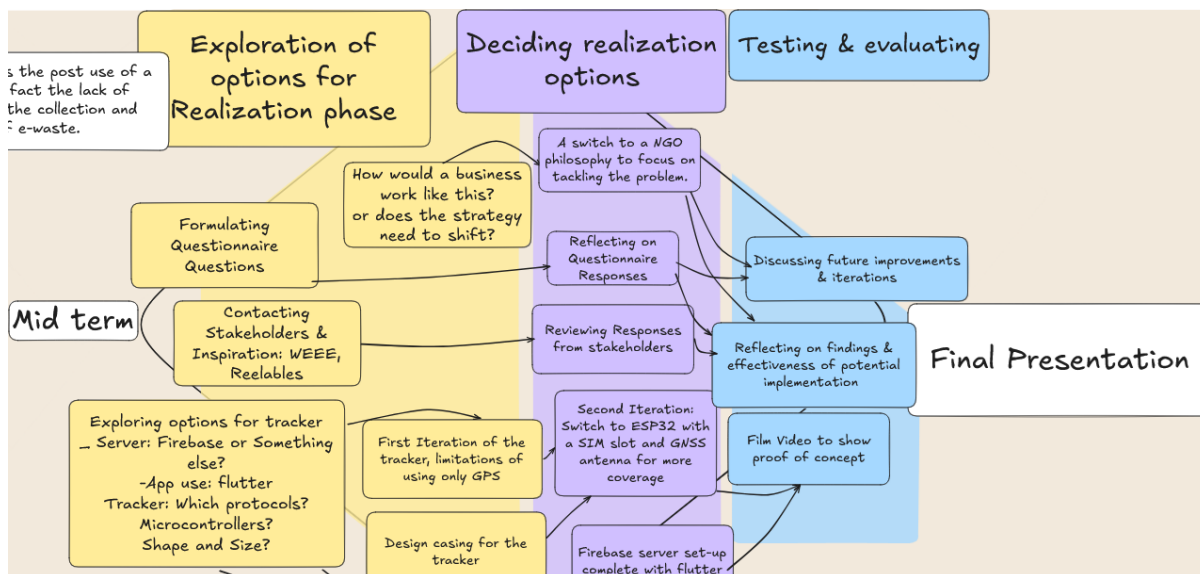


Figure 2.7: The second diamond

- Creating the software and the app for the tracker to send data to.
- Creating the physical tracker.

Questionnaire insights

To better understand the attitudes of potential users of the app, a survey was conducted. Its goal was to explore the current behaviors of the public and help us to evaluate the potential effectiveness of a reward-based recycling system. The questionnaire was online and could be filled out through a link. The mixed format survey design consisted of 15 questions ranging from demographic questions to questions measuring current attitudes towards e-waste, motivation, and openness to change, which could be answered either by multiple choice answers or a Likert scale. The questionnaire is included in Appendix A.

The results of the questionnaire show that most participants care about the environment and are already taking some steps to live more sustainably, such as using public transport or cycling and repairing rather than replacing broken items. Although respondents are aware of the issue with electronic waste, they currently rarely properly dispose of them. Most of the respondents have a minimum of three electronic devices and replace or upgrade them every 2 years or less frequently than that. 46.2 % of participants currently keep the old, unused electronics at home, while 20.5 % give them to someone else, indicating that there is need for change in the current e-waste recycling system. Almost all respondents indicated that if they had to make a small extra effort, they would dispose of the electronics properly.

In addition, 33.3 % of respondents would like to track the whereabouts of their e-waste, while another 33.3% would not mind tracking it. This indicates that there is some demand for the transparency of the e-waste proper disposal from the users themselves.

The findings of the questionnaire validate the projects direction, showing that there is public interest in the proper disposal of e-waste, especially if the process is convenient, transparent, and clear.

Software Process

After the mid-term presentation, we started developing the software part of our solution. Because of the time constraint and some previous experience we decided to use Google's Flutter [flutter], an open-

source framework for building natively compiled (translated directly to machine code without the need for an interpreter or virtual machine at runtime), cross-platform applications. We agreed on building a web application because of better user accessibility. However, using Flutter would allow us to easily expand to mobile apps for Android and iOS using the same codebase. Flutter also makes it easy to integrate Google Maps or other mapping APIs with ready made plugins.

To support a robust project like this, we also needed a database. Mainly to store the user credentials and the tracking data. We decided to use Firebase [**firebase**], a cloud hosted, no SQL database. Firebase offers two database solutions, Firestore[**firestore**] and Realtime Database[**rtldb**]. They differ in structure, Firestore works with collections of documents and other nested collections whereas the Realtime Database is a single JSON tree, which makes it more limited, but better for basic lookups and simple real-time updates. Firestore is more suitable for storing complex data models and allows advanced filtering, sorting and aggregation functions.

Eventually, we ended up using both of them, but at first we only started with integrating the Firestore database with a generic Flutter web app project.

Once we established communication between the web app codebase and the database, we started experimenting with displaying location data stored in the database on a map embedded into our web app. After some trial and error, we managed to display a zoomable world map marking geographic locations stored in the database. Moreover, the marks would react to updates in the database in real time.

Once this was done, we focused on the frontend. We implemented a simple login system and a nicer layout, where the user can see an itemised list of their deposited devices with their latest locations, as well as see them all marked on a world map.

We ran into some issues when trying to integrate the readings from our prototype gps tracker into the system, because Firestore does not allow client authentication on such a low level, as the code that can run on the tracker. However, the simpler Realtime Database also offered by Firebase does allow this. Therefore, we opted for a workaround, where we would publish the live tracker location readings into the Realtime Database and then sync this data with the Firestore database essential for the rest of the software.

The tracker underwent a couple of iterations: setting the requirements, limitations, and parts. The original chip we wanted to use was, but that became unrealistic because of shipping, and cost. The next step was to use an ESP32 together with a NEO M8N GPS module, but given the flaws of GPS that can't be accounted for with other protocols, this iteration was dropped in favor of a Walter[**Walter**] ESP32-S3 microcontroller, which has everything protocol, and features we need built in. After the parts were finalized we designed a shell around the microcontroller.

In the end, we managed to create a system that reads location data from a tracker and displays it user-friendly through a web application.

3 Recycling electronics: of our solution

3.1 What is E-Track?

E-track is an NGO that aims to make the electronics’ recycling process more transparent and efficient. To do so, a web application is used with an "electronic waste tracking system" to give customers a more transparent view of the entire process, providing them with information along the way, and to help detect any fraudulent activity committed by the recycling centers. The optimal solution contains some high-end technologies such as paper-based sticker trackers from "Reelables", which allows the tracker to also have almost no electronic waste added to the electronics that were collected. Due to the lack of communication provided by Reelables, the final product could not contain the paper-based trackers, so an alternative version was made to demonstrate the process of how the software follows trackers that are installed.

3.1.1 The Software

In order to clearly provide all possible information to the user, a web application was designed. Behind the web application, a Firebase Database rests at the heart of the whole system. In this database, trackers upload live information. This information is then read real-time by the web application. The database contains users, each providing their credentials and a collection of their associated devices. This structure provides incredible flexibility as this makes it very easy to add extra users, devices or information about users. In order to automatically upload tracker locations to the database, a python script was made.

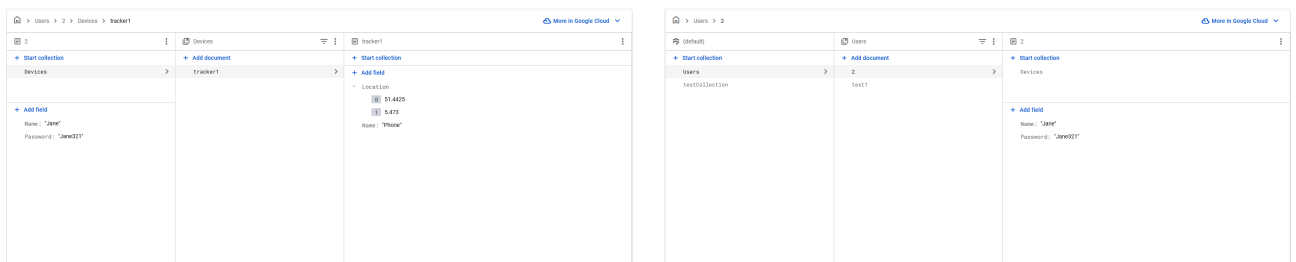


Figure 3.1: Overview of the database structure

Now on to the website itself, this consists of a login screen, which will check provided input against the database to see if it is valid. Once this has been verified, a new main screen will open. This main screen will show the trackers associated to the user who just logged in, it will display these in a list and on a map.

