The Cost of Ownership Tool

The quantitative spreadsheet based cost of ownership tool with accompanying labeling scheme

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Preface:

The completion of this master thesis would not have been possible without the supervision and expertise of Dr. Faludi, J.and Dr. ir. Flipsen, S.F.J. I switched from my bachelor’s Industrial Design at the Technical University in Eindhoven to the Master of Integrated Product Design at the Delft University of Technology. This decision was initially made for the faculty of Industrial Design Engineering has a massive amount of knowledge and research potential in the field of design for repair and circularity. And as my supervisory team showed me, this switch was well worth it.

I would like to thank MSc. Ir. Dangal, S. for the provision of valuable information and the interesting insights you provided during the various meetings we had. I would also like to thank M.Depypere repair policy engineer at iFixit for making himself available twice to enthusiastically talk with me about legislation and repair.

I would like to thank everyone who supported me during this absurd journey beginning with my sister who always had fantastic tips & tricks to lift my work a level higher. Her enthusiasm for Industrial design is why I initiated my bachelor’s industrial design to begin with. I would also like to thank my parents for endlessly supporting me throughout my whole university career. And lastly Julia (Juju), Dean (Deanno.) and my sister Iris for proofreading parts my thesis. I also want to thank my laptop, for staying with me throughout my 6.5-year university career.

Lastly, I want to thank myself, the journey of my thesis was not an easy one but with the help of the people around me managed to keep my head up.

Glossary

Abbreviations

API	Application Programming Interface
AsMeR	Assessment Matrix for ease of Repair
COO	Cost of ownership
DGCCRF	Direction Générale de la concurrence. De la Consommation et de la Répression des Fraudes
eDIM	ease of Disassembly Metrix
EoL	End of Life
ErP	Electronic Product
FRI	French repairability Index
GHG	Green House Gasses
MOST	Maynard Operation Sequencing Technique
RCO	Repair cost of Ownership
TCO	Total Cost of Ownership
TCOT	Total Cost of Ownership Tool

Terms:

Manufacturer: A company that is responsible for a product, in this case the owner of the product.

Customer: The end-user of a product. The word consumer is explicitly not used for the shift to a circular economy requires us to decouple consumption from resource use.

Legislator: a person who is responsible for the making of new legislation.

take-make-waste: a description of the currently dominant linear economy. Raw materials are being mined, made into a product, and shipped off to a landfill or incinerated after its use.

Durability: "Durability is the ability of a physical product to remain functional, without the requiring excessive maintenance or repair, when faced with the challenges of normal operation over its design lifetime" (Cooper, 1994).

Repairability: "The characteristic of a product that allows all or some of its part to be brought back to working condition after failure in a reasonable amount of time for a reasonable price without having to replace the entire product" (Bracquené et al.,2018)

Product: Something that is marketed and sold as a commodity, in this thesis mainly in the form of a device.

Device: A piece of equipment or mechanism designed to serve a special purpose or perform a special function

Consumable: An item required for the functionality of a product that is not considered to be a part. Vacuum bags for example.

Self-repair and individual repair: A repair executed by the end-user or customer, of a product or device. This includes channels like the repair café or the help of a handy neighbour.

Abstract

This Thesis report covers the creation and validation of a spreadsheet-based self-declared quantitative cost of ownership tool. The accompanying labelling Scheme informs customers about the Total Cost of Ownership (TCO) of their products with a focus on the Repair Costs. The Total Cost of Ownership Tool (TCOT) offers customers a better comparative potential with regard to the longevity of products.

The tool distinguishes itself from currently existing initiatives and tools for it provides a quantitative scoring of the cost of ownership and repair. This quantitative scoring is detrimental to the fair comparison of products. Previously existing tools mainly provided a qualitative grading. For this concept to work product manufacturers will be obliged by legislative organs to fill in the TCOT to get a corresponding label that needs to be displayed at the place of purchase. The tool in return provides the manufacturers with valuable data on how to improve their products. The newly obtained quantitative data can be used by legislators to assess the progress of longevity of products to assess the effectiveness of the newly adopted TCOT legislations.

To explore this solution space the cost of ownership and repair needed to be expressed in a mathematical formula. Thereafter the factors that influence the variables in this formula needed to be quantitatively expressed. One major qualitative element however remained. The grading of the chance of a successful repair was performed by including conditions and criteria of the French Repairability Index (FRI).

The development of the tool relied on iterative cycles of performing case studies with data on smartphones. The early iteration cycles revealed that small variations in the input variables resulted in significant differences in the outputs. Not only was the available literature on some of these variables limited. Often sources provided contradicting figures making conclusive results difficult to obtain. To test the technical aspects of the tool and assess the individual impacts of the input variables, different scenarios were explored. This provided insights into how the tool deals with the varying input data. The outcome of these tests fell within the bounds of expectation and revealed what further steps need to be undertaken to further develop the TCOT.

The quantitative display of these often unknown and intangible ownership costs provides the customer with the information that she needs to better be able to choose a longer-lasting product. This newly acquired transparency towards the customer can help legislators nudge manufacturers into producing longer-lasting products. The further development of the tool and its accompanying label scheme will help with the transition towards the envisioned circular European Union by 2050

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1. Introduction

Products break, and even the best of repairable products can become too expensive to be repaired. This Thesis report explores a spreadsheet-based Tool with an accompanying labelling Scheme that will inform customers about the Total Cost of Ownership (TCO) of their products with a focus on the Repair Costs. The Total Cost of Ownership Tool (TCOT) will ultimately help customers to make better decisions in terms of the longevity of products and in this way positively impact the environment and their wallet. In this chapter, a more detailed picture, of the problem statement, the scope, the context, and the main stakeholders, will be sketched.

1.1. Problem statement

A *take makes waste* economy has been the predominant form of economy over the past few decades. This unsustainable way of perpetrating has led to many shortages in raw materials and the increase of waste streams (ELSHKAKI et al., 2005) with E-waste being one of the fastest-growing forms of waste (Herat, 2007). The European Union and the Dutch government have acknowledged these issues and have pledged to move to a circular economy by 2050(Ministerie van Infrastructuur en Waterstaat, 2019) (European Commission, 2020).

Keeping products in use longer, with proper repair and maintenance is the most effective way to mitigate waste (European Commission, n.d.) and other environmental impacts and is considered as the most resource efficient and favourable strategy in the circular economy (Ellen MacArthur Foundation, 2013). Although tools and initiatives aimed at individual repair can have a valuable contribution to keeping products in use longer, the willingness or capability to repair is not always with the individual. Consumers that are willing to repair their broken products are often met with, sometimes intentional, Barriers (Tecchio et al., 2019). Which often leads to replacing the product rather than repairing it.

Tools like the French repairability Index (FRI) and others have been put forward to inform consumers about the repairability of products. This empowers the consumers to make better decisions when buying a product in terms of repairability and longevity and so nudges manufacturers into designing longer-lasting products to score better. However, the qualitative nature of these tools makes fair comparison between products and legislation very hard. Current methods almost all ignore the issue of the actual cost of a repair (Right to Repair, 2021).

Consumers and legislators need to be supplied with quantitative information on the price of the ownership of products so they can make well-informed decisions on purchases and policies. An obligatory self-declared spreadsheet-based repair and ownership score filled in by manufacturers with an accompanying labelling scheme could be a solution. This thesis report is focused on the development of such a conceptual quantitative tool that provides insight into ownership costs to empower the customer, legislators, and manufacturers with this valuable quantitative information. This tool would be called the Total Cost of Ownership Tool (TCOT) and will ultimately help in the transition towards longer-lasting products and a circular Europe by 2050.

1.2. Research Questions

The main goal of this thesis project is to:

Create and validate a quantitative total cost of ownership tool with an accompanying labelling scheme, that allows for comparing products on their ownership costs, with a focus on repair.

A Tool that captures the lifetime costs of devices touches upon various fields and topics. Next to the technical functionality of the tool, existing tools and initiatives, there is the positioning of the tool in between the fields of customers, legislators, and manufacturers. These points have been captured in the following research questions. From now on the Total Cost of Ownership Tool will be referred to as TCOT or the tool.

RQ 1. What factors and actors need to be considered when designing a quantitative Cost of Ownership tool?
What is the context in which the tool will be operating?
Who are the stakeholders and how are they involved with the tool?
What tools and initiatives are already out there?

RQ 2. What is the Total Cost of ownership, and how can this be calculated?
What factors influence the cost of ownership and repair?
How can these factors be quantitatively expressed?
How will the tool respond to changing input variables?
How does the outcome of the score of the tool compare to existing scoring methods?

RQ 3. How will the tool display the information to the stakeholders?
What is the most effective way to display the outcome to the customer?
What information do Legislators need?
How will the tool display information to the manufacturer?
How will the tool be implemented?

1.3. Scope

This thesis report is focused on the development of a conceptual quantitative scoring tool that provides insight in ownership costs of products. This will empower costumers to make better decisions with regards to longevity of products, and so nudge companies into producing longer lasting products to ultimately benefit the environment.

To explore this solution space this thesis report investigates the grading and quantifying the costs of ownership with a focus on the costs of professional repairs. This means that the factors that influence the cost of a professional repair need to be discovered and expressed into quantitative values. The implementation of such a mandatory tool and labelling scheme would require legislation but will be beneficial for legislators as well since it will provide them with a quantitative way to benchmark companies and to base new legislation on. Hence this report investigates the field of legislation and legislators. Finally, the labelling scheme will be tested for its efficacy in conveying the information to the customers.

The scope is therefore the costs of professional repair and the successful implementation of the tool and its labelling scheme by legislators, to positively benefit the choices of customers in the Netherlands.

Although the tool is set up in such a way that it could be used for multiple different product groups this report focuses on the usage and implementation of data on smartphone repairs and spare part prices.

1.4. Context

In this subchapter, the context in which the TCOT will operate will be further elaborated upon. Since there is an emphasis on the possibility of this tool to benefit the transition towards the circular economy there will be a short introduction into the circular economy. After that a glimpse into the repair market will be provided, existing tools and initiatives will be discussed, and the main stakeholders will be addressed. The chapter closes off with the Key findings and how the TCOT will handle these findings.

1.4.1. The circular economy

The predominant take-make-waste consumption pattern within our economy has accelerated the depletion of raw materials and causes huge amounts of waste and environmental damages. The Circular economy opposes this current ‘cradle to grave’ pattern by being regenerative and restorative by intention and design (Ellen Macarthur Foundation, 2013). The circular economy replaces the ‘end-of-life’(EoL) with restoration, shifts towards renewable energy and aims to eliminate waste through superior design of materials, products, and systems.

The circular economy focusses on closing resource loops as figure 1 indicates. The most energy and material efficient cycle for a product to go through is the cycle of repair and maintenance, then redistribution, refurbishment, and as final option recycling. By keeping a product in use longer the product will stay in the most energy and material-efficient cycle. This will put less strain on the environment. This is described by the Ellen mc Arthur foundation as the Power of circling longer. To make products undergo more cycles several design strategies can be applied to increase their lifespan. According to Bakker et al.(2019) and Bocken et al.(2016) products can be designed for:

- Attachment and trust
- Durability
- Standardization & compatibility
- Ease of Maintenance & repair
- Upgradability & adaptability
- Refurbishment & remanufacturing.

The development of this tool however mainly focusses on the Ease of maintenance and repair and Durability of products. Therefore, these will be highlighted.

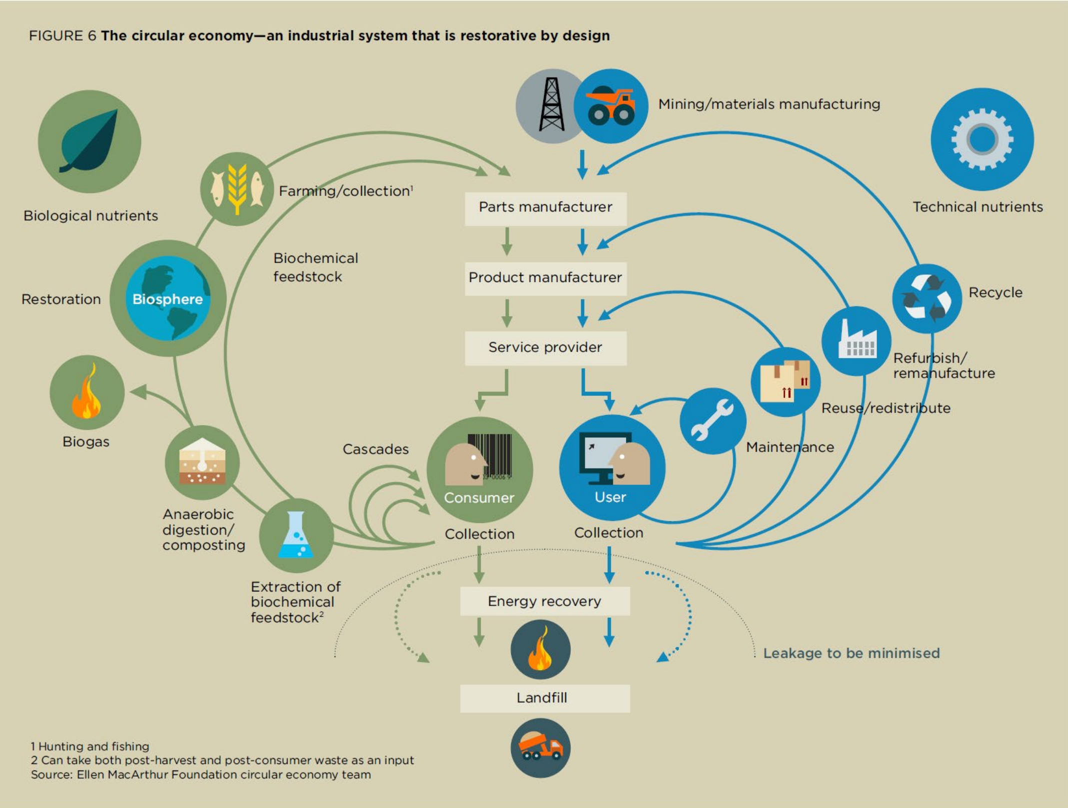


Figure 1: the circular economy (Ellen MacArthur Foundation, 2013)

1.4.2. Durability and repairability

Both durability and ease of repair methods help to keep products in use longer and so mitigate waste which is desirable for the environment (Bakker et al.,2014). Although both durability and Ease of repair design strategies are not mutually exclusive, they do have some differences in how they are achieving longevity. Henceforth Ease of repair and maintenance will be referred to as repairability.

What is durability?

> *"Durability is the ability of a physical product to remain functional, without the requiring excessive maintenance or repair, when faced with the challenges of normal operation over its design lifetime" (Cooper, 1994).*

And ease of repair, or repairability.

> *"The characteristic of a product that allows all or some of its part to be brought back to working condition after failure in a reasonable amount of time for a reasonable price without having to replace the entire product" (Bracquené et al.,2018)*

The main difference between the two definitions is that design for durability tries to prevent repairs and maintenance by designing robust products, while the ease of repair strategy focusses on making repairs as easy as possible, which also entails the availability of information, ease of repair and service provision. A durable product is designed to last longer without maintenance and repair it is therefore safe to assume that more effort and materials went into the production. whereas design for repair efforts largely go into service provision.

Repair or maintenance:

The difference between repair and maintenance can be challenging to point out. Maintenance aims to avoid the need for a repair through proper product use and care. However as Bracquené et al.(2018) point out in their research; consumers often regarded replacing vacuum cleaner filters as a failure requiring repair. Whereas the manufacturers classified the changing of a filter as maintenance.

Spare part or consumable:

A similar classification issue arose when looking at spare parts and consumables. Bracquené et al.,(2021) point out that carbon brushes used in washing machine motors could be regarded as consumables, as they might need to be replaced quite often. Other manufacturers made their brushes thicker or even redundant by integrating a brushless motor. Consumables would be hard to integrate into the total costs of a product. The costs of consumables highly depend on the usage frequency of the device. Take a bagged vacuum cleaner for example. Not only does the frequency determine how much will be spent on bags but also what brand the user buys. Consumables are therefore out of scope.

These classification and terminology issues need to be addressed in the design of the TCOT and can be covered with standardization documents with set rules on how to properly organize the nomenclature to prevent skewed results.

1.4.3. The repair market

What are the possibilities for a customer when their products break? Bracquené et al. (2018) have split up the different actors in a possible repair activity where a customer can turn to when a product needs repair. The repair actors are divided into Individual and professional repair with a further subdivision of professional repair into 3 categories, In-house repair, Industrial repairers, and independent repairers (see figure 2).

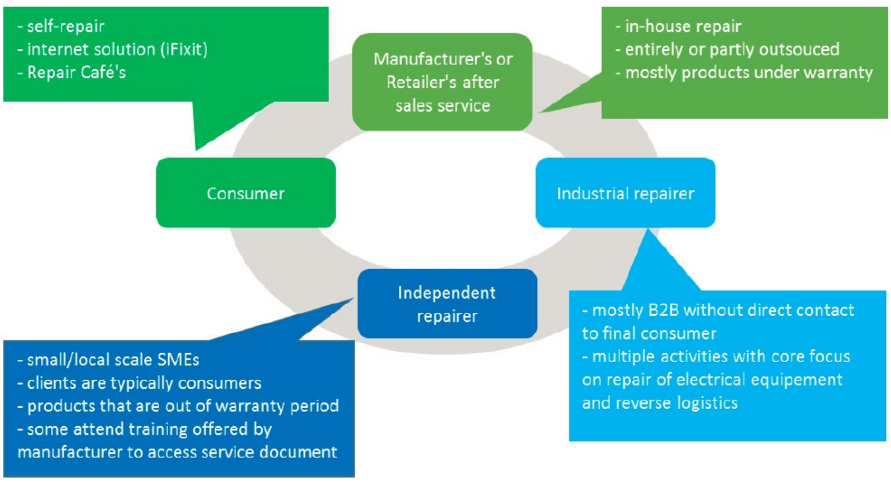


Figure 2: Different potential actors in a repair cycle (Bracquené et al., 2018)

Products under warranty:

When a product is within warranty the customer most likely turns to the **manufacturers or retailers after sales service**. There the Repair will be assessed for its technical feasibility by an in-house repair team or by a third-party **industrial repairer**. If the repair is technically and economically repairable the in-house team or the industrial repairer will repair the product and makes sure the customer gets their product back. However, if the repair is technically unfeasible or too costly the customer will be provided with a replacement product.

Products out of warranty:

When a product is out of warranty the customer can decide to opt for self-repair, which might include the help of a repair café, or handy neighbour. Or the customer can bring their product to an independent repairer. A repairability assessment will be performed to decide whether the product is technically and economically feasible to repair. Although the labour costs will not directly influence the repair costs with self-repair, the customer should still consider what their own time is worth, and if it is worth the effort.

This Thesis report mainly looks at products that are out of the warranty period. Therefor there will be an emphasis on the independent repairer, with a small tangent into self-repair.

1.4.4.Existing Tools and Regulations.

Europe's Green new deal (European Commission, 2021), mandate 543 (European Commission, n.d.), and European Union's plans to promote the ease of repair (European commission, 2020). Sparked a great variety in tools, standards, regulations, and initiatives aimed to increase the longevity of products through repair.

For the design of this tool a lot of inspiration was drawn from these existing tools and initiatives. Since they will be cited quite often further on in the report they will be shortly explained here. Not only will inspiration be drawn from the currently exiting tools, but a critical review also allowed for points of improvement that the TCOT was going to tackle.

Cen Cenelec EN NEN 45554:2020

After Europe commissioned mandate 543 the European standardization organizations set up a technical committee CEN/CENELEC, charged with working out general standards for the assessment of electronic products (ErP's). 3 standards came out; the general standard methods for the assessment of durability and the ability to repair, reuse or upgrade energy related products (EN 45554:2020) and the evaluation of durability and ability of ErPs to be remanufactured (EN45552) and a series of terms and definitions related to material efficiency (pr EN 45550:2018).

From these the EN 45554:2020 standard was used most for this tool. The document provides guidance for the identification of priority components, lists of product-related parameters influencing repairs, upgrades and reuse. Moreover, does the document contains examples of possible classification and rating criteria for these parameters, like lists of tools, fasteners, and diagnostic support.

The information on the assessment of repairability forms a great basis for the development of the TCOT and is often cited further on in the report.

The French Repairability Index

The most similar tool to what I was achieving with the TCOT is the French Repairability Index (FRI). The FRI was put into place in 2019 by the French government to clearly display the repairability of electronic equipment. The Index aims for consumers to buy more repairable electronic products and so nudge manufacturers into improving their products in terms of repairability.

The Index is a self-declaration spreadsheet system that provides transparency towards customers and other stakeholders and to the control of the Direction Générale de la concurrence. De la Consommation et de la Répression des Fraudes (DGCCRF).

The tool is obligatory by law from the 1st of January 2021 onwards for 5 product categories:

- Smartphones
- Laptops
- Televisions
- Washing machines
- Lawnmowers

Manufacturers within these product categories must use a spreadsheet to assess their products on 5 criteria, being: Documentation, disassembly, availability of spare parts, price of spare parts and product-specific aspects (software related for televisions, smartphones, and laptops). The Index and the sheet calculating the final grade should always be given upon request by the customer providing transparency to the customer. With the FRI products are scored from 1 to 10 (see figure 3).

Figure 3: The final score of the FRI.

