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UNIVERSIDAD PONTIFICIA

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GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

REDESIGN OF A CELL PHONE TO IMPROVE ITS RECYCLABILITY

Autor: Teresa Jarabo Sastre

Director: Leon Liebenberg

Madrid

Junio de 2020

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

REDESIGN OF A CELL PHONE TO IMPROVE ITS RECYCLABILITY

en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el curso académico 2019/2020 es de mi autoría, original e inédito y no ha sido presentado con anterioridad a otros efectos. El Proyecto no es plagio de otro, ni total ni parcialmente y la información que ha sido tomada de otros documentos está debidamente referenciada.

Teresa Jarabo

Fdo.: Jarabo Sastre, Teresa. Fecha: 25 / 06 / 2020

Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

Fdo.: Liebenberg, Leon. Fecha: 25 / 06 / 2020

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REDISEÑO DE UN TELÉFONO MÓVIL PARA MEJORAR SU RECICLABILIDAD

Autor: Jarabo Sastre, Teresa.

Director: Liebenberg, Leon

Entidad Colaboradora: ICAI – Universidad Pontificia Comillas

RESUMEN DEL PROYECTO

1. Introducción

Los residuos tecnológicos conforman el flujo de deshechos con mayor tasa de crecimiento. La Figura 1 muestra la generación anual de residuos tecnológicos en todo el mundo desde 2010 a 2018. En 2018 se estimó que, para el año 2021, la basura tecnológica sobrepasaría la alarmante cifra de 52,2 millones de toneladas en todo el mundo (ACOS18). Ha habido varias estrategias que se han introducido con el objetivo de reducir los residuos electrónicos. La Responsabilidad Extendida del Productor es una de ellas y confiere la responsabilidad del impacto ambiental del producto a lo largo de toda su vida a los productores. De esta manera, las compañías tienen que tomar medidas para proteger el medio, introduciendo métodos como el Diseño para la Reciclabilidad o el uso de materiales no perjudiciales. Esta iniciativa tiene sus raíces en la transición a una economía circular. El objetivo de la Responsabilidad Extendida del Productor es animar a los productores a fabricar productos que (HEST09):

- Reduzcan o eliminen el uso de materiales peligrosos
- Usen mayores cantidades de materiales reciclados
- Se puedan eliminar o reciclar fácilmente al final de su vida
- Minimicen los residuos
- Puedan ser reutilizados
- Usen pocos recursos a lo largo de sus vidas

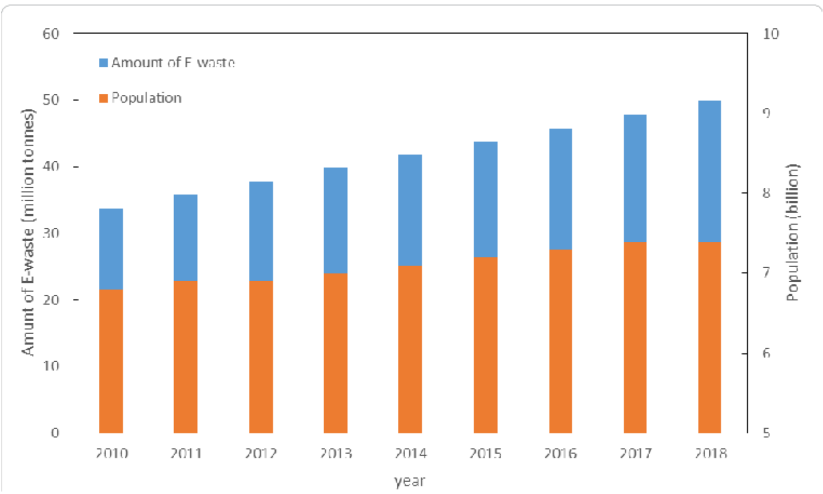


Figura 1. Residuos tecnológicos de 2011 a 2018 en todo el mundo

No se puede insistir lo suficiente en la importancia de reciclar aparatos electrónicos. Para empezar, los recursos son limitados. Para continuar, algunos productos contienen materiales peligrosos que son malos para el entorno y que pueden dañar nuestra salud. Además, los residuos tecnológicos tienen un valor recuperable alto; si se reciclan correctamente se puede obtener de ellos un beneficio, reduciendo a la vez el impacto del producto en el ambiente. Los teléfonos móviles contienen una gran cantidad de materiales, entre ellos el cobre, el hierro, el aluminio, el silicio, el plástico, el litio… La primera opción para reciclar teléfonos móviles es su reacondicionamiento o la reutilización de sus componentes. Cuando esto ya no es posible, el esfuerzo se concentra en la recuperación de materiales. En el pasado se ha dado más importancia a la recuperación de metales preciosos con el proceso de fundición, sin tener en cuenta otros materiales como el plástico.

En cuanto al Diseño para la Reciclabilidad, se pueden distinguir dos métodos: tecnología de clasificación y diseño para el desmontaje. Las estrategias cuyo objetivo es incrementar la vida de un producto, como la reparación, la reutilización, y la recolecta de componentes, se basan en la facilidad de desmontaje del producto. Por eso es importante facilitar el desmontaje de la carcasa: para facilitar el acceso a los componentes internos para su inspección y reparación, y para reciclar componentes valiosos de los productos que ya no se van a usar más. Si la eliminación de un producto es considerada desde el principio del diseño se encontrarán soluciones más eficientes para reciclar y reutilizar componentes y materiales.

2. Metodología

En este proyecto, se analiza un teléfono móvil fuera de uso para exponer la importancia de introducir la metodología Diseño para la Reciclabilidad en el diseño de cualquier producto, así como mostrar cuán simple puede ser. El Proceso de Realización del Producto es el método por el que se crean productos nuevos o mejorados. Implica la combinación de distintas áreas y métodos, explicados en los siguientes párrafos.

El producto analizado es un teléfono móvil de la compañía BQ y de modelo Aquaris E5, que fue sacado al mercado en 2014. El primer paso es desmontar el móvil y obtener la Lista de Materiales que incluye la cantidad de cada parte, el tamaño, y su función.

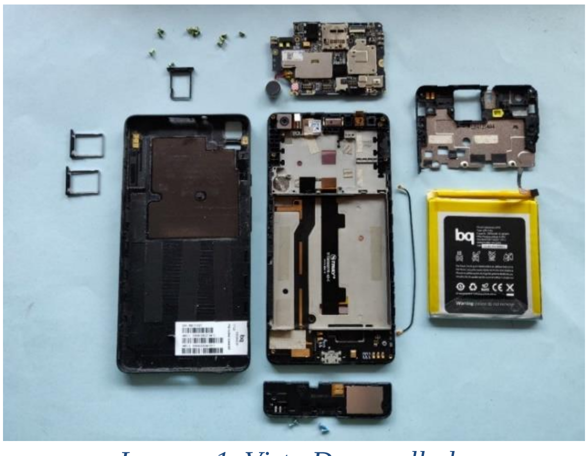


Imagen 1. Vista Desarrollada

Cinco partes del móvil son modeladas con CAD utilizando el software Creo Parametric 4.0. Estas cinco partes son: la tapa trasera del móvil, la montura delantera, la tapa de metal de un circuito, la bandeja de la tarjeta SIM y la bandeja de la tarjeta SD. Usando estos modelos en CAD, se puede estimar el precio de cada parte, teniendo en cuenta los costes variables y los costes fijos.

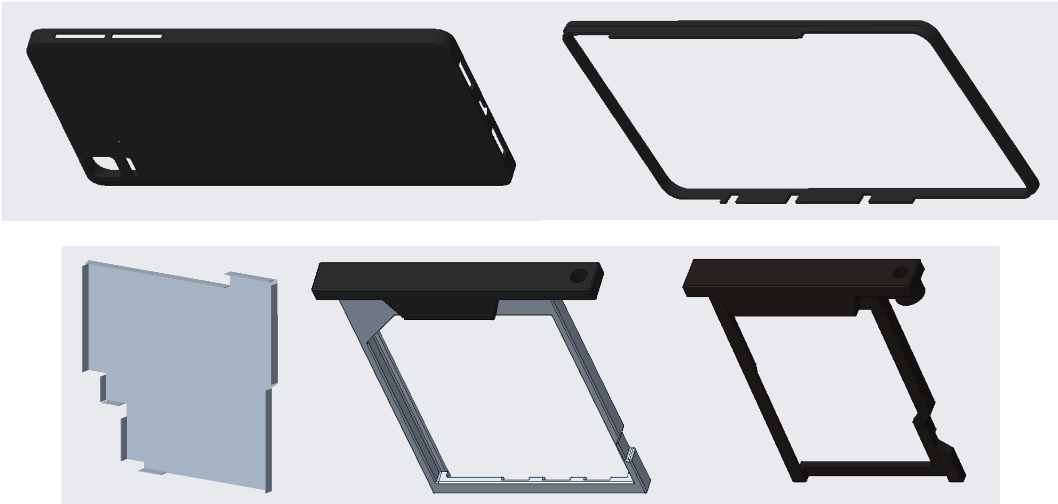


Imagen 2. Modelos en CAD

La Especificación del Diseño del Producto es un documento con los requisitos necesarios para crear un buen producto. Se usan las Fronteras del Diseño para definir estos requisitos (p. ej. tamaño, peso, rendimiento, vida útil, seguridad, etc.).

El siguiente paso es construir una matriz de Despliegue de la Función de Calidad para conocer los requisitos del consumidor respecto del móvil. Este método se basa en la experiencia del usuario, con el objetivo de cumplir con los requisitos en modelos futuros. Este método traduce los requisitos del consumidor en requisitos de diseño, mostrando cuáles de estos son más importantes para el consumidor.

El siguiente paso es el análisis con el Diseño para la Fabricación y el Montaje. El Diseño para la Fabricación se centra en los componentes individuales, estudiando maneras de reducir el número de componentes, y eliminando formas complejas que incrementan la complejidad de fabricación. El Material y el Proceso de Fabricación de cada uno de los componentes es explicado en esta sección. El Diseño para el Montaje se centra en la reducción y estandarización de partes y de montajes. En este proyecto, se utiliza para determinar el número mínimo de partes y el tiempo de montaje. Tradicionalmente, estos dos métodos han sido utilizados de manera separada. Sin embargo, se ha podido comprobar que la combinación de ambos proporciona los mejores resultados en cuanto a la reducción de tiempo y de coste.

El objetivo de este proyecto es rediseñar el teléfono móvil para aumentar su reciclabilidad. Se proponen tres ideas diferentes: el rediseño del montaje de la carcasa, el rediseño de la batería, y el rediseño de los materiales usados en la carcasa. Usando una Matriz de Pugh, uno de los conceptos es elegido y desarrollado. La Matriz de Pugh es un procedimiento por el cual se comparan y evalúan diferentes ideas, permitiendo seleccionar la más idónea.

Una vez se ha elegido un concepto, se crea el modelo en CAD del producto rediseñado. Utilizando Autodesk MoldFlow Adviser, se simula el proceso de moldeado por inyección de la tapa trasera del móvil, usando diferentes ajustes de la máquina, para obtener la mejor predicción de calidad.

Finalmente, se usa el Diseño de Experimentos para analizar el producto rediseñado. Diseño de Experimentos consiste en el análisis de la recopilación de un conjunto de datos en el que hay variación, y el posterior análisis factorial. Como entrada se usan dos variables de diseño: el ángulo en el cuerpo del móvil (a) y la longitud extrusión de la tapa trasera del diseño de encaje a presión (b). La variable de salida es el número de veces que la tapa trasera se abre en diez lanzamientos del móvil desde una altura de cuatro metros. Se distinguen dos niveles para las dos variables (factores), alto y bajo, dando lugar a un diseño factorial 2^2 usado para calcular los efectos de los factores. Con el Análisis de la Varianza, se determina si estos factores y su combinación son realmente significativos.

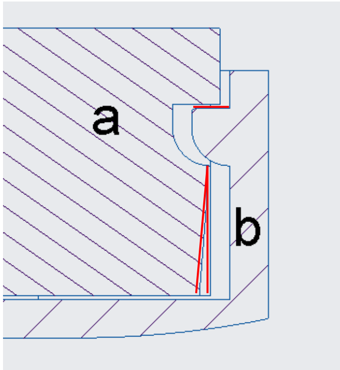


Imagen 3. Variables de Diseño

3. Resultados

Estimando el coste de material, la mano de obra, gastos administrativos directos y la amortización de la inversión para las partes modeladas en CAD, el coste total es:

Tabla 1. Coste Estimado

Parte	**Coste Estimado ($)**
Tapa Trasera	1.385
Montura Delantera	0.035
Tapa de Metal del Circuito	0.285
Bandeja de la tarjeta SIM	0.193
Bandeja de la tarjeta SD	0.193

De la matriz de Despliegue de la Función de Calidad se obtiene que la vida útil del móvil es el requisito con mayor importancia, seguido de la vida útil de la batería y de la memoria RAM. Es importante darse cuenta de que, si los requisitos de diseño son cumplidos, estos contribuyen al incremento de la vida útil del móvil.

Con el análisis de Diseño para la Fabricación y el Montaje se obtiene que el número de partes puede pasar de 33 a 15 si se sustituyen los tornillos por pegamentos o diseños de encaje a presión, y si la tapa del circuito es eliminada o integrada con la tapa trasera del móvil. Además, se estima que el Tiempo de Montaje es de 160.7 segundos, dando lugar a una eficiencia de Diseño de Montaje del 28%. Esta eficiencia indica que no todas las partes del producto son esenciales para el montaje, como los tornillos.

De las tres ideas propuestas, con la Matriz de Pugh se obtiene que la idea que genera la mayor mejora con respecto al diseño original es la primera: rediseño del montaje de la carcasa. Esta idea se basa en que las bandejas de las tarjetas SIM y SD oponen suficiente resistencia en sus respectivos lados a que la tapa trasera se abra. El borde inferior se deja sin un mecanismo de cierre. El último borde tiene dos encajes a presión (snap fits).