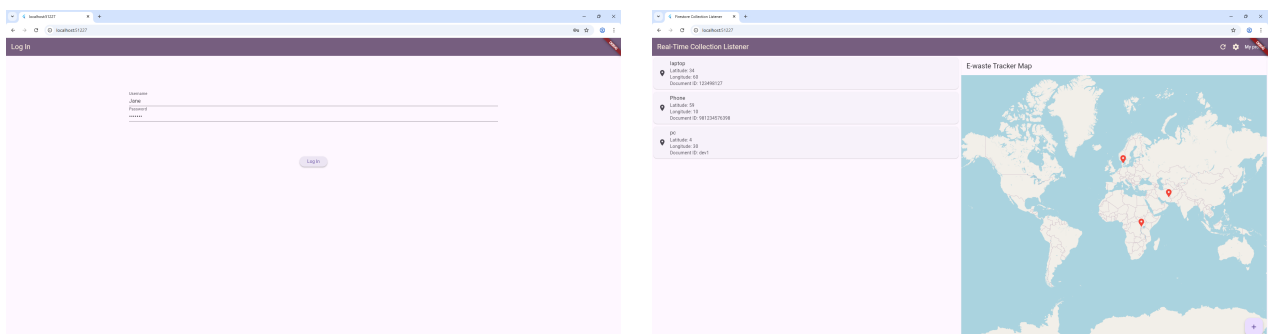


Figure 3.2: Overview of the website

3.1.2 The Tracker Design

To complete the proof of concept, we created a physical tracker. The design of the tracker uses a Walter microcontroller[Walter] which has an ESP32-S3[ESP32] chip with a Monarch 2 GM02SP[Monarch] module built in, the tracker makes use of LTE and GNSS protocols to relay messages. We made the assumption of global coverage of LTE within the Netherlands, which means the tracker should be able to send messages wherever you are in the country. The GNSS protocol functions as a backup in case the LTE can't connect for one reason or another, the biggest limitation of it being that it needs to be in direct contact with a satellite to function properly. Additionally, both require an antenna, which we used the Taoglas FXP611[Taoglas_GNSS] and Taoglas FXUB63.[Taoglas_LTE] The GPS module uses the GNSS protocol, which helps with the software integration process.

This microcontroller is fitted into a 3D printed shell made from PLA. It consists of two parts connected by a pressure fit mechanism. The CAD model for this tracker was created in Fusion 360, and the technical drawings are in the appendix chapter D.

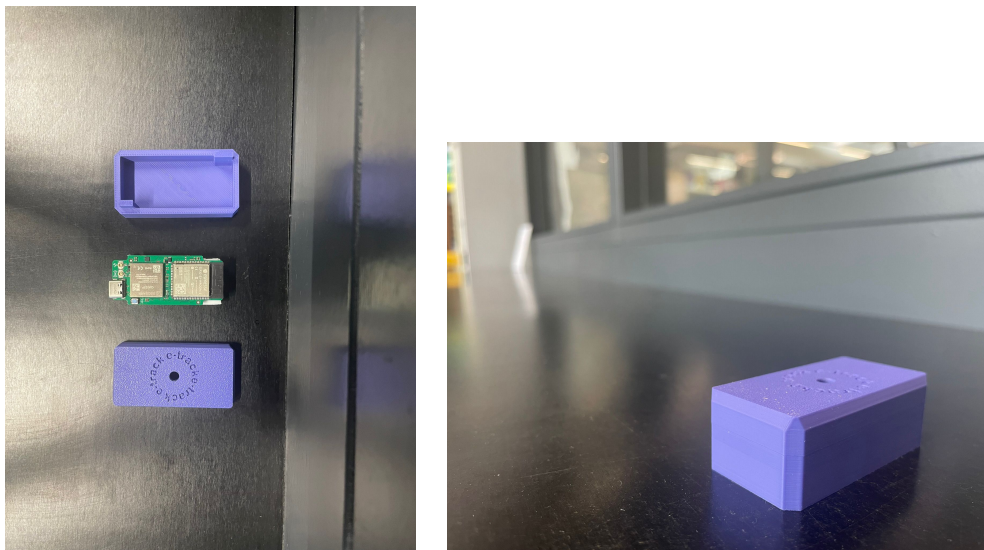


Figure 3.3: The physical tracker

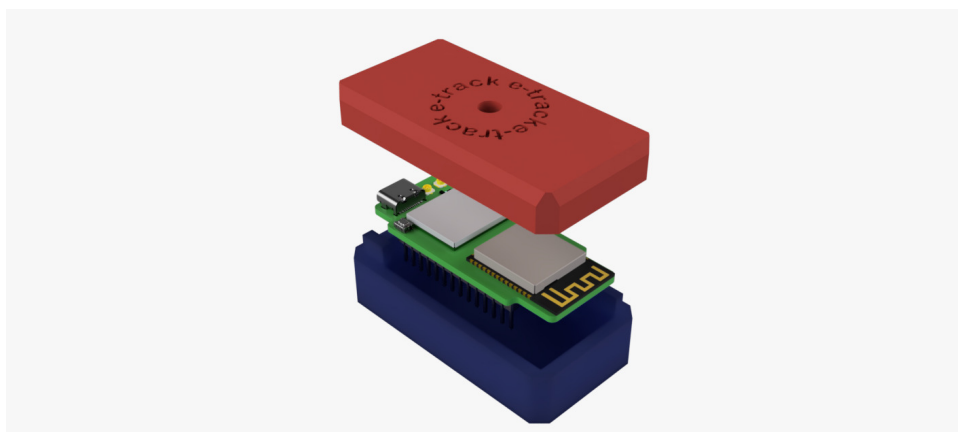


Figure 3.4: Exploded view of the tracker made within Fusion 360

After everything was done and initial tests were working, we set out to go around campus to test the tracker and film a video.

3.2 Integration of different expertise

3.2.1 Computer Science

The Computer Science background of two of our group members came in handy during the implementation phase of our project. We wanted to develop a working proof of concept for our solution, which relies heavily on a nice user interface with the tracking information. To this end, we designed and implemented a web application with a functional backend using theoretical knowledge from past Computer Science courses (like databases, software design and programming) in practice.

3.2.2 Electrical Engineering

Electrical engineering is one of the main areas of expertise that is highly related to this project and the design process. The knowledge that an electrical engineer provides to this interdisciplinary project can range from the simple electronics knowledge that would help better understand the requirements needed to analyze an electronic device, and how it could be better designed to be recycled later on, to designing a tracker module in the case of this specific project.

3.2.3 Industrial Design

Industrial Design is at the core of this project, documenting the process and an open-ended design process where iteration is king. Industrial Design offers a variety of disciplines, meaning that it includes CAD design, prototyping with electronics, mapping out stakeholders, and systems maps. Industrial Design is working towards a well-thought-out concept for a complex issue by analyzing and considering all stakeholders. Getting to control the process in a way that everyone has their part represented in the concept.

3.2.4 Industrial Engineering

Industrial engineering is closely related to this project. It contributes knowledge of circular economics, logistics and supply chain, as well as human factors engineering. Its broad perspective helped to shape the overall concept of the solution, ensuring that the right systems and stakeholders are critically analyzed. Industrial engineering works toward optimizing a practical and scalable framework in a sustainable way.

3.2.5 Mechanical Engineering

Mechanical engineering is also very related to this project. Following some courses such as signals and systems or materials helped me to contribute in this project. Indeed, in our case, we are building a localizer from A to Z and the knowledge I gained from the courses involving coding or building with electronics helped for sure in this CBL. We also learned how to use CAD (Siemens NX), a software that could be helpful in designing some pieces for this project.