Although the Index does award points for the costs of spare components the value quickly gets converted to a qualitative grading which together with all the other separate criteria form an overall grade. This qualitative grading offers the legislators and customers little to no comparative potential. One cannot say that a product scoring an 8, is twice as repairable, or twice as good as a product scoring a 4. Another point that the FRI does not cover is the Individual repair. The direct spare part provision to customers is being graded but it is impossible for Customers to find whether a product is repairable by the individual.

In reality a repair is often deemed unfeasible if a product scores very low on the criteria of disassembly or cost and availability of spare parts. However, in the FRI the poorly scoring criteria can be covered by the other criteria and provide a very good (>8/10) overall repair score nonetheless. This is something the organization Halte à L'obsolescence programmée(2022) pointed out in their report reviewing FRI one year after its launch.

Some other points of critique are the fact that companies will never be completely transparent towards consumers and outsiders for most information surrounding their products is confidential. So, transparency is limited.

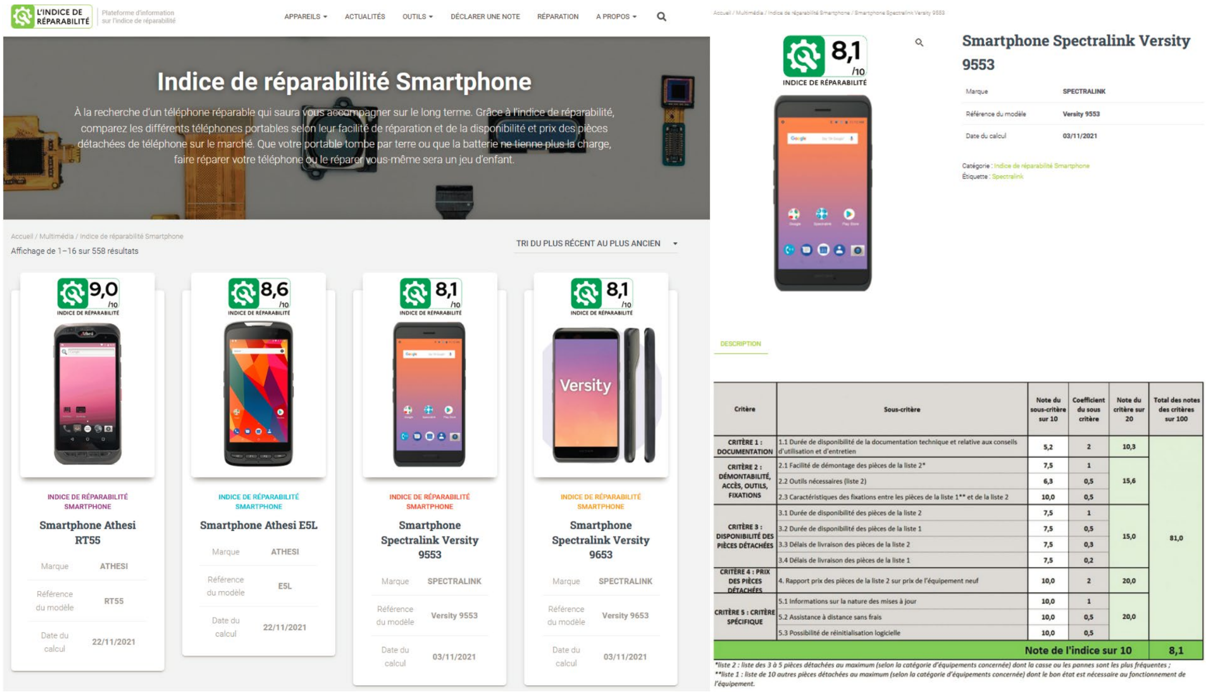


Figure 4: Screenshots of the website of the FRI.

iFixit Repairability scores

The iFixit repairability scores are qualitative scores produced by the company iFixit. The company has assessed laptops and Smartphones on their repairability. The scoring system considers repairability indicators like ease of disassembly, modular design, types of fasteners used availability of service manuals, necessary tools, and possibility to upgrade the device. iFixit scores products from 0 to 10 themselves after which the scores and good and lesser points discovered during the disassembly are displayed on their website.

The scoring of with the iFixit tool is very qualitative by nature but still gives the user lots of information on the repairability of their future device.

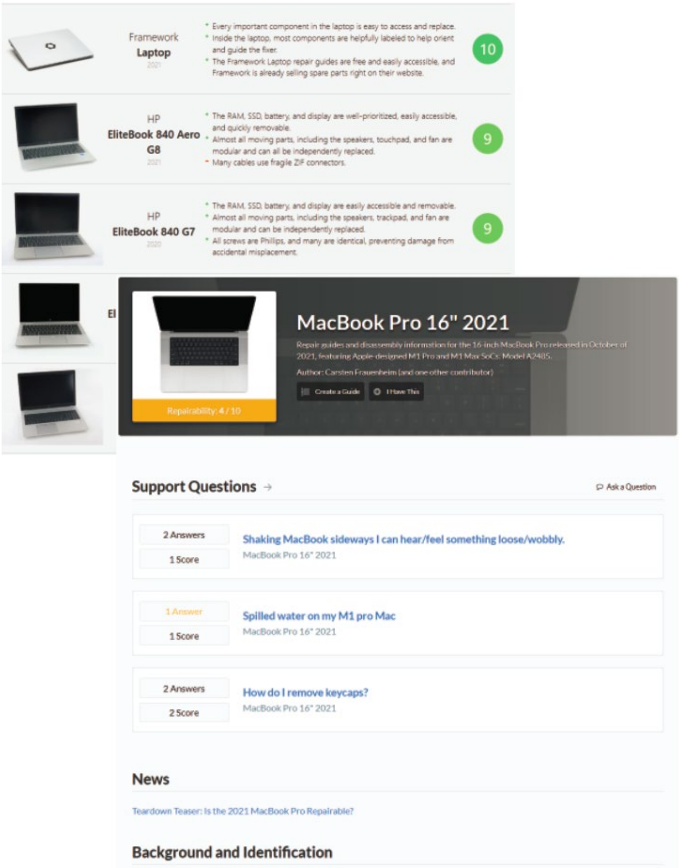


Figure 5: Snapshot of the iFixit website: https://www.ifixit.com/laptop-repairability

Ease of Disassembly Metric

The ease of Disassembly metric(eDIM) (Vanegas et al., 2018b) is a quantitative method to calculate the disassembly time of products based on the type of operations that are executed. By filing in the corresponding proxy times from the list one gets a quantitative indication of disassembly time and therefore ease of disassembly. eDIM is based on the Maynard Operation Sequence Technique (MOST). The proxy times for repair steps in this method make the result verifiable and unambiguous. This Quantitative manner of calculating the disassembly times makes the eDIM very suitable for legislators to use in policy creation and levels the playing field for manufacturers.

A downside to eDIM is that it is not possible to verify all products for no proxy times or certain disassembly steps exist yet. Furthermore, some of the proxy times still far from realistic and will probably stay that way. Take for example the pealing of glue. As M. Depypere pointed out, the condition of glue is very susceptible for the environmental conditions it is exposed to during its lifetime. Glue can become brittle or sticky over time leading to different results in disassembly times for the exact same product.

A downside to eDIM is that it does not cover the whole repair process, it does not take the availability of spare parts into consideration and can therefore not be used as a stand-alone tool. However, it is an interesting tool that can be used to build upon.

1.4.5. Stakeholders

The main stakeholders of the TCOT will be manufacturers, legislators, and Customers. Manufacturers will use the tool to label their products, these labels will be used by customers to compare products with each other. The information provided by the tool will help legislators with benchmarking product and the making of new legislation.

- **Customers:** people that buy products in the shops or online
- **Manufacturers:** companies that manufacture/design products within the chosen categories.
- **Legislators:** people that work on policies for the EU regarding the circular economy.

This chapter will highlight each of the Stakeholders. Who are they and what are their goals? This subchapter will show how the TCOT will help them in achieving these goals. To form an idea on the perspective of the legislators and manufacturers a meeting had been planned with M. Depypere, a repair policy engineer at iFixit. This provided valuable insights on two of the main stakeholders.

Customers:

For customers it is hard to compare products with each other, especially when they want to compare products with each other based on longevity and repairability. Currently, tools and initiatives qualitatively assess products on their repairability; however, this does not give the customer an objective comparison between products. Next to that is the actual cost of a repair often left out of the question, while the cost of a repair is often the reason to execute the repair or not. Customers feel that more expensive products in general last longer, but there is no objective quantitative way to compare products with each other. This can leave the consumer with unpleasant surprises later. If there would be a quantitative way to compare products with each other there has to be trust towards the honesty of the values. A form of transparency or control will be needed to assure the figures are correct. More and more people are aware of the impact their electronics have on the environment and try to limit it as much as possible. Not only will a longer-lasting product save them money, but it will also help them to achieve their sustainability goals.

Wants:

- Have an easy quantitative comparison between products to be able to choose the longest lasting product, to save money and work towards a better environment.
- Transparency into how the grading came to be, or market surveillance authorities that check companies for their truthfulness.

“Goedkoop is duurkoop”
(English: Buying cheap is expensive)
- Dutch proverb-

Manufacturers/companies:

With the exception of a few manufacturers, will it be highly unlikely that companies are looking forward to filling in a tool like the TCOT, that puts them in direct comparison with their competitors. But since the tool will be obligatory by law the manufacturers will have to do it. This does not mean that they can have no wants or wishes from the tool.

Manufacturers will be the ones filling in the tool. The tool therefor needs to be designed in such a way that is intuitive and clear how to fill it in. Next to that they should be assured that the input data is not compromised, since can be very sensitive data that should not leave the company. When there is an audit by a market surveillance authority the manufacturer should be able to show an excerpt from the tool that the tool itself produced to prevent as much hassle as possible. And finally, the tool should allow for companies to distinguish themselves, there should be some wiggling space to improve their products in their own way. This is mean that there is the possibility to setup their own lists of priority parts, as long as there is data to back it up.

wants

- An intuitive tool that requires little effort to fill in.
- Simple to make excerpt for audits by market surveillance authorities.
- Confidentiality of sensitive information.
- Not be too constraint to pre-determined lists.

Legislators:

For legislators to be able to write policy proposals for companies to act in a certain way they need to have a level playing field for all the companies with as little ambiguity and as much verifiability as possible. This will increase the effectiveness of their proposals as well as produce less resistance from the companies/people that are being influenced by their policies.

Wants

- A quantitative unambiguous way to measure the repairability and longevity of products to be able to set thresholds that manufacturers must tend to.
- A quantitative way to display the hidden costs (cost of ownership) of products.
- verifiable data way to assess the input data from the manufacturers.

1.5. Key findings

The main take-away from this chapter is that there is a need for quantitative data on the costs of ownership of products. Objective Quantitative data will allow for the fair comparison between products which will help customers when buying a new product and legislators when making new policies. Empowering the customers with the opportunity to choose for longer lasting products will result in less products being thrown away and a possible market push for longevity. This will be beneficial for the environment and will be a good step into the transition to a sustainable and circular European union in 2050.

Current tools, although a wonderful step in the good direction, don’t provide these quantitative insights. With the FRI it is possible to score relatively well overall even though the spare part provision is scoring insufficient on its own. Next to that are most Tools and initiatives critically ignoring the price of repairs, which is in many cases the main reason to, or not to repair a product in the first place.

Manufacturers on their own have enough data and knowledge to provide customers with the information they need, but they don’t. Therefore, legislation and law-making come in to enforce the transfer of information. However, manufacturers are still powerful stakeholders and should be met in their wishes.

There seems to be a discrepancy between the transparency that customers want and what companies can provide. Customers want more transparency, to be sure that the comparison they are faced with is legitimate, and companies want to keep as much of their confidential information and data within their company.

There is much to say for creating a level playing field for the manufacturers by supplying them with lookup tables and predetermined lists of components per product group. This will provide a more equal playing field and less debates. But as shown before not every product group can be covered by tools like eDIM. Moreover, can products within a product group widely differ and will their most frequent failure, a great determining factor in the cost of a repair, not be the same either. Data on costs and failure frequencies should be leading in the filling of the TCOT.

Not everyone can or wants to repair their own products, however, exclusively covering professional repair costs doesn't provide the most realistic cost of ownership output. There are repairs that can definitely be performed by users.

1.6. Conclusion context research

With context and the points highlighted in the previous chapter in mind a preliminary sketch of how the tool will tackle these issues and fit current context will follow. In the form of a set of requirements.

The tool will be a self-declared spreadsheet-based tool with an accompanying labelling scheme. The manufacturers of certain product groups are obligated by law to fill in the sheet, which will produce a label. This label needs to be published at the place of purchase, either online or offline. The accompanying labelling scheme will inform the customer of the cost of ownership and repair and awards a grade. Direct transparency towards the customer will not be possible, but market surveillance authorities will perform regular checks to assure the legitimacy of the labels.

The tool itself will need to be as quantitative as possible to create a realistic and comparable result for customer and legislator alike. All the factors that influence the cost of a repair need to be found and expressed quantitatively. The manufacturers will have quite some freedom while filling in the tool. But there needs to be substantial data to support the input data. The cost of a repair needs to be broken down in such a way that possibilities for improvements are easy to spot. This in turn will provide value to the manufacturers.

Although the Tool mainly focuses on professional repair, efforts must be put into integrating individual repair to some degree.

2. Methods

The creation of this tool is a highly iterative process and the step-by-step approach described below is not an exact chronological representation of how the project was be performed.

2.1. Process

The First important step was to become aware of the context. From the context valuable information could be drawn to move to the second step where a first draft version of the tool was made.

The first important step was to investigate the context. Questions like, what is repair, who are the stakeholders and what does the repair industry look like, needed to be answered. And other tools and initiatives needed to be analysed. Analysing existing tools provides valuable inspiration and insights into what needed to be improved and what complexities may lie ahead.

After the context has been set the cost of ownership needed to be defined. The factors that influence the cost a of a repair needed to be discovered to gain a better understanding of how they might possibly be expressed quantitatively. A preliminary tool was conceived to gain an understanding of the importance of these factors and how they influence the final score.

To see how the tool performs case studies with well documented and researched products were carried out. This helped with comparing the TCOT to existing tools and find points for improvement.

Once the Tool was sufficiently tested with the case studies for its technical abilities, tests were needed to be performed to improve its usability. Next to that a visualisation of the label that came out of the tool was proposed, followed by a user survey to find out if the labelling scheme made sense.

A final step was to reflect on the Tool and how it could be implemented in the future. A roadmap was made.

2.2. Methodologies

The development of a tool like the TCOT, thrives on the iterative process involving multiple diverging and converging phases which roughly mimic the double diamond design approach.

Pressure cookers, field study & literature study

Creating a tool like the TCOT felt like opening a massive can of worms. It was therefore important to not go into every rabbit hole you come across, this will make one lose sight of the end goal. To force myself to make decisions quickly, two so-called ‘pressure cookers’ were performed. A pressure cooker is a form of a *design sprint*, or *design in a day*, in which a whole project will be performed in a predetermined period, mostly a week. This technique forces the person undertaking the pressure cooker to make decisions fast, for there is only little time. Due to this pragmatic way of handling the information you gather and come across there is a high chance that it leads one into dead ends. However, this can then become a topic for reflection later.

During the start of this project two pressure cookers had been performed, the first one taking a week, and the second one spanning two weeks. The first pressure cooker started right after the kick-off and included a **Field study** existing of volunteering at a Repair café, visits to electronic stores and smartphone repair shops to perform semi-guided interviews. With this information, a simple first version of the tool was hacked and tested with a small dataset on smartphones. The reflection on the outcome of the preliminary tool provided a solid basis for a more focused **literature study**. This was then followed by a second pressure cooker where other product groups were studied, and more functionality was added.

Iterative Case studies

The validation of the technical side of the TCOT was performed by doing case studies. As the tool progressed so did the dataset that the tool was tested with. Each new version of the tool was filled in with the up-to-date data set. The results were analysed, new literature was sought, and new variables were added each iteration round. Once the tool was in its final stage a final case study looked specifically at how certain data input scenarios influenced the results.

Stakeholder analysis

To determine what the tool needed to achieve in regard to the people most likely affected a stakeholder analysis was performed.

User tests

To validate the tool on its ability to fulfil the stakeholder's wishes user tests were performed. Questionnaires were used to determine the understandability of the labels. To check what label was most clear in displaying the final score a pairwise comparison questionnaire had been set up. The intuitiveness and usability of the tool were tested and improved with user tests followed by semi-structured interviews.

Expert Interviews/meetings

Next to the field study interviews 2 informal qualitative semi-guided interviews were planned with M.Depypere a repair policy engineer at iFixit .

3. The Total Cost of Ownership Tool

This chapter looks at how Total Cost of Ownership Tool (TCOT) works. After an explanation of what the Total cost of Ownership (TCO) is a step-by-step approach will dissect the inner workings of the tool and show in detail how the tool has been built up. This step-by-step approach will show what steps the manufacturer has to go through and what factors have been considered and how these factors have been quantitatively expressed to finally come to a label. Each step contains references to the literature that supports the claims and decisions.

As described in the methods section the tool underwent various rounds of case studies. In total seven different version and numerous small variations have been conceived to get to the final TCOT.

3.1. What is the Total Cost of Ownership?

The TCO) s the purchase price of an asset plus the cost of its operation (Twin, 2019). In this report the TCO is calculated for the user of the product. The cost of ownership is therefore the Retail price of the product plus its operation costs during its service life. Service life is the period in which a product is kept in operating state by a user (Bracquené et al., 2018). Beneath follows a formula that expresses the TCO.

$$TCO = P + O$$

$P =$ Retail price
$O =$ Operating costs

Is the maintenance included in the operation costs?

For this report the operation costs are further broken down into operational costs, like electricity, consumables and water, and repair and maintenance costs. As written before the distinction between repair and maintenance can sometimes be quite hard to make. But if maintenance contributes significantly to the cost of ownership it needs tobe included. Therefor the maintenance and repair costs are included and put under one variable.

$$O = R + E$$

$O =$ Operating costs
$R =$ Repair/maintenance costs
$E =$ Electricity, consumable and water costs

When these are divided by the product lifetime one gets the Total Costs of Ownership per year.

$$TCO(year) = \frac{P + R + E}{S}$$

$P =$ Retail price
$R =$ Repair/maintenance costs
$E =$ Electricity and water costs
$S =$ Service life(years)

Operating costs:

The operational costs of a device can represent quite a significant proportion of the operational costs. This is especially true for devices which are in frequent or continues use and consume high amounts of electricity, consumables and/or water. Although this can be a major part of the TCO of certain products like Washing machines, vacuum cleaners, refrigerators, and dishwashers it will be out of scope for this project. Energy labels do already exist for most of these products, and the TCOT mainly focusses on repair costs compared to retail prices. As previously stated, the use of consumables highly depends on the frequency of the usage of the device by the user, it is therefore left out of scope.

Repair cost:

Although not equally relevant for every product, a large part of the cost of ownership can be the repair and maintenance cost. The factors that influence the cost of a repair are the price of the spare part, the repair time and accompanying Labour costs and the variable costs, like administration and overhead costs.

The TCOT will look at the average repair costs of products. The total repair cost of a product during its lifetime is the average cost of a repair multiplied by the frequency of it occurring.

$$Repaircosts = frequency\ repair\ \cdot average\ repair\ costs$$

The cost of an individual repair highly depends on what component breaks down, and what the costs of this component and its repair are. Certain components are more prone to breaking and will therefore represent a bigger share of the average repair price. To get the total average repair price the failure frequency of each relevant(priority) component needs to be multiplied by the costs. This produces the following formula per component.

For every component separately:

$$R_i = L_i(A_i + (T_i \cdot U_i) + V_i)$$

$R =$ Repair costs
$L =$ Chance priority failure mode/repair
$A =$ Cost of spare parts
$T =$ Repair Time
$U =$ Labour costs
$V =$ Variable costs (administration, Overhead,)

Lastly there is always a chance that a part cannot be repaired after a breakdown. In the TCOT this means that the cost of the repair would be the retail price of the product in question. This is indicated with the first part of the formula $(100 - F_i) \cdot P$. then the chance of a successful repair needs to be multiplied by the costs of the repair for the instance in which the repair is successful. When expressing this information in a formula you get the following formula below.

For every individual component:

$$R_i = L_i((100 - F_i) \cdot\ P + F_i(A_i + (T_i \cdot U_i) + V_i))$$

$R =$ Repair costs
$L =$ Chance priority part failure/repair
$F =$ Chance successful repair
$P =$ Retail price
$A =$ Cost of spare parts
$T =$ Repair Time
$U =$ Labour costs
$V =$ Variable costs (administration, Overhead costs,…)

Then the formula for the Repair costs or *Repair Cost of Ownership* (RCO) per year can be found by adding all the individual component repair costs and multiply them by the frequency of a repair happening.

$$RCO = \frac{C}{S} \cdot \sum_{i}^{g} (L_i(100 - F_i) \cdot P + F_i(A_i + (T_i \cdot U_i) + V_i))$$

$L =$ Chance priority part failure/repair
$F =$ Chance successful repair
$P =$ Retail price
$A =$ Cost of spare parts
$T =$ Repair Time
$U =$ Labour costs
$V =$ Variable costs (administration, Overhead,…)
$S =$ Service life(years)
$C =$ Chance of repair needed
$g =$ Total number of priority components

When adding the retail price (P/S) per year you get the following formula which represents the Total Cost of ownership as it is being used in the TCOT.

$$TCOT = \frac{P}{S} + \frac{C}{S} \cdot \sum_{i}^{g} (L_i(100 - F_i) \cdot P + F_i(A_i + (T_i \cdot U_i) + V_i))$$

3.2. What Factors influence the TCO?

Now that the formula for the TCOT has been revealed as previously described there are various factors that possibly influence the cost of a repair and the total cost of repairs during the service life of a product. To explain how the TCOT expresses these factors into quantitative numbers a step-by-step approach of how the tool would be filled in will follow. All the functionalities will be thoroughly explained, substantiated with literature, and further elaborated upon.