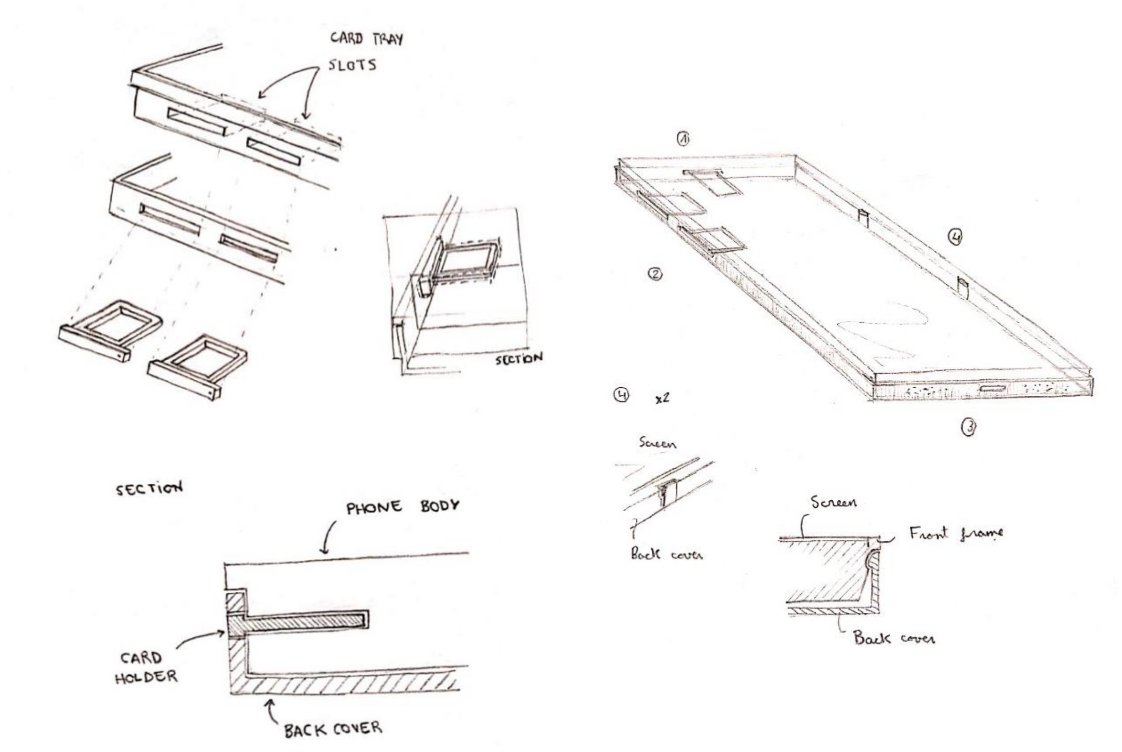


Imagen 4. Idea 1

El objetivo de esta idea es conseguir una facilidad de desmontaje. El nuevo proceso de desmontaje se puede ver en la Imagen 5. En primer lugar, se retiran las bandejas de las tarjetas SIM y SD. Después, se abren los cierres a presión tirando de la extrusión de la tapa trasera hacia fuera. Aprovechando el chaflán en el cuerpo del móvil, la extrusión se desliza hacia abajo, ayudando con el desmontaje de la carcasa. De esta manera, se alcanza el objetivo del rediseño.

Imagen 5. Nuevo Proceso de Desmontaje

Una vez finalizado el análisis del moldeado por inyección de la tapa trasera rediseñada en MoldFlow, se obtiene que el uso de los ajustes estándar del proceso, temperatura de molde 100ºC, temperatura de fundición 310ºC y máxima presión de inyección de la máquina 180 MPa, dan lugar a una calidad inaceptable. Sin embargo, si la temperatura del molde se incrementa hasta los 290ºC, la predicción de calidad es alta en el 98,8% de la tapa. El inconveniente de incrementar tanto la temperatura del molde es que el ciclo es 66 veces más largo (603,18 segundos) porque el tiempo de enfriamiento es mayor.

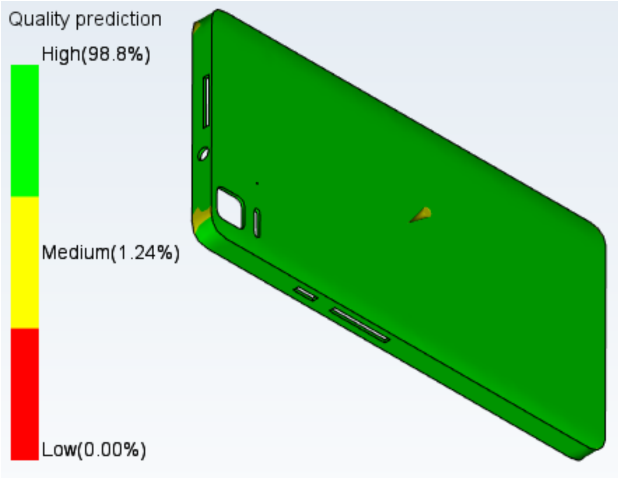


Imagen 6. Predicción de Calidad

Finalmente, del Diseño de Experimentos se puede concluir que tanto el ángulo como la longitud de la extrusión son significativos, pero que su interacción no lo es. Con la ecuación característica del sistema, se puede calcular una estimación del número de veces que se abre la tapa trasera. La combinación que da el menor número de veces, una (1) vez, es el ángulo en bajo (4,57º) y la longitud de la extrusión en alto (1,1 mm).

$$\hat{Y} = 2.583 + \frac{1.5}{2}x_1 - \frac{0.833}{2}x_2$$

4. Conclusiones

Con este proyecto se ha demostrado la importancia del reciclaje de los aparatos electrónicos y cómo los diseñadores y fabricantes pueden trabajar en la eliminación del producto, desde el comienzo del diseño del producto, escogiendo materiales más ecológicos, o aumentando la facilidad de desmontaje.

El coste de fabricación del producto rediseñado no aumenta con respecto al diseño original. Prácticamente se usa la misma cantidad de material, y los demás costes, gastos administrativos o amortización de inversiones, no cambian. Sin embargo, el coste de desmontaje sí que se reduce ya que el proceso necesita menos tiempo.

Más importante aún, la reciclabilidad del producto aumenta. Es necesario mejorar la facilidad de desmontaje para acceder al interior del producto, al objeto de reparar los componentes cuando se rompan o reutilizarlos y reciclarlos al final de la vida útil del producto. De esta manera, los residuos disminuyen y se consume menos materia prima.

Finalmente, este Proyecto está relacionado con el Objetivo de desarrollo Sostenible número 12, que trata la implementación del consumo y los patrones de producción responsables. El Diseño para la Reciclabilidad está en línea con este objetivo ya que se enfoca en la disminución de los residuos y la sostenibilidad de las prácticas en todos los sectores de la economía. Es necesario tomar medidas para evitar la sobreexplotación de recursos o la degradación de recursos ambientales (UN__19).

5. Referencias

[PHIL19] Philpott, M., N. Dornik, B. Ellis, P. Hong, C. Warning, "Design for Manufacture", aPriori Education, 2019.

[HEST09] Hestler, R. E., R. M. Harrison, "Electronic Waste Management", The RoyalSociety of Chemistry, 2009.

[ACOS18] Acosta, Y. "Solo el 37% de los españoles ha reciclado alguna vez su móvil viejo", Ciencias Ambientales. November 23, 2018. https://www.google.com/amp/s/www.cienciasambientales.com/es/noticias-ambientales/certideal-37-espanoles-ha-reciclado-alguna-vez-su-movil-viejo-17028/amp

[UN__19] United Nations, "Sustainable Development Goal 12". United Nations. 2019. https://sustainabledevelopment.un.org/sdg12

https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.researchgate.net%2Ffigure%2FGlobal-e-waste-generation-from-2010-to-2018-data-source-1_fig1_289976734&psig=AOvVaw0_QbHR_LZRqt5BxYH0q1rV&ust=1592905966868000&source=images&cd=vfe&ved=0CAIQjRxqFwoTCICN6LeTleoCFQAAAAAdAAAAABAJ

REDESIGN OF A CELL PHONE TO IMPROVE ITS RECICLABILITY

Author: Jarabo Sastre, Teresa.

Director: Liebenberg, Leon

Collaborating Entity: ICAI – Universidad Pontificia Comillas

PROJECT SUMMARY

1. Introduction

Technological waste is the waste stream with the highest growth rate. Figure 1.1.1 shows the global technological waste from 2010 to 2018. In 2018, it was estimated that by 2021 technological waste would surpass the alarming figure of 52.2 million tons per year (ACOS18). There have been several strategies introduced that aim to reduce this waste. Extended Producer Responsibility (EPR) is one of them and it makes manufacturers responsible for the environmental impacts of the product throughout its lifecycle. This way, the companies have to take measures to protect the environment, introducing methods such as Design for Recycling, or using less harmful materials. This initiative is rooted in the transition to a circular economy. In summary, EPR's goal is to encourage producers to manufacture products that (HEST09):

- Reduce or eliminate the use of hazardous materials
- Use greater amounts of recycled material
- Can be easily treated at end of life
- Minimize waste
- Can be reused
- Use few resources throughout their life

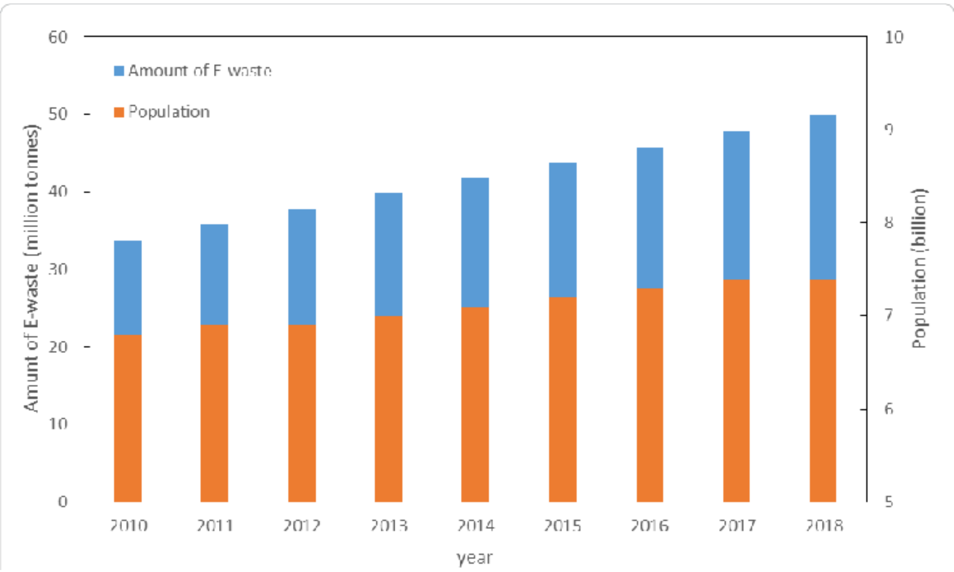


Figure 1.1.1. Global Technological Waste from 2010 to 2018

The importance of recycling electronics cannot be stressed enough. Firstly, the resources are limited. Secondly, some of these products contain hazardous materials that are bad or the environment and that can harm our health. Technological waste has a high recoverable value that, if recycled, can bring profit to the company while reducing the product's impact on the environment. Many materials can be found in cell phones: Copper, Iron, Aluminum, Silicon, Plastic, Lithium… Phone refurbishing and component reuse is the first way to recycle cell phones. When this is no longer possible, the energy goes into the recovery of materials. Traditionally, most of the attention has gone to the recovery of precious metals using a smelting process without considering other materials such as plastic.

In terms of Design for Recyclability, two main methods have been traditionally used: sorting technology and design for disassembly. Strategies that aim to increase the product's lifetime, such as repair, reuse and product harvesting for component reuse, rely on an easy access to the product's components. That is why it is important to ease the disassembly of the housing parts: to facilitate the access to internal components for their inspection and repair, as well as to disassemble obsolete products to recover valuable components that can be recycled. If the disposal of a product is considered and thought of at the early stages of its design, a more efficient solution will be found to recycle and reuse components and materials.

2. Methodology

The analysis of an obsolete phone is carried out in this project with the aim of showing the importance of introducing Design for Recyclability in the design process of any product as well as showing how simple it can be. The Product Realization Process is the way new or improved products are designed and it involves the combination of different methods, explained in the following paragraphs.

The analyzed product is a cell phone from the company BQ and model Aquaris E5, released in 2014. The first step is to disassemble the product and make a Bill of Materials (BOM) with all the components, including the quantity, the size, and the function.

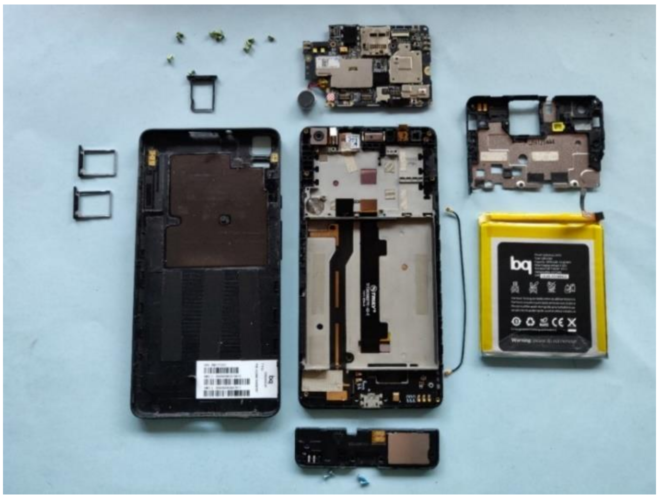


Image 1.1.1. Exploded View

A CAD model for five parts of the phone is developed using the software Creo Parametric 4.0. These five parts are the phone's back-cover, the front frame, a metal circuit cover, the SIM card holder, and the SD card holder. Using these CAD model, the part price can then be estimated, taking into account the variable costs, the piece part costs, and the fixed costs.

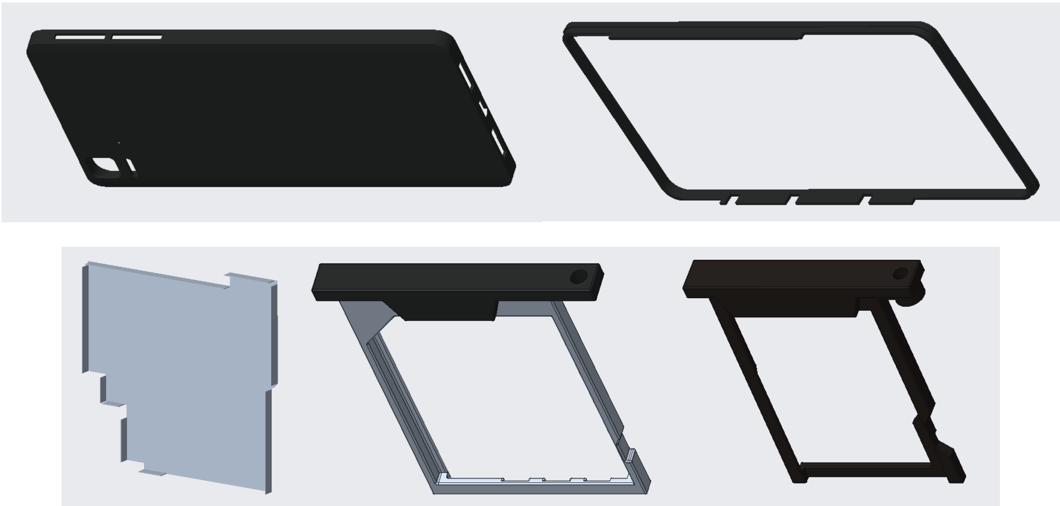


Image 1.1.2. CAD Models

The Product Design Specification (PDS) is a structured document with agreed requirements that must be met in order to build a successful product. The Design Boundaries are used to define these requirements (e.g. size, weight, performance, service life, safety, etc.).

Next, a Quality Function Deployment (QFD) matrix is built to better understand the customers' requirements for the phone. This method is based on the user's experience, with the goal of meeting the requirements in future designs. These requirements are then translated to design requirements, showing which requirements need more attention, considering the customer's preference.

The next step is the Design for Manufacture and Assembly (DFMA) analysis. Design for Manufacture focuses on the individual components, studying ways to reduce the number of components, and to eliminate intricate features that increase the complexity of manufacture. The Material and the Manufacturing Process is determined for each of the parts listed in the Bill of Materials. Design for Assembly focuses on the reduction and standardization of parts and assemblies. It is used to determine the theoretical minimum number of parts, and the assembly time. These two methods have been traditionally separated. However, it has been shown that the combination of both yields the best results with time and cost minimization.

The goal of this project is to make the cell phone more recyclable. So, three different concepts are proposed: redesign of the chassis assembly, redesign of the battery, and redesign of the chassis material. Using a Pugh Matrix, one of the concepts is chosen to develop it further. A Pugh Matrix is a matrix procedure for comparing and evaluating a number of different concepts; and converging onto the best and/or improved concept.