4 Future directions

4.1 The Plan of Action

In the end, what we have achieved with this project is mainly an idea for a bigger problem. The prototype will need to go through several more iterations to have something that can be deployed into the field. Another would be to create a system with the stakeholders to collaborate on tackling this issue. The result of this project is not necessarily a well-functioning prototype; the problem is a lot bigger than the current version can handle. We are inclined to believe that for this problem, governmental or regulatory partners are necessary to create a lasting solution that can be scaled up. Acting as a private stakeholder or NGO doesn't make much sense other than creating awareness through smaller scale research like BAN did. For this scale-up, technology like paper-based electronics are ideal as they function as disposable trackers without becoming e-waste themselves. Paper-based electronics are still in their early days, and will improve with time. The database could be improved with time to handle requests from multiple trackers and the front end needs work in displaying more information, and can add more features.

4.2 Limitations

Despite everything we've done and all the future prospects outlined above, our project has its limitations. One of these is the financing of the project. Indeed we have to buy trackers to place on the objects, pay the servers, lockers to put the objects in before they are picked up and so on. The good news is that it is possible to find a solution. For example, we could get partners or sponsors to give us the locators. Our project would also be an NGO. We would then have access to public and private funding (grants, donations, calls for projects and partnerships). NGO status also gives our project greater credibility. Finally, this status allows us to benefit from tax advantages such as exemption from certain taxes (VAT, border tax). So a solution to this funding problem is still possible, but it's not so simple. Another limitation is the coordination we would need to have with recycling centers to successfully implement our project. In fact, we contacted WEEE (Waste Electrical and Electronic Equipment) and presented our project in a few sentences by email. We got an answer a few days later and they did show some doubts regarding the project: (talking about recycling centers "[...]Because they are on the end of the chain they are mostly not the owner of the material. I do understand the use of tracking from the moment it becomes disposal if you want to know what happens then."). Our project could therefore become more realistic according to them if we are using disposable trackers such as the reelables that we mentioned above. Indeed as explained higher in the report, we wanted to take the initiative of building our own tracker. The positive point is that it offers more control on what we want to do with the tracker (we designed the outer box, we chose the components that we want and that are the most adapted). The negative aspect of it is that our "homemade" tracker is much bigger than the ones that are sold by big companies. Our current tracker can therefore be seen as a limitation not in terms of what it does but more in terms of how big it is (its format). Using a tracker such as Reelables would remove this limitation. It's a future improvement to the current limitation.

4.3 Possible improvements

4.3.1 Reelables

Reelables is a company that presented a prototype of smart tracking labels just this January at the CES 2025. These labels fall into the category of paper-based electronics and are therefore lightweight and more eco-friendly than traditional tracking devices and most importantly they do not introduce a significant amount of extra e-waste.



Figure 4.1: 5G labels

The Smart 5G Shipping Labels are supposed to track shipments on cellular and Wi-Fi networks with the label lasting 3 weeks with reporting every 20 minutes, 6 months reporting once a day and up to 12 months reporting every other day. One severe limitation is the constrained transmission range, which is just up to a few kilometers so far. The accuracy ranges from 25 to 500 meters on average depending on location (higher accuracy in urban areas).

The labels are single use with a non-lithium battery making them non-toxic. According to sustainability report by Smurfit Westrock (see in the appendix) on the recyclability of smart tags (not specifically by Reelables) on corrugated boxes, the labels do not have a significant impact on recyclability of the boxes and do not have to be treated as e-waste.

Because of these properties, smart labels seem like a sensible option for a tracking device for our solution. They would solve the issue of imposing additional e-waste and easy detectability by the parties in the recycling process. We tried contacting the company to request a demo kit they offer through their website, but unfortunately got no response.

4.4 Reflection

Our project addresses the global issue of electronic waste. With a combination of research, stakeholder forums, prototyping, and coding, we have come up with the possible solution of electronic waste with E-Track.

Throughout the process the app for tracking transparency of the recycling process of waste as well as a working GPS tracker prototype was made. However there is a lot of further potential in this project as technology improves and e-waste free trackers start to become affordable. Participation is key if this project wants to be deployed into the existing system. This will hopefully reveal good and bad actors, have less critical materials shipped off, contributes to the circular economy by preventing more "leakages", and tackle this unsustainable system for developing nations.

As for our teamwork, we learned how to work together and make use of our expertises. How to integrate software with physical computer design and casing, creating a questionnaire and contacting stakeholders to get more insight into the potential implementation and feasibility as a business or NGO. Although there were some communication issues at times by using terms that not everyone always understood. Additionally, there were some issues with having everyone being on time for meetings. However, this was a smaller problem and did not impact the overall outcome. Everyone contributed their fair share to the project.

A Appendix 1

A.1 Questionnaire

You have been invited to take part in the research project E-Track, because you saw a link or question to fill out this questionnaire from one of the researchers.

Participation in this research project is voluntary: the decision to take part is up to you. Before you decide to participate, we would like to ask you to read the following information, so that you know what the research project is about, what we expect from you and how we deal with processing your personal data. Based on this information you can indicate via the consent declaration whether you consent to take part in this research project and the processing of your personal data.

You may of course always contact the researcher / research manager via m.r.m.verhaak@student.tue.nl, if you have any questions, or you can discuss this information with people you know.

This research project will be managed by Lorenzo Ceccarelli. The purpose of this research project is to create transparency within the recycling process of e-waste.

You will be taking part in a research project in which we will gather information by asking you to fill in a questionnaire 1 time about your behavior in the recycling of e-waste.

This study will be completely anonymous, and the data obtained from the study will not be traceable to you. For your participation in this research project, you will not be compensated.

Your participation in this research project does not involve any physical, legal or economic risks. You do not have to answer questions which you do not wish to answer. Your participation is voluntary. This means that you may end your participation at any moment you choose by letting the researcher know this. You do not have to explain why you decided to end your participation in the research project. Ending your participation will have no disadvantageous consequences for you.

The raw and processed research data will be retained for a period of 1 year. Ultimately after expiration of this time period the data will be either deleted or anonymized so that it can no longer be connected to an individual person. The research data will, if necessary (e.g. for a check on scientific integrity) and only in anonymous form be made available to people outside the research group.

Your anonymized data can be made available for future research, for example by sharing those data with fellow researchers or making anonymized/pseudonymized data available via a data archive or repository.

By filling out the questionnaire you consent that:

- 1) You are sufficiently informed about the research project and that you have read the information above.
- 2) You take part in this research project voluntarily. There is no explicit or implicit pressure for you to take part in this research project. It is clear to you that you can end participation in this research project at any moment, without giving any reason. You do not have to answer a question if you do not wish to do so.

Questions:

1. What is your age?

- under 18
- 18 – 24
- 25 – 34
- 35 – 44

- 45 – 54
- 55 – 65
- 65+

2. What is your gender?

- Male
- Female
- Prefer not to say

3. What is your highest level of education completed?

- No formal education
- High school
- Vocational training
- Bachelor's
- Master's
- Doctorate

4. How much would you say you care about the environment?

(Scale: 1 = Not at all, 5 = Very much)

5. What steps do you take to live more sustainably? (Select all that apply)

- Sorting my trash
- Using public transport or biking
- Repairing instead of replacing broken items
- Choosing energy efficient household appliances
- Buying from sustainable, ethical brands
- Avoiding single-use plastics (e.g., reusable bags, containers, bottles)

6. How many electronic devices (phones, laptops, TVs, etc.) do you or your household currently own?

- 0 – 2
- 3 – 5
- 6 – 10
- 10+

7. How often do you replace or upgrade your electronic devices?

- Multiple times a year
- Every year
- Every 2 – 3 years
- Less than once every 3 years

8. How often do you dispose of electronic devices?

(Scale: 1 = Never, 5 = Always)

9. How do you dispose of old electronics?

- Keep them at home
- Throw them away
- Donate / Recycle
- Give to someone else
- Other: _____

10. What would encourage you the most to change your current disposal habits?

- Concern about the environment
- Financial incentives
- Fees / taxes
- Social pressure
- Convenience
- Legal obligations
- Other: _____

11. If you had to make a small extra effort, would you do it to dispose of electronics properly?

(Scale: 1 = Definitely no, 5 = Definitely yes)

12. Depending on your answer, what would this effort be?

- Handing it in at my local store
- Handing it in at a mailbox
- Getting money back from my e-waste
- Donating it to a second hand store or a charity
- Other: _____

13. How motivated are you to change your current e-waste disposal habits, if you knew the impact it has?

(Scale: 1 = Not motivated at all, 5 = Extremely motivated)

14. Would you make the effort of properly disposing of your old electronic device if you got 10 euros in return for it?

- Yes
- No
- Maybe

15. Would you like to track the whereabouts of your e-waste and the environmental impact of your proper disposal of e-waste?