3.3. User experience and step-by-step explanation of the TCOT

After the user gets some basic information on how to use the tool, she must go through seven steps to get the label which grades her product. The same 7 step structure will be applied to the explanation of the tool. The following list and figure briefly illustrate these seven steps in executive order, see figure 6.

1. Filling in general information. Information like retail price, service life, brand, date etc. are filled in. some information will go straight onto the label.
2. In step 2 the priority parts and failure modes will be selected, this is an important step for it greatly determines the outcome of the score. In this step the likelihoods of the priority parts breaking will also be filled in. a cut-off percentage will be applied to save on calculative efforts.
3. In the third step the prices of the components will be looked up, put in the sheet with sources. The sheet will calculate worst- and best-case scenarios.
4. Step four is a special step, here one can choose to either fill in known repair prices of the repairs that one can find online, after which the tool calculates the labour costs, or if these prices are not available a disassembly metric can be filled in. The disassembly metric will help them to assess the labour costs of the repairs for each individual part or failure mode.
5. At the 5th step the user looks determines the repairability by assessing the individual priority failure modes and parts with criteria from the FRI. The parts get graded on several criteria, like documentation, the use of tools, ease of disassembly and spare part availability. The final grade will determine the chance of a successful repair. Next to that the tool will check if certain components are possible to be repaired by a customer themselves. If individual repair, repair by a customer, is possible no labour costs need to be calculated for this specific component, decreasing the repair cost of that component and the repair as a whole
6. Step 6 is a summary of all the previous steps. one gets to see the graphs that show the user what the individual priority components cost, and it displays a breakdown of the total ownership costs.
7. In the final step After this the user gets directed to the page where the label is displayed. By printing or exporting this page, the use of the tool has been completed and the label will come out.

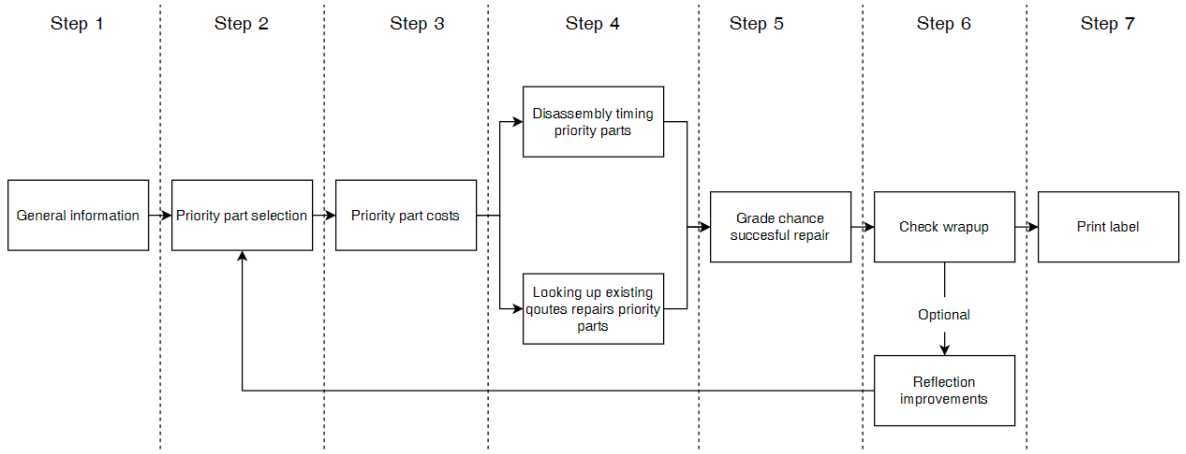


Figure 6: all the steps the user goes through.

Step 1: Filling in General information into the TCOT.

The first step of the tool is to fill in the General information of the device for which the tool will be used. The user fills in the following information:

- Brand
- Model
- Type of product
- Date of filing
- Average retail price (best-case and worst-case)
- Average Service life (best-case and worst-case)
- Chance of failure (best-case and worst-case)

The Brand, Type of Product, Model, date of filing and date of first appearance are the input that will be displayed on the label after the Tool has been filled out. However, the average retail price, service life and the chance of a repair will be slightly harder to determine. The factors that are being filled in with this step are highlighted in red in the formula below.

$$TCOT = \frac{P}{S} + \frac{C}{S} \cdot \sum_{i}^{g} \left(L_i \left(100 - F_i \right) \cdot P + F_i \left(A_i + \left(T_i \cdot U_i \right) + V_i \right) \right)$$

$P =$ Retail price
$S =$ Service life(years)
$C =$ Chance of repair needed

To get a score that is relative to the price of a product the average retail price (P) of the product must be filled in. Since the TCOT uses Best and worst-case scenarios the user of the tool must fill in the highest and lowest retail price that can be found at the day of filling in the tool. The retail prices that are filled in must be free of discounts and contractual subscription agreements.

The service life and chance of a repair needed, show more complexity. The manufacturer needs to find the service life and chance of a repair needed either in literature, its own (after sales) data on comparable products, lab tests or an educated guess as last resort. Where the data comes from and important notions regarding the input data need to be noted in the *'notes'* column.

Aftersales services

Most manufacturers possess an after sales-service or have a 3rd party that handles the warranty claims of their products. Warranty claims cost a company a lot of money so data is being gathered to mitigate these costs as much as possible. Data on the claim and supplementary data are being used to improve the spare part provision strategies and design of products (Blischke et al., 2011). This data can also be used for filling in the TCOT.

Why best-case worst-case?

The tool works with a best-case and worst-case scenario. Initially the tool exclusively has been filled in with average values. However, the output of the tool did not contain any uncertainty, which is a highly unlikely situation. The uncertainty was added with each step to provide a more realistic result. But the amount of uncertainty was poorly supported and was mainly formed with gut feeling. Since then, the Best-and-Worst-case scenarios have been integrated into the tool.

Step 1:

General product information

In this step all the general information of the device will be filled in, the first entry will be what is displayed on the label(full product name). The field contain a Best-case and Worst-case scenario. Best-case in this scenario means the input that provides the lowest costs per year, so a lower chance of repair needed and lower retail price and chance of failure are considered best case.

Full product Name	Google pixel 4a
Brand	Google
Type of product	Smartphone
Model	Pixel 4a
Date of Filing	08/03/2022

	unit	Best case	Worstcase	**Notes**
Retail price	€	€ 350,00	€ 400,00	
Sevice life	years	5	4	
Chance of repair	%	47%	49%	

Figure 7: Step 1 in the tool.

Step 2: Selection of priority failure modes/parts and frequency

$$TCOT = \frac{P}{S} + \frac{C}{S} \cdot \sum_{i}^{g} \left(L_i \left(100 - F_i\right) \cdot P + F_i \left(A_i + \left(T_i \cdot U_i\right) + V_i\right)\right)$$

$L =$ Chance priority part failure/repair
$g =$ Total number of priority components

To be able to estimate the average price of a repair it is necessary to compile a list of priority failure modes and parts. The likelihood of each failure mode must be decided. For this a company can use literature, aftersales data, and user questionnaires.

The distinction between *'failure modes'* and '*priority failure modes'* highly depends on what criteria have been set to which the mode or part has to attain to. These criteria can vary widely depending on the result one is after.

What characterizes a priority part?

In the Hotspot Mapping Tool (Flipsen et al., n.d.) parts are being graded on their “(1) importance for functionality, (2) frequency of breakdown, (3) environmental impact, and (4) embodied economic value. Whereas the NEN EN 45554 standard (CEN-CENELEC, 2020) looks at the "(1) the likelihood of the need to replace or upgrade the part; (2) the suitability of the part for reuse;(3) the functionality of the part". And adds that parts prone to breaking should be added to the priority parts list.

The TCOT focuses on the repair costs and retail price, therefore the environmental and embodied economic value will be out of scope. This defines a priority part and a priority failure mode through the following criteria (1) high importance for the functionality of the product, (2) high frequency of breakdowns and repairs.

Priority failures and priority parts:

The terms priority failure modes and priority parts have been used numerously in the literature and the various tools and initiatives that have been looked through during this thesis. There is however a major difference between the two that is worth highlighting.

If a phone screen stops working, the failure mode will be 'screen stopped working'. It is possible that the battery is broken. In this case the failure mode results in a battery(part) replacement. It could be that this failure mode is regarded as a priority failure mode (it happens frequently for example). But that does not necessarily imply that the battery is also a priority part. It could also be the case that the screen is broken and needs replacement, which is more likely in this case. However other examples can lead to a more tedious process where product failure modes imply a wide variety of issues. This problem occurs with washing machines for example. *'The machine does not drain the water'* can be regarded a priority failure mode but it could simply be jammed by a coin, or it could be a fault in the control board. If it is indeed a coin that causes the failure mode a certified repairer might come by and solves the issue. There will be no parts cost, but labour costs, nonetheless.

In the TCOT it needs to be estimated how often a certain failure mode requires the replacement of a specific part, or when it only requires labour costs to be repaired. A practical example will be displayed with the case study where water damages are included.

The Cut-off rule,

After the priority failure modes have been selected and graded with their frequency the list will be filtered high to low on the likelihood of occurring. Then the cut-off rule will be applied.

Essentially all the components and parts in a product could break. However, to prevent extensive calculative efforts which will only ever so slightly improve the result, a cut-off rule needs to be applied (Bracquené et al., 2021). A cut-off rule can be applied in different ways. A short-list with a certain number of parts or could be made, with for example the top 5 most likely to occur failures. Another method is to assign a weighting (percentage) to each priority part and organize them in a descending order. The percentages are added until the cut-off percentage is met, for example 75%. Each component within the 75% will be used to further work out the tool. The rest will not be considered.

Like the Assessment Matrix for ease of Repair (AsMeR) method the priority part weights, which are directly related to part failure rates are specific for each product group and model. The weight assigned to each part should be verified and validated with data from literature, lab tests, field studies, companies after-sales repair services and as final resort well educated guesses.

The cut-off frequency in the tool is set to 85%. This could however be changed as long as it is changed for the whole product group to prevent unfair comparisons between products.

Why not have predetermined lists for priority parts?

Having predetermined lists of priority parts for each product group would save a lot of effort and could level the playing field for the manufacturers. However, within a product family, priority parts can vary. Take headphones and washing machines as examples. A brushless Direct current engine engine does not require carbon brushes to function, which are one of the main causes for engine failure in models that do have carbon brushes in their motors.

Another such case was discovered during a headphone disassembly session. Some headphones have an aux cable, some are wireless. For a cabled pair of headphones, the cable is necessary for the headphones to function where this is not the case for wireless headphones. The wireless headphones do have a battery that tends to degrade in quality over time making the battery a priority component.

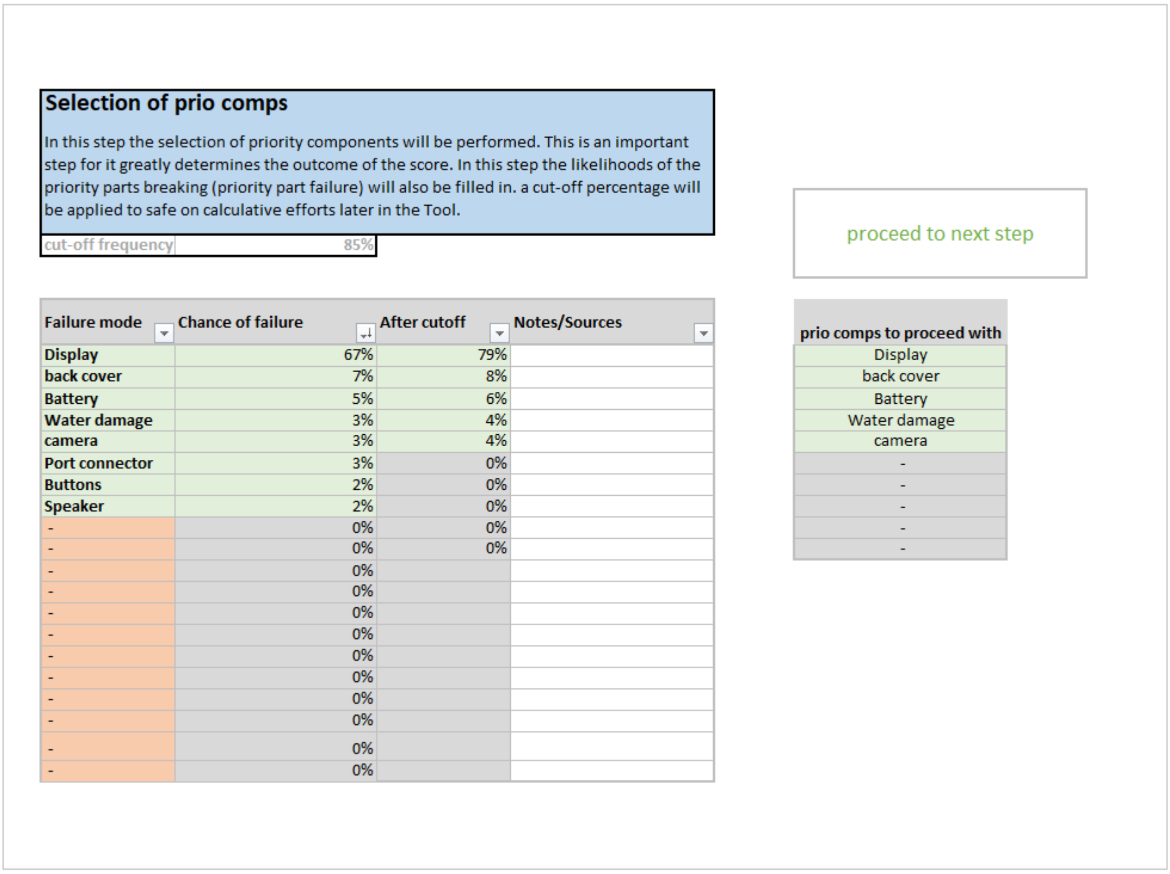
Moreover, it is highly likely that manufacturers will object predetermined lists. As Maarten Depypere pointed out during a meeting: companies will always object to lists of priority components for they claim to have an unbreakable version of the part in their product, making it therefore not fit the criteria of high frequency of breakdown.

“When there is a list of priority parts including vacuum cleaner wheels, Phillips will say that their vacuum cleaner wheels won’t break”

- Translated quote M. Depypere(employee IFixit) -

In the case of the TCOT the list can consist of any set of parts or failure modes, as long as it is backed up by data proving that these are the most relevant parts.

Step 2:



Selection of prio comps

In this step the selection of priority components will be performed. This is an important step for it greatly determines the outcome of the score. In this step the likelihoods of the priority parts breaking (priority part failure) will also be filled in. a cut-off percentage will be applied to safe on calculative efforts later in the Tool.

cut-off frequency 85%

proceed to next step

Failure mode	Chance of failure	After cutoff	Notes/Sources
Display	67%	79%	
back cover	7%	8%	
Battery	5%	6%	
Water damage	3%	4%	
camera	3%	4%	
Port connector	3%	0%	
Buttons	2%	0%	
Speaker	2%	0%	
-	0%	0%	
-	0%	0%	
-	0%		
-	0%		
-	0%		
-	0%		
-	0%		
-	0%		
-	0%		
-	0%		
-	0%		
-	0%		

prio comps to proceed with
Display
back cover
Battery
Water damage
camera
-
-
-
-
-

Figure 8: Step 2 in the tool.

Figure 9: Step 2 in the Tool.

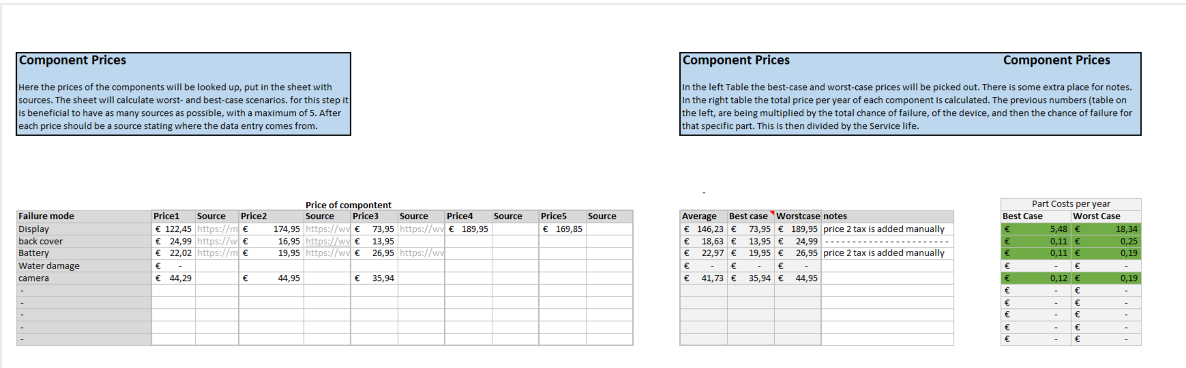
Step 3: Finding the prices of the priority components.

$$TCOT = \frac{P}{S} + \frac{C}{S} \cdot \sum_{i}^{g} \left(L_i\left(100 - F_i\right) \cdot P + F_i\left(A_i + \left(T_i \cdot U_i\right) + V_i\right)\right)$$

$A =$ Cost of spare parts

In the third step, the prices of spare parts will be looked up. This must be done manually. The user tries to find as many data inputs as possible, with a maximum of 5 inputs per part. The prices of spare parts must be found online, in the case of a product that has not reached the market yet, an estimation must be made looking at previous models or with estimated prices and markups. All prices are including tax and excluding shipping. After each price there should be an entry in the sources column on where the data comes from. The sheet will take the best-case worst-case and average part costs. Later in this report an alternative, less labour intensive method to get the input prices will be proposed.

Step 3:



Component Prices

Here the prices of the components will be looked up, put in the sheet with sources. The sheet will calculate worst- and best-case scenarios. for this step it is beneficial to have as many sources as possible, with a maximum of 5. After each price should be a source stating where the data entry comes from.

Component Prices **Component Prices**

In the left Table the best-case and worst-case prices will be picked out. There is some extra place for notes. In the right table the total price per year of each component Is calculated. The previous numbers (table on the left, are being multiplied by the total chance of failure, of the device, and then the chance of failure for that specific part. This is then divided by the Service life.

	Price of compontent									
Failure mode	Price1	Source	Price2	Source	Price3	Source	Price4	Source	Price5	Source
Display	€ 122,45	https://m	€ 174,95	https://wv	€ 73,95	https://wv	€ 189,95		€ 169,85	
back cover	€ 24,99	https://w	€ 16,95	https://wv	€ 13,95					
Battery	€ 22,02	https://m	€ 19,95	https://wv	€ 26,95	https://wv				
Water damage	€ -									
camera	€ 44,29		€ 44,95		€ 35,94					
-										
-										
-										
-										
-										

Average	Best case	Worstcase	notes
€ 146,23	€ 73,95	€ 189,95	price 2 tax is added manually
€ 18,63	€ 13,95	€ 24,99	- -
€ 22,97	€ 19,95	€ 26,95	price 2 tax is added manually
€ -	€ -	€ -	
€ 41,73	€ 35,94	€ 44,95	

Part Costs per year	
Best Case	Worst Case
€ 5,48	€ 18,34
€ 0,11	€ 0,25
€ 0,11	€ 0,19
€ -	€ -
€ 0,12	€ 0,19
€ -	€ -
€ -	€ -
€ -	€ -
€ -	€ -
€ -	€ -

Figure 10: Step 3 of the tool.

Step 4: Repair prices or Disassembly metric.

$$TCOT = \frac{P}{S} + \frac{C}{S} \cdot \sum_{i}^{g} \left(L_i\left(100 - F_i\right) \cdot P + F_i\left(A_i + \left(T_i \cdot U_i\right) + V_i\right)\right)$$

$T =$ Repair Time
$U =$ Labour costs
$V =$ Variable costs (administration, diagnosis costs,…)

Just before the user arrives at the fourth step, she gets to decide whether she wants to use online price references to determine the actual repair prices, or whether she wants to use the disassembly metric to estimate the labour costs.

If the user decides to opt for the online price reference option a similar table as the previous step will be filled in. However labour and other variable costs, overhead and administration are included in the total repair price. To distinguish the part price and labour price the tool subtracts the part price from the total price of the repair. However, the labour price has the other variable costs integrated, so it is not purely labour costs.