Once the concept is chosen, the CAD model of the redesigned product is developed. Using Autodesk MoldFlow Adviser and the previous CAD model, the injection molding process is simulated, using different process settings to obtain the best quality prediction.

Finally, a Design of Experiments (DOE) with the new design is carried out. A DOE is the design of any information-gathering exercise where variation is present, and the subsequent use of factorial design statistical techniques. As input, it considers two design variables: the angle in the phone body (a), and the extrusion length of the back-cover of the snap fit (b). The output is the number of times the back-cover opens when the phone is thrown ten times from a 4-meter height. Considering two levels for the two variables, high and low, a 2^2 factorial design is used to calculate the effects of the factors. Using Analysis of Variance, the significance of the effects of the different variables (factors) is determined.

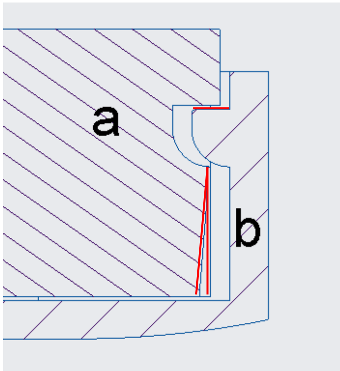


Image 1.1.3. Design Variables

3. Results

Estimating the material cost, the labor cost, the direct overhead and the amortized investment, the total cost of the different parts that were modeled in CAD is found out to be:

Table 1.1.1. Estimated Cost

Part	**Estimated Cost ($)**
Back-cover	1.385
Front Frame	0.035
Metal Circuit Cover	0.285
SIM Card Holder	0.193
SD Card Holder	0.193

From the Quality Function Deployment matrix, it was found out that the lifespan of the product is the most important design requirement, followed by battery life and a high RAM. It is important to realize that most of the design requirements, if met, will contribute to the increase of the product lifespan.

DFMA analysis showed that the number of parts can go from 33 to 15, if adhesives or snap fits are used instead of two types of screws, and if the circuit cover is integrated with the phone's back-cover. Additionally, the Assembly Time is estimated to be 160.7 seconds, which yields a DFA Efficiency of 28%. This efficiency indicates that there are parts of the product that are not essential, such as the screws.

From the three proposed concepts, the Pugh Matrix method concludes that the concept that will yield a higher improvement with respect to the original design is the first one: the redesign of the chassis assembly. This concept is based on the belief that the SIM and SD card holders provide enough resistance to the back-cover opening, in two of the sides. Another side does not have any locking mechanism. The last side has two snap fits.

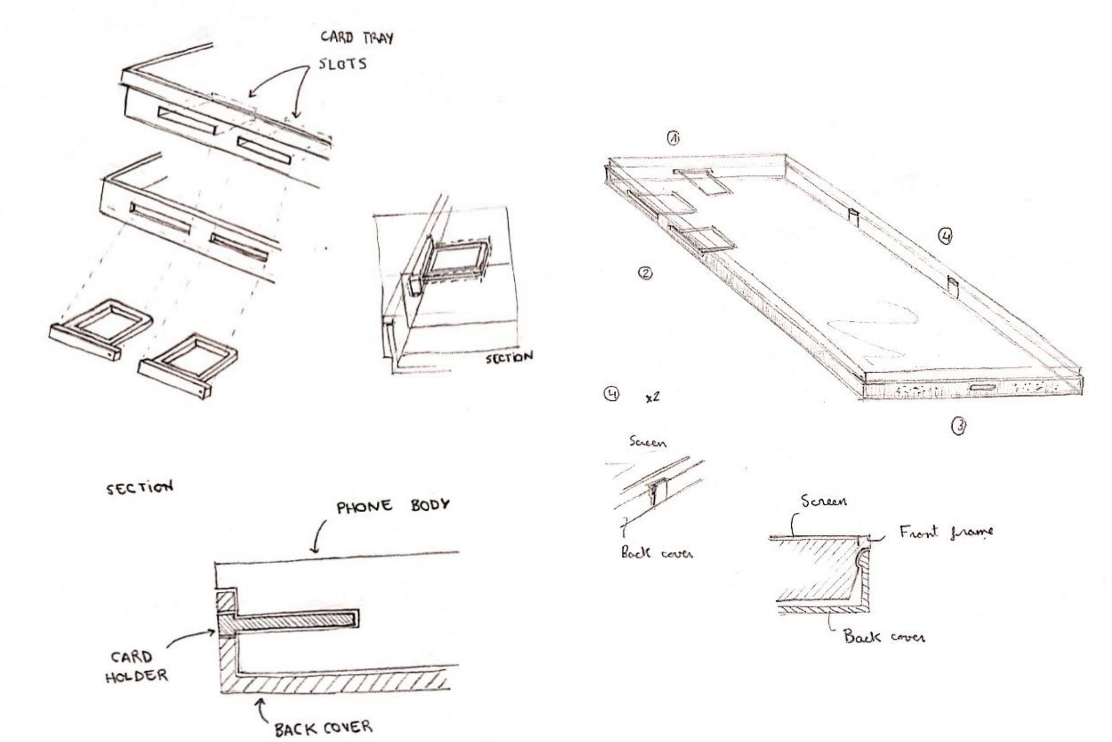


Image 1.1.4. Concept 1

Ease of disassembly was the main objective of this concept. Image 1.1.5 shows the new disassembly process. First, the SIM and SD card holders are taken out. Second, the snap fits are opened by pulling outwards the extrusion on the back-cover. Using the slope on the phone body, the snap fits will slide downwards, contributing to the disassembly of the chassis. Thus, the objective of the redesign is met.

Image 1.1.5. New disassembly process

The analysis from MoldFlow shows that using the standard process settings, mold temperature 100ºC, melt temperature 310ºC, and maximum machine injection pressure 180 MPa, the predicted quality is unacceptable, but if the mold temperature is increased to 290ºC, the predicted quality is high in 98.8% of the part. The drawback of increasing the mold temperature is that the cycle time increases 66 times (603.18 seconds) because the cooling time is longer.

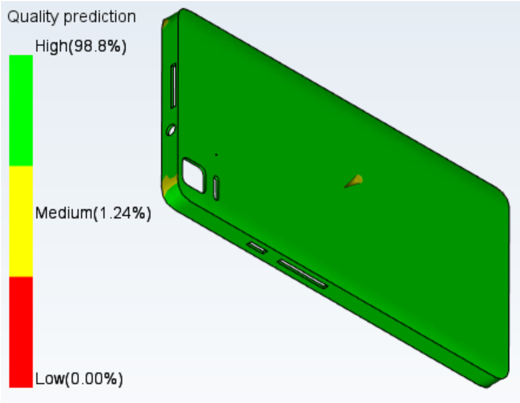


Image 1.1.6. Quality Prediction

Finally, from the Design of Experiment it can be concluded that both the angle and the extrusion length are significant when determining the number of times the back-cover will open, but their interaction is not significant. With the system characteristic equation, an estimate of the number of times the back-cover opens can be calculated. The combination that gives the lowest output, one time throughout the whole experiment, is a high extrusion length (1.1 mm), and a low angle (4.57º).

$$\hat{Y} = 2.583 + \frac{1.5}{2}x_1 - \frac{0.833}{2}x_2$$

4. Conclusions

This project has shown the importance of recycling electronics and how designers and manufacturers can work on the product’s disposal since the conception of the product, by choosing greener materials, or increasing the ease of disassembly.

The manufacturing cost of the redesigned part does not increase with respect to the original design. Almost the same amount of material is used, and the other costs as direct overhead or amortized investment do not change. However, the disassembly cost does reduce since this process requires less time.

More importantly, the recyclability of the product increases. Ease of disassembly is necessary to make the interior more accessible so that the components can be repaired when broken or reused and recycled at the end of the product's life. This way, waste is decreased, and less raw materials are consumed.

Finally, the project is related with the Sustainable Development Goal number 12, that addresses the implementation of **responsible consumption and production patterns**. Design for Recyclability is in line with the objective of this SDG since it focuses on the reduction of waste and the mainstream sustainability of practices across all sectors in the economy. Urgent action is needed to avoid the over extraction of resources or the degradation of environmental resources (UN__19).

5. References

[PHIL19] Philpott, M., N. Dornik, B. Ellis, P. Hong, C. Warning, "Design for Manufacture", aPriori Education, 2019.

[HEST09] Hestler, R. E., R. M. Harrison, "Electronic Waste Management", The RoyalSociety of Chemistry, 2009.

[ACOS18] Acosta, Y. "Solo el 37% de los españoles ha reciclado alguna vez su móvil viejo", Ciencias Ambientales. November 23, 2018. https://www.google.com/amp/s/www.cienciasambientales.com/es/noticias-ambientales/certideal-37-espanoles-ha-reciclado-alguna-vez-su-movil-viejo-17028/amp

[UN__19] United Nations, "Sustainable Development Goal 12". United Nations. 2019. https://sustainabledevelopment.un.org/sdg12

https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.researchgate.net%2Ffigure%2FGlobal-e-waste-generation-from-2010-to-2018-data-source-1_fig1_289976734&psig=AOvVaw0_QbHR_LZRqt5BxYH0q1rV&ust=1592905966868000&source=images&cd=vfe&ved=0CAIQjRxqFwoTCICN6LeTleoCFQAAAAAdAAAAABAJ

Index.

Acronyms.

BOM. Bill of Materials
CI. Confidence Interval
CSR. Corporate Social Responsibility
DFA. Design for Assembly
DFMA. Design for Manufacture and Assembly
DVT. Design Validation Test
EPR. Extended Producer Responsibility
GF. Glass Fiber
IEC. International Electrotechnical Commission
LiPo. Lithium Polymer
MTBF. Mean Time Between Failure
MTTR. Mean Time To Repair
PC. Polycarbonate
PLA. Polylactic Acid
QFD. 4.5. Quality Function Deployment
SAR. Specific Absorption Rate

1. Introduction

Nowadays, the world is fully technologized. Electronic components are present in almost everything –from our cell phones, to the AC of our cars, and our home appliances. This is not a bad thing. However, the problem appears when these products break down or reach the end of their useful life. As it is known, these products are made of different materials that cannot be disposed of as domestic waste. Instead, they must be taken to a recycling facility for electric and electronic devices. But this takes time and the user sometimes fall into not recycling them.

When it comes to cell phones, this problem cannot be overlooked. Technology companies such as Apple, Samsung, or Xiaomi have been competing with each other to create the newest software, discover the best processor, increase the storage, improve the camera, launching all kinds of smartphone models, with small differences. Most people want to have the latest version of a smartphone; therefore, they buy the new model even though their old phone still works. In other cases, the phone becomes obsolete, because the hardware does not allow new updates and versions, making the owner buy a new phone. Also, a component of the phone might break and require being fixed. Finally, the phone can reach its end of life. So, at the end of the day, there are a lot of phones that become unused, and end up in the wrong waste stream. For example, in a study performed by Certideal in Spain in 2018 (ACOS18), only 37% of the people had recycled an old phone, 40% did not know that phones are bad for the environment, and 13% did not know where to recycle electronic devices.

Certideal's study also states that by 2021 technological waste would surpass the alarming figure of 52.2 million tons. Among the materials used in phones are aluminum, copper, and cobalt. These elements yield high CO2 emissions, create soil and water pollution risks, and cause health problems due to exposure to high concentrations of cobalt. Furthermore, the study also mentions that over 50 years, an average person that changes phone every two years, will have used more than a ton of natural resources. Therefore, it is crucial to become aware of the importance of properly recycling these devices.

Lately, there have been several initiatives with the aim of improving the recycling of electronic and electrical parts.

One of these initiatives is the implementation of the Extended Producer Responsibility (EPR), that makes the manufacturer responsible for the environmental impacts the product has through its entire lifecycle. This way, the companies are more inclined to take measures to protect the environment, introducing methods such as design for recycling, or using less harmful materials. This initiative is rooted in the transition to a circular economy. In summary, EPR's goal is to encourage producers to manufacture products that (HEST09):

- Reduce or eliminate the use of hazardous materials
- Use greater amounts of recycled material
- Can be easily treated at end of life
- Minimize waste

- Can be reused
- Use few resources throughout their life

It is important to raise awareness of the environmental footprint. The people must know that the choices they make individually have direct repercussion on the environment, with different consequences. The European Week for Waste Reduction (EWWR) has been observed since 2009 and it aims to raise awareness about waste reduction across Europe. During this week, they promote sustainable waste reduction strategies, encouraging change in the behavior of Europeans in everyday life, by addressing these five matters: excess waste, better production, better consumption, a longer life for products, and waste disposal reduction.

Some people have taken matters into their own hands and have started their own company to contribute towards a sustainable future. In Spain, there is a company called Certideal that reconditions phones and tablets, and acts as an intermediary between sellers and buyers. This company was created in 2015, when the founders had to buy secondhand devices, but they failed to find a trustworthy company to do so. That is when they decided to launch their own company, with the objectives of providing a good quality service, and committing to the environment. Since then, Certideal has obtained several certifications, including the ISO 14001, that attests the company's strong commitment to CSR (Corporate Social Responsibility).

1.1. Project Objectives

The project objectives are to:

- Understand the importance of electronics recycling.
- Get familiar with Design for Recyclability and the different shapes it can take.
- Apply Design for Recyclability to a cell phone:
    - Disassemble the product, obtain the Bill of Materials, model in CAD some of the parts, and estimate their cost.
    - Use a Quality Function Deployment matrix to get to know the customer's requirements and translate them into design requirements.
    - Write down the Product Design Specification with the elements of the Design Boundary to establish the characteristics and specifications of the product.
    - Use Design for Manufacture and Assembly to determine the materials and the manufacturing process of all parts, as well as the theoretical minimum number of parts and the assembly time.
    - Apply Design for Recyclability to the cell phone by generating new concepts to redesign the product and choosing one of the concepts using a Pugh Matrix.
    - Further explain the chosen concept and CAD models.
    - Simulate the Injection Molding process of the redesigned product.
    - Perform a Design of Experiment on the new design to analyze its performance.

2. Recycling of Electronics

One of the biggest issues with this industry is the amount of waste it generates. Recycling end-of-life electronic products and waste is different from domestic recycling because electronic waste contains precious and non-precious metals and other reusable components (SODH01). If these materials end up in the regular waste stream, two things happen. First, material recovery is possible. Furthermore, the cost of electronic waste collecting and processing is sometimes lower than the revenue resulting from the sale of precious metals. Second, some electronic waste contains hazardous materials that harm the environment, such as LiPo (Lithium Polymer) batteries, that require a complex elimination process.

In some industrialized countries, recycling of electronic devices is generally automated. This strategy has a high rate of recovery of certain materials such as steel and aluminum but is not as efficient when it comes to the recovery of precious metals, critical metals, and some plastics. Electronic waste is one of the waste streams that is growing faster. It encompasses over 1000 substances, some of which still have market value or are dangerous. Investing in material recovery reduces the environmental burden of production and disposal of electronic components (VANE17). Image 1.1.1 shows typical recovery values of the materials that can be found in electronic waste.