- Yes
- No
- Maybe

B Code

B.1 Flutter main class

```
import 'package:etrack/tracker_map_page.dart';
import 'package:firebase_auth/firebase_auth.dart';
import 'package:flutter/material.dart';
import 'package:firebase_core/firebase_core.dart';
import 'package:cloud_firestore/cloud_firestore.dart';
import 'package:flutter_dotenv/flutter_dotenv.dart';

void main() async {
  await dotenv.load(fileName: "assets/.env");
  WidgetsFlutterBinding.ensureInitialized();
  await Firebase.initializeApp(
    options: FirebaseOptions(
      apiKey: dotenv.env['FIREBASE_API_KEY']!,
      appId: dotenv.env['FIREBASE_APP_ID']!,
      messagingSenderId: dotenv.env['FIREBASE_MESSAGING_SENDER_ID']!,
      projectId: dotenv.env['FIREBASE_PROJECT_ID']!,
    ),
  );
  runApp(MaterialApp(home: LogIn()));
}

class MyApp extends StatefulWidget {
  final CollectionReference user;
  MyApp({required this.user, Key? key}) : super(key: key);

  @override
  State<MyApp> createState() => MainScreen();
}

class MainScreen extends State<MyApp> {
  final FirebaseFirestore firestore = FirebaseFirestore.instance;

  @override
  Widget build(BuildContext context) {
    CollectionReference user = widget.user;

    return MaterialApp(
      title: 'Firestore Collection Listener',

      home: Scaffold(
        appBar: AppBar(
          title: const Text('Real-Time Collection Listener'),
          backgroundColor: const Color.fromARGB(200, 80, 52, 92),
          foregroundColor: const Color.fromARGB(255, 248, 236, 220),
          actions: [
            IconButton(
              icon: const Icon(Icons.refresh),
```

```

        onPressed: () {
          setState(() {
            // Trigger a rebuild to refresh the data
          });
        },
      ),
    IconButton(
      icon: const Icon(Icons.settings),
      onPressed:
        (
          // You can add functionality here if needed
          // For example, navigate to a settings page
        ) {
          // Navigate to settings or another page if needed
        },
    ),
    IconButton(
      icon: Text('My profile', style: TextStyle(color: Colors.white)),
      onPressed: () {
        setState(() {
          // Trigger a rebuild to refresh the data
        });
      },
    ),
  ],
),

body: Row(
  children: [
    Expanded(
      child: StreamBuilder<QuerySnapshot>(
        stream: user.snapshots(),
        builder: (context, snapshot) {
          print('Listening to user collection changes...');
          if (snapshot.hasError) {
            return const Center(child: Text(' Error loading data'));
          }
          if (!snapshot.hasData) {
            return const Center(child: CircularProgressIndicator());
          }

          final docs = snapshot.data!.docs;

          return ListView.builder(
            itemCount: docs.length,
            itemBuilder: (context, index) {
              final doc = docs[index];
              final data = doc.data() as Map<String, dynamic>;

              return Card(
                child: ListTile(

```

```

        title: Text('${data['Name']} ?? 'No tracker)'),
        leading: const Icon(Icons.location_on),
        subtitle: Column(
          crossAxisAlignment: CrossAxisAlignment.start,
          children: [
            Text(
              'Latitude: ${data['Location'][0]?.toString() ??
            ),
            Text(
              'Longitude: ${data['Location'][1]?.toString() ??
            ),
            Text('Document ID: ${doc.id}'),
          ],
        ),
      ),
    ),
  );
},
);
),
),
Expanded(
  child: Card(child: TrackerMapPage(devices: user)),
),
],
),
floatingActionButton: FloatingActionButton(
  onPressed: _addNewDocument,
  child: const Icon(Icons.add),
),
),
);
}

Future<void> _addNewDocument() async {
  await firestore.collection('testCollection').add({
    'message': 'New message at ${DateTime.now().toIso8601String()}',
  });
  print('New document added');
}
}

class LogIn extends StatefulWidget {
  const LogIn({super.key});

  @override
  State<LogIn> createState() => _LogInState();
}

class _LogInState extends State<LogIn> {

```

```
final FirebaseFirestore firestore = FirebaseFirestore.instance;

@override
Widget build(BuildContext context) {
  String userentered = '';
  final TextEditingController userController = TextEditingController();
  final TextEditingController passController = TextEditingController();

  return Scaffold(
    appBar: AppBar(
      title: const Text('Log In'),
      backgroundColor: const Color.fromARGB(200, 80, 52, 92),
      foregroundColor: const Color.fromARGB(255, 248, 236, 220),
    ),

    body: Row(
      children: [
        Expanded(flex: 2, child: Container()),
        Expanded(
          flex: 6,
          child: Column(
            children: [
              Spacer(flex: 1),
              TextField(
                decoration: InputDecoration(
                  border: UnderlineInputBorder(),
                  labelText: 'Username',
                ),
                onChanged: (String username) {
                  // Handle username submission
                  userentered = username;
                },
                controller: userController,
              ),

              TextField(
                decoration: InputDecoration(
                  border: UnderlineInputBorder(),
                  labelText: 'Password',
                ),
                obscureText: true,
                controller: passController,
              ),
              Spacer(flex: 1),

              ElevatedButton(
                onPressed: () {
                  CollectionReference users = firestore.collection('Users');
                  users
                    .where(
                      'Name'.toString(),
```

```

        isEqualTo: userController.text,
      )
      .limit(1)
      .get()
      .then((snapshot) {
        if (snapshot.docs.isNotEmpty) {
          // User exists, proceed with login
          DocumentSnapshot user = snapshot.docs.first;
          print(user.data());
          if (user['Password'] == passController.text) {
            Navigator.of(context).push(
              MaterialPageRoute(
                builder: (context) => MyApp(
                  user:
                    user.reference.collection('Devices')
                      as CollectionReference,
                ),
              ),
            );
          } else {
            ScaffoldMessenger.of(context).showSnackBar(
              SnackBar(
                content: Text('Invalid username or password'),
                duration: Duration(seconds: 2),
              ),
            );
          }
        } else {
          ScaffoldMessenger.of(context).showSnackBar(
            SnackBar(
              content: Text('User not found'),
              duration: Duration(seconds: 2),
            ),
          );
        }
      });
    },

    child: const Text('Log In'),
  ),
  Spacer(flex: 5),
],
),
),
Expanded(flex: 2, child: Container()),
],
),
);
}
}

```

B.2 Flutter Map Widget

```
import 'package:flutter/material.dart';
import 'package:flutter_map/flutter_map.dart';
import 'package:cloud_firestore/cloud_firestore.dart';
import 'package:latlong2/latlong.dart';

class TrackerMapPage extends StatelessWidget {
  final CollectionReference devices;
  TrackerMapPage({required this.devices});

  @override
  Widget build(BuildContext context) {
    return Scaffold(
      appBar: AppBar(title: Text('E-waste Tracker Map')),
      body: StreamBuilder<QuerySnapshot>(
        stream: devices.snapshots(),
        builder: (context, snapshot) {
          if (!snapshot.hasData)
            return Center(child: CircularProgressIndicator());

          final markers = snapshot.data!.docs
            .map((doc) {
              final data = doc.data() as Map<String, dynamic>;
              final lat = data['Location'][0]?.toDouble();
              final lng = data['Location'][1]?.toDouble();
              final label = data['Name'] ?? 'Unknown';

              if (lat == null || lng == null) return null;

              return Marker(
                width: 40.0,
                height: 40.0,
                point: LatLng(lat, lng),
                child: Tooltip(
                  message: label,
                  child: Icon(
                    Icons.location_pin,
                    color: Colors.red,
                    size: 30,
                  ),
                ),
              );
            })
            .whereType<Marker>()
            .toList();

          return FlutterMap(
            options: MapOptions(center: LatLng(20.0, 0.0), zoom: 2.0),
            children: [
              TileLayer(
```

```
        urlTemplate:
            'https://{s}.tile.openstreetmap.org/{z}/{x}/{y}.png',
        subdomains: ['a', 'b', 'c'],
    ),
    MarkerLayer(markers: markers),
],
);
},
),
);
}
```