Total repair costs

Fill in as many (max5) prices and their source in the fields, the tool will calculate the average costs of the repairs per year. Together with the

Repair Prices											Best-worst-case and Average			
Failure mode	Price 1	Source	Price 2	Source	Price 3	Source	Price 4	Source	Price 5	Source	Average	Best case	Worstcas	notes
Display	€ 159,99	https://gef	€ 249,00	https://ww	€ 249,00	https://ww	€ 199,95	https://ww	€ 179,95		€ 207,58	€ 159,99	€ 249,00	
Buttons	€ 199,00	https://gef		https://ww		https://ww	€ 119,99	https://ww			€ 159,50	€ 119,99	€ 199,00	
back cover	€ 89,99	https://gef	€ 99,00	https://ww	€ 89,00	https://ww	€ 69,95	https://ww	€ 79,95		€ 85,58	€ 69,95	€ 99,00	
Battery	€ 29,90		€ 59,00		€ 29,95		€ 29,99				€ 37,21	€ 29,90	€ 59,00	
-	€ 149,00		€ 129,00				€ 149,99				€ 142,66	€ 129,00	€ 149,99	
-														
-														
-														
-														
-														

Just like the previous step this table picks out the best and worst-case scenarios. Notes can be added.

Labour & other costs			
Average	Best Case	worst Case	Notes
€ 61,35	€ -	€ 175,05	
€ 140,87	€ 95,00	€ 185,05	
€ 62,60	€ 43,00	€ 79,05	
€ 37,21	€ 29,90	€ 59,00	
€ 100,94	€ 84,05	€ 114,05	

Here the total labour and other costs per year are being calculated, just like the previous step these values are per year.

Labour and other Costs per year		
Best Case	worst Case	Average
€ -	€ 16,51	€ 8,26
€ 0,82	€ 2,08	€ 1,45
€ 0,33	€ 0,78	€ 0,55
€ 0,16	€ 0,42	€ 0,29
€ -	€ -	€ -
€ -	€ -	€ -
€ -	€ -	€ -
€ -	€ -	€ -
€ -	€ -	€ -
€ -	€ -	€ -

Figure 11: Input for repair prices, one of the options within step 4 of the tool.

Prices are unknown or not online yet

When a product is new and hasn't reached the market yet or simply because there are no definitive repair prices online the user can use a disassembly metric. The disassembly metric provides an alternative whenever no, or little, data is available for the product that is being graded. With the disassembly metric, the time that is required to repair each priority part will be determined. During the 'repair' a timer will be started after which the product will be disassembled up to the priority part to be reassembled to working order, then the timer is stopped, and the time is noted in the metric. This process needs to be repeated 10 times after which an average is calculated.

By filling in the best-and-worst-case prices of a repair professional per hour one gets an estimate of the price of the labour. This does not yet include the other variable costs, like overhead and administration, which need to be estimated. If a ratio between part cost, labour costs and other variable costs is known the tool will estimate the other variable costs.

Disassembly Timing

If no repair prices are known for this specific product(catogory) one has to "repair" each priority component 5-10 times to get an estimate for the time spend for the repair of each priority component. In order to get the estimated other costs one has to fill in the right ratio of repair cost of the subsequent parts

	Ratio	
parts	labour	other
2	1	4

labour costs(hour)	Best Case	Worst Case	note
	€ 40,00	€ 50,00	(Mijnzzp, 2022)

Repair time in seconds												labour costs	
	Try 1	Try 2	Try 3	Try 4	Try 5	Try 6	Try 7	Try 8	Try 9	Try 10	average	Best Case	Worst
Display											0	€ -	€ -
Buttons											0	€ -	€ -
back cover											0	€ -	€ -
Battery											0	€ -	€ -
-											0	€ -	€ -
-											0	€ -	€ -
-											0	€ -	€ -
-											0	€ -	€ -
-											0	€ -	€ -
-											0	€ -	€ -

Estimation of other costs
here I explain what happens beneath

Estimation other costs	
best case	worst
€ -	€ -
€ -	€ -
€ -	€ -
€ -	€ -
€ -	€ -
€ -	€ -
€ -	€ -
€ -	€ -
€ -	€ -
€ -	€ -

labour and other costs per year
here I explain what happens beneath

Labour an other costs per year		
Best case	Worst Case	Average
€ -	€ -	€ -
€ -	€ -	€ -
€ -	€ -	€ -
€ -	€ -	€ -
€ -	€ -	€ -
€ -	€ -	€ -
€ -	€ -	€ -
€ -	€ -	€ -
€ -	€ -	€ -
€ -	€ -	€ -

Figure 12: The disassembly metric, one of the options within step 4 of the tool.

Why timing:

Using proxy times, like the ease of Disassembly Metric (eDIM) method, for the calculation of the disassembly times has some great advantages when looking at creating a level playing field. All companies will have the same rules to work with. However, eDIM is not suitable for all product groups yet and can still be very far off from reality. Therefor the TCOT uses actual timing to gain an insight in the time the disassembly requires. For some product groups the eDIM is very suited and can maybe be implemented, products like washing machines have been thoroughly tested with the eDIM.

Step 5: Grading the chance for a successful repair

In this step the chance of a failed repair attempt will be calculated. If a component cannot be repaired the Customer has to buy a new product. So, the price of an unsuccessful repair is the chance of an unsuccessful repair times the retail price. The chance of a successful repair also calculates the repair costs in case of a successful repair. Together they provide the total repair price.

Next to estimating the chance of a successful repair will this step also determine if a priority part can be repaired at all, and if it can be repaired by the individual. Individual repair influences the labour costs in the next step as well.

$$TCOT = \frac{P}{S} + \frac{C}{S} \cdot \sum_{i}^{g} (L_i(100 - F_i) \cdot P + F_i(A_i + (T_i \cdot U_i) + V_i))$$

$F =$ Chance successful repair
$U =$ Labour costs

To assess a component on its repairability and chance for a successful repair, it must be graded in multiple criteria. In previous version of the TCOT these criteria and their conditions had been setup by me, and it was quickly discovered that it is incredibly hard to assess a product on its repairability. Each of the criteria; ease of disassembly, availability of service manuals, availability of spare parts, necessary tools, and ease of diagnosis, could be worth writing a thesis about. Therefor this step integrates large parts of the currently existing French Repairability Index.

A major difference between the FRI and the TCOT however is the way the grading is applied. The FRI grades a predetermined set of parts individually (see figure 13 list 1 and list 2). After which the grading is combined to form an overall grading. The TCOT however uses the same criteria and grading but keeps the grades of the components separate. In this way manufactures can spot possible room for improvements per part or failure mode. This does however not apply to the Documentation criterion; this will be graded separately and counts the same for all the components.

Criteria	Sub-criteria	Score of subcriterion /10	Weighting factor of subcriterion	Score of criterion /20	**Total criteria scores /100**
CRITERION 1 : DOCUMENTATION	**1.1 Availability of the technical documentation and other documentation related to user and maintenance instructions**	**0**	**2**	**0**	**0**
CRITERION 2 : DISASSEMBLY, ACCESSIBILITY, TOOLS, FASTENERS	**2.1 Ease of disassembly parts from List 2***	**0**	**1**	**0**	
	2.2 Necessary tools (List 2)	**0**	**0,5**		
	2.3 Fasteners characteristics parts from List 1 and List 2**	**0**	**0,5**		
CRITERION 3 : AVAILABILITY OF SPARE PARTS	**3.1 Availability over time parts from List 2**	**0**	**1**	**0**	
	3.2 Availability over time parts from List 1	**0**	**0,5**		
	3.3 Delivery time parts from List 2	**0**	**0,3**		
	3.4 Delivery time parts from List 1	**0**	**0,2**		
CRITERION 4 : PRICE OF SPARE PARTS	**4. Ratio between price of parts from list 2 to the price of the product**	**0**	**2**	**0**	
CRITERION 5 : SPECIFIC CRITERION	**5.1 Information about type of updates**	**0**	**1**	**0**	
	5.2 Free remote assistance	**0**	**0,5**		
	5.3 Possibility to reset softwares	**0**	**0,5**		
			Reparability index on 10		**0**

Figure 13: The Final grid of the FRI, this part is publicly available.

From the above sheet, the TCOT uses criterion 1, globally and criterion 2 and 3 per component. The overall grading of the parts or failure modes determines the chance of a successful repair. The criteria Price of spare parts and Specific criteria are not used, for previous steps of the tool cover the spare parts prices, and the specific criteria do not apply to all product groups.

Next, the conditions and grading of each of the criteria will be explained. The criteria to which the components are graded are divided into three main groups, grading the documentation, ability to be disassembled, and the availability and delivery time of spare.

Documentation:

The documentation of a product can help individuals and professional repairers alike when repairing a product. The grading of the documentation is different from the other criteria since it is a criterium that grades the product as a whole for its documentation, not per spare part. The list of Conditions and grading are copied from the FRI and can be graded in the TCOT to get to a final grade. The grade is determined by the availability of the documentation and the duration of this availability.

		Points
A	if X ≥ 7 years	7
B	if X = 6years	6
C	if X = 5 years	5
D	if NA or X ≤ 4 years	0

Documentation				
Conditions	Duration of Availability	points		
The enequivocal identification of the product(type of prodcut, trademark, trade name, model ,and possibly, serial number)	B: if X = 6years	6		
		0		
A dissasembly mapr orexploded view	B: if X = 6years	6		
Wiring and connection diagrams	C: if X = 5 years	5		
Electronic boards diagrams	B: if X = 6years	6		
List of necessary repair and testt equipment	A: if X ≥ 7 years	7		
Technical manual of insturctions for repair	A: if X ≥ 7 years	7		
Diagnostic fault and error codes	A: if X ≥ 7 years	7		
Component and diagnosis information	A: if X ≥ 7 years	7		
Instructions for software and firmware(including reset software)	C: if X = 5 years	5		
information on how to access data records of reported failure incidents stored on the product	C: if X = 5 years	5		
	C: if X = 5 years	5		
Technical Bulletins	C: if X = 5 years	5		
Guidance for self-repair(rcommended operations safety and repair instructions)	B: if X = 6years	6		
How to get acces to professional repairers	D: if NA or X ≤ 4 years	0		
Failures detection and required action(consumers approach)	C: if X = 5 years	5		
User and maintenance instructions	D: if NA or X ≤ 4 years	0		
		82	7,8	/10

Figure 14: the conditions and criteria of the documentation.

Grading ability to be disassembled

The ability to be disassembled is divided into three subcategories; Necessary tools, Ease of disassembly and types of fasteners used. Below the grading of each of these criteria is shown.

Necessary tools:

The type of tools required for the repair (or disassembly) greatly influence the repairability of a product. If a product is designed for repair, it is often the case that it can be repaired with basic or no tools. The FRI gives the best grading to a product when it can be disassembled with 'basic tools' to determine what basic tools are they refer to the European Standard NF EN 45554 (see appendix A).

		Points
A	Removable with basic or no tools	4
B	Removable only with specific tools	2
C	Removable only with proprietary tools	1
D	Not removable	0

When the user of the tool arrives at this step a reference is made to a tab (ANNEX_1) with a list of the basic tools.

Ease of disassembly:

Here the ease of disassembly will be graded on the number of steps that are needed to reach the priority components. The FRI describes a disassembly step as:

"*The disassembly sequence is defined as the order of steps needed to remove a part from a product (which might include getting access to fasteners). A step consists of an operation that finishes with the removal of a part or a component, and/or with a change of tool.*

A component may include one or several parts."

Some more important notions are:

"The hand is not considered a tool" and "A fastener is not considered as a part"

Information on the counting of the disassembly steps are displayed under the ANNEX_2 tab in the tool.

		Points
A	if DDi < 6	3
B	if 11 > DDi ≥ 6	2
C	if 16 > DDi ≥ 11	1
D	if NA or DDI ≥ 16	0

Types of fasteners used:

The types of fasteners will also be graded. The types of Fasteners that the person executing the disassembly comes across will be graded with the following criteria.

		Points
A	Removable and Reusable	2
B	Removable but not reusable	1
C	Neither removable nor reusable	0

The grading of the total disassembly looks like this in the TCOT.

	Disassembly									
	Necessary tools for disassembly			Ease of disassembly			Types of Fastners used			
Failure mode	Type of Tools used for disassembly	points	weight	Number of steps required for disassembly spare part	points	weight	Tpyes of fastners used	points	weight	grade /10
Display	A: Removable with no tools, or simple tools	4	2	A: if DDi < 6	3	4	A: Removable and Reusable	2	4	10,0
Buttons	A: Removable with no tools, or simple tools	4	2	A: if DDi < 6	3	4	A: Removable and Reusable	2	4	10,0
back cover	B: Removable with basic tools	2	2	C: if 16 > DDi ≥ 11	1	4	A: Removable and Reusable	2	4	5,7
Battery	A: Removable with no tools, or simple tools	4	2	D: if NA or DDI ≥ 16	0	4	A: Removable and Reusable	2	4	5,7
-	D: Removable only with proprietary tools	1	2	B: if 11 > DDi ≥ 6	2	4	A: Removable and Reusable	2	4	6,4
-	Select a grading	0	2	Select no. of steps	0	4	Select type	0	4	0,0
-	Select a grading	0	2	Select no. of steps	0	4	Select type	0	4	0,0
-	Select a grading	0	2	Select no. of steps	0	4	Select type	0	4	0,0
-	Select a grading	0	2	Select no. of steps	0	4	Select type	0	4	0,0
-	Select a grading	0	2	Select no. of steps	0	4	Select type	0	4	0,0

Figure 15: the grading of the disassembly.

Grading the spare part availability and delivery time:

Before the user goes to the next step where the availability and delivery time of spare is going to be graded. A question will be asked per failure mode if filling in the grading of spare parts would make sense. Spare part availability is not relevant for water damage and should therefore not be included in the total score.

The tool elaborately investigates spare part prices and their repair costs. However, the availability as well as the delivery time of spare parts, or spare priority components can influence the ease of repair. As stated at the beginning of this report are a substantial number of repairs is not executed for the lack of spare parts. The availability of spare parts is very subject to time. The availability of spare parts likely goes down over time rendering long term usage of many products impossible. Therefore the commitment of spare part availability will be filled in. The provision of spare parts will be graded for four different actors: Producers, spare part retailers, Repairers, and customers. Companies cannot guarantee 3rd party sellers will keep selling the parts. But the provision to the 3rd party sellers can still be guaranteed for a certain number of years.

		Points
A	if X ≥ 7 years	7
B	if X = 6years	6
C	if X = 5 years	5
D	if NA or X ≤ 4 years	0

Spare part delivery time:

Lastly, the parts delivery time will be graded. Even though a spare part might be available for a repair, if it takes too long to ship the customer is more likely to opt for a replacement product.

		Points
A	if X ≤ 3days	3
B	if 5 days ≥ X > 3 days	2
C	if 10 days ≥ X > 5 days	1
D	if NA or X >10 days	0

	Part availability									
	Producer		Spare parts retailers		Repairers		Customers			
Failure mode	Duration of availablility	points	Duration of availablility	points	Duration of availablility	points	Duration of availablility	points	grade /10	weight
Display	A: if X ≥ 7 years	7	A: if X ≥ 7 years	7	A: if X ≥ 7 years	7	B: if X = 6years	6	9,6	1,5
Buttons	C: if X = 5 years	5	C: if X = 5 years	5	C: if X = 5 years	5	D: if NA or X ≤ 4 years	0	5,4	1,5
back cover	A: if X ≥ 7 years	7	C: if X = 5 years	5	C: if X = 5 years	5	C: if X = 5 years	5	7,9	1,5
Battery	C: if X = 5 years	5	C: if X = 5 years	5	C: if X = 5 years	5	C: if X = 5 years	5	7,1	1,5
-	C: if X = 5 years	5	C: if X = 5 years	5	C: if X = 5 years	5	C: if X = 5 years	5	7,1	1,5
-	Select amount of years	0	Select amount of years	0	Select amount of years	0	Select amount of years	0	0,0	1,5
-	Select amount of years	0	Select amount of years	0	Select amount of years	0	Select amount of years	0	0,0	1,5
-	Select amount of years	0	Select amount of years	0	Select amount of years	0	Select amount of years	0	0,0	1,5
-	Select amount of years	0	Select amount of years	0	Select amount of years	0	Select amount of years	0	0,0	1,5
-	Select amount of years	0	Select amount of years	0	Select amount of years	0	Select amount of years	0	0,0	1,5

total grade
7,0
3,4
6,1
4,3
4,3
0,0
0,0
0,0
0,0
0,0

	Delivery time									
	Producer		Spare parts retailers		Repairers		Customers			
Failure mode	Duration of availablility	points	Duration of availablility	points	Duration of availablility	points	Duration of availablility	points	grade /10	weight
Display	A: if X ≥ 7 years	3	A: if X ≥ 7 years	3	A: if X ≥ 7 years	3	A: if X ≥ 7 years	3	4,3	0,5
Buttons	C: if X = 5 years	1	C: if X = 5 years	1	C: if X = 5 years	1	C: if X = 5 years	1	1,4	0,5
back cover	A: if X ≥ 7 years	3	A: if X ≥ 7 years	3	A: if X ≥ 7 years	3	A: if X ≥ 7 years	3	4,3	0,5
Battery	C: if X = 5 years	1	C: if X = 5 years	1	C: if X = 5 years	1	C: if X = 5 years	1	1,4	0,5
-	C: if X = 5 years	1	C: if X = 5 years	1	C: if X = 5 years	1	C: if X = 5 years	1	1,4	0,5
-	select no. days	0	select no. days	0	select no. days	0	select no. days	0	0,0	0,5
-	select no. days	0	select no. days	0	select no. days	0	select no. days	0	0,0	0,5
-	select no. days	0	select no. days	0	select no. days	0	select no. days	0	0,0	0,5
-	select no. days	0	select no. days	0	select no. days	0	select no. days	0	0,0	0,5
-	select no. days	0	select no. days	0	select no. days	0	select no. days	0	0,0	0,5

Figure 16: the grading tables for the spare part availability and delivery times.

The higher the score that comes out of step five the easier a repair. This result in a higher chance of a successful repair. The grade that comes out of the assessment of the components gets transformed into a percentage of successful repairs. An 8.5 becomes 85%. In the case study, this feature will be discussed.

Is self-repair possible?

During the disassembly of headphones, it was discovered that most earpads are easily replaced by hand without the use of any tools. To send back a headphone for a repair like an ear pad is very futile.

The same goes for products like the Fairphone and Gerard Street where extensive efforts have been put in the repairability of their products.

Although the TCOT is mainly focused on estimating the price for professional repairs some repairs can easily be performed by the users themselves. This would dramatically cut costs of the repairs of a specific priority component or failure mode. To judge the priority components on whether they are repairable by individuals the tool checks the values that have been filled in at some of the criteria.

The criteria that are being checked are necessary tools, types of fasteners used and the ease of disassembly. If they all score an A and minimally a B for ease of disassembly the tool checks the spare part availability and documentation. Here the tool checks mainly for the availability of spare parts for customers. If this reaches at least 5 years (Grade C) and the documentation is at least graded with an 8. Then the priority part can be regarded as repairable for the individual. This will cut the costs of labour in the total price of the repair for this specific part.

This also works vice versa, if a Part scores a D for necessary tools or has no availability of spare parts at all the scores will automatically be 0 and the price of the repair is the retail price.

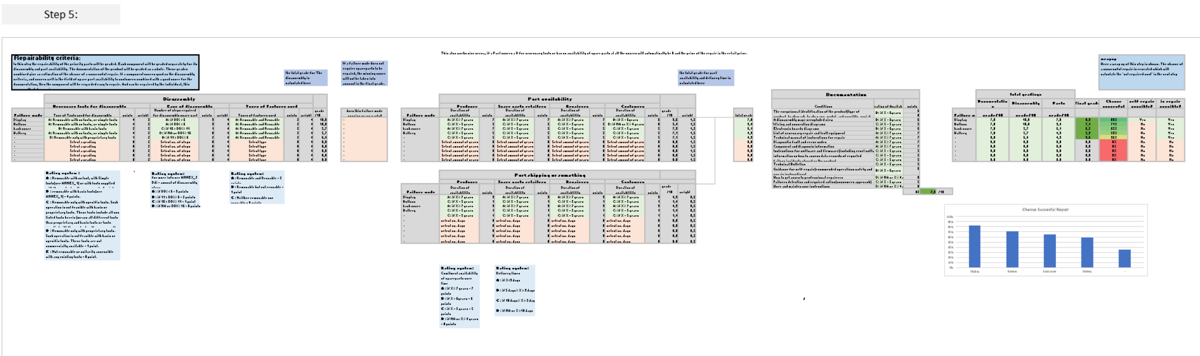


Figure 17: a zoomed out screenshot of step five.

Step 6: check-up data

After everything has been filled in the User can go to step 6 where an overview of all the data output is shown. The graphs show the user what the repair prices of the priority parts are and what the total ownership costs of their product will be. If the manufacturers spots surprising values for some of the parts, they can try to improve those in future versions to score better.

Step 6:

wrapup(per year)

this summary of all the previous steps. Here the graphs that show the user what the individual priority components cost, and it displays a breakdown of the total ownership costs are shown.

Labour Costs				Part Cost			not			total	
Failure mode	Best	Worst	avera	Best	Worst	avera	Best	Worst	avera	Best Cas	Worst Case
Display	-	-	-	5,35	17,92	11,64	4,41	6,57	5,49	9,77	24,49
Buttons	0,82	2,08	1,45	0,12	0,28	0,20	0,89	1,32	1,10	1,83	3,69
back cover	0,33	0,78	0,55	0,15	0,27	0,21	0,92	1,37	1,14	1,39	2,41
Battery	0,16	0,42	0,29	-	-	-	0,77	1,14	0,96	0,93	1,56
-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-

Repair Costs(year)	13,92	32,15
Retail price(year)	70,00	100,00
Total Cost of Ownership	83,92	132,15

Figure 18: a complete overview of all the relevant data displayed in the tool at step 6.