Material	Percentage	Quantity	Value ($ per lb)	Total Value ($)
Copper	20.000%	400	0.98	392
Iron	8.000%	160	0.045	7.2
Nickel	2.000%	40	2.23	89.2
Tin	4.000%	80	2.35	188
Lead	2.000%	40	0.21	8.4
Aluminum	2.000%	40	0.71	28.4
Zinc	1.000%	20	0.48	9.6
Gold	0.100%	2	3885.57	7771.14
Silver	0.200%	4	34.4	137.6
Palladium	0.005%	0.1	5019.16	501.916
Plastics	30%	600	0.1	60

Image 1.1.1. Typical recovery values from 1Tm of electronic waste

The European 2020 strategy for smart, sustainable, and inclusive growth recognizes the importance of transitioning into a circular economy. The European Commission identifies product design as a pillar of circular economy. Three design strategies are considered: increase of material efficiency, product life extension and recycling efficiency improvement (VANE17). To reduce the mass disposal of end of life electronical products, many countries have legislation (or are adopting it) that makes manufacturers retrieve electronic products at the end of their useful life. In Europe, an EPR system makes the producer responsible for the environmental impacts the product has through its entire lifecycle.

Product lifetime extension can be achieved with the reduction of disassembly time and access to product components that facilitate the product’s repair and reuse. Moreover, disassembly has the potential to increase the purity of metals and plastics obtained from the products. Consequently, the European Commission and other labels have included design for disassembly as a requirement.

Strategies that aim to increase the product’s lifetime such as repair, reuse and product harvesting for component reuse rely on an easy access to the product components. That is why it is important to ease the disassembly of the housing parts: to facilitate the access to internal components for their inspection and repair, as well as to disassemble obsolete products to recover valuable components that can be recycled.

The main methods for recycling electronic devices are disassembly, bulk recycling, and smelting (SODH01).

Disassembly comprises the separation of a product into parts, components, or subassemblies. The product can be completely or partially disassembled to retrieve the wanted material. It is an arduous task where the cost is proportional to the time and effort put in removing the material. The recovery value of a disassembled product can be obtained from the value of the material content and the weight. This method is usually combined with bulk recycling when the hazardous materials are removed.

Bulk recycling is used for material recovery. Once the hazardous materials are removed, the device is shredded. Then, separation of the materials is done taking advantage of the physical properties of the different materials. The flakes are first separated into four categories (SODH01): ferrous metals, non-ferrous metals, plastics, and a composite residual mixture.

Smelting is used to separate lower value materials (Copper, Aluminum, Lead, etc.) from high value materials (Gold, Silver and Platinum). This process takes advantage of the different melting temperatures of the materials and chemical processes.

2.1. Circular Economy

Circular economy is a model that aims to reinvent the current take-make-waste industrial model (ELLE20). It is a regenerative system in which the resources and the waste are reduced as well as the emissions, using renewable energy.

This strategy is based on the following principles:

- Reduce the use of raw materials
- Design waste and pollution out of the system
- Keep products and materials in use
- Regenerate natural systems

Image 2.1.1. Circular Economy

According to the Ellen MacArthur Foundation, the model differentiates between two cycles: technical and biological.

- Biological cycle: materials from this cycle are designed to be reintroduced in the biosphere through methods such as composting, regenerating living systems such as soil. These materials are consumed (e.g. vegetables, wood, cereal).
- Technical cycle: it recovers materials through processes like reuse, repair, or recycling.

The idea of this model is to transform the current lineal life cycle resource-product-waste to a circular model, resource-product-recycle. The circular life cycle is achieved by implementing the 3R's: Reduce, Reuse, and Recycle.

Image 2.1.2. The 3 R's

2.2. Materials used in cell phones

In 2010, the following materials were used in a phone (GARC18):

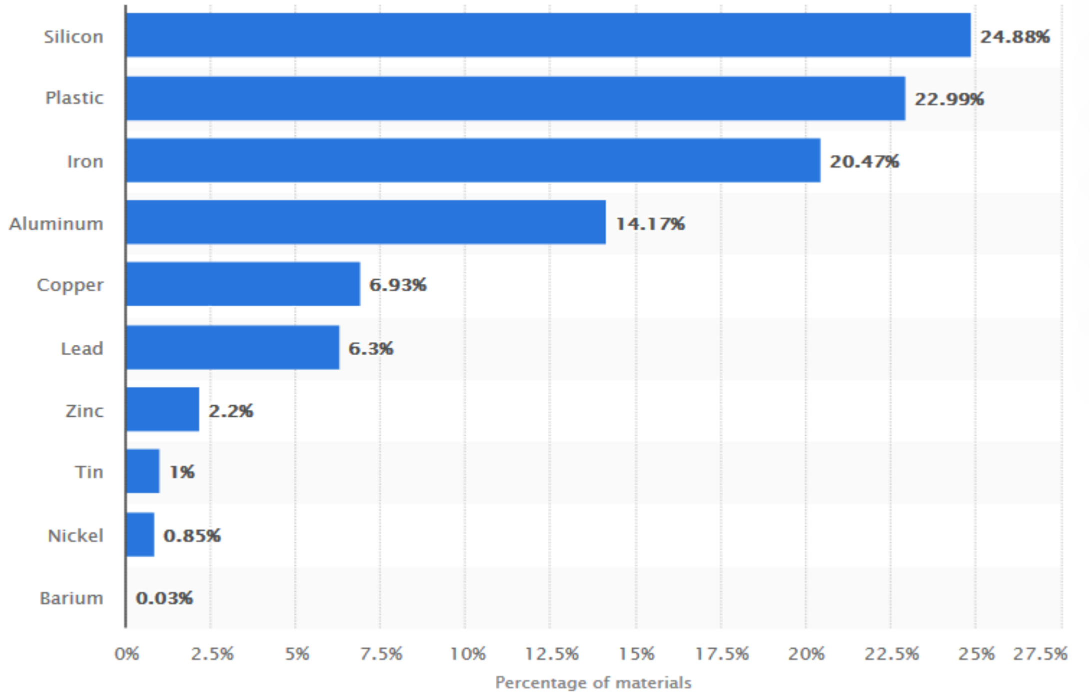


Image 2.2.1. Percentage of most used materials in a smartphone

- Silicon: it is primarily used to manufacture the chips inside the phone.
- Plastic: it is used to manufacture the chassis of the phone. More and more, this material is transitioning into more robust materials.
- Iron: it can be found in an alloy of neodymium, iron, and boron, in the magnets found in the microphone and phone speaker.
- Aluminum: it is used to make the battery case and the transistors on the circuit board.
- Copper: it can be found in the wiring of the phone.
- Lead: it is used for the welding of components
- Zinc: it can be found in the microphone and phone speaker.
- Tin: a thin layer is applied to the screen to make it touch-sensitive.
- Nickel: it used to be found in the batteries.

However, since 2010 the material percentages have changed. For example, lithium is not mentioned in the list, and it is now used for the batteries, instead of nickel.

Glass is used for the screen. Specifically, it is made from aluminum oxide and silicon dioxide with a thin layer of indium tin oxide.

Using plastic in a cell phone's case improves the phone's resistance to damage when it is dropped or scratched. It can stand temperature fluctuations, it is very flexible, and it does not cause reception problems. Most companies use polycarbonate filled with glass fiber to make their phones, because it is very flexible and cheap.

2.3. Recycling of cell phones

Cell phones are the most valuable electronic products in electronic waste. The creation of new models with improved technology make the cell phone's lifecycle very short, often becoming obsolete after one or two years of use.

In 2010, the Minerals Education Coalition (LEVO10) stated that about 130 million cell phones are annually retired in the US, amounting to 14,000 tons of weight, 2,100 tons of copper, 46 tons of silver, 3.9 tons of gold, 2 tons of palladium, and 0.04 tons of platinum.

Phone refurbishing and component reuse is the first way to recycle cell phones. When this is no longer possible, the energy goes into the recovery of materials. Traditionally, most of the attention has gone to the recovery of precious metals using a smelting process without considering other materials such as plastic.

The plastic used in the cell phone is usually found in the phone's chassis and it is usually ABS or PC. Polymers' physical and mechanical properties worsen during their service life and when they are recycled. However, this issue can be overcome by blending the polymer with a raw material, or by adding plasticizers and additives (HEST09).

In the past decades, the use of non-fossil-fuel-derived plastics for cell phone cases was studied as an alternative to the conventional plastic materials. For example, polylactic acid (PLA) was considered. It had not been used in the past because of its insufficient strength and heat resistance. In March 2006, a PLA bioplastic reinforced with kenaf was developed and used in phones in Japan (HEST09).

Between 65 and 80% of the material in a cell phone can be recycled and reused (HEST09). The batteries contain valuable materials such as the cobalt in lithium-ion batteries, that can be recycled and used in magnetic alloys. The metal materials of the cell phone are recovered with bulk recycling and smelting processes. However, plastics are not considered as important and often end up not being recycled, when using the plastic as fuel can be used to recover its energy, increasing its total recovery rate to over 90% (HEST09).

3. Design for Recyclability

Environmental awareness is becoming one of the main focuses in the design process of any product. In the electronics industry, where products become obsolete really fast, the companies are responsible for the environmental impact of their products during the manufacturing process, the use of the product and, with the EPR, they are responsible for the disposal of their products at the end of their lives. Expensive product retirement is avoided by introducing design for recyclability in the design process from the beginning.

Design for Recyclability focuses on the following end-of-life paths (ROSE99): remanufacturing, recycling, and disposal. Since most products are disassembled, ease of disassembly is crucial. At Carnegie Mellon University, Artificial Intelligence was used to make computers determine an optimal disassembly sequence as well as ways to improve the design to boost disassembly (ROSE99). Most research focuses on disassembly and sorting technologies. For example, new types of fasteners are studied, so that they meet the design's requirements and are quickly assembled and disassembled. The fastening and joining methods significantly affect the cost of recycling as well as the recyclability of a product. Fasteners that are accessible and easily removed will decrease the time, the cost, and the scrap of a product disassembly. Additionally, the cost-effectiveness of plastics recycling decreases when different plastics or plastic and non-plastic materials are joined (ROSE99).

It can be concluded that design for disassembly is an effective way of introducing design for recyclability in the design process. Six disassembly tasks can be identified (VANE17):

- <u>Tool Change</u>: it refers to picking up and putting back a tool, as well as the preparation of the tool.
- <u>Identifying Connectors</u>: it refers to the time invested in finding the location of connectors and identifying the type of connector and the required tool.
- <u>Manipulation</u>: it accounts for the time used in handling the part to find the connector.
- <u>Positioning</u>: it refers to the positioning of the tool relative to the connector.
- <u>Disconnection</u>: it is the actual time used for the disconnection of a fastener.
- <u>Removing</u>: it is the time needed for handling the unfastened components.

4. Case Study: Redesign of a Cell Phone to Improve its Recyclability

4.1. Introduction to the Case Study

The amount of waste that is generated in the electronics industry is overwhelming. It has become clear that one important factor to reduce this is introducing design for recyclability in its design process. If the product's disposal is considered from an early stage of the product development, and the producer is made responsible of the disposal, designers and manufacturers will turn to greener and non-hazardous materials, that can be recycled or reused at the end of the product's life, as well as identify ways to increase the recyclability of the product, such as introducing design for disassembly.

The Product Realization Process is the way new or improved products are conceived, designed, and manufactured (PHIL19). It is a multi-disciplinary analytical process, and success comes from effective analyses and communication between all the parties involved. Over the years, many methodologies have been conceived in each of the stages of the process. Mike Philpott writes about the following (PHIL19):

- QFD – Quality Function Deployment: A methodology for translating customer requirements into design and manufacturing requirements.
- PDS – Product Design Specification: A structured document defining the agreed requirements to be met by all aspects of the product or process to achieve a successful new model or result.
- DFM(A) – Design for Manufacture (and Assembly): The process of designing the highest quality product for consistent production at the lowest cost.
- Controlled Convergence (Pugh Matrix): A matrix procedure for comparing and evaluating a number of different concepts; and converging onto the best and/or improved concept.
- DOE – Design of Experiments: the design of any information-gathering exercise where variation is present, and the subsequent use of factorial design statistical techniques is used to help identify the source(s) of variation.

4.2. Product choice and disassembly

For this project an old phone, no longer of use, is disassembled. This phone is a BQ Aquaris E5. It belongs to the Spanish company BQ. The phone was designed in Spain and assembled in China. It was released in July 2014 at a launch price of 199 €.

Image 4.2.1. BQ Aquaris E5

The main characteristics of this phone can be found in Annex 7.Annex A. . BQ Aquaris E5 HD Technical characteristics.

Most electronic devices cannot be thrown away using regular means. At the end of its lifetime, neither the phone nor its accessories can be disposed as domestic waste. In order to avoid damage to the environment and human health it is important to correctly recycle the products. This promotes the sustainable reuse of material resources.

Image 4.2.2. Do not throw away with domestic waste

a. Product Disassembly

The disassembly process of the phone is as follows:

1) The card trays are removed and the back-cover is separated from the phone body

Image 4.2.3. Step 1 of Disassembly

2) The screws from the circuit board cover are removed and the cover is separated

Image 4.2.4. Step 2 of Disassembly

Image 4.2.5. Step 2 of Disassembly

3) The screws on the circuit board are taken out and the flexes are disconnected

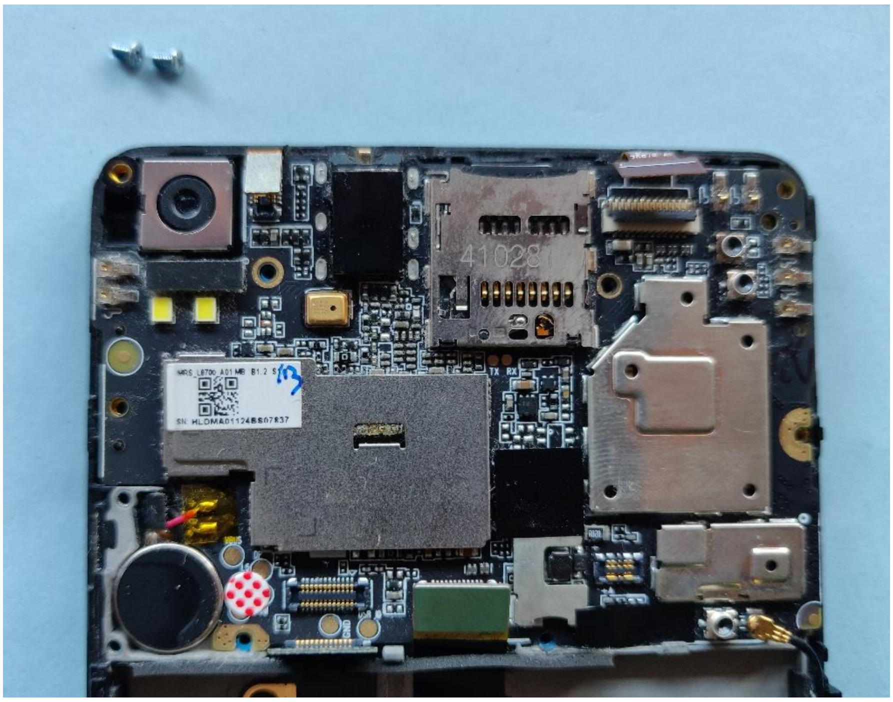


Image 4.2.6. Step 3 of Disassembly

4) The circuit board is removed, as well as the metal covers in the circuit board