B.3 Python Database Synchronisation Script

```
import firebase_admin
from firebase_admin import credentials, firestore, db
from typing import List
import time

LOCATION = "python_db_interaction\location.json"
DIRECTORY = "python_db_interaction\\"
SERVICE_ACCOUNT_KEY = "python_db_interaction\serviceAccountKey.json"

cred = credentials.Certificate(SERVICE_ACCOUNT_KEY)
default_app = firebase_admin.initialize_app(cred, {
    'databaseURL': 'https://etrack-607ac-default-rtdb.europe-west1.firebaseio.com'
})

firestore_db = firestore.client()

# Access Realtime Database
rtdb_ref = db.reference('/device_data/wifi_tracker1/location')

# Get a Firestore client
db_fs = firestore.client()

#updates a document specified by doc_ref to a specified array value
def update_loc():
    location = rtdb_ref.get()
    print(location)
    try:
        loc = [float(location['lat']), float(location['lng'])]
        print(loc)
        tracker = 'tracker1'
        doc_ref = db_fs.collection("Users").document("2").collection("Devices")
        doc_ref.update({
            "Location": loc
        })
```

```

    except:
        print("invalid location")

#polling
last_value = None

while True:
    value = rtdb_ref.get()
    if value != last_value:
        update_loc()
        last_value = value
    time.sleep(2)

```

B.4 ESP32 code for prototype

```

// =====
// E-track proof of concept
// For this proof of concept we used wifi to test the Google Geolocation API
// and connect to the internet via a hotspot.
// To make this tracker work with GNSS and SIM, some GNSS functions need to be a
// and for LTE, swap out the Wifi library for the tinyGSM library
// and change the functions according to that library.
// It should function similarly
// =====

// STEP 1: Enable the required library features.
#define ENABLE_DATABASE
#define ENABLE_SERVICE_AUTH

#include <FirebaseClient.h>
#include <WiFi.h>
#include <HTTPClient.h>
#include <ArduinoJson.h>
#include <FirebaseJson.h>
#include "ExampleFunctions.h"

// --- Wi-Fi Credentials ---
#define WIFI_SSID "Wifi name or Hotspot name"
#define WIFI_PASSWORD "Wifi password"

// --- Google Geolocation API Key ---
String GOOGLE_API_KEY = "API_KEY";

// --- Firebase Service Account Credentials ---
#define FIREBASE_PROJECT_ID "etrack-607ac"
#define FIREBASE_CLIENT_EMAIL "firebase admin email"
#define FIREBASE_DATABASE_URL "database url"
const char FIREBASE_PRIVATE_KEY[] PROGMEM = "-----BEGIN PRIVATE KEY-----\n"

```

```
// The full string is too long to keep in one line for the ESP to handle,
// parse the string after every \n
// 15 lines of private key strings later
"-----END PRIVATE KEY-----\n";

// --- Global Firebase Objects ---
ServiceAuth sa_auth(FIREBASE_CLIENT_EMAIL, FIREBASE_PROJECT_ID,
FIREBASE_PRIVATE_KEY, 3600);
FirebaseApp app;
RealtimeDatabase db;

// --- Declare SSL and AsyncClient objects
SSL_CLIENT ssl_client;
using AsyncClient = AsyncClientClass;
AsyncClient aClient(ssl_client);

// --- Timing Control ---
unsigned long lastUpdateTime = 0;
const long updateInterval = 60000; // 60 seconds

void setup() {
  Serial.begin(115200);
  WiFi.begin(WIFI_SSID, WIFI_PASSWORD);
  Serial.print("Connecting to Wi-Fi");
  while (WiFi.status() != WL_CONNECTED) {
    Serial.print(".");
    delay(300);
  }
  Serial.println();
  Serial.print("Connected with IP: ");
  Serial.println(WiFi.localIP());

  // --- Firebase Initialization ---
  set_ssl_client_insecure_and_buffer(ssl_client);
  app.setTime(get_ntp_time());
  initializeApp(aClient, app, getAuth(sa_auth));
  app.getApp<RealtimeDatabase>(db);
  db.url(FIREBASE_DATABASE_URL);
}

void loop() {
  // Handle Firebase tasks on the background
  app.loop();

  // Check if Firebase is ready and if the update interval has passed.
  if (app.ready() && millis() - lastUpdateTime > updateInterval) {

    lastUpdateTime = millis();

    // --- Step 1: Scan for WiFi Networks ---
```

```
Serial.println("[1] Scanning for WiFi networks...");
int n = WiFi.scanNetworks();

if (n == 0) {
    Serial.println("[!] Scan failed: No WiFi networks found. Starting again.");
    Serial.println("-----\n");
    return; // Exit this update cycle
}
// Serial.printf("[1] Scan complete. Found %d networks.\n", n);
// ----- For debugging

// --- Step 2: Create JSON payload for Google ---
Serial.println("[2] Creating JSON payload for Google API...");
DynamicJsonDocument jsonBuffer(2048);
JsonArray wifiAccessPoints = jsonBuffer.createNestedArray("wifiAccessPoints");

int numNetworksToSend = min(n, 10);
// Serial.printf("[2] Limiting payload to the strongest %d networks.\n"
, numNetworksToSend); //----- For debugging

for (int i = 0; i < numNetworksToSend; ++i) {
    JsonObject wifi_object = wifiAccessPoints.createNestedObject();
    wifi_object["macAddress"] = WiFi.BSSIDstr(i);
    wifi_object["signalStrength"] = WiFi.RSSI(i);
}
String payload;
serializeJson(jsonBuffer, payload);
Serial.println("[2] Google JSON payload created."); // ----- for debugging

// --- Step 3: Send request to Google Geolocation API ---
HTTPClient http;
String url = "https://www.googleapis.com/geolocation/v1/geolocate?key="
+ GOOGLE_API_KEY;
http.begin(url);
http.addHeader("Content-Type", "application/json");

// Serial.println("[3] Sending POST request to Google..."); ----- for debugg
int httpCode = http.POST(payload);
// Serial.printf("[3] Google response received. HTTP Code: %d\n", httpCode); -

if (httpCode > 0) {
    Serial.println("[4] Reading Google's response...");
    String response = http.getString();

    Serial.println("[4] Parsing Google's JSON response...");
    DynamicJsonDocument doc(1024);
    deserializeJson(doc, response);

    if (doc.containsKey("location")) {
        Serial.println("[4] Location key found in response.");
    }
}
```

```
double lat = doc["location"]["lat"];
double lng = doc["location"]["lng"];
double accuracy = doc["accuracy"]; // ----- confidence of the data p

Serial.printf("Location: %.6f, %.6f\n", lat, lng);

// --- Step 5: Create JSON payload for Firebase ---
// Serial.println("[5] Creating JSON object for Firebase...");
// ----- for debugging
FirebaseJson json;
json.set("location/lat", lat);
json.set("location/lng", lng);

String path = "/device_data/wifi_tracker1";
// Serial.printf("Sending data to Firebase path: %s\n", path.c_str());
// ----- for debugging

// --- Step 6: Send data to Firebase
String jsonString;
json.toString(jsonString, false);
// Convert the FirebaseJson object to a string
Serial.printf("--> Attempting to send this JSON: %s\n",
, jsonString.c_str()); // for debugging

Serial.println("[6] Sending data to Firebase using set<object_t>...");

if (db.set<object_t>(aClient, path, object_t(jsonString))) {
    Serial.println("[6] Firebase update successful.");
} else {
    Serial.println("[!] Firebase update failed.");
    //----- for debugging
    Firebase.printf("Error, msg: %s, code: %d\n", aClient.lastError().
message().c_str(), aClient.lastError().code());
    //----- for debugging
}
} else {
    // Serial.println("[!] Google response did
    // not contain a 'location' key.");
    //----- for debugging
    // Serial.printf("Full Google Response: %s\n", response.c_str());
    //----- for debugging
}
} else {
    // Serial.println("[!] HTTP request to Google failed.");
    //----- for debugging
}

// Serial.println("[7] Cleaning up HTTP client..."); //----- for debugging
http.end();
// Serial.println("[7] Cleanup complete."); //----- for debugging
```

}

}

C Smart labels details

4" x 8"
(101 mm x 200 mm x 0.5 mm)



Smart 5G Shipping Labels from Reelables

Print, ship, and track —
around the world.