Step 7: print label

Then the final step leads the user to another tab, where the label is displayed. Here the label can be printed.

3.4. Labelling scheme

The cost of ownership and repair label is the final result of the TCOT. The label's classification schema and aesthetics have been inspired by the European label for energy usage. The latter is commonly used in practice to certify goods regarding their operational energy consumption.

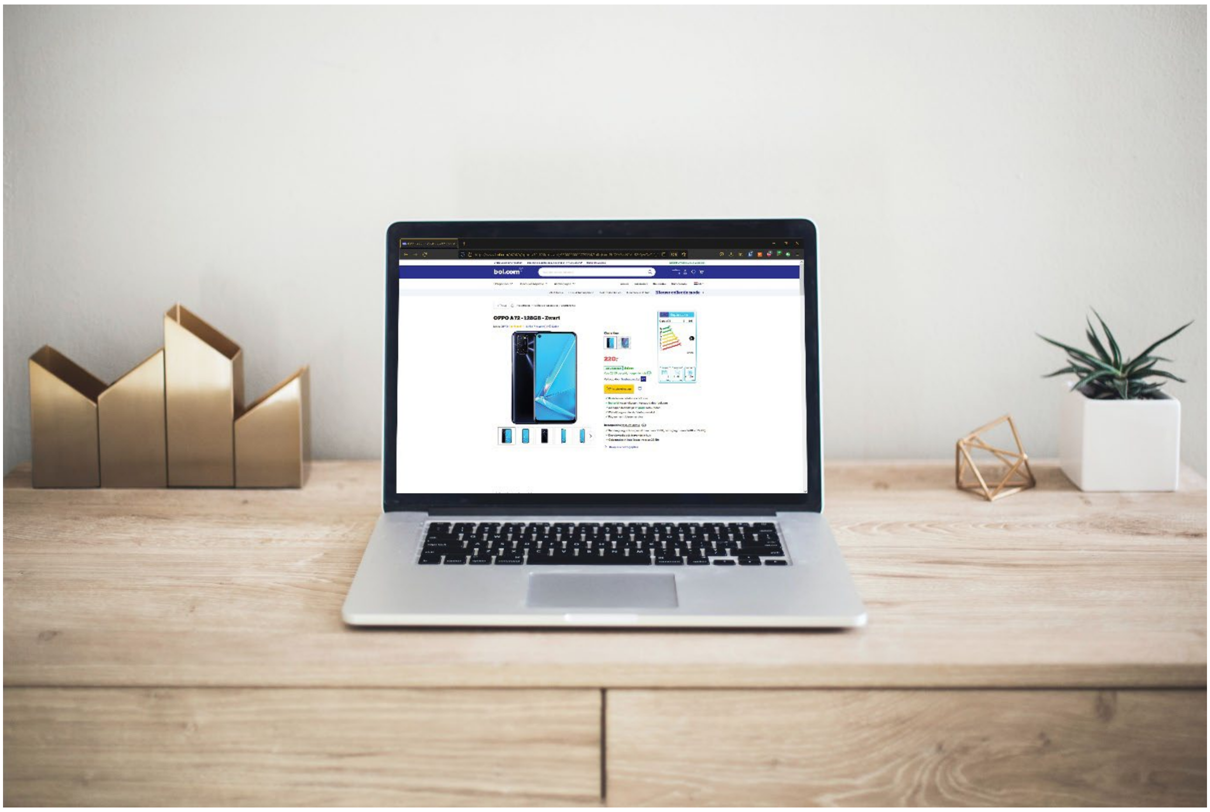


Figure 19: Label at an online website, photo by Kari Shea from unsplash.

On the label, the most important values regarding the total cost of ownership are displayed. It shows the name of the product, the retail price, expected service life, the repair costs per year and the total costs of ownership per year. Next to the grading A to G a percentage is shown. This is the percentage of the repair costs per year compared to the retail price.

A table to determine the grade is displayed below. More on the user testing of the label follows in chapter 5 the validation.

Grade	Condition
A	If X ≤ 5%
B	if 5% < X ≤ 10%
C	if 10% < X ≤ 15%
D	if 15% < X ≤ 20%
E	if 20% < X ≤ 25%
F	if 25% < X ≤ 30%
G	If X > 30%

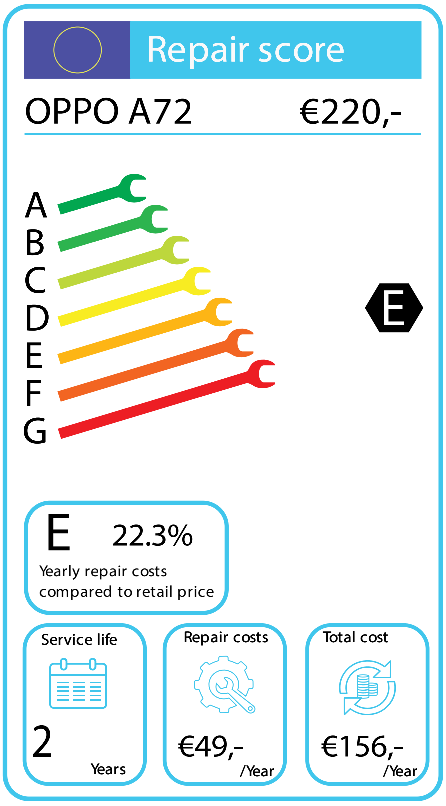


Figure 20: the final label.

4. Case Study: Smartphones

In this chapter ,the Tool will be demonstrated by a Case study with Smartphones. The chapter will give a short introduction to smartphones and their ecological footprint and service lives. After this, the input information used to test the tool with ,will be elaborated upon. After that multiple scenarios will show how the tool behaves with the change of certain inputs. The chapter will be closed of with the main takeaways.

The TCOT was initially set up asa universally applicable tool. However, it was quickly revealed that it takes a lot of time to test multiple product groups with the tool. Not only did testing multiple product groups take away the momentum from the iterative process it was also hard to get enough useful data to use the tool properly. Finally, the product group smartphones was chosen as the sole focus. Before choosing smartphones there have been iterations that looked at headphones(2nd pressure cooker) and washing machines (see appendix B).

Figure 21: one of the headphones during the disassembly timing of the second pressure cooker.

4.1. Introduction

The production and sales of smartphones have risen rapidly since their first introduction in 2007, the estimated number of units sold worldwide in 2021 is 1.54bn units (Statista, 2021). The production of smartphones brings with it a lot of greenhouse gas (GHG) emissions and is thought to surpass the individual contribution of GHG emissions of the production of desktops, laptops and displays (Belkhir & Elmeligi, 2018). Not only does the production of smartphones produce a lot of greenhouse gasses. a Smartphone contains various precious metals and minerals of which some rare earth elements like

Erbium, Europium and Neodymium. Extracting suchrare-earthh elements puts a lot of pressure on the surrounding ecosystems and groundwater supplies with the creation of toxic by-products (Logsdon, 2013). Other minerals like gold and Cobalt often turn out to be conflict minerals (Taffel, 2015) (Olesen, 2016).

The average service life of a smartphone is 21 months (Counterpoint, 2017) which is quite similar to the duration of the average contractual agreement with smartphone and network providers. Often smartphones are discarded long before their technical lifespan due to psychological aspects, like perceived obsolescence (Makov and Fitzpatric,2019). This perceived obsolescence increases when a product starts to malfunction and is in need of repair.

Touching these issues clarifies the need for smartphones to last longer, and for customers to be sensitized and empowered to make better decisions regarding the longevity of phones.

Smartphones are an interesting product for a case study with the TCOT since they can be considered a big-ticket item that gets repaired quite often. The 3rd party repair market is mature and consists of a range of small players as well as bigger affiliated repair shops. Where a mature repair market delivers valuable information regarding the prices of repairs, retail prices, and spare part costs, the academic literature on Smartphones remains scarce.

Where there is data on the service life, priority part failure rates and Smartphone failure rates the sources generally tend to vary widely in the data that they provide. This case study, therefore, looks at different data inputs and how they influence the outcome of the tool.

4.2. Input information & the scenarios

During the iterative process of shaping the tool the dataset to test it with has changed as well. Although smartphones eventually became the main scope of the tool earlier versions that looked at washing machines and headphones have helped to shape new iterations of the tool earlier on in the process.

Initially, the dataset comprised of 10 and eventually 12 phones, after which it was decided that the quality of the data was preferred over quantity. Five phones were eventually chosen to perform the final case study with. They were selected to be from different brands, price categories and it was checked whether they appeared in the iFixit repair index and the FRI for later comparison of the results.

The input of the tool will be described in the same stepwise order in which the tool was described in the previous chapter and how the user would fill it in. after the input data has been displayed the scenarios will investigate the way the tool handles changes in some of these data inputs.

Step 1: Retail price, service life, chance of repair Priority part failures:

Next to general information, this step requires the user to fill in the information regarding the service life, the chance of a repair needed and the retail price.

The retail price:

For the case study prices were sought on websites in the Netherlands, the prices were sim only and preferably came from the website of the brand itself. The values for retail price stay the same throughout all the scenarios.

Service life:

This data entry was a lot harder to determine. As stated in the introduction the average service life of a phone is 21 months, a little under 2 years (Counterpoint, 2017). This data is not brand specific, however. Other sources like de Consumentenbond (see figure 22) are more brand-specific and give a much more optimistic image of how long smartphones from different brands last. (Mansens, 2021b)

Smartphones

Wanneer wordt een smartphone gemiddeld vervangen vanwege gebreken of verminderde werking?

Merk smartphone	Na hoeveel jaar vervangen?
Nokia	5,2
Apple	4,5
HTC	4,1
Samsung	4,0
LG	3,9
Sony	3,8
Microsoft	3,4
Motorola	3,4
Huawei	3,3

Figure 22: Service life of Smartphones according to de Consumentenbond (Mansens 2021b).

In the different scenarios, service life is among one of the variables that get experimented with. The service life has a huge implication on the eventual score that is displayed on the label. Next tot that is it hard to imagine that someone would pay €1350,- for an iPhone 12 Pro Max every 2 years.

Failure rate:

A survey performed by Bullitt Research Group(2017) (n=5130) found that over a period of 3 years 34% of European smartphone users experienced breakdowns that would require repair or replacement of the device. This percentage can be used as an indication of how likely it is that a repair is needed. However, a paper by Cordella et al, (2021) stated that 47% of failures were reported in the first two years of use, while the other 39% of failures occurred between the second and third year of usage. One of the scenarios plays with these variables.

Step2: priority part selection and failures

In this step of the tool the priority failure modes and corresponding parts were being chosen. In the product category of smartphones, the failure modes align well with the priority parts breakdowns, if a screen does not work, it is highly likely that the screen is broken, the repair will be to replace the screen. The failure mode of water damage can often be solved with a chemical treatment, or with the changing of a component or part. Since the data is separated per repair it is assumed that water damage resulting in a broken screen would show up in the display results and not in the water damage results.

The data on the likelihood of a certain part to fail, or failure mode to occur is quite scarce and mostly generalist by nature (average damages in phones, instead of separated per brand). The picking of the percentages therefore remains a lot of guesswork. Consequently the differences between phones were kept at a minimum to prevent a very uncertain variable to interfere with the results too much. However, for the phones with a glass back cover the chance of breaking was made a little higher.

For the change of breaking the following graphs were used from the paper by Cordella et al.(2021).

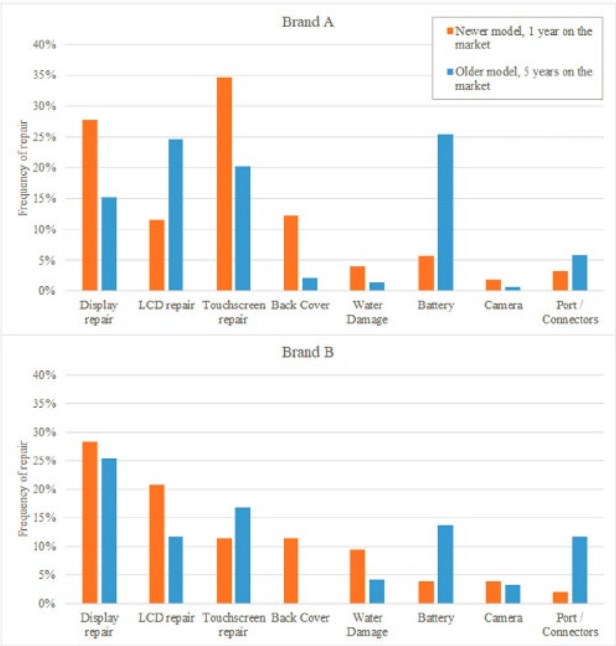


Figure 23: Likelihood priority part breakdown 2 different brands, (Cordella et al.2021)

The three most occurring smartphone breakdowns in newer models(orange) in both brands A and B are the display, LCD, and touchscreen. Although these three components are displayed separately, they all result in the replacement of a display. There are phone repair shops that put in the effort to only replace the screen or LCD instead of the whole display but due to a lack of data on the price of the separate parts these 3 parts are fused into one. This results in the replacement of a complete display to account for 67%.

The back cover is an interesting part since more modern phones now tend to have a glass back cover which is more susceptible to breaking. Of the selected phones the iPhone has a glass back cover and so it was graded with a higher possibility of breaking.

Batteries typically start showing signs of deterioration only after the period of 2-3 years, if this tool were to be filled in for a longer service life the results would be different. Underneath is a table with the failure modes and frequencies per phone displayed.

	iPhone 12 Pro Max	Samsung s 21+	Fairphone 3+	Google pixel 4a	OPPO A72
display lcd and touchscreen	67%	67%	67%	67%	67%
back cover	13%	7%	7%	7%	7%
battery	7%	5%	5%	5%	5%
water damage	4%	4%	5%	5%	5%
camera	3%	3%	4%	4%	4%
port connectors	2%	3%	2%	2%	2%
volume button	2%	2%	2%	2%	2%
speaker	2%	2%	2%	2%	2%

Cut-off

In the TCOT the cut-off frequency was set to 85% which left 5 priority parts for all phones except the iPhone which only had 3 parts left after the cut.

Step 3/4: priority part Costs, overall repair costs

To get data on the costs of priority parts several smartphone parts whole sales websites were manually scanned through. One of them required a business account which I could make. Not all the components could be found on parts retailers' websites, so Google shopping was also used. All the prices include tax, or tax was added manually in case the data was excluding tax.

The phone repair costs were found online on various 3rd party repair shop websites. The goal was to get as much data entries for the components with a maximum of five. This was not possible for a lot of parts.

Already an interesting thing was noticed when looking at the inputs for part prices and repair prices, repair shops often claim to be able to repair your phone within 30 minutes. So, the difference of 20 euro's for an apple might not be purely because of time put in the repair. Beneath a table with the average display repair prices, part prices and calculated labour is shown.

	total	part	labour
iPhone 12 Pro Max	€ 389,25	€ 301,00	€ 88,25
Samsung S21+	€ 249,25	€ 184,52	€ 64,73
Fairphone 3+	€ -	€ -	€ -
Google Pixel 4a	€ 207,58	€ 146,23	€ 61,35
OPPO A72	€ 107,60	€ 62,48	€ 45,12

Step 5: Repairability Criteria

In the TCOT the grading of the parts with the integration of the FRI was kept separately so every part would get its own score which could then be translated in a chance of success. However, on the website of the FRI (L'indice Réperabilité, n.d.) only the final grading sheet could be found, and not the individual data points that brought these figures about (see figure24). To be able to include these more generalist figures an alternative version (see figure 25) of the tool was made where the numbers could be filled in to get to ta repairability chance

Critère	Sous-critère	Note du sous-critère sur 10	Coefficient du sous critère	Note du critère sur 20	Total des notes des critères sur 100
CRITÈRE 1 : DOCUMENTATION	1.1 Durée de disponibilité de la documentation technique et relative aux conseils d'utilisation et d'entretien	8,5	2	16,9	87,3
CRITÈRE 2 : DÉMONTABILITÉ, ACCÈS, OUTILS, FIXATIONS	2.1 Facilité de démontage des pièces de la liste 2*	10,0	1	20,0	
	2.2 Outils nécessaires (liste 2)	10,0	0,5		
	2.3 Caractéristiques des fixations entre les pièces de la liste 1** et de la liste 2	10,0	0,5		
CRITÈRE 3 : DISPONIBILITÉ DES PIÈCES DÉTACHÉES	3.1 Durée de disponibilité des pièces de la liste 2	7,9	1	14,4	
	3.2 Durée de disponibilité des pièces de la liste 1	6,4	0,5		
	3.3 Délais de livraison des pièces de la liste 2	6,7	0,3		
	3.4 Délais de livraison des pièces de la liste 1	6,7	0,2		
CRITÈRE 4 : PRIX DES PIÈCES DÉTACHÉES	4. Rapport prix des pièces de la liste 2 sur prix de l'équipement neuf	8,0	2	16,0	
CRITÈRE 5 : CRITÈRE SPÉCIFIQUE	5.1 Informations sur la nature des mises à jour	10,0	1	20,0	
	5.2 Assistance à distance sans frais	10,0	0,5		
	5.3 Possibilité de réinitialisation logicielle	10,0	0,5		
				Note de l'indice sur 10	8,7

Figure 24: the data inputs from the FRI that have been used with the case study.

	grade	weight	grade per 20	per 10
1,1 Documentation grade	8,5	2	17	8,6
2,1Ease of disassembly	10	1	20	
2,2 Necessary tools	10	0,5		
2,3 Fastners	10	0,5		
3,1 commitment availability list1	7,9	1	14,45	
3,2 commitment availablitiy list 2	6,4	0,5		
3,3 delivery time part list2	6,7	0,3		
3,4 delivery time part list3	6,7	0,2		

Final grade	Chance succesful repair	self repair possible?
8,6	86%	Yes
8,6	86%	Yes
8,6	86%	Yes
8,6	86%	Yes
8,6	86%	Yes
0,0	0%	-
0,0	0%	-
0,0	0%	-
0,0	0%	-
0,0	0%	-

Figure 25: alternate version for the input of the FRI data.

4.3. Scenarios

The Iterative cycles of shaping testing and reflecting on the tool revealed that small variations in the input could result in big differences at the output. As the previous subchapter showed, the already scarcely available data, varies widely in their outcomes. It is interesting to show how these changes in input can influence the results. To show how the tool deals with the different inputs different scenarios had been set up. Each scenario explains what inputsweree used, what sources and assumptions were made, then it shows the results. If it is relevant it shows the results compared to previous results. After that follows the key findings of the case study will follow.

Scenario 1: 21 months service life

According to Counterpoint (2017) the average service life of a smartphone in Europe is 21 months. To see how the different phones would score with this input the service life was set to 1.5 years worst-case and 2 years Best-case.

The chance of a repair was set to 45% best-case and 49% worst-case since the service life would not exceed 2 years. Cordella et al,(2021) stated that 47% of failures were reported in the first two years of use.

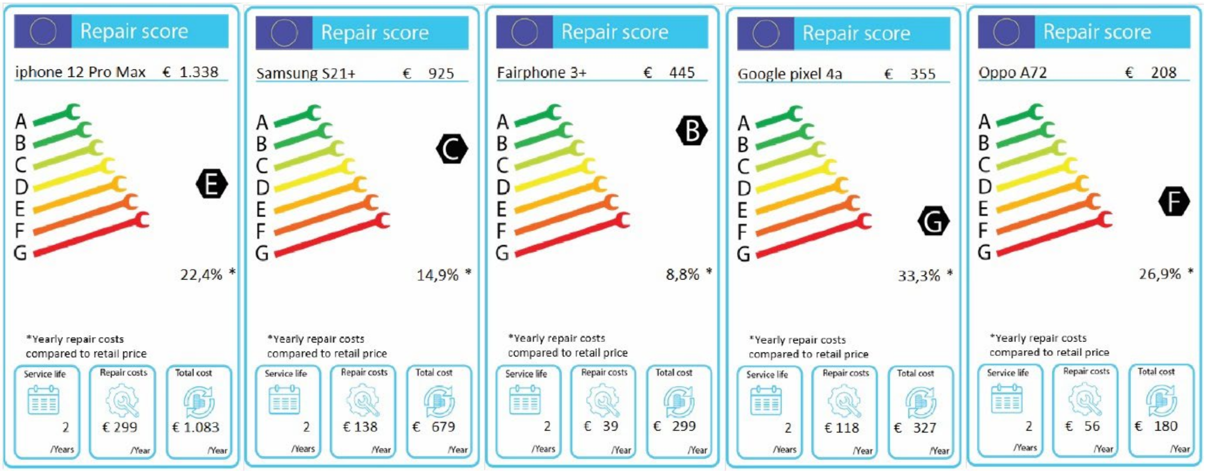


Figure 26: TCO labels scenario 1

The Tool determines its grading on the Repair costs per year compared to the Retail price therefore cheaper phones are scoring quite low. The more expensive phones score slightly better, since their Retail price is simply very high. Fairphone gets the best score, due to its lower repair costs. However, the total cost of ownership per year provides a very different picture. The iPhone easily costs more than €900,- per year. The same goes for Samsung, which receives quite a good repair score, but its cost of ownership is quite high.

Figure 27: TCO and repair cost scenario 1.

Scenario 2: Service life according to price

In the previous scenario the service life of only 21 months produces the highly unlikely scenario that a person with a €1338,- iPhone 12 Pro Max will pay more than €900,- per year to own their device. And will have to buy a new one every 1.5 to 2 years.