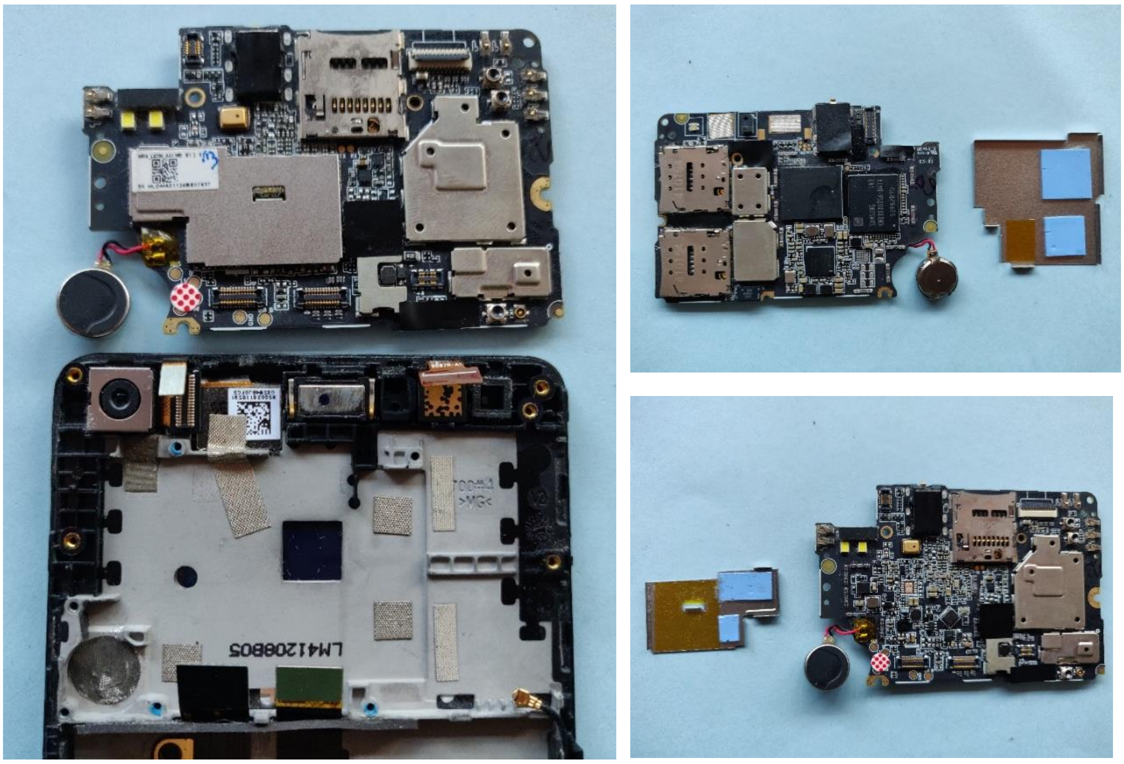


Image 4.2.7. Step 4 of Disassembly

5) The battery, the screws at the bottom part of the phone body, and the other electronic components (cameras, microphone, receiver…) are taken out

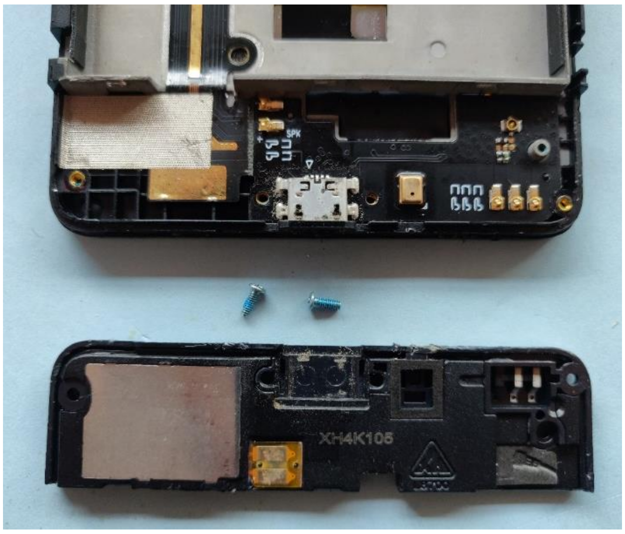


Image 4.2.8. Step 5 of Disassembly

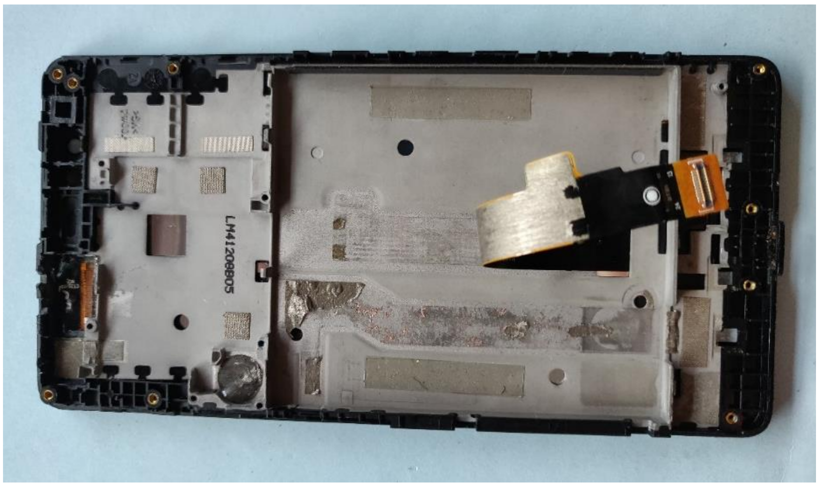


Image 4.2.9. Step 5 of Disassembly

Image 4.2.10 shows and exploded view of the phone.

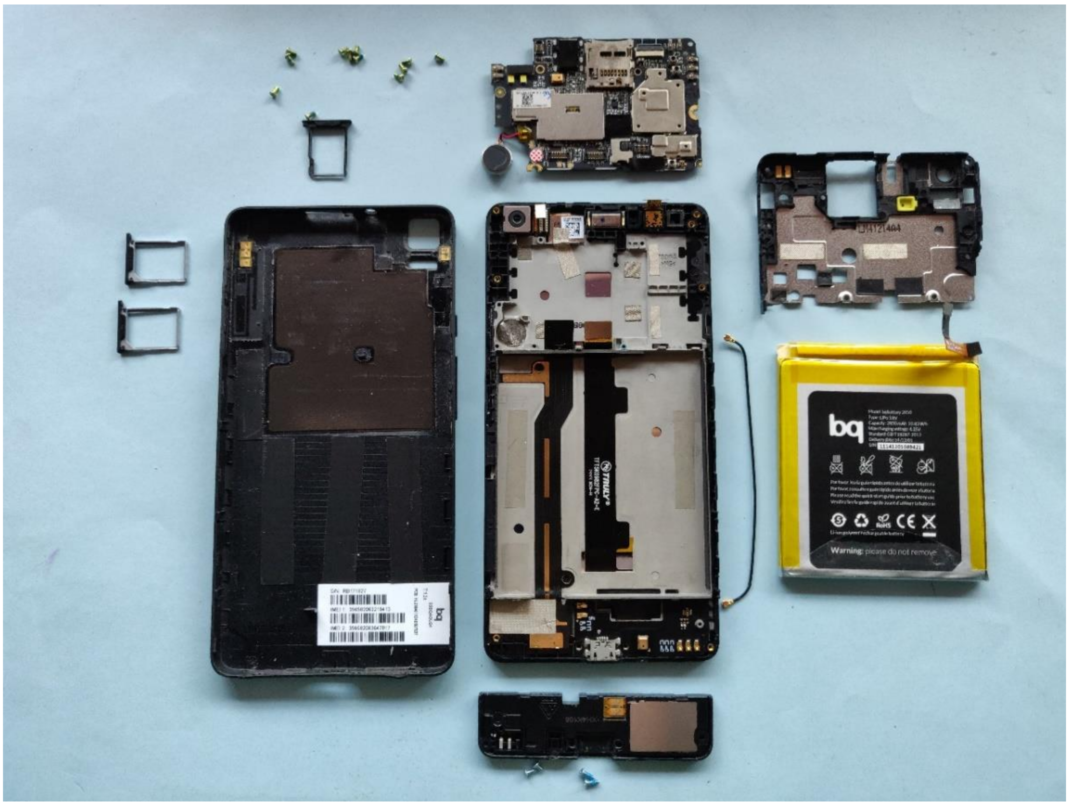


Image 4.2.10. Exploded View

After this process, it was observed that the disassembly of the phone is very hard; the separation of the covers, which are joined with snap fits, is very difficult, especially if you are trying not to break them. Consequently, it makes it more difficult to recycle or repair than if they were easier to separate.

b. Bill of Materials

Table 4.2.1 shows a detailed Bill of Materials which includes the Part Name, the Quantity, the Dimension, the Material, the Manufacturing Process, and the Function of the different parts of the cell phone.

Table 4.2.1. BOM

	Part Name	Qty	Dimension (mm)	Material	Manufacturing Process	Function
1	Back-cover (case)	1	142 x 71 x 6	PC	Plastic Injection Molding	Covers the phone body that supports the circuit board, battery, and electronic components
2	Front Frame	1	142 x 71 x 6	PC	Plastic Injection Molding	Supports the screen
3	Phone body	1	140 x 69 x 4	PC	Plastic Injection Molding + Solvent Bonding	Supports the phone body that supports the circuit board, the battery, and other electronic components
4	PN screw (3 mm)	12	3 mm	Stainless Steel	purchased	Structural support
5	PN screw (4 mm)	2	4 mm	Stainless Steel	purchased	Structural support
6	Circuit Board & Circuitry	1	67 x 45 x 4	Epoxy-fiberglass composite + Platinum + tungsten	purchased	Support for circuitry
7	Circuit Board Cover	1	69 x 47 x 4	PC + aluminum	Sheet Metal Forming&Pressing + Plastic Injection Molding	Protects circuit
8	SD Card Holder	1	19 x 16 x 2	PC + aluminum	Sheet Metal Forming + Plastic Injection Molding	Supports the SD card

	Part Name	Qty	Dimension (mm)	Material	Manufacturing Process	Function
9	SIM Card Holder	2	19 x 17 x 2	PC + stainless steel	Sheet Metal Forming + Plastic Injection Molding	Supports the SIM card
10	Battery	1	67 x 63 x 4	Lithium Polymer	purchased	Powers the phone
11	Metal Circuit Cover	2	32 x 32 x 2	Steel	Sheet Metal Stretch Forming	Protects circuit
12	Camera	2	9 x 9 x 5	Glass + aluminum + PC	purchased	Used to take pictures
13	Microphone	1	20 x 14 x 2	Silicon wafer	purchased	Used to record the voice
14	Speaker	1	7 x 4 x 2	Piezoceramics + shim (metal materials)	purchased	Used to play sound
15	Receiver	1	12 x 6 x 3	Plastic + Copper + Aluminum	purchased	Used to hear the phone calls
16	Screen	1	141 x 69 x 1	Glass	purchased	Used to display and interact with the phone
17	Wiring	1		Gold + copper + silver	purchased	Electrical connection
18	Insulating tape	1		Vinyl + Plastic	purchased	Provides physical and electrical insulation

4.3. CAD modeling of existing product

A detailed CAD is developed for five significant parts of the existing model using Creo Parametric 4.0. The measurements are in millimeters.

1- Phone Cover (case)

The first CAD shows the phone's back-cover.

Image 4.3.1. Phone Cover CAD model

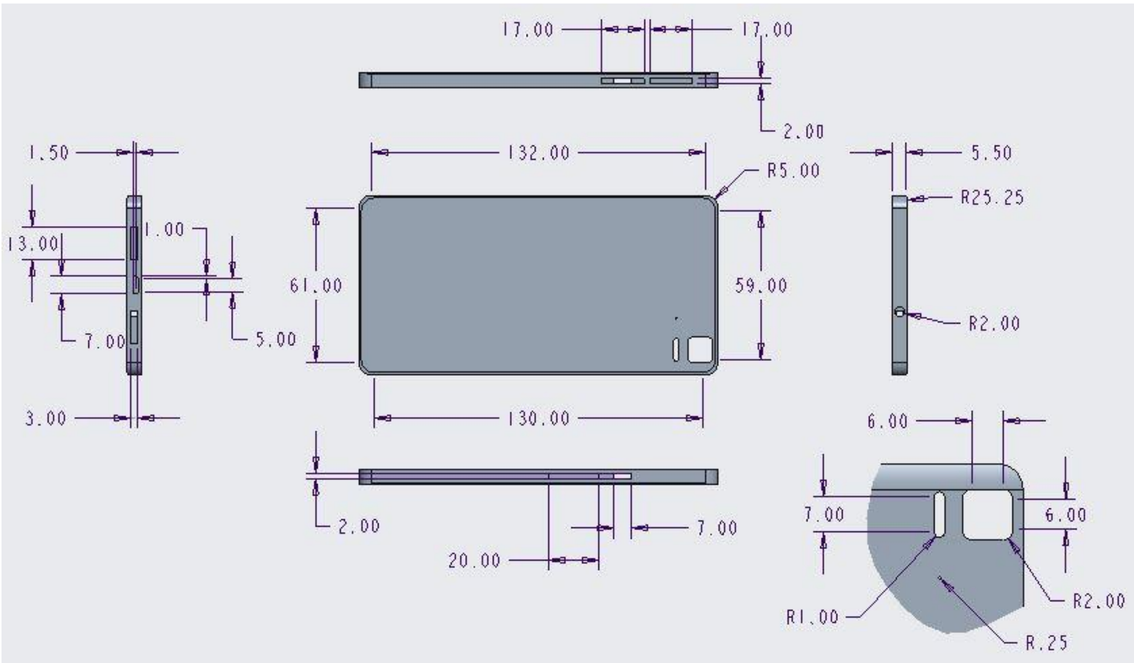


Image 4.3.2. Phone Cover Measurements

2- **Front frame**

The second CAD model shows the front frame. This part is where the screen is placed. It is also joined with the phone body.