Introducing Reelables 5G labels, the world's first paper-thin, printable shipping label that tracks shipments on cellular and Wi-Fi networks.

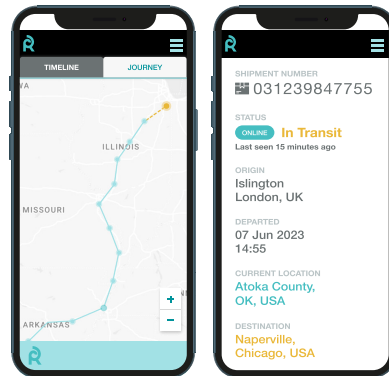
Finally, know for real where your package is and when it will arrive. Keep track of time-critical shipments in real-time to plan ahead, ensure accountability, and proactively address shipping exceptions.

It's simple. Just print on Reelables 5G labels as you would normally using thermal barcode printers. The flexible, ultra-thin electronics inside begin tracking location the moment they're printed, tapped with an NFC-enabled device, or torn in the corner. No batteries, no buttons, no special processes or extra work.

Once provisioned, the location of your shipment is tracked online with a sharable link. The label will last three weeks with 20-minute reporting, six months with once-a-day reporting, and 12 months with every-other day reporting.

Reelables 5G labels are also disposable and recyclable on ordinary corrugated paper boxes. No return logistics required. A non-lithium battery directly coated on the label substrate means the labels are nontoxic and non-dangerous goods.

Whether you're a shipper, supplier, consignee, or logistics provider, get started today with an early adopters kit of ten labels, [available here](#).



Features

- Printable in off-the-shelf barcode printers
- Print, tap, or tear to activate
- Single use, no return logistics required
- NB-IoT/Wi-Fi/Bluetooth functionality
- Non-Lithium battery (not dangerous goods)

Key Parameters

- Active lifespan: 3 weeks, 6 months, or 1 year
- Storage shelf life: 1 year
- Transmission range – Urban: 1 km (0.5 mi)
– Rural: 5 km (3 mi)
- Accuracy (average): – Urban: +/- 25 m
– Rural: +/- 500 m
- Temperature logging: +/- 0.5 °C

reelables.com

Detailed specifications

Thermal Transfer (TT)

Material Construction	
Facestock	Direct thermal paper
Adhesive	Permanent acrylic
Liner	120 gsm glassine
Total thickness (±10%)	0.56 mm
Environment	Indoor/Outdoor IP62

Temperature Performance

Minimum application temp.	8 °C (46 °F)
Operating temp. range	-20 °C to 60 °C (-4 °F to 140 °F)

Recommended Printers and Ribbons

Printers	Sato CLNX4, WWCLP180ZNR
Ribbons	N/A

Adhesive Strength

Corrugate	0.14 N-m (20 oz in)
Polycarbonate	0.39 N-m (55 oz in)
Polyethylene	0.24 N-m (34 oz in)

Chemical Resistance

Weak chemicals	Test in application
Harsh chemicals	Not recommended

Electrical specification

- NB-IoT:
 - Release 14 Cat. NB2 IoT
 - Supported bands: 5, 8, 12, 13, 20, 28, 85
 - 20 dBm transmit power (PowerClass 5)
- Bluetooth
 - Bluetooth version 5.1
 - Frequency 2.402 GHz to 2.480 GHz
 - Beacon interval (active) 10 sec
- NFC
 - Passive HF NFC 13.56 MHz
- Wi-Fi
 - 2.4 GHz (2.4835 GHz) Location Services
- Battery coating Zinc-Manganese
- No Lithium components

Environmental

- RoHS Directive 2011/65/EU
- (EU) 2015/863 Annex II

Regulatory

- FCC-ID 2A7TQRN0001
- CE, DO-160



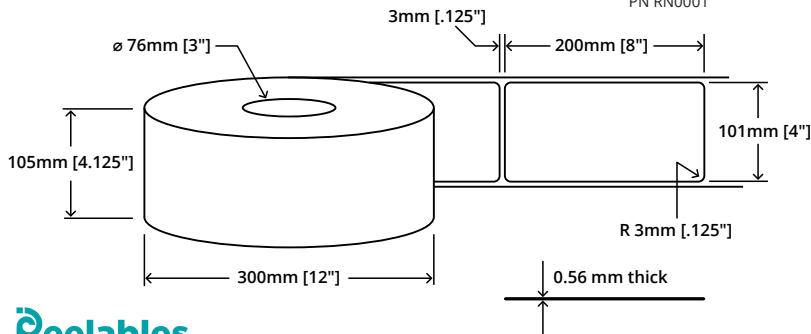
Current coverage

USA, UK, China, Hong Kong, Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Malta, Mexico, Netherlands, Norway, Portugal, Romania, S. Africa, Slovenia, Spain, Sweden, Switzerland, Taiwan

Coverage is continuously updated. Contact Reelables for the latest list.

Ordering information

PN RN0001





RESEARCH SUMMARY

Smart Tags and Recyclability

Paper | Packaging | Solutions

Summary

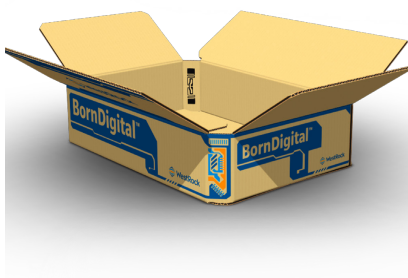
Connectivity with devices, such as smartphones and logistics systems in warehouses and retail stores, is needed for asset tracking. To connect packages with those devices, the primary technology is smart labels, which use small antennas to emit radio waves. With the need for asset tracking and the increasing market shift to sensor-enabled packaging, brands concerned with the sustainability are asking questions about the impact of smart tags on the recyclability of their corrugated packaging within typical recycling systems.

Smurfit Westrock worked with Western Michigan University (WMU) to conduct a recyclability study on corrugated boxes with smart labels used for asset tracking. The study evaluated a variety of labels including RFID and BLE (Bluetooth low-energy) technology laminated with both plastic and paper backings.

The general results of the pilot work showed that the smart labels did not have a significant impact on the recyclability of corrugated boxes. Based on analysis and observations, repulpability and on-machine processing were not impacted by the tags in this study.



Background



NCASI (National Council for Air and Stream Improvement) previously studied the recyclability of RFID tags at the request of the Fibre Box Association (FBA) in 2005. This study was also performed in the recycling pilot plant at WMU, and it included both laminated copper antennas and printed silver antennas. Laminated tags separated during the repulping process with little negative impact. NCASI further evaluated the concentrations of silver, the metal used to print the antenna of the tag, in environmental outputs and found that regulatory limits would not be exceeded.

Although the industry has previously studied the impact on recycling boxes with RFID tags, there have been significant technological changes in the size and composition of smart labels since that time. This study builds on and evolves the previous work.

Scope

Using a pilot plant scale recycling and paper making lab, this study evaluated the impact on technical recycling of a standard-sized box tagged with a single smart label. There was no presumption that the tags themselves would be separated for recycling. The study was designed to cover a range of smart labels and was performed at WMU's Paper Pilot Plant with analysis at Smurfit Westrock laboratories.