In this scenario the service life of each phone will be determined by the Retail price. For this hypothetical scenario. Inspiration has been taken from the Techniek Nederland (n.d.). Techniek Nederland made a table for the service life one should be able to expect of washing machines when looking at their retail prices.

Groot huishoudelijk (witgoed)		
Aankoopprijs	In jaren	In maanden
€ 0 - 199	2	24
€ 200 - 299	3	36
€ 300 - 399	4	48
€ 400 - 499	5	60
€ 500 - 599	6	72
€ 600 - 699	7	84
≥ € 700	8	96

Figure 28: Life expectancy of washing machines. (Techniek Nederland, n.d.)

Applying a similar distinction for phones would make a lot of sense. One should be able to assume that more expensive phones not only outperform cheaper phones, but also outlast them. If the same principle for price ranges is used to determine the service life of the phones. The following table will be the input for this scenario.

Retail Price	Service life Best-case	Service life worst-case
€0 - 199	2	1
€200 - 399	3	2
€400 - 599	4	3
€600 - 799	5	4
>= €800	6	5

The used inputs for service life are now:

	Retail price	Service life best-case	Service life worst-case
iPhone 12 Pro Max	€1338,-	6	5
Samsung S21+	€925,-	6	5
Fairphone 3+	€445,-	4	3
Google Pixel 4a	€355,-	3	2
OPPO A72	€208,-	3	2

Due to their longer service life, the repair costs per year become lower and this influences the scoring of the phones.

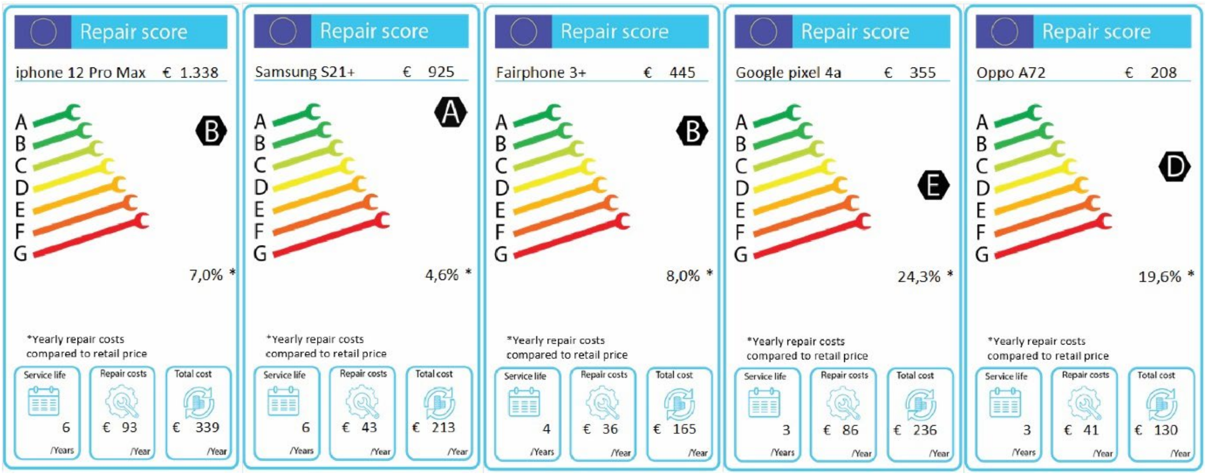


Figure 29: the TCO labels of scenario 2

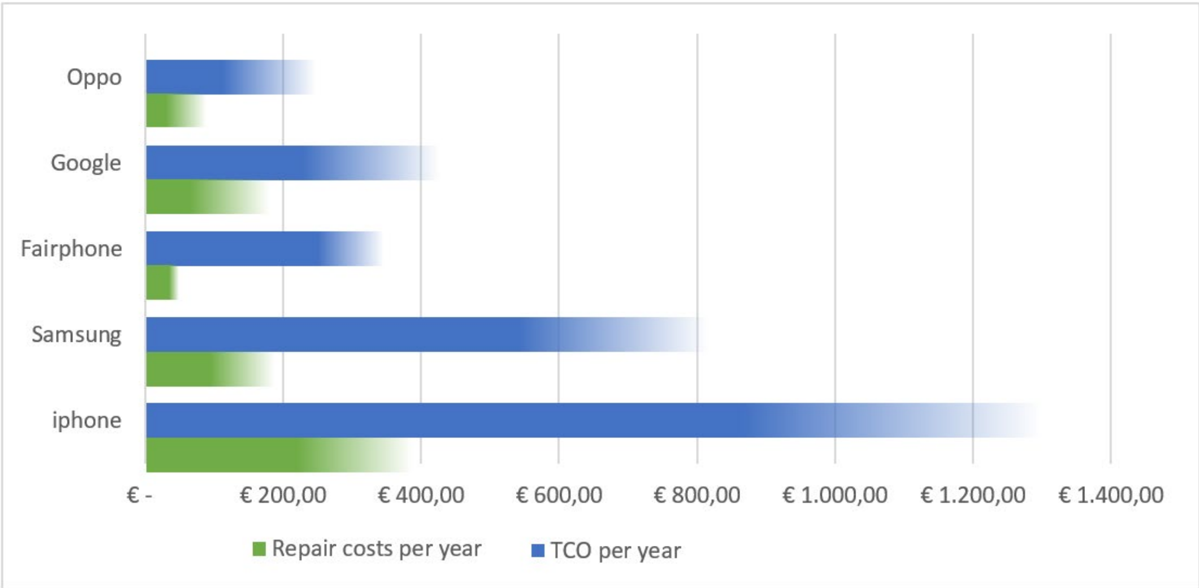


Figure 30: the TCO and repair costs of scenario 1

In general, all phones become cheaper in their total cost of ownership per year, as well as their repair costs per year. However, the biggest change happens in the more expensive phones. In this scenario the Google pixels worst-case repair costs and TCO are higher than the iPhone's best-case TCO and repair costs.

Figure 31: The TCO and repair costs of scenario 2.

Scenario 3: Longer service life, the higher the chance of breaking.

If a device is in use longer the chance of a failure goes up, this was considered in the previous scenario. In this scenario the longer-lasting phones will have a higher chance of needing repair. As with the previous scenario the phones that last 1-2 years will have a value between 45-49% and any phone lasting longer 84-88%. This is derived from the paper by Cordella et al,(2021) which stated that 47% of failures were reported in the first two years of use, while the other 39%(total 86%) of failures occurred between the second and third year of usage.

Another thing that changes over time is the frequencies of the individual failure modes. Take batteries for example. Batteries tend to last 2-3 years, so if a phone only lasts 2 years the chance of a battery replacement remains low, but if the phone lasts longer than the service life of a battery the frequency goes up. Although there is much to say for changing the individual failure mode frequencies. This is out of scope for lack of data and for the sake of changing as few variables as possible at the same time.

The input variables are derived from this table:

Retail Price	Service life Best-case	Service life worst-case	Chance repair worst	Chance repair best
€0 - 199	2	1	45%	49%
€200 - 399	3	2	45%	49%
€400 - 599	4	3	84%	88%
€600 - 799	5	4	84%	88%
>= €800	6	5	84%	88%

These are the input variables.

	Retail price	Chance repair best-case	Chance repair worst-case
iPhone 12 Pro Max	€1338,-	84%	88%

Samsung S21+	€925,-	84%	88%
Fairphone 3+	€445,-	84%	88%
Google Pixel 4a	€355,-	84%	88%
OPPO A72	€208,-	45%	49%

The difference compared to the previous scenario is that the longer-lasting phones became more expensive to repair per year. It is shown that the lower-priced phones are relatively more expensive to get repaired.

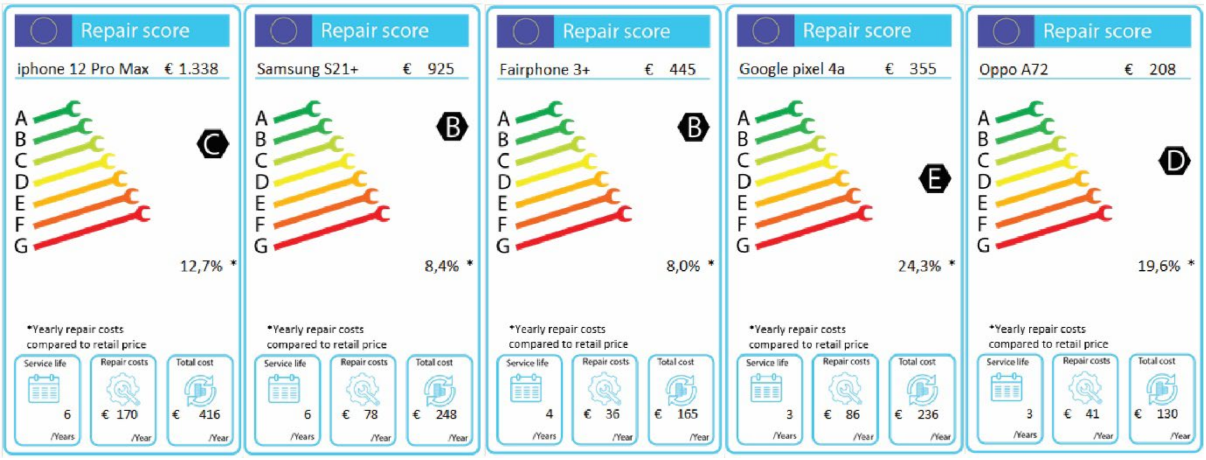


Figure 32: the TCO labels of scenario 3

Figure 33: TCO and repair cost Scenario 2.

An interesting change in data is that the Google Pixel is not far away from the iPhone in cost of ownership. And in some cases can exceed the iPhone in costs per year.

Figure 34: the TCO and repair cost scenario 3.

When you put the scores from the TCOT in comparison with the FRI and iFixit scores you see a very strong correlation between the FRI scores and the TCOT scoring. This is less the case between the iFixit and RCO score.

	Retail price	FRI score	iFixit score	RCO(TCOT)
Iphone 12 Pro max	€ 1.350,00	6,0	6,0	12.7%
Samsung S21 plus	€ 930,00	8.2	4,0	8.4%
Fairphone	€ 439,00	8,7	10,0	8%
Google pixel 4a	€ 350,00	6,3	6,0	24.3%
Oppo A72	€ 170,00	6.8	-	19.6%

Scenario 4: Apple announces self-repair service

In this scenario, the announcement of Apples' self-repair service (BBC News, 2021) will be tested for its impact on the score.


Apple announces self-service repair scheme in win for campaigners

17 November 2021

Figure 35: Screenshot of article header source: https://www.bbc.com/news/technology-59322349

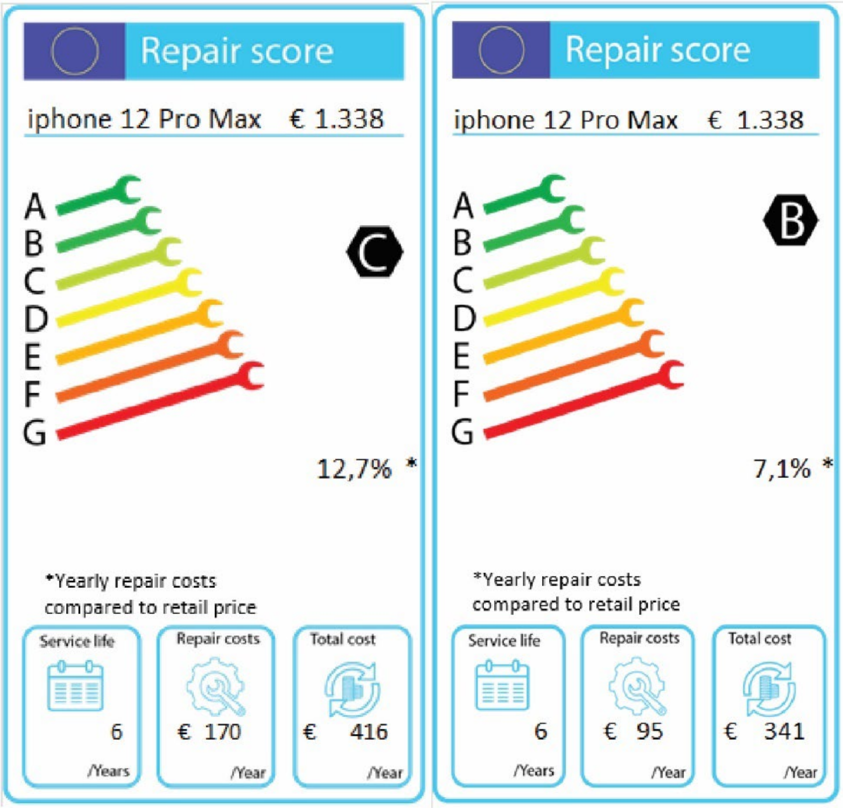
The possibility of self-repair is being graded in the TCOT at step 5. If certain values are met in the FRI grading system a component or failure mode will be regarded repairable by the individual. For this test the original score (see figure 36 left) is altered. As can be seen on the right, the iPhone now score a 7.3. The 8 for documentation is a minimal requirement for self-repair within the TCOT.

	grade	weight	grade per 20	per 10
1,1 Documentation grade	6,2	2	12,4	4,6
2,1Ease of disassembly	2,5	1	5,95	
2,2 Necessary tools	1,9	0,5		
2,3 Fastners	5	0,5		
3,1 commitment availability list1	6,5	1	9,36	
3,2 commitment availablitiy list 2	1,3	0,5		
3,3 delivery time part list2	6,5	0,3		
3,4 delivery time part list3	1,3	0,2		

	grade	weight	grade per 20	per 10
1,1 Documentation grade	8	2	16	7,3
2,1Ease of disassembly	7	1	14	
2,2 Necessary tools	7	0,5		
2,3 Fastners	7	0,5		
3,1 commitment availability list1	7	1	14	
3,2 commitment availablitiy list 2	7	0,5		
3,3 delivery time part list2	7	0,3		
3,4 delivery time part list3	7	0,2		

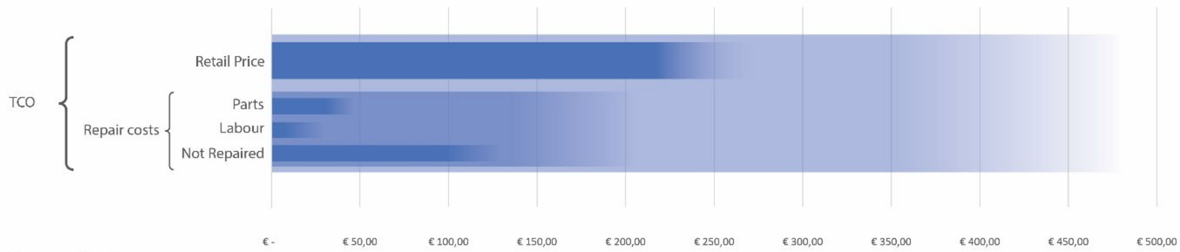
Figure 36: FRI input, left the real values, right altered values.

The iPhone would immediately jump from a C to a B grading and would become €75,- per year cheaper in repair costs.



As can be seen in the graphs below, the labour price disappears and the price of not repaired goes down considerably.

Scenario 2



Scenario 4

4.4. Key findings:

From the comparison with the other currently existing tools and scenario 4 it can be concluded that phones that score well in the FRI also score well in the TCOT. This is mainly because the FRI has a big impact on the repairability of a product and so the chance of a successful repair and in turn the costs of a repair.

Service life has a very strong influence on the outcome of the data. This makes sense since everything is eventually divided by the service life to get to a cost per year. Perhaps it would be good to show the total repair costs compared to the total retail price as well.

Varying the input variables in the scenarios has shown their relative impact on the actual scoring of the phones. Still, it would be interesting to see what the impact of a longer service life is on the frequency of individual part breakdowns and how this influences the repair costs.

Predetermined lists for the service life of phones in relation to their price would help the push for longevity. However, the problem with these lists is that a small change in price (from €199 to €201) would result in a much longer service life and a better score. There must be an actual connection between the service life in the tool and real life.

The chance of a successful repair is directly connected to the grading of the FRI in the 3 criteria mentioned in step 5. As stated before, this value influences the outcome considerably, so tweaking might be needed regarding the directness of the way the FRI grading is translated into the chance of a successful repair. Otherwise, an alternative method of estimation will be needed.

During the case study the disassembly metric was not used. Still, it has been tried out in smaller tests. To estimate the other variable costs, an estimation of the ratio of labour costs, parts cost and other cost had to be made. With the available data on the 5 phones, such an estimation was possible. But that is because the repair price and part costs are known. Moreover, a significant difference could be noticed in the ratio of costs. Too little investigation went into the disassembly metric to say something about it.

5. Validation

The Smartphone case study helped to gain insight into how the tool would respond to major and minor changes in the data input. The technical aspects of the tool have been tested. Still, the Tool needed to be validated with the stakeholders to see how well it helps the stakeholders to achieve their goals.

In this chapter, the perspectives of the main stakeholders will be described and key findings from interviews, user tests, and questionnaires will be discussed.

5.1. Customer perspective

Figure 37: impression of what it could look like with a label on a product picture from GSM Dome(2018).

One of the goals the customer has was:

- *Have an easy quantitative comparison between products to be able to choose the longest lasting product, to save money and work towards a better environment.*

To test if the customer would understand the user tests had been done. The first questionnaire was aimed at finding out if the respondents understood how to make a decision based on what was displayed on the label (N=16). The first question asked the respondent to choose one criterium from the list that they found most important if they would buy a new phone. Then 5 labels were shown from which one could be chosen. In general, it could be concluded that the respondents understood the labels. Yet the questionnaire had not been thoroughly thought through and contained too many variables to draw any hard conclusions on.

Pairwise comparison:

After the label had been progressively improved a second questionnaire was used to deduce what people found the best way to display the grading and value of the repair costs (N=10). For this the pairwise comparison method was used.

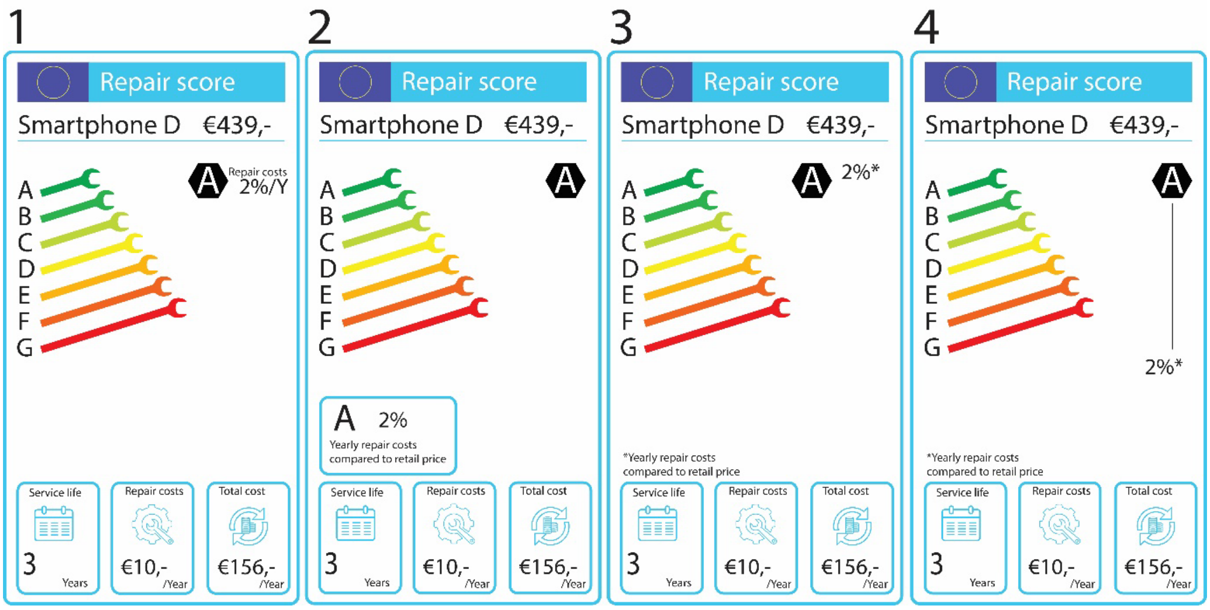


Figure 38: different versions tested with the pairwise comparison.

Each question from the questionnaire was a comparison between two of the labels. In the matrix the winner of each comparison is noted, and the total amount of wins are displayed in the table on the right. Label number 2 won 3 comparisons and was therefore regarded as the best label according to this questionnaire.

	1	**2**	**3**	**4**
1		2	3	1
2			2	2
3				3
4				

	No. wins
1	1
2	3
3	2
4	0

A lot of the customer validation focussed on the aesthetics and intuitiveness of the label. However, from the customer's perspective, there was also a remark on the tool.

The TCOT assesses the individual failure modes for their ability to be repaired. One of the used criteria to judge this is the basic tools list of the EN 45554 norm. Still, many of these so-called Basic tools will not be in most people their houses nor will a layperson know how to use them. Not every individual can be expected to have tools like a soldering iron and multi-meter and the skills to operate them. Hence there should be a distinction in this list between basic tools (scores well) and the use of no tools or simple tools (scoring best) to be able to judge a product for its repairability by an individual. A proposal for such a list is shown in appendix B.

A final remark needs to be made towards the display of expected service life to customers. The way the expected service life is communicated to customers can also negatively influence the actual service life and detention time (Van Den Berge et al., 2021). The argument made in their paper is that people might opt for buying a new product if it is nearing its expected service life instead of getting it repaired.