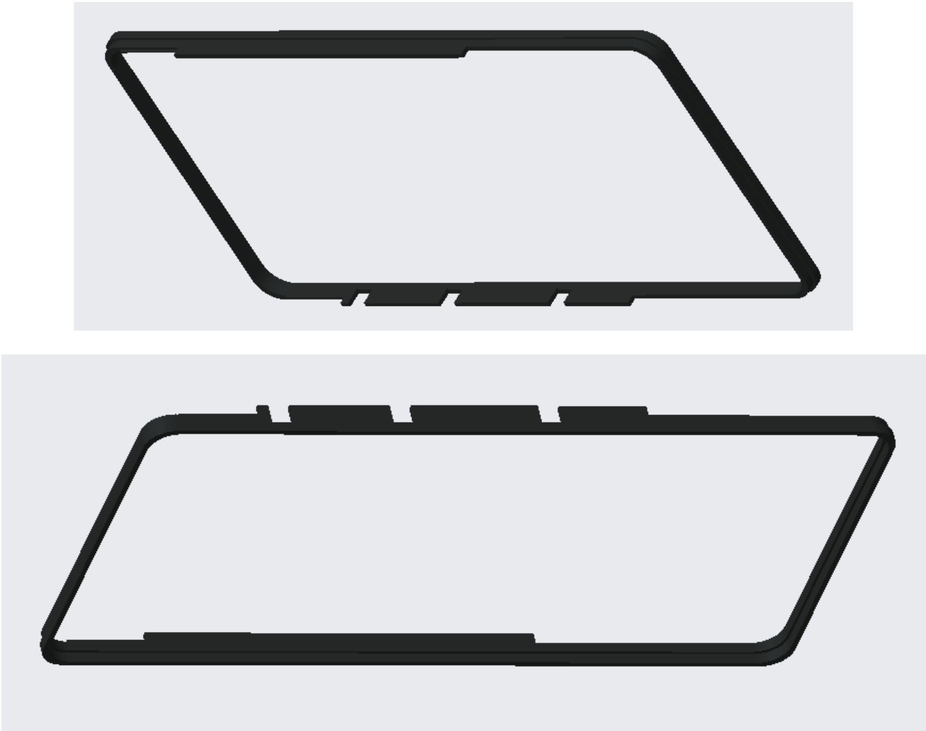


Image 4.3.3. Front Frame CAD model

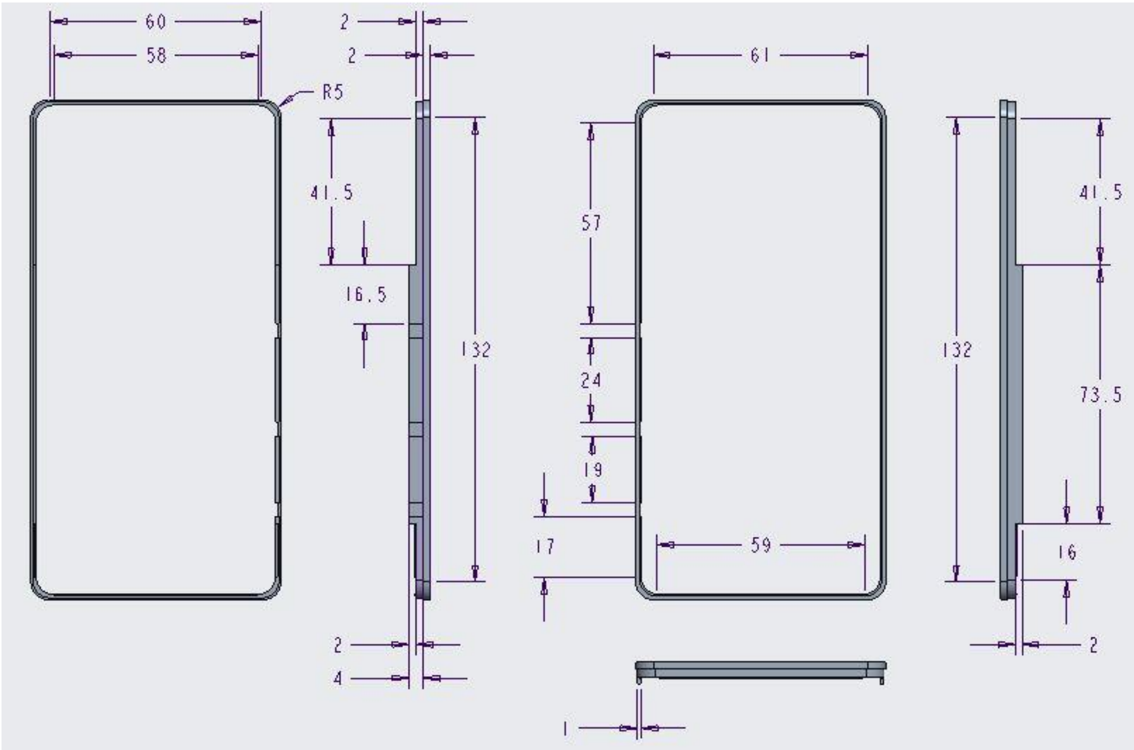


Image 4.3.4. Front Frame Measurements

3- **Metal Circuit Cover**

This part is used in the PCB to cover some of the components. In particular, this covers the Qualcomm processors.

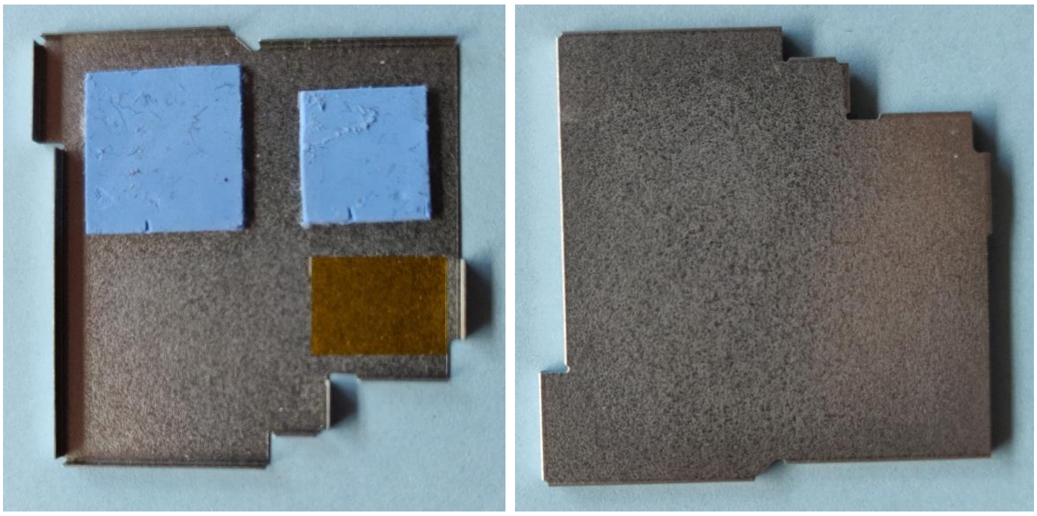


Image 4.3.5. Metal Circuit Cover

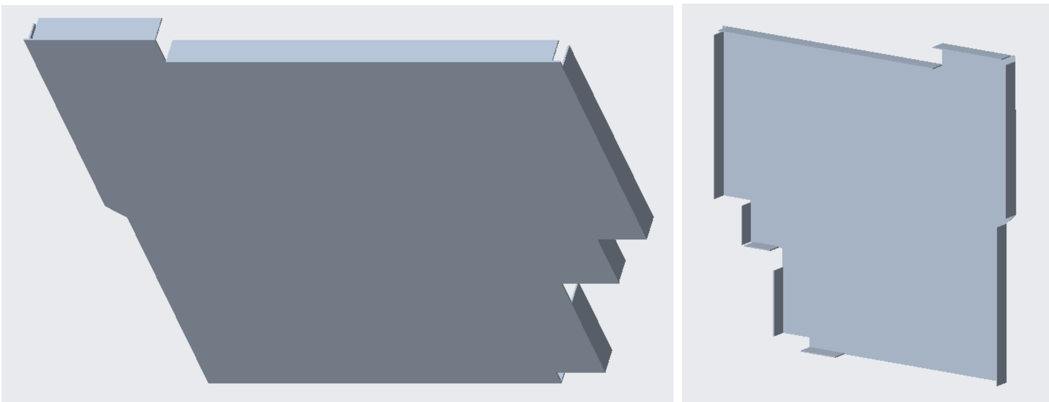


Image 4.3.6. Metal Circuit Cover CAD model

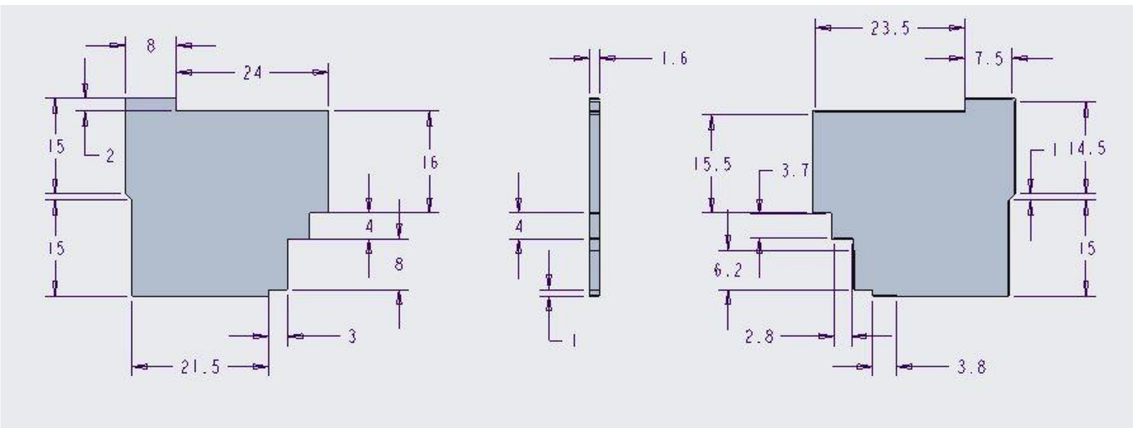


Image 4.3.7. Metal Circuit Cover Measurements

4- **SIM Card Holder**

There are two SIM card holders in the phone since it is a Dual SIM model. They are inserted into the card slot and can be ejected using the Molex card tray ejector. They go in on the left side of the phone, looking at the screen.

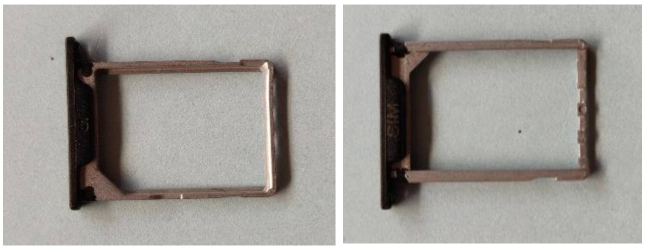


Image 4.3.8. SIM Card Holder

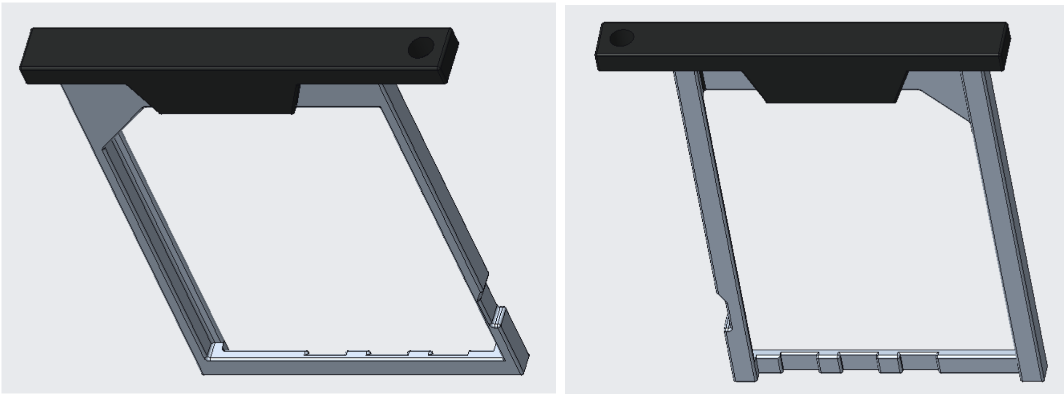


Image 4.3.9. SIM Card Holder CAD model

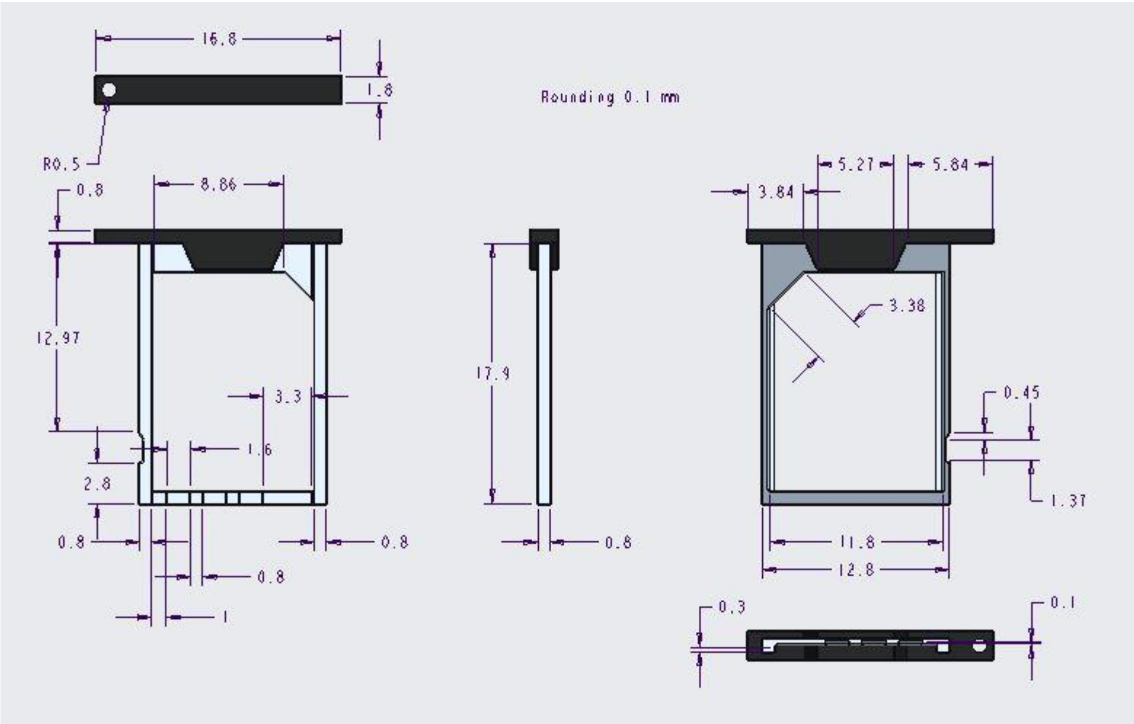


Image 4.3.10. SIM Card Holder Measurements

5- SD Card Holder

Similarly to the SIM card holder, SD card holder is ejected using a Molex tray ejector. It goes in at the top side of the phone.