Label Selection Criteria: Smurfit Westrock designed the test using a variety of labels commonly used for asset-tracking worldwide, including RFID, BLE, active (battery-enabled) and passive. The four labels selected for this study were meant to represent the various smart labels commonly used in the U.S. marketplace. These labels were not meant to be, and should not be, viewed as Smurfit Westrock recommendations.

Tag Type	Plastic-Backed RFID	Paper-Backed RFID	BLE No Battery	BLE with Battery
Tag Size	70 x 14.5 mm (2.8" x 0.6")	92 x 27 mm (3.6" x 1.1")	44 x 28 mm (1.7" x 1.1")	101 mm x 48 mm (4" x 1.9")
Technology	UHF RFID	UHF RFID	Bluetooth	Bluetooth
Battery Y/N	No	No	No	Yes
If Y, Battery Composition	-	-	-	Zn-Mn carbon and silver electrodes
Carrier or Inlay Material	Clear PET	Paper	PET	Polyurethane foam
Antenna Material	Aluminum	Printed silver	PET copper laminate	Aluminized PET
Facing Materials	Opaque PET	Unknown	Black polyester, white PET/PP, clear PET	Polypropylene top laminate
Weight	0.00042 lb / 0.191 g	0.00129 lb / 0.585 g	0.00076 lb / 0.343 g	0.00632 lb / 2.869 g

Recyclability test method and results

WMU conducted the study over three days using untagged boxes as a control and the smart tags as the only variable. Each box was labeled with one of four different types of smart labels.

The batch size was 135 boxes, with one smart label per box, and weighed 200 lbs.

To recycle boxes, they need to be "repulped" so the fiber can be extracted to make new boxes. For processing, the boxes are added to a pulper, which agitates the boxes with water to form a pulp slurry. The pulp is then pumped through extraction plates to remove any large non-fibrous materials (in this case, the smart labels).

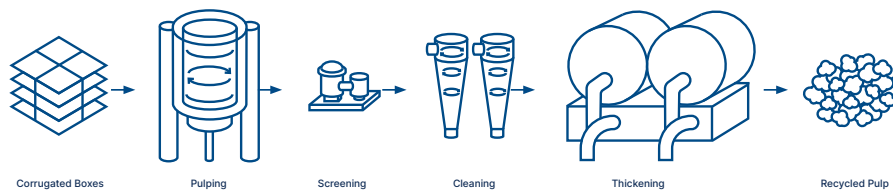
At the end of each pulper run, the operator entered the pulper (following safety procedures) and removed any labels that did not pass through the extraction plates. The smart

labels with plastic backings were separated from the fiber at the pulper extraction plate. The repulpable labels passed completely through the extraction plates and were repulped along with the boxes.

Following pulp production, the batches were screened, cleaned and used to produce paper on the pilot machine. These steps of the process indicated no differences between the control and the tagged boxes.

Acquiring WMU certification for recyclability was not possible with this study because the protocol calls for pulping 20% of the studied product with 80% of a control. This study called for labeling 100% of the test boxes.

The Recycling Process



During this study, smart labels separated from the fiber during this process and were collected from the pulper after the completion of the recycling run.

Metal content and detection

Metal detection is used in many industries as a safety critical control parameter, and metal particles in packaging can trigger these systems. Because metals are used in printing smart label antennas and the repulpable labels were repulped along with the boxes, we needed to study whether that metal would end up in the paper samples made from the repulped boxes. Also, if metal did exist in the samples, would concentrations be high enough to be detected by metal detectors?

We tested the paper samples we made from the repulped boxes for residual metals. None of the paper samples contained sufficient metals to trigger metal detection on the typical equipment currently used for evaluating consumer packaging board. A Safeline metal detector was used to check for metal content and none of the sheets made with pulp from the smart-tagged corrugated boxes triggered a response.

Limitations and implications

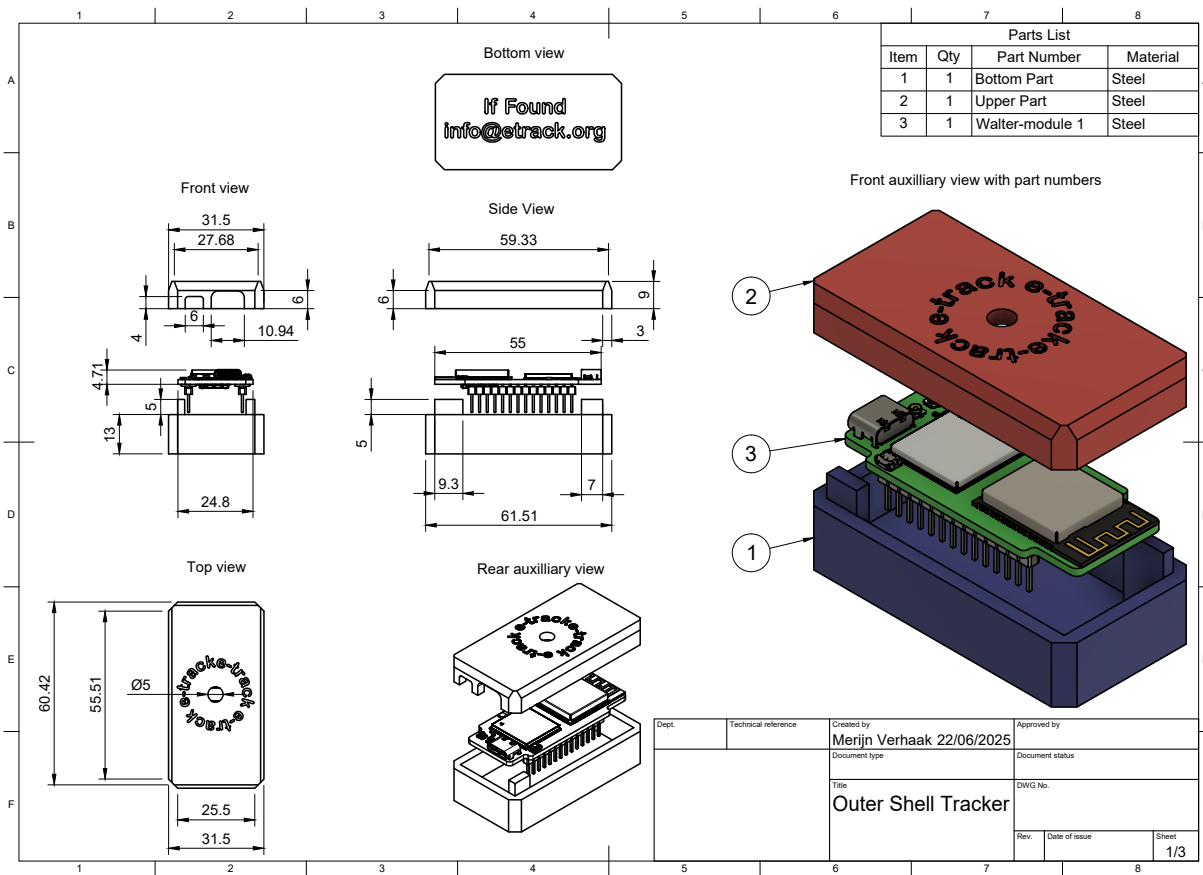
The fiber recycling process at the WMU pilot plant is a batch process (not continuous). As a result of the lack of secondary screening/cleaning and small amounts processed, the total fiber yield across the pilot process is approximately 50%, which is significantly lower than commercial yield. Additionally, the process water is not recirculated, so it is not possible to investigate possible contamination build-up from the short runs. This study was not intended to generate environmental impact data.