Transparency:

The second goal was:

- *Transparency into how the grading came to be, or market surveillance authorities that check companies for their truthfulness.*

The TCOT does not allow for people to see how the actual grading was calculated and what input variables have been used. It might be interesting for a future version to have an overview sheet made publicly available. For now, the public must trust the market surveillance organizations that are authorized to see the input data.

5.2. Legislator perspective

Two informal qualitative semi-guided interviews had been planned with M.Depypere, Depypere is a repair policy engineer at iFixit. The first interview took place early in the thesis project and mainly covered what to pay attention to when making a repair scoring tool. Depypere tipped me that it will be important to focus instead of diverging too much. In the topic of repair costs there are numerous rabbit holes to go down into and there must be a clear line. Furthermore, did the interview provide me with background information on how the cooperation with the industry goes when new legislation needs to be put in place.

During the second meeting, the TCOT was more or less in its final shape. Next to discussing some shortcomings in current tools and how the TCOT tackled them we discussed a very interesting notion. Ever since the beginning of this thesis project I assumed that legislators would want the TCOT to be able to benchmark products and punish manufacturers when they would underperform. So gradually products that score low would be phased out. However, Depypere gave me the very important insight that legislators have two ways of working, and he mentioned the carrot and the stick analogy. This basically entails that legislators can enforce benchmarks (the stick) or nudge companies into ‘better’ behaviour (the carrot).

The TCOT turned out to be more a carrot method than a stick method. Legislators would have to enforce the tool itself upon manufacturers, but consumers will have the opportunity to choose for longer-lasting products with the newly acquired transparency on the total costs of products.

This does not mean that the quantified way of displaying the information is not needed for legislators. The quantified data output is still a valuable method for legislators to see if the legislation put in place is effective. However, it also indicates that the labels and their design are more important than previously assumed and will need more attention in future iterations.

Referring to the goals from the introduction it can be concluded that indeed quantifiable information will be needed, but not exactly for the enforcement of benchmarks.

- A quantitative unambiguous way to measure the repairability and longevity of products to be able to set thresholds that manufacturers must tend to.
- A quantitative way to display the hidden costs (cost of ownership) of products.
- verifiable data way to assess the input data from the manufacturers.

More information on how such a tool would be developed follows in the next chapter.

5.3. Manufacturer's perspective

The tool has been put through its paces with the case study, which has been a valuable method to iterate on the tool. The filling in of the tool still had to be tested. Two tests were performed to attempt to improve the intuitiveness of the tool for the user, which would be the manufacturer. Unfortunately, no manufacturers replied to emails sent out for interviews, but another student was called in for a user test.

The test took place over Microsoft Teams. The user was given an empty tool and a sheet with input data. He was asked to fill it in the tool while sharing the screen and thinking out loud.

Similarly, to chapter 3.3 the participant went through the steps as the landing page of the tool explained. However, in the attempt to make the tool as simple as possible explanation on the calculation of key values lacked. This made the tool feel like a black box. Much explanation was still needed during the test, and the tool was a bit overwhelming due to a lack of colour coding and basic feedback.

These points had been integrated into the last version of the tool to provide a clear and less intimidating tool. More information on the usage of the tool had been added with each step and conditional formatting showed the participant where data still needed to be filled in and whether he could proceed to the next step. The improvements made were noticed by the user during the second user test.

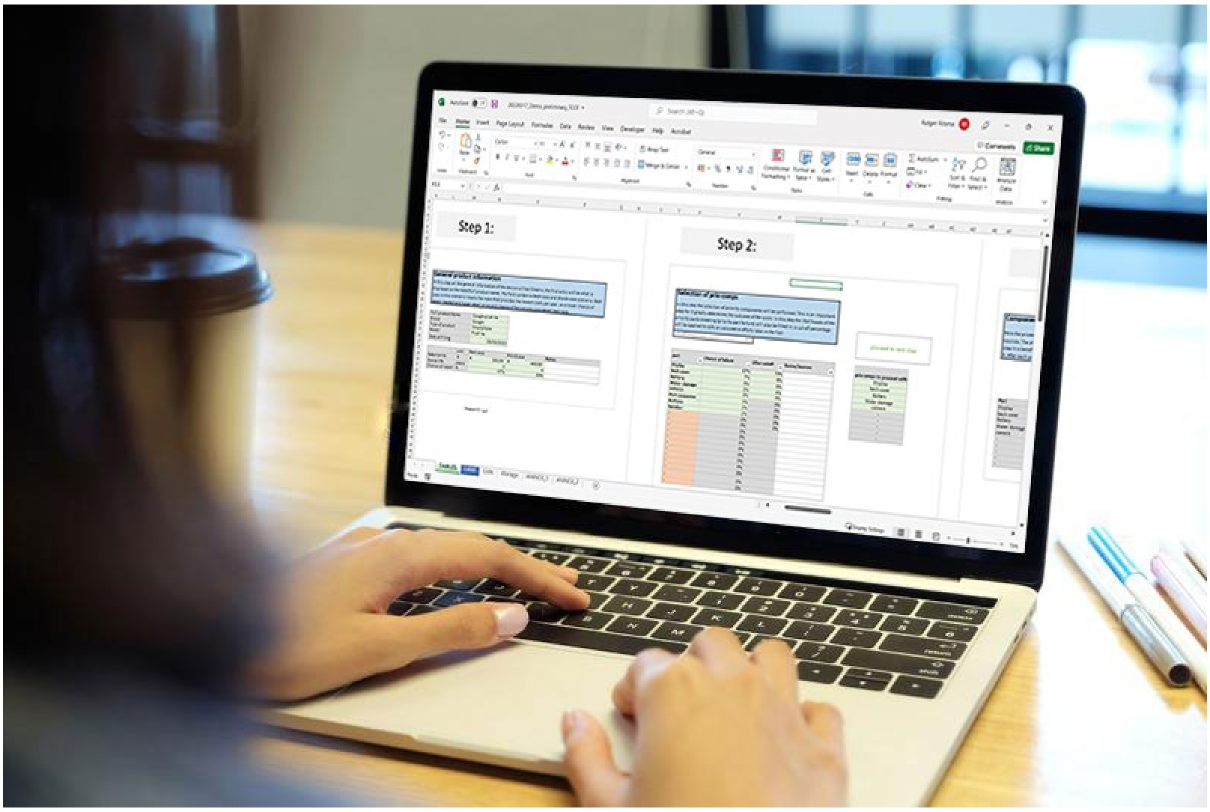


Figure 39: an impression of a manufacturer filling in the tool. (picture from adobe stock)

Looking back at the initial goals:

- An intuitive tool that requires little effort to fill in.
- Simple to make an excerpt for checks by authorities
- Confidentiality of sensitive information.

- Room for distinguishing themselves

It can be concluded that the tool itself now serves as an excerpt for checks by market surveillance authorities, instead of a specific page. Only allowing market surveillance authorities to see the filled-in tool provides the safety of sensitive information. The intuitiveness of the tool needs more attention. But as a proof of concept, it showed that it is possible to work with the tool.

6. Implementation

This chapter briefly touches upon the implementation of the TCOT. The parties involved will be discussed as well as what steps need to be undertaken to eventually implement the tool. The development of a tool like the TCOT requires a lot of collaboration from different parties, spanning many years. Some steps in the process will be highlighted and elaborated upon with regard to information and insights found during the development of the TCOT.

Phase 1: setting up

After funding has been found the first step would be to reach out to potential partners. Different representatives from consumer organizations, market surveillance authorities, manufacturers, environmental organizations and of course legislator organs need to be involved with the project.

The tool needs to be tested with real data from manufacturers to be able to re-evaluate each of the steps in the TCOT. This data can be used to tweak the tool to produce the most realistic values. The tool will never provide an exact representation of reality so a consensus must be reached on how precise the output must be for it to be sufficient.

Although the initial idea was to make the TCOT a universally applicable tool, a set of product groups must be selected to start applying to the tool. A first step would be to take the product groups that are tested in the FRI. Electronic products form a strong entry point in the implementation of the TCOT, for their relatively high environmental impact and costs. However, it would be very interesting and important to make a step towards a tool that could also assess other products, for example, outdoor jackets.

A set of standards will have to be conceived, standards on what is considered a part, a consumable and what is considered maintenance and what is considered repair? These issues need to be addressed early in the project to prevent confusion later.

Phase 2: added functionality

After the set of products standards and the teams have been established the next phase would be to integrate new functionality into the tool. The quantitative approach of the eDIM could be implemented in the disassembly metric of step 4, an Application Programming Interface (API) could be used to scrape data off the internet or a database to automatically fill in the prices.

Integrate eDIM for the disassembly metric:

using proxy times, like the eDIM method, for the calculation of the disassembly times presents some advantages considering the creation of a level playing field for manufacturers. All companies will have the same rules to work with. However, eDIM is not suitable for all product groups yet and can still be very far off from reality and will need to be adjusted accordingly. For some products, it is already interesting to look at implementing eDIM, like washing machines. eDIM has been tested with washing machines before.

Integrating API:

Much effort can be prevented if the tool has an automatic system to look up data on the prices of spare parts and repairs online. Websites like tweakers (see figure 40) have implemented such systems in their website.

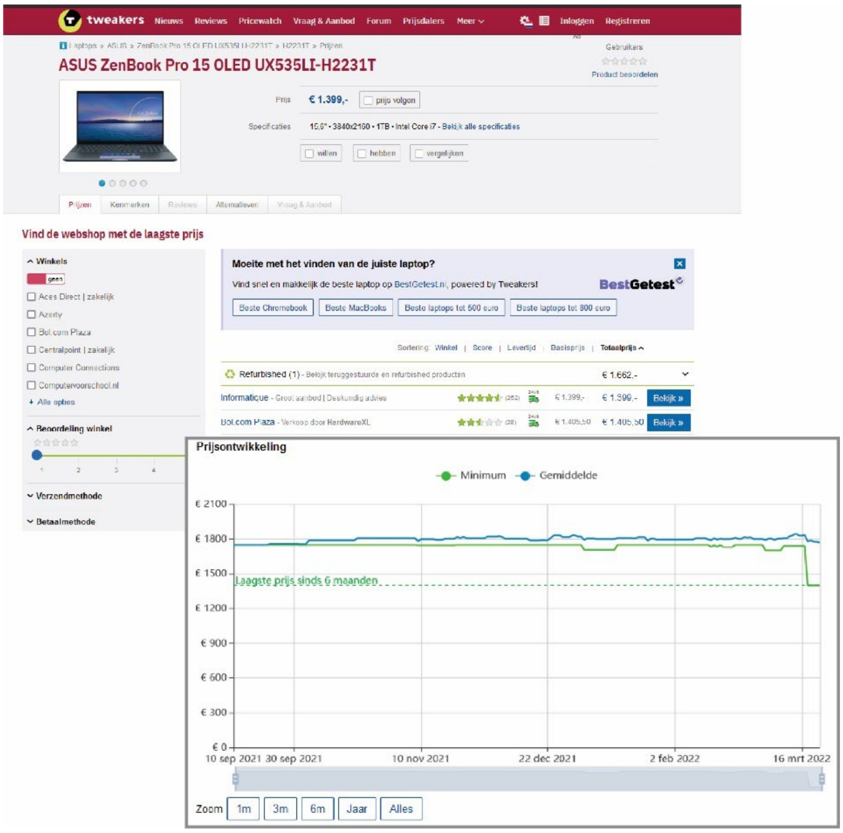


Figure 40: Tweakers.net showing a list of places to buy the laptop, below a historic price graph. (Tweakers, n.d.)

API is an acronym for application interface. An API is a set of rules that defines how software applications can talk to each other essentially making API a software intermediary. A piece of software can be written for 'data scraping'. A data scraping API, much like the name implies, scrapes a database or internet for data, which can be input for the TCOT. Many websites have a set of API rules allowing for communication with the website, and the data displayed on it, without opening the website.

Integrating a data scraping API will also allow the tool to be up to date. However, it must be decided whether that is desirable or not.

Keep evolving:

As the implementation of the tool progresses new product groups should be added, and the European wide implementation should be considered.

7. Conclusions

The reflection on the main goal of this thesis will take place in this chapter. The individual research questions will be covered in appendix E.

Main goal:

Create and validate a quantitative total cost of ownership tool with an accompanying labelling scheme, that allows for comparing products on their ownership costs, with a focus on repair.

The TCOT provides valuable insights into the cost of ownership of a device. The quantitative display of these often unknown and intangible costs provides the customer with the information that she needs to better be able to choose for a longer-lasting product. Of course, the choice for one product over another often relies on gut feeling, brand loyalty and personal values. However, providing a total cost of ownership to the customer allows to better couple other specifications to costs. In one of the scenarios, a cheaper Google Pixel phone was relatively comparable in ownership costs as the technologically more advanced iPhone.

No quantitative cost of ownership or quantitative repair tools exists yet. The number of different variables that are to be researched and the amount of standardization documents that will need to be conceived is considerable. This thesis attempted to cover as many of these variables as possible and provide valuable insight into how to quantify the costs of ownership. However, decisions had to be made on what to cover and what to leave out which leaves room for improvements that will be discussed in the recommendations.

Existing tools provided valuable information for the making of this tool. The integration of the FRI was a valuable contribution to the TCOT to be able to grade the chance of a successful repair of individual components. The issues that the literature research laid bare were evaded as much as possible. The TCOT does include the integration of self-repair, and if a part scores bad on specific criteria the part is regarded as unrepairable. The final grades of the tool are hard to compare with existing tools but there is a strong correlation with the grades of the FRI, this is mainly due to the integration of the FRI to assess products for their repairability. The iFixit tool gives quite different results for it is a tool focussed on self-repair and not so much on the professional repair.

The scenarios are no actual depictions of reality as the case study revealed. The input data contained too many inconsistencies. However, in the scenarios, the TCOT produced values that fall within expectations. In general, cheaper phones scored quite bad, and the Fairphone, a phone designed for easy repair and longevity continuously scored well.

Although initially designed to be universally applicable for multiple product groups, the testing of the TCOT and creation of the tool was largely performed with Smartphones. Therefore, it will be necessary to tweak and adapt the tool per product group. This was something I wanted to avoid at the onset of the project. The differentiation between product groups might result in the integration of eDIM on some product groups where this is possible, like washing machines. The tool will need a lot of tweaking but if it can provide the same result with actual data that would be a very good step in the right direction.

Nearing the end of the project a revelation happened during one of the meetings with M. Depypere. He told me that legislators much prefer to work with nudging than with punishing, something that I thought the quantitative data of the tool would be used for. Still, the quantitative information will be valuable for tracking the overall improvement of products to see if the new TCOT legislations are having an impact. The label that came out of the tool was therefore way more important for the transition towards a circular Europe by 2050 than initially assumed.

8. Recommendations

The making of the TCOT made me look at repair from various perspectives and angles. Moving from a very broad perspective to trying to sort out the nitty-gritty details of course allowed me to answer a lot of questions. But this always tends to raise more questions than answer them. As I consider myself quite critical of my own work, I could write multiple pages full of recommendations, here the most important recommendations.

Carrot and stick

The shift in focus from punishing manufacturers to nudging manufacturers into producing longer-lasting more repairable products, means that more attention needs to be put in the labelling scheme. It is eventually what is going to help the customer decide for longer-lasting products and it will be the main selling point of the tool. As a legislator it is much easier to sell a label, than to say, I have this obligatory tool that you need to fill in, it only takes 4 days.

This also means that more effort should go into the design of the label. Is the information that is displayed on the label the right information for customers to make a comparison, or does it need to be presented differently? These kinds of questions have only partly been answered with this thesis and will need further research.

Priority part vs priority failure modes.

The next version of the tool should have a better way of dealing with the failure modes and priority parts. With the case study of the smartphones, the failure mode of water damage could easily be hacked into the tool for the available data set allowed this. However, if in other product groups certain failure modes could have 3 parts that need replacement and two repairs of this failure mode in which the costs only exist of labour. This will be harder to hack into the tool, a matrix that splits the failure modes into parts and labour could be an option.

Qualitative input of the FRI.

This topic has elaborately been discussed in the report, the integration of the FRI. The FRI is a tried and tested way of grading a product on its's repairability. The TCOT however mainly grades individual failure modes and priority parts. Therefore the FRI had to be adapted to suit this approach. The TCOT combats two major points of critique towards the FRI, the lack of self-repair, and the possibility for a product to score well overall, while scoring badly on spare part availability. However, one of the criteria for self-repair is the tools that are being used during the repair. The basic tools list of the EN NEN 45554 that is used as a reference contains many tools that arguable not a lot of people will have nor have the skills to work with. Therefore I propose to integrate an alternate version of these tools which splits them in 'simple tools'(scores best) and 'basic tools'(scores good) in appendix A proposed alteration to the list can be found.

In the TCOT the grade that comes out of the FRI criteria is directly translated to a percentage value of the successful repair. A grade of 7.4 would become a 74% chance of a successful repair. The impact of this variable on the overall grading and repair costs is considerable. Therefore, more research needs to be done on how to translate repairability into a chance of successful repair. Moreover, should this method be tested for its credibility to integrate the chance of a successful repair in the first place?

Perhaps the chance of a successful repair should be estimated with historical data. This will however require a homogenous database that is accessible to manufacturers, consumer organizations and repair companies. This will allow for the most accurate data but will also require collaboration and standardization on a large scale. This database would however be valuable for other purposes than only quantifying the chance of a successful repair in the TCOT.

Including or excluding taxes:

Providing data to the customer and manufacturer will probably require the data to be split into data with and without tax.

Estimating costs with disassembly metric needs improvement:

When a product is new and hasn't reached the market yet or no known repair prices are online the manufacturer can use a disassembly metric at step 4 of the tool. The disassembly metric provides an alternative whenever no, or little, data is available for the product that is being graded. However, this function of the tool did not receive enough attention during the iterative case studies. It was briefly covered during some tests, but much research will still be needed. If a manufacturer uses timing to get to an estimated repair cost, the costs do not include the administration and other variable costs. These are included when prices er taken from the internet. The tool tries to solve this by filling in a ratio of part, labour, and variable costs. This is however a very inaccurate way to estimate the total variable costs of a repair.

Moreover, it was noticed during the field studies and literature study that repair shops don't really use the repair time to price their repairs in the field of smartphones and other small electronics. The price of competitors or a price that seems reasonable much more determines the actual repair price than the time it takes.

The universality of the tool.

The tool was initially set up to be universally applicable for all products but was eventually mainly iterated upon with Smartphone data. Making a general tool will allow multiple products to be graded but will provide a less accurate result. And having tailormade tools per product group will allow for more accurate data but will provide less coverage. Probably a decision must be made to decide either one.

Averages, best-case and worst-case issues:

The definitions of Worst-case and Best-case need to be standardized. In the tool I integrated a 47% chance of failure by having a best-case of 45% and a worst-case of 49%. If you really integrate worst-case and best-case inputs the extremes would become the input, so a chance of failure of 0% and 300%, this however does not allow for usable results. This is of course extreme, but it needs to be addressed in future research.

Warranty:

The tool left out the possibility of warranty. The label therefore displays the price of ownership and repairs with products that fall out of warranty. Although it can be assumed that dropping a phone and cracking a screen is out of warranty there will be instances where failures fall within warranty. The influence of this is not considered and might vary a lot between product groups. It could be worth looking into for it can have a big impact on the costs of repairs and ownership in the first 2 years.

diagnosis costs:

in the TCOT the diagnosis time and cost are not included. A product can either be repaired or not. The tool does not consider that diagnosis costs can be made even though the product was not repaired. For smartphones, this was not an issue for most 3rd party repair companies in the Netherlands work with a 'no cure no payment' agreement, and often subtract the made diagnosis costs from the actual repair costs if the owner of the phone decides to get their phone repaired. This might not be the case with other product groups.

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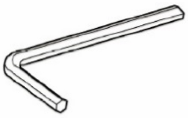
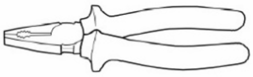
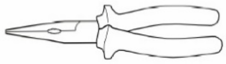
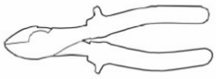
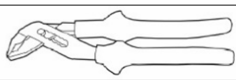
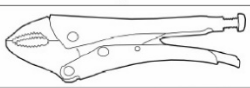
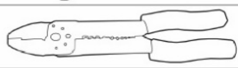
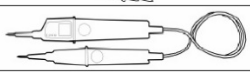
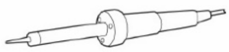
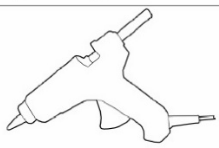
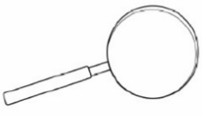
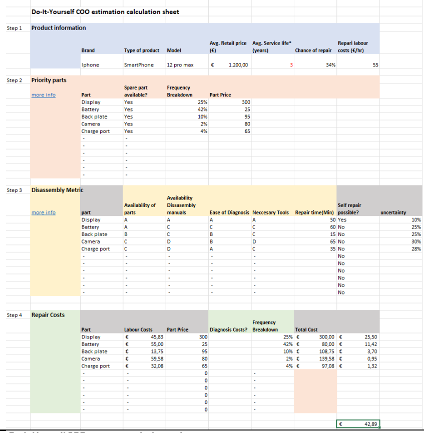
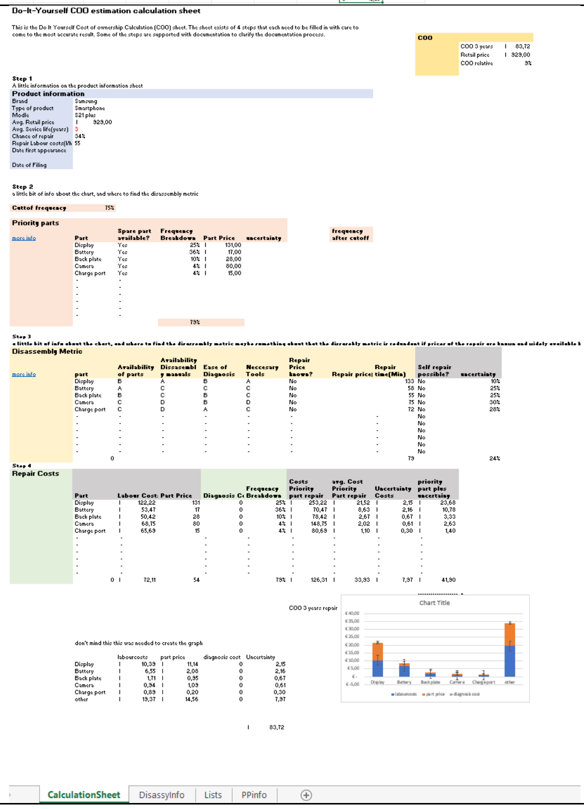
10. Appendix

10.1. Appendix A:

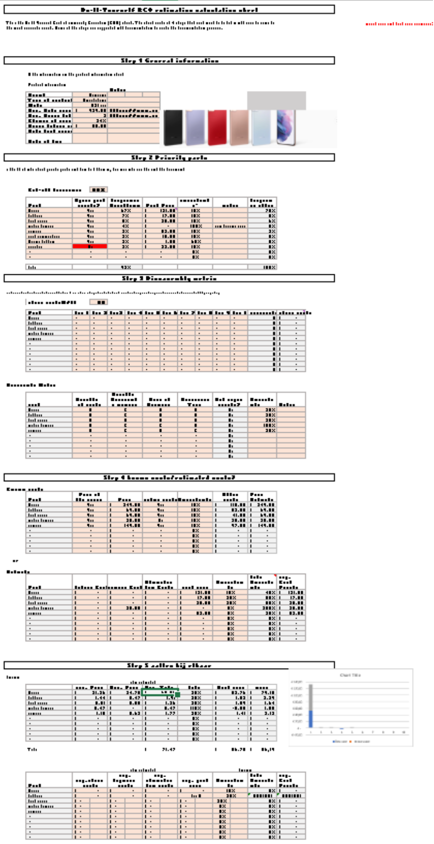
Falls under grade	Tool type	Illustration (informative example)	Reference
A: Simple	Hexagon socket key		ISO 2936
A: Simple	Combination wrench		ISO 7738
A: Simple	Combination pliers		ISO 5746
B: Basic	Half round nose pliers		ISO 5745
B: Basic	Diagonal cutters		ISO 5749
B: Basic	Multigrip pliers (multiple slip joint pliers)		ISO 8976
B: Basic	Locking pliers		
B: Basic	Combination pliers for wire stripping and terminal crimping		
B: Basic	Prying lever		
A: Simple	Tweezers		
A: Simple	Hammer, steel head		ISO 15601
A: Simple	Utility knife (cutter) with snap-off blades		
B: Basic	Multimeter		
B: Basic	Voltage tester		
B: Basic	Soldering iron		
B: Basic	Hot glue gun		
B: Basic	Magnifying glass		
	NOTE 1 Most tools come in different sizes. This list only refers to the tool type. Although some sizes are more common than others, for practical purposes, any size of the listed tools is considered to be a basic tool.		

This is an adapted form of the list from the EN NEN 45554. A distinction is made between simple and basic tools. In a proposed future version of the tool the simple tools will be a prerequisite for self-repair.

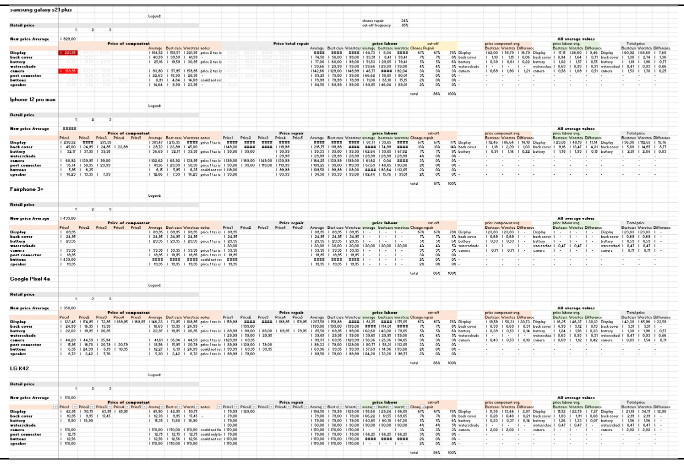
10.2.Appendix B:

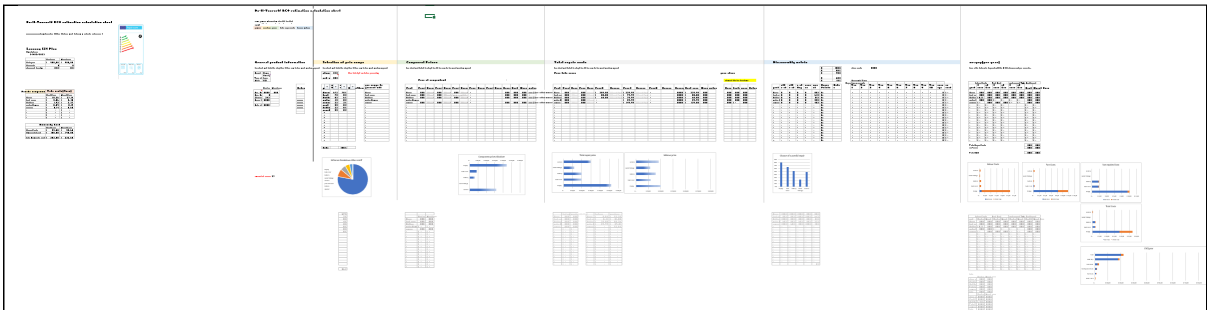
	Older versions of the tool
V1.0: This was the first version of the tool which was conceived during the first pressure cooker. Already the failure modes were being assessed separatiely.	
V2.0 This was the tool that came out of the second pressure cooker, on an other page the disassembly metric could be filled in. this tool was made with the disassembly of headphones.	

V3.0
This version of the tool included everything on one page.

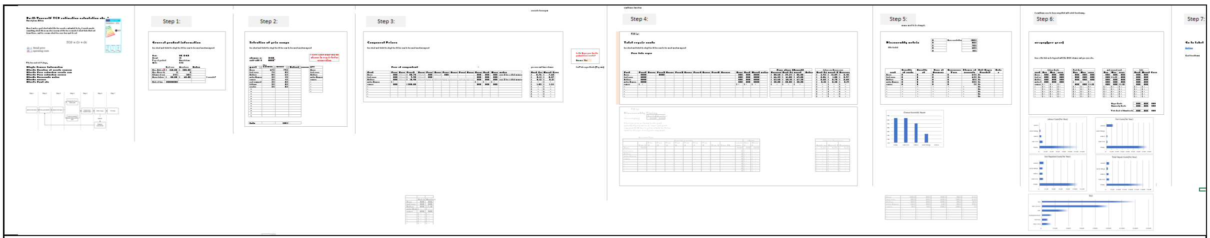


V4.0
The fourth version was not really a tool. This was the backbone of what would be the next version. By having all the data of the 5 phones on one sheet it was easier to experiment with the data to see how the



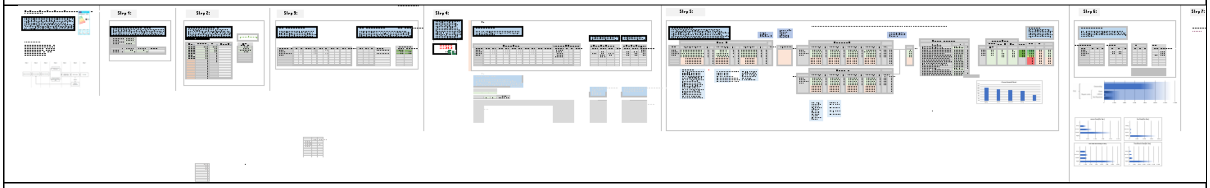


V5.0 the first horizontal tool.
This version of the tool was the first version to use the horizontal orientation.



V6.0 First automatic label
This version of the tool integrated a qualitative step with self-made criteria to assess the repairability of the individual parts to be able to estimate the chance of a successful repair.

This was also the first version that had a separate sheet that produces a label according to the values that come out of the tool.



V7.2 The final version:
FRI integrated and responsive triple graph.

10.3. Appendix C:

The old repairability criteria:

Availability spare parts:

A -very available	Spare parts are available on the website of the manufacturer. It is clear to what model the parts belong and what they cost.
B- available	Spare parts are available from third party sellers, it is clear to what model the part belongs.
C- limited available	The parts are only available for licenced companies and/or wholesale.
D- hard to find	Spare parts are only available through third party websites, the originality and to what model the part belongs is hard to find out or unknown.
E- unavailable	Spare parts are not available at all.

Availability of disassembly manuals:

A – Very availabel	Links of Disassembly Video's and manuals are displayed on the website of the manufacturer or can easily be found online. It is clear for what model and part the video is meant.
B - available	Links to the disassembly manuals can be found online, but only through third party websites or individuals.
C – limited available	Similar product disassembly video's can be found online that might help with the disassembly of this product. Or Manuals and video's can only be access by licenced persons.
D – hard to find	Assembly manuals are proprietary
E - Unavailable	There are no disassembly manuals

Ease of diagnosis:

A	The diagnosis of the fault is easy if in 80% of the cases:

	-The fault is clearly visible upon first inspection. -An error code shows which has a corresponding webpage/manual page provided by the manufacture which provides insights in what could be the problem. -A webapp on the website that walks you through a decision tree -The diagnosis can be performed without Tools
B	The diagnosis of the problem requires a disassembly of the product. However, the tools are graded A or B
C	The diagnosis of the problem requires a disassembly of the product. However, the tools are graded C or up.
D	Diagnosis is only possible by a professional.
E	Diagnosis is impossible.

Necessary tools:

A	The repair is feasible with: -The use of no tools -Tools provided with the spare part or device -Tools from table A3 of the NEN EN 54445. (exept desoldering, and multimeter)
B	Feasible with product specific tools.
C	Feasible with other commercially available tools.
D	Feasible with proprietary tools.
E	Not feasible with any existing tools.

10.4. Appendix D:

The graduation brief

INTRODUCTION **
Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

Products break, in the linear economy that has been the dominant mode of economy the past few decades even the best repairable products can be too expensive to get repaired by a professional repair company within Europe. The time it takes to perform diagnosing, ordering of spares and the repair itself combined with high labour costs often means that certain repairs are simply too expensive. This leads to many products not being fixed if deemed too costly. Which disappoints customers when their product has a seemingly simple breakdown.

Many initiatives and tools, like the EU Right to Repair, IFixit, PROMPT consortium and Repair cafes have been put forward to empower people to repair their own products. Although individual repair can have a valuable contribution to keeping products in use longer, the willingness or capability to repair is not always with the individual. Therefor improving professional repair will be important for increasing the lifespan of products.

Currently product design companies don't have an accurate way to assess their products repairability in terms of costs of repair. Assessing the time it will take to perform a specific repair and the eventual cost remains to be a lot of guesswork even with tools like eDIM, NEN-EN 45554 and the French repairability index. Most of the currently existing tools that help with the repair assessment are qualitative by nature and are mainly focussed on electronic products. These tools don't provide companies with €/hour rates and makes product scores hard or even impossible to compare for customers and policy makers.

Having a quantified €/hour rating for the most common repairs will help product companies to spot possibility for improvement in their product lines and safe money when products break within warranty. The repair costs compared to the value of a product could be derived for the most common repairs which can be provided to costumers. This allows them to better be able to choose between products when replacing or buying a new product for the long run. Not only will this data be valuable for costumers and manufacturers. The quantified data can help policy makers in clearly defining rules and regulations in the transition to a circular economy that the Dutch government strives to achieve in 2050.

Stakeholders:

The primary stakeholders are Product (design) companies, Customers, and policy makers, they all value the amount of money and time a repair will take/cost to better be able to compare products.

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

The main problem with professional repair is the cost of a repair, time is money and thinking that a certain repair might be too expensive already deems it unfeasible to be fixed. Since the current qualitative tools and indexes to assess repairability don't offer objective and quantitative data on €/hour they cannot reliably be used to tell companies which of their products need improvement and where. Nor can they tell customers what products to avoid, to prevent unpleasant surprises in the future.

The solution to this will be a tool with added protocol that helps to find the costs and €/hour rate of the most common repairs of multiple types of products. Products can then be benchmarked to provide a clear insight in how they compare to each other and what needs to be improved. These costs can be converted into a score that can be displayed through a label to the customer to provide transparency upon buying or replacing a new product.

As well as costumers and companies, policy makers also need quantitative numbers to base their policies around, this is an interesting solution space that will be explored.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

Develop a quantitative repair value scorecard that expresses the most common repairs in euros per hour and euros per repair saved.

The outcome of this project will be a tool that helps companies to quantitatively assess the €/hour and total price of the most common repairs within their product portfolio. The tool will be accompanied by a protocol to guide the company to get the most accurate results. The score that comes out of this trajectory will be used to provide customers with an insight to decide what product is best to buy in the long run considering repairability and their wallet. Policy makers will be consulted to find out what it is that they need from a tool like this to build their policies around.

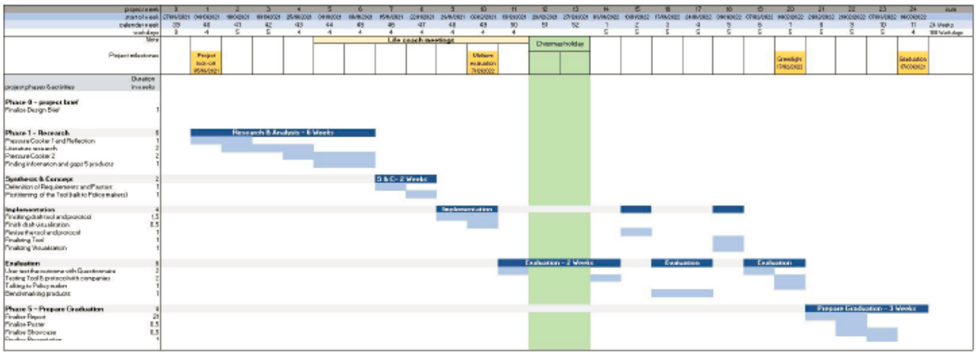
First the factors that influence the time and costs of a repair must be found. To support calculations for these factors experts and companies need to be consulted. Next to that extensive data needs to be gathered about different products and their priority components through literature and by disassembling them. This data comprises of how frequently priority parts break down, how much on average replacement parts cost and more importantly, how long does the repair take. And finally, this information needs to be translated into a tool and a protocol so companies can score various products themselves with repeatable and consistent results, which also needs to be compared to other currently existing tools.

To test its transparency towards the customer, user tests will be performed.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 5 - 10 - 2021 | 17 - 3 - 2022 end date



To create an entry point into the massive amounts of knowledge and possibilities the project will be kicked off with a pressure cooker directly followed a literature study and another pressure cooker.

A pressure cooker is a design method in which you perform your whole project in 5 days which forces you to make quick decisions and produce a quick and dirty outcome. During the pressure cooker the factors that influence the cost of a repair will be explored and an attempt will be made to express them quantitatively for one product or maybe a product family. The result will be a quick and dirty assessment tool which expresses the cost of the repair in hours and money. The knowledge of experts, small repair shops and a visit to a repair café will help with setting up this first tool. It might be interesting to do a second pressure cooker which will take 10 days after the evaluation of the first one.

During this pressure cooker the insights gained during the first session will be extrapolated to a wider range of products. The result will be an improved and expended version which will help to identify bottlenecks for such a tool. After finishing up the research phase the parameters and a list of requirements will be made that the tool should cover. A new version will be made including all the insights from the pressure cookers and literature research. This tool will be finetuned in iterative cycles of ideation, validation and creation, by doing user tests with companies and customers, benchmarking different products and by talking to a policy maker.

Throughout the project I will write and work on the report which will be partly finished at the greenlight after which I will shift my attention from improving the tool towards making the final presentation, poster, and report.

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

I have always had an interest tinkering with products, I have opened and fixed many products, from fishing rods and phones to scooters and surfboards. For me products gain value the longer you keep them in service, dents in the material merely give the product more character. During my bachelors Industrial Design in Eindhoven, I decided that I wanted to design for transparency and ownership. I believed ownership could be returned by designing transparent products, products of which its origins are clear, which are designed with repair, maintenance, and regeneration in mind.

To pursue the design for repair and circularity path in my curriculum I decided to do my masters at Tu delft. During my masters I focussed on open source projects, design for sustainability and I chose to do an extracurricular internship at SPARK design and innovation to gain insight into the world of product design. For me the next logical step would be to do a graduation project that fitted this line of development. I think that a quantitative Design for repair scorecard will provide companies with insights on how to improve their businesses to become more circular and will provide transparency and ownership to users. This graduation project is therefor the next logical step.

During this project I want to submerge myself in the world behind design for repair. I want to get to know the major actors, the legislation and issues. I want to dive into the currently existing tools like Hotspot Mapping and the disassembly map and find a way to make this tool adhere to already existing initiatives.

The design for repair scorecard will involve quite some Data processing. During some of my projects and electives I got myself familiar with Python and noticed that it could be a very strong tool when handling data and during my internship I found out that it is a very valuable skill to have in a company. I would therefore like to train myself in using the Python language During this project.

Sources used:

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10.5. Appendix E:

RQ 1. What factors and actors need to be considered when designing a quantitative Cost of Ownership tool?

The TCOT focuses on providing quantitative information on the costs of professional repairs that fall out of warranty. The three main stakeholders are manufacturers, legislators, and customers. Each Stakeholder wants the quantitative data that the tool provides, but they all have a different reason. Manufacturers will be forced to use the tool to grade their products, but the tool will provide information on how to improve their products. Legislators will implement the tool and can use the data to see how products evolve over time to last longer, or shorter. And customers can use the label that the tool provides to better be able to compare products on their longevity, repairability and costs of ownership. And this in turn will nudge manufacturers to make longer lasting, easier to repair products.

Existing tools provided valuable information for the making of this tool. The integration of the FRI was a valuable contribution to the TCOT. The issues laid bare in the context research like no integration of self-repair and impossible to repair products getting good scores were evaded as much as possible.

RQ 2. What is the Total Cost of ownership, and how can this be calculated?
RQ 2.1 What factors influence the cost of ownership and repair?
RQ 2.2 How can these factors be quantitatively expressed?

No quantitative cost of ownership or repair tools exists yet, and it is probably because there are numerous different variables that need to be researched and lots of standardization documents will be needed to. This thesis attempted to cover as many of these variables as possible and provide a valuable insight in how to quantify the costs of ownership. However, Decisions had to be made on what to cover and what to leave out which leaves room for improvements that will be discussed in the recommendations.

A list of variables and a mathematical formula have been created to dissect the total cost of ownership into its individual values. These variables have been elaborated upon and ways had been found to express them quantitatively. There are still various qualitative elements in the tool that need attention. Especially step 5 of the tool where the integration of the FRI criteria and grading grades the repairability of products, this qualitative outcome is quantitatively expressed. Int the recommendations this will be further elaborated upon.

RQ 2.3 How will the tool respond to changing input variables?
RQ 2.4 How does the outcome of the score of the tool compare to existing scoring methods?

As the case study indicated are the scenario's no actual depictions of reality. The input data contained too many inconsistencies. However, in the scenarios the TCOT produced values that fall within expectations. The tool will need to be tweaked but if it can provide the same result with actual data that would be a very good step in the right direction. The final grades of the tool are hard to compare with existing tools but there is a strong correlation with the grades of the FRI, this is mainly due to the integration of the FRI to assess products for their repairability. The iFixit tool gives quite different results for it is a tool focussed on self-repair and not so much on professional repair.

RQ 3. How will the tool display the information to the stakeholders?
RQ3.1 What is the most effective way to display the outcome to the stakeholders?
RQ3.2 What information do the stakeholders need
RQ3.3 How will the TCOT be implemented in the future?

Although initially designed to be universally usable for multiple product groups, the testing of the TCOT and creation of the tool was largely done with Smartphones. Therefore, it will probably be necessary to tweak and adapt the tool per product group, which was something I wanted to avoid at the onset of the project. This might even go as far as to include eDIM on some product groups where this is possible, like washing machines. The tool will need a lot of tweaking but if it can provide the same result with actual data that would be a very good step in the right direction.

Nearing the end of the project a revelation happened during one of the meetings with M. Depypere. He told me that legislators much prefer to work with nudging than with punishing, something that I thought the quantitative data of the tool would be used for. Still the quantitative information will be valuable for tracking the overall improvement of products to see if the new TCOT legislations are bearing fruits. The label that came out of the tool was therefor way more important for the transition towards a circular Europe by 2050 then the information of the tool for legislation.