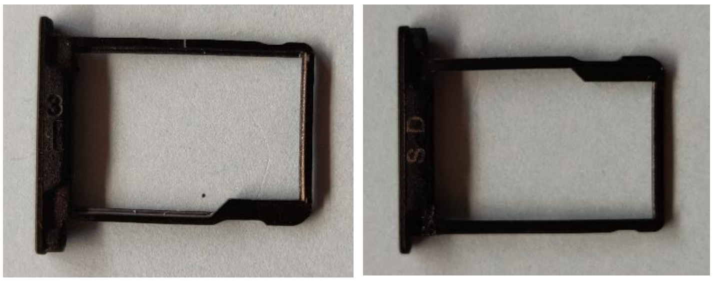


Image 4.3.11. SD Card Holder

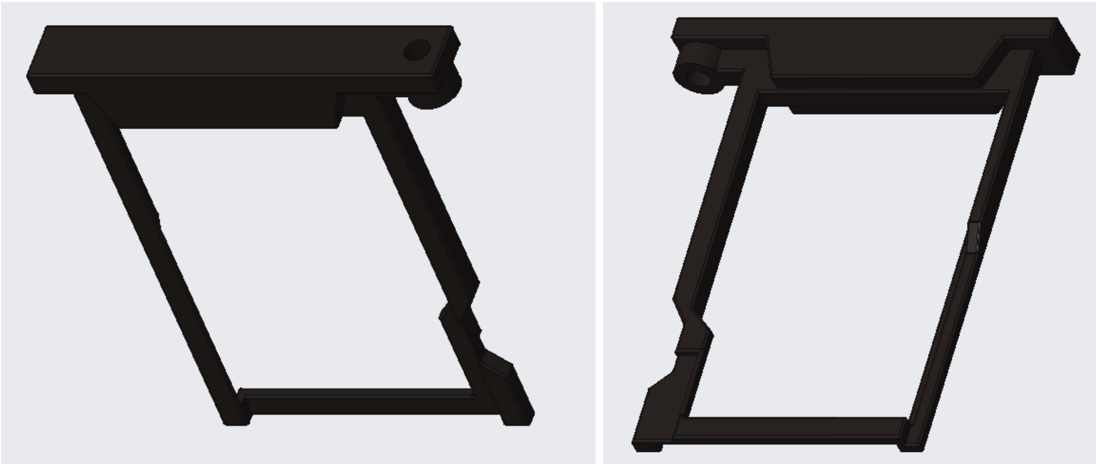


Image 4.3.12. SD Card Holder CAD model

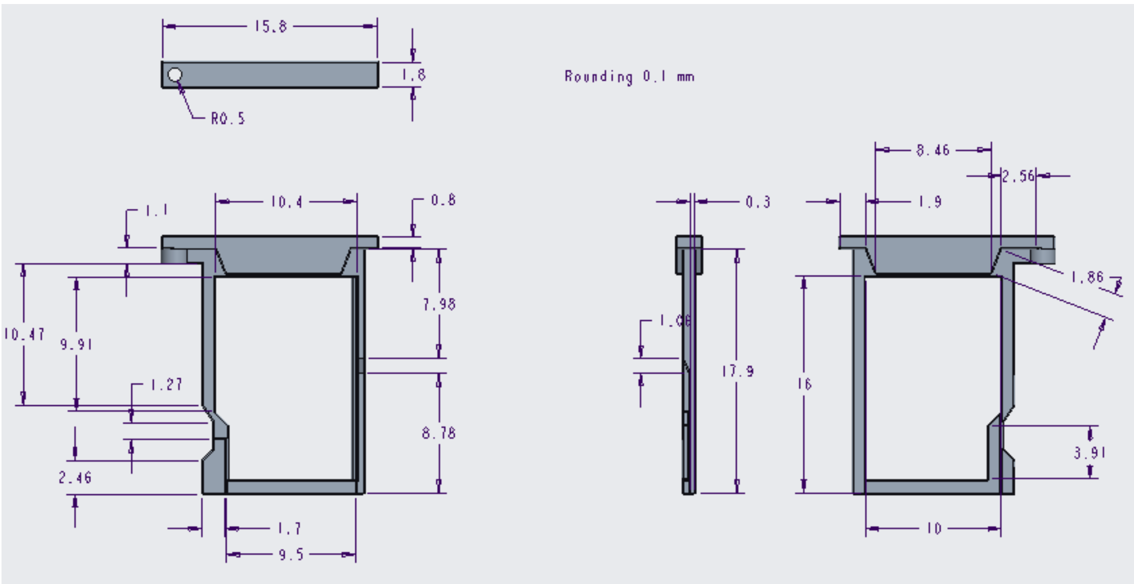


Image 4.3.13. SD Card Holder Measurements

4.4. Manufacturing Cost Analysis of Existing Product Parts

DFMA considers the ease and economics of manufacture. With 3D CAD several tools have been created that help with the process (e.g. Finite Element Analysis). Simulating the manufacture of a part in the early stages of its design can help to decide the geometry and material that will yield the lowest cost manufacturing solutions (PHIL19).

Some companies adopt a Design to Cost strategy that requires cost estimates throughout the whole development process of the product. This is possible if advanced CAD-integrated cost analysis tools are used, such as aPriori.

The cost can be divided into variable costs, piece part costs, and fixed costs.

Variable costs

Variable costs are recursive costs. That is, they are incurred every time a part is made.

- Material Cost: it includes the cost of the material used in manufacturing the part, as well as the scrap material from the manufacturing process. If the scrap material can be reused in the manufacturing process, as in plastic molding, then it is not wasted. Material is usually purchased by weight, and the following equation can be used (PHIL19):

$$Material\ cost = Material\ Utilization \times Part\ Volume \times Cost\ /unit\ of\ weight\ (\$/kg)$$

Where Material Utilization is a constant times the material's density. The constant represents whether the process requires more material for the final product or not. For example, the constant for injection molding will be one because the scraps can be reused.

- Labor: it includes hourly wages and benefits (PHIL19).

$$Labor\ Cost = Labor\ Time \times Labor\ rate(\$/hr)$$

$$Labor\ Time = Cycle\ Time \times Number\ of\ Operators \times Labor\ Time\ Standard$$

Where the Cycle Time is the period of time the machine is working on a part. For some processes as injection molding and sheet metal pressing, one operator can take care of both machines, and the Number of Operators will be 0.5. Labor Time Standard considers fatigue, adding time; but if the process is simple, its value is 1.

- Direct Overhead: it includes the costs for owning and using the machine. For example, it can be manufacturing supervisor and plant management salaries, factory rent, building insurance, equipment maintenance, etc. (PHIL19). The computation of this cost can be quite complex. The following equation can be used to ease the estimate:

$$Direct\ Overhead\ Cost = Overhead\ Rate\ (\$/hr)\ \times Cycle\ Time$$

- Logistics: it is the cost of transportation between supply chain facilities.

- Expendable Tooling:

$$Expendable\ Tooling\ Cost = Cost\ of\ a\ Tool/Number\ of\ Parts\ per\ Tool$$

$$Number\ of\ Parts\ per\ Tool = Tool\ Engagement\ Time\ per\ Part/Tool\ Life$$

- Total Variable Costs: sum of all the previous costs. It is the marginal cost of the part, that is, the cost of making one more part.

Piece Part Costs

It is the total cost to make each part including period overhead and profit margin (PHIL19).

- Period Costs: they represent costs in a financial period that cannot be directly assigned to a specific part.
- Margin: it is the profit margin for each part

Fixed/Capital Costs

These costs are upfront investments that happen before the production stage. For a long term "expended cost", the amortized cost can be computed (PHIL19):

$$Amortized\ Fixed\ Cost = Total\ Capital\ Cost/(Annual\ Production\ Volume \times Product\ Life)$$

- Hard Tooling: it refers to custom tooling used to manufacture one specific design (e.g. molds, dies).
- Fixture Cost: it includes the cost to hold a part in the correct orientation.
- Programming Cost: cost of developing a computer program.

a. Cost Estimate

Not being able to use aPriori, estimating the cost of each part is not trivial, and several assumptions are needed.

Each of the five parts that were modeled in CAD can be analyzed to estimate the total cost. However, some of the explained costs are not obvious. Assuming an annual production volume of 500,000 phones, the following costs can be estimated.

Back-cover

The back-cover is made of Polycarbonate and 10% Glass Fiber. Its manufacturing method is Plastic Injection Molding. In injection molding, the “waste” can be used in other processes, so the material utilization can be set to 1. The product volume can be obtained from Creo Parametric. Searching on the Internet, it can be found that a kilogram of this material can cost between $1 and $4. Assuming a cost of 4$/kg, the material cost can be computed.

$$Material\ cost = 1 \times 1.08 \times 10^{-6}\ kg/mm^3 \times 11599\ mm^3 \times 2.5\ \$/kg = \$0.05$$

Injection molding does not require the operator’s whole attention, so the labor time standard is 0.5. Assuming a wage of 2 $/hr, the labor cost is calculated.

$$Labor\ Cost = 0.19\ hr \times 2\ \$/hr = \$0.38$$

$$Labor\ Time = 0.19\ hr \times 2 \times 0.5 = 0.19\ hr$$

Assuming and overhead rate of 5 $/hr:

$$Direct\ Overhead\ Cost = 5\ \$/hr \times 0.19\ hr = \$0.95$$

$$Amortized\ Fixed\ Cost = \$5{,}000/(500{,}000\ per\ year \times 1\ years) = 0.001$$

Front Frame

The back-cover is also made of Polycarbonate and 10% Glass Fiber. Its manufacturing method is Plastic Injection Molding.

$$Material\ cost = 1 \times 1.08 \times 10^{-6}\ kg/mm^3 \times 1938\ mm^3 \times 4\ \$/kg = \$0.009$$

$$Labor\ Cost = 0.003\ hr \times 2\ \$/hr = 0.006\ hr$$

$$Labor\ Time = 0.003\ hr \times 2 \times 0.5 = 0.003\ hr$$

$$Direct\ Overhead\ Cost = 5\ \$/hr \times 0.003\ hr = \$0.015$$

$$Amortized\ Fixed\ Cost = \$5{,}000/(500{,}000\ per\ year \times 2\ years) = \$0.005$$

Metal Circuit Cover

The metal circuit cover is made of steel and its manufacturing method is sheet metal stretch. The material cost of this part can be calculated as the cost of a sheet divided by the number of parts that can be manufactured with that sheet.

$$Material\ cost = \ Cost\ per\ sheet\ (\$/sheet)/Number\ of\ parts\ per\ sheet$$
$$= 10\ /40 = \$0.25$$

Assuming the process takes around 10 seconds, the labor cost is:

$$Labor\ Cost = 0.0015\ \ hr \times 2\,\$/hr = \$0.003$$

$$Labor\ Time = 0.003\ hr \times 1 \times 0.5 = 0.0015\ hr$$

$$Direct\ Overhead\ Cost = 5\,\$/hr \times 0.003\ hr = \$0.015$$

If the sheet metal press machine costs $84,500 and the metal circuit cover lasts 10 years, the amortized cost can be computed as follows:

$$Amortized\ Fixed\ Cost = \$84{,}500/(500{,}000 \times 10) = \$0.017$$

SIM Card Holder

The SIM card holder is made of two different materials: PC + 10% GF and aluminum. For the purpose of simplification, the whole part will be assumed to be made of aluminum, and its manufacturing process sheet metal press. The different costs can be calculated in the same way as with the metal circuit cover.

$$Material\ cost = \ Cost\ per\ sheet\ (\$/sheet)/Number\ of\ parts\ per\ sheet$$
$$= 9\ /100 = \$0.09$$

$$Labor\ Cost = 0.0015\ \ hr \times 2\,\$/hr = \$0.003$$

$$Labor\ Time = 0.003\ hr \times 1 \times 0.5 = 0.0015\ hr$$

$$Direct\ Overhead\ Cost = 5\,\$/hr \times 0.003\ hr = \$0.015$$

$$Amortized\ Fixed\ Cost = \$84{,}500/(500{,}000 \times 2) = \$0.085$$

SD Card Holder

The SD card holder is made of two different materials: PC + 10% GF and aluminum. For simplifying purposes, the whole part will also be assumed as made of aluminum, and its manufacturing process sheet metal press.

$$Material\ cost = \ Cost\ per\ sheet\ (\$/sheet)/Number\ of\ parts\ per\ sheet$$
$$= 9\ /100 = \$0.09$$

$$Labor\ Cost = 0.0015\ \ hr \times 2\,\$/hr = \$0.003$$

$$Labor\ Time = 0.003\ hr \times 1 \times 0.5 = 0.0015\ hr$$

$$Direct\ Overhead\ Cost = 5\ \$/hr \times 0.003\ hr = \$0.015$$

$$Amortized\ Fixed\ Cost = \$84{,}500/(500{,}000 \times 2) = \$0.085$$

Finally, the different costs can be added to obtain the piece part cost and the total cost, as Table 4.4.1 shows. It is important to remember that these costs are based on assumptions of salary, machine cost, material cost, etc. Therefore, they are only estimates and might greatly differ from the actual figures.

Table 4.4.1. Cost Estimate

	Back-cover	**Front Frame**	**Metal Circuit Cover**	**SIM Card Holder**	**SD Card Holder**
Material Cost	0.05	0.009	0.25	0.09	0.09
+ Labor Cost	0.38	0.006	0.003	0.003	0.003
+ Direct Overhead	0.95	0.015	0.015	0.015	0.015
= Piece Part Cost	**1.38**	**0.03**	**0.268**	**0.108**	**0.108**
+ Amortized Investment	0.005	0.005	0.017	0.085	0.085
= Total Cost	**1.385**	**0.035**	**0.285**	**0.193**	**0.193**

The final estimated costs for the five parts are shown in Table 4.4.2.

Table 4.4.2. Final Estimated Cost

Part	**Estimated Cost ($)**
Back-cover	1.385
Front Frame	0.035
Metal Circuit Cover	0.285
SIM Card Holder	0.193
SD Card Holder	0.193

4.5. Product Design Specification (PDS)

As one of the key methodologies of the Product Realization Process, the Product Design Specification focuses on the requirements of the new product model and new manufacturing process.

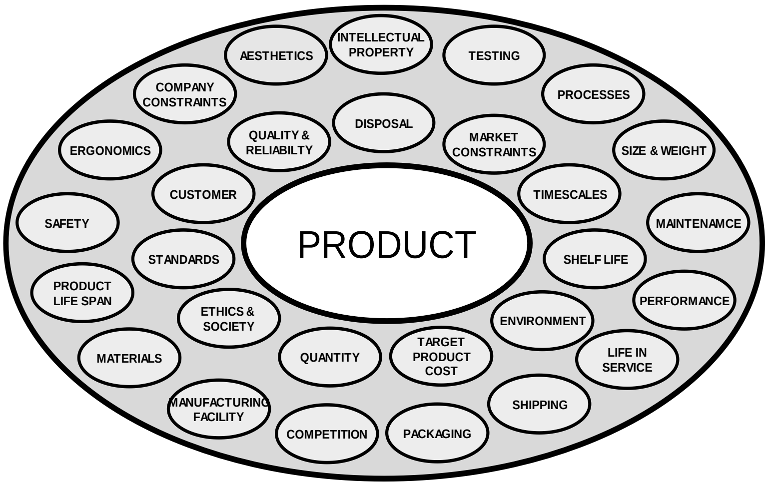


Image 4.5.1. Primary Elements of a PDS

Using the primary elements of a PDS that form the Design Boundary, shown in the previous image (PHIL19), the objective goals can be established, and an idea of the requirements for the cell phone can be drawn.

1) Performance

The phone's processor is a Mediatek Cortex A7, with 4 nuclei, that yields a speed of 1.30 Ghz. The problem with using this processor is that it does not support any updates. It is advisable to have a CPU that can have updates, so it can adapt to newer versions, and consequently last longer. It has 1 GB of RAM, but it should be larger. Newer phones have up to 16 GB RAM, but 8 GB is enough for the phone to work adequately.

2) Environment

The product's likely environment is the same as the user's, so it can vary a lot depending on where the user lives, as well as the season. A cell phone can be used by anybody, so the degree of abuse of the device will vary from one user to the other.

The optimal range of temperatures is between 15 and 20 ºC. If the temperature goes below -40 ºC or above 45 ºC, the phone will malfunction.

When it comes to water, the cell phone has to resist up to 100% of humidity, and it needs to have some resistance to rain or splashing. Moisture protection can be measured using an IP Code established by the International Electrotechnical Commission (IEC). BQ phones have an IP52, where IP stands for Ingress Protection. The first digit indicates the solid particle protection, and the second digit indicates the liquid ingress protection (CRES20).

5 – Dust protected: Ingress of dust is not entirely prevented, but it must not enter in sufficient quantity to interfere with the satisfactory operation of the equipment.
2 – Vertically dripping water shall have no harmful effect when the enclosure is tilted at an angle up to 15° from its normal position.

It should be able to withstand falls from up to 1.50 meters without having a huge impact on the phone's performance.

Cell phones get very dirty as time goes by. It needs to have some kind of protection that will stop dirt and dust from going into the phone, through the Micro USB slot, the speaker, or the receiver. This is also measured by the IEC classification.

3) Service Life

The service life of the cell phone should be long. The advantages of having a short life are that high product turnover creates more jobs, consumers like updated products, etc. The advantages of having a long lifetime are that the product is associated with higher quality, and, more importantly, the technological waste decreases, and less resources are used.

Phones are used between 1 and 2 years on average. However, in order to reduce the technological waste, it would be better for them to last 5 years or longer.

4) Maintenance

The phone does not require maintenance, but it does need to be repaired if it breaks. Repair is possible and highly recommendable. The company offers to repair defects in the design, the material, and manufacturing, while the device is in warranty. However, it usually takes a long time, and customers are unhappy with this. On average, a cell phone takes 1 hour to repair, but the logistics make this process last longer. A goal of 2 to 3 days should be established.

In order to make repair easier, standard components are used in different models. This way, repair time and difficulty decrease.

5) Target Costs

The manufacturing cost of a phone includes the cost of the different components as well as the manufacturing processes. The most expensive components are the core electronics, memory, and camera. On average, this translates into a 65% profit margin. However, BQ pride themselves for not over profiting and wanting to give the buyer what he is paying for. So, if the launch price of the BQ Aquaris E5 HD was 199 €, the manufacturing cost must be around120-150 €.

However, this means that the margin profit is not that high, and they have to be careful with their predictions.

The cell phones they sell have very good quality as reported in user reviews and a very good price / quality ratio compared to their competitors. In the last years, with the success of Chinese phone companies, all phone companies have had some trouble since many users have given it a try.

6) Competition

BQ phones bring a medium to high quality experience with a much lower price than multinational phone companies such as Apple or Samsung. That is why lots of users have decided to give these phones a try and have been satisfied with the outcome of the experience.

7) Shipping

The cell phone is sold through different channels. It can be bought directly from the company's website, or through retailers such as Amazon. Therefore, the product is shipped from the company's warehouses to the buyer, or the retailer, and then to the buyer. They do this by mail order, so they do not have their own distribution fleet.

Also, the BQ Aquaris E5 model was assembled in China, and it had to be shipped to Spain, mostly by ship.

8) Packaging

Packaging is required for shipping the product. Also, the package includes the phone, a charger, and headphones. Everything is put into a box, along with the instructions, and the warranty information. The packaging will ensure that nothing in the interior breaks during the shipping, and that nothing is lost during this process.

9) Manufacturing facilities

This particular model was designed in Spain and assembled in existing plants in China. In 2012, they assembled the phones using existing Chinese models in their manufacturing facilities in China. However, the company changed its approach to the industry and decided to design their own phones from scratch. In 2018, they sold 51% of their capital to Vingroup, a Vietnamese phone manufacturer, as a way of delegating the manufacturing of the phone to another company and introducing BQ phones into Vietnam's market.

10) Size (overview of key features)

Size is very important when designing a cell phone. It has to fit in the hand and in pockets and bags. The current measurements are 142x71x8.7 (L x W x T) in mm. The size of the cell phone is the optimum size. Compactness and portability requirements are met, while trying to meet other customer requirements, and having a large enough screen, 5".

11) Weight

As with size, maximum, minimum, and/or optimum weight have to be considered. The current weight is 134 grams. Many aspects influence the weight, such as the size, the battery, and the rest of the components. The smaller the weight, the better, since it will be more comfortable for the user. However, this is difficult to achieve since other requirements yield higher weight, such as a longer duration battery, since bigger batteries can last longer. So, a balance must be reached.

12) Aesthetics

Although it is difficult to specify and to measure, the company must focus on the design, so it is elegant and pleasant. It is difficult to please everybody with the design, so different color options are often included. In this case, the model was available in two colors: black and white. The texture is another important design feature. Users have different preferences on the material of the phone. Again, there are usually different “finish” options, but this was not the case.

13) Materials

For the exterior, PC is used. However, there are a lot of components in a phone that require different materials. For instance, the circuit board needs to have a non-conducting material for the board and conducting material for the circuits. The first is usually made of fiberglass reinforced with ceramic materials, and the second uses copper filaments.

The most common materials used in cell phones are glass for the screen, a variety of metals such as aluminum alloys, gold, copper and silver, and plastic (PC).

14) Product Lifespan

The phone BQ Aquaris E5 has a lifespan of 1.5 years, on average. Ideally, the product lifespan should be of 5 years, for environmental reasons among other things. However, longer duration is accompanied by higher cost.

Nowadays, phones are soon outdated since phone companies are constantly developing new models with updated features. So, phones usually remain in production for 2 years, at most.

15) Ergonomics

The design of the phone has to be ergonomic in order to maximize the customer experience. It has to be designed to fit the user’s hand. This is deeply related to the size of the product. Similarly, the weight cannot be too much, it should be under 140 grams.

16) Customer

Customer reviews are the best way to gain insight about their requirements and suggestions, for future designs. Feedback is always important, and through customer satisfaction surveys the customer’s requirements can be learnt and put in practice.

17) Quality and Reliability

To make sure the product has good quality and is reliable, the phone is put through several tests. The Mean Time Between Failure (MTBF) should be as long as the phone’s lifespan, that is, 1.5 to 2 years. Ideally, the number of years will increase in the future. The phone may have problems with the battery duration, the camera, the buttons, the screen, etc. Therefore, another interesting parameter is the Mean Time To Repair (MTTR), and, on average, the MTTR is of 1 hour. However, depending on the degree of extent of the damage, the company will require more or less time.

18) Shelf life

To combat decay, shelf life is limited. If not used, the battery ends up deteriorating and the phone is no longer of use. Therefore, shelf life should be less than 1.5 years.

19) Manufacturing processes

The phone was manufactured in China in an existing plant. This plant has to have an injection molding machine to manufacture the phone covers and the body. Additionally, it needs to have a machine that follows an automated process, placing the different components of the phone: the circuit board, the camera, the microphone, the speaker, etc. This process can also be done by workers, but it would require a large number of workers, and time. In the automated process there are workers that ensure everything is going as planned, and participate in part of the process, as snap fitting the back-cover.

20) Timescales

Building a new phone model requires a period of time of 9 to 12 months. There are five stages for BQ that comprise prototyping, product validation where a hundred phones are made, Design Validation Test (DVT), manufacturing to make sure the product is ready to be mass produced, and support.

21) Testing

First, one hundred phones are manufactured in China and brought to Spain, and they go through the initial tests where the issues are found and solved. After that, around a thousand phones are manufactured and go through the DVT (PERE18). First, the connectivity tests are done to ensure 2G/3G/4G coverage requirements are met, and that the GPS/GLONASS/Galileo have the correct precision. To measure the coverage and reception, an anechoic chamber is used, as well as a human-like hand used to see if it interferes with the coverage. Secondly, the SAR (Specific Absorption Rate) radiation levels are measured, to ensure they do not exceed the 2 W/kg limit, thought their goal is to be under 1.5 W/kg, averaged over 10 grams of tissue. Then, the phones go through mechanical and resistance tests. Endurance and durability are tested through vertical falls, and constant knocks, to see how many cycles the phone lasts. The reliability tests are made to see how the phone performs with time, and they are the bend test, to simulate sitting down with the phone inside the back pocket, and adding weights to different parts of the phone to check if it endures the pressure. The accelerated aging tests are also important, and they use a machine that presses the buttons more than 300,000 times, connects and disconnects the 3.5 mm jack more than 10,000 times, and touches the screen dozens of times to make sure that the screen response in all areas is correct. Resistance to water and dust is also tested with a machine that throws water at varying pressures, given that the phone’s resistance to water and dust is IP52. Finally, other tests include a resistance meter at high temperatures, and a control of battery bloating after 300 cycles.

22) Safety

The phone must follow all the safety standards and legislation in this area. The most important to follow is the SAR. It stands for Specific Absorption Rate, and it refers to the amount of energy absorbed by a biological tissue. In Europe, the SAR must not exceed 2 W/kg for 10 grams of tissue on average. In the US, it must not exceed 1.6 W/kg for 1 gram of tissue on average. BQ’s goal is to have its phones under 1.5 W/kg.

The user needs to be careful with how he or she uses the phone, using it responsibly. It must not go over or under the temperature limits.

The phone instructions state the following safety precautions:

- Handle and discard batteries and chargers carefully. Do not handle damaged or leaking lithium-ion batteries.
- Replacing the battery with one that has not been approved by the manufacturer may cause it to explode
- Prolonged exposure to high levels of sound volume can cause permanent damage to the user’s hearing.

23) Company constraints

The company is constrained by its previous products. When the first model was launched, they acted as assemblers. They later decided to design and manufacture the phones from scratch, but some people still believe they are rebranding Chinese phone models.

24) Market constraints

In Spain, BQ holds a significant market share. However, Chinese models have gained recognition in the past years, and the competition is high. The advantage of BQ’s phones is that they are a good choice in terms of value for money.

25) Disposal

With EPR, the manufacturer can no longer forget about the item after it is purchased by the customer. Here is where Design for Recyclability comes into play. Some materials used in the phone have a high recoverable value and can be reused.

At the end of the product’s life, the company offers to retrieve the phone.

4.6. Quality Function Deployment (QFD)

A Quality Function Deployment matrix is a procedure in which key customer requirements are transformed into design requirements. The advantages of using this methodology includes improved customer satisfaction, early customer 'ownership' of product, customer inspired engineering change, and an efficient mechanism for organizing data and extracting information, among others.

The following steps show how a QFD is done and how it is summarized in a "house of quality".

Step 1 – Customer Requirements

The first step is to identify all the key customer requirements. Ideally, direct interaction with customers would be the most accurate way to get this information. For this project, the focus is going to be in two parts: reviews of the product on various websites, and a user (myself).

Once the Customer Requirements are identified, the relative customer importance is filled (1-5; 5 = very important)

Step 2 – Design Requirements

The customer requirements can know be translated into "Design Requirements" (measured parameters). A target or limit value is determined for each design requirement, and the technical difficulty is assessed (1-4; 4 = most difficult).

Additionally, the "Direction for Improvement" can be identified:

- ▲ – Up arrow: the objective is to maximize value to improve customer satisfaction
- ▼ – Down arrow: the objective is to minimize value to improve
- X – target value is optimum

Step 3 – Relationships (symbols in the middle of the matrix)

In this step, the relationship between customer requirements and design requirements is decided, using the following symbols:

- Θ – Strong Relationship (9)
- O – Moderate Relationship (3)
- ▲ – Weak Relationship (1)
- Nothing if there is no relationship

The Weight/Importance is then calculated as the sum of the customer importance times its relationship value. The relative weight is then determined by ranking in order of Weight/Importance (i.e. 1= highest weight, 2 = next highest weight…)

Step 4 – Correlations (roof of the house)

In this step the correlation between design requirements is determined using the following symbols:

- ++ Strong positive correlation
- + Positive correlation
- - Negative correlation
- ▼ Strong Negative Correlation

Where a negative correlation indicates that improving one design requirement will have an undesirable effect on the other design requirement.

Step 5 – Competitor analysis (right hand block)

The competitors' products and previous models are rated on how well they meet the customer requirements (0 = Worst, 5 = Best).

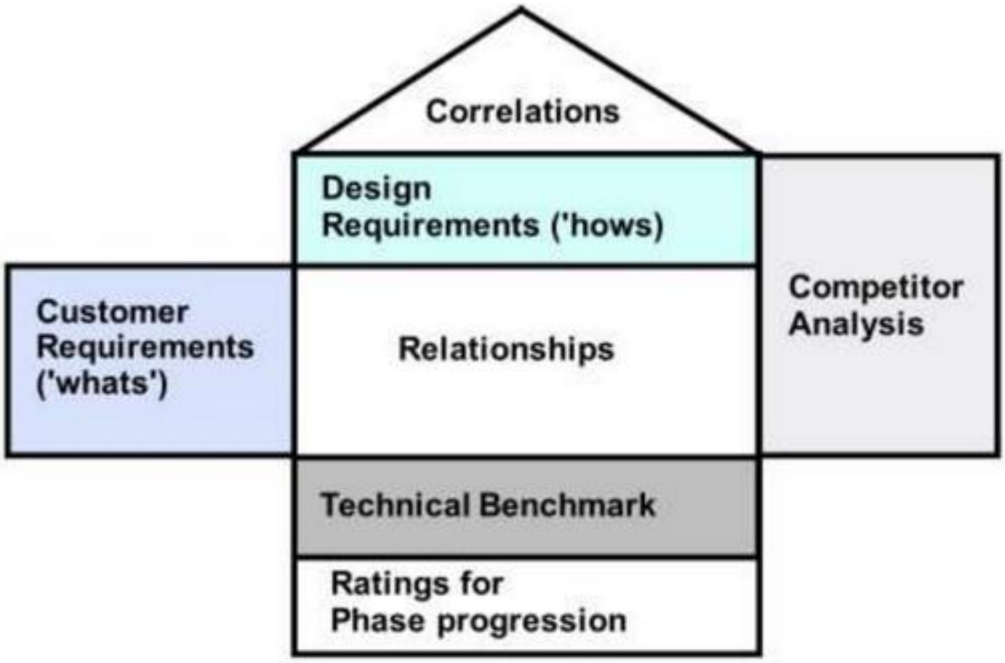


Image 4.6.1. Rooms of the house

Image 4.6.1, taken from Mike Philpott's book (PHIL19) shows what the Quality Function Deployment matrix will look like.

a. Customer Requirements

To identify key customer requirements, product reviews really help in gaining insight. Reading Amazon's reviews of this product the following ideas are mentioned with higher frequency:

DISCLAIMER: this phone model was launched in 2014, so the company's procedures might have changed since then.

- The camera does not work very well; the autofocus fails and the pictures turn out blurry
- Problems with WiFi connection, having to restart the phone in some cases
- After a year of use, the battery starts to fail, and the phone overheats
- The battery does not last very long
- The battery is not changeable unless it is done by an authorized distributor, increasing the maintenance costs
- Customer support does not work well, and technical support is very poor
- The repair service is not very efficient
- Repairing the phone (e.g. the screen) takes very long and is very expensive (up to 50% of the phone's price)
- After sales service is not very efficient
- Warranty limited
- The weight is a little higher than other phones
- Some problems when transferring apps and other data to the SD card
- When transferring media to the PC, the WhatsApp folder does not appear so the content cannot be transferred directly to the computer. Other means are used, such as Bluetooth, which is time consuming
- When exposed to direct sunlight, the screen is somewhat difficult to read
- Some people were not happy with the processor, MTK, because it does not have firmware updates
- The screen appears to break easily when it falls
- After two years of use, it starts overheating and working slower. Some apps close without any reason and others take a very long time to start
- The company was supposed to be updating the firmware, but they ended up not doing it for this model
- Not a very aesthetic design, but a phone case can be used
- Some problem with the GPS not working
- At the beginning, it works well but, after a year, several things start to malfunction: the GPS, battery life is significantly reduced, some apps close

These reviews can be translated into the following Customer Requirements, with the corresponding Importance rating (1-5; 5 = most important).

Customer Requirement — Importance

1. Size
    a. Lightweight …… 3
    b. Slim design …… 2
    c. Compact enough to fit in a pocket …… 2
2. Ergonomics
    a. Adjusted to the hand …… 3
3. Aesthetics
    a. Aesthetically pleasing …… 2
4. Battery
    a. Long duration …… 5
    b. Removable …… 3
5. Camera
    a. High quality …… 4
6. Customer support
    a. Efficient warranty …… 3
    b. Good technical support