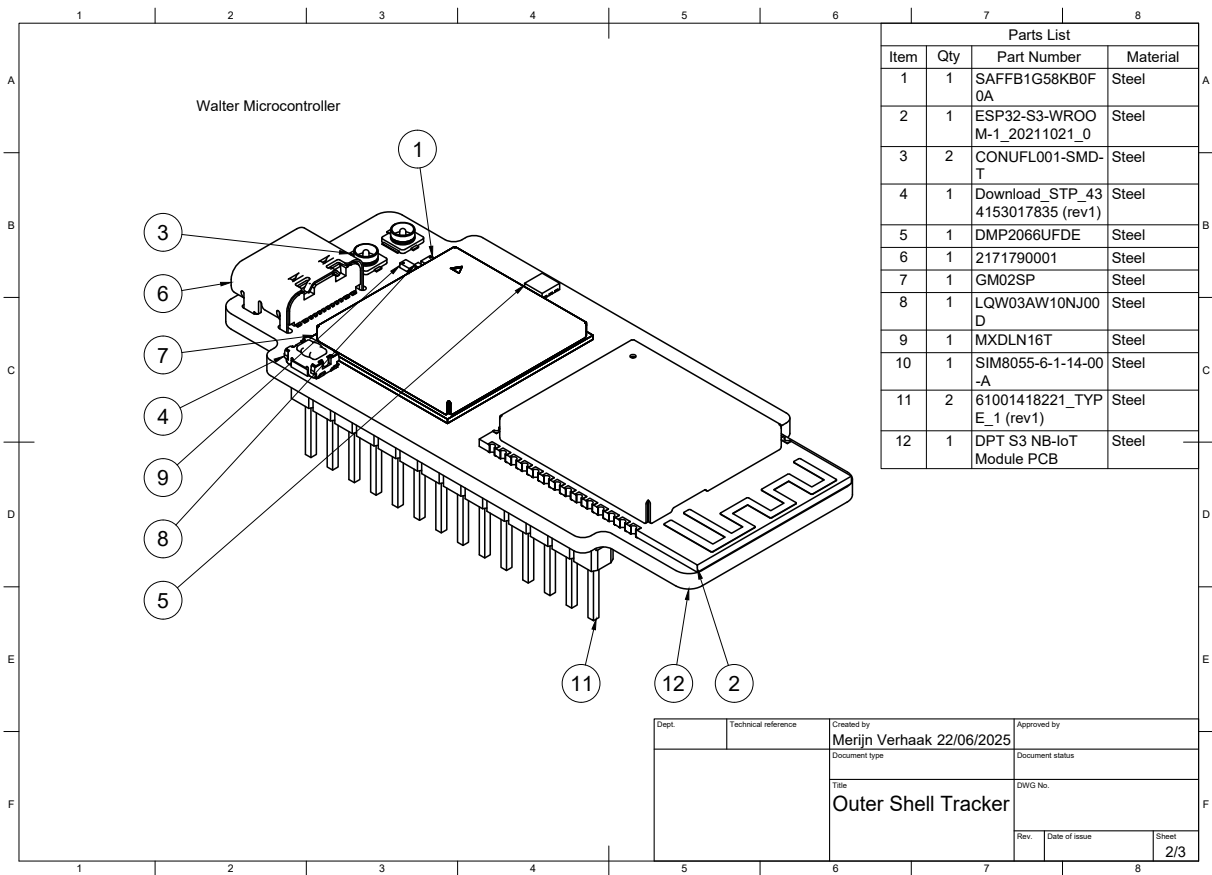
Conclusion

The general results of the pilot work showed that the smart labels did not have a significant impact on the recyclability of corrugated boxes. Based on analysis and observations, repulpability and on-machine processing were not impacted by the tags in this study. Further studies, including real-condition environment tests, would be the next logical step to expand the scope and implications of this work.

©2024 Smurfit WestRock Company and/or its affiliates. Smurfit WestRock and the Smurfit WestRock logo are trademarks owned by Smurfit WestRock Company and/or its affiliates. All rights reserved.

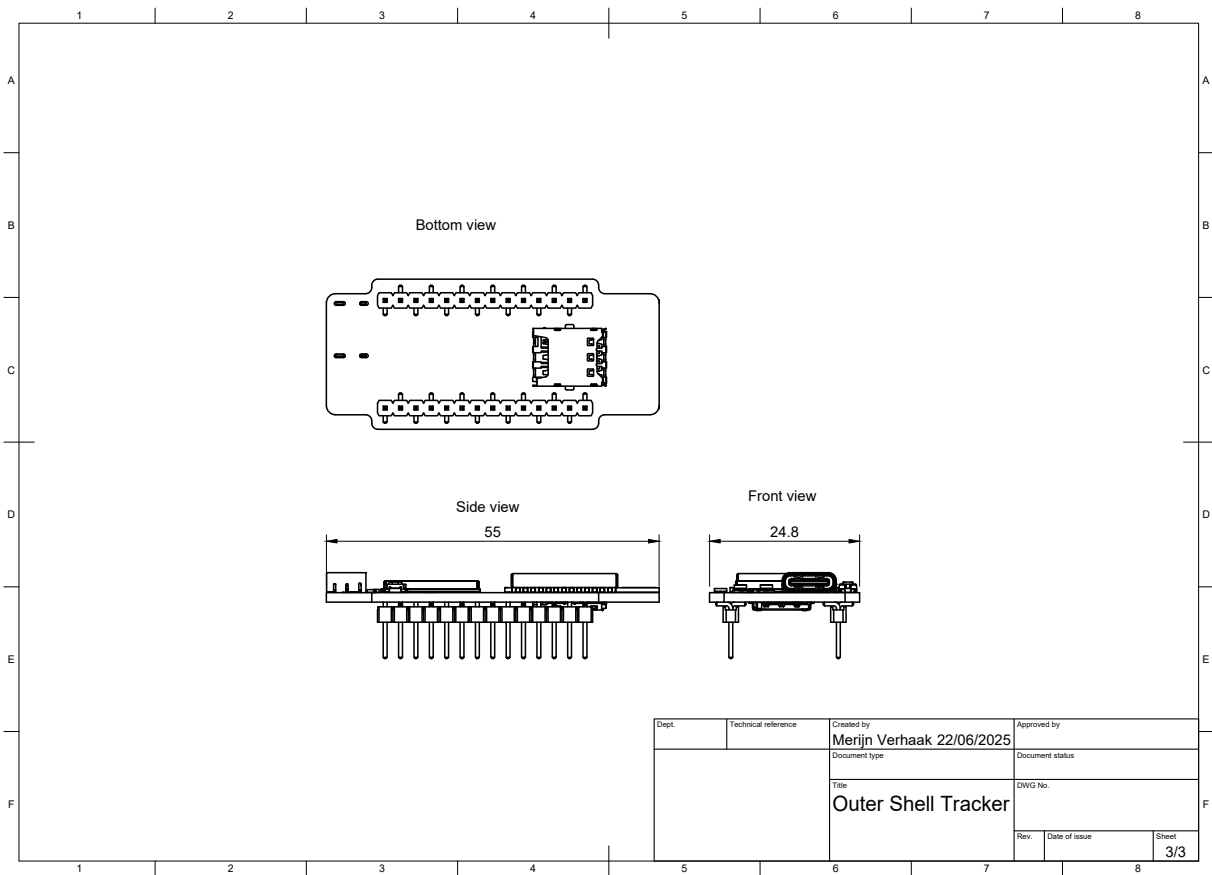
D CAD drawings





Parts List			
Item	Qty	Part Number	Material
1	1	SAFFB1G58KB0F0A	Steel
2	1	ESP32-S3-WROOM-1_20211021_0	Steel
3	2	CONUFL001-SMD-T	Steel
4	1	Download_STP_434153017835 (rev1)	Steel
5	1	DMP2066UFDE	Steel
6	1	2171790001	Steel
7	1	GM02SP	Steel
8	1	LQW03AW10NJ00D	Steel
9	1	MXDLN16T	Steel
10	1	SIM8055-6-1-14-00-A	Steel
11	2	61001418221_TYP E_1 (rev1)	Steel
12	1	DPT S3 NB-IoT Module PCB	Steel

Dept.	Technical reference	Created by Merijn Verhaak 22/06/2025	Approved by
		Document type	Document status
		Title Outer Shell Tracker	DWG No.
		Rev.	Date of issue
			Sheet 2/3



Dept.	Technical reference	Created by Merijn Verhaak 22/06/2025	Approved by
		Document type	Document status
		Title Outer Shell Tracker	DWG No.
		Rev.	Date of issue
			Sheet 3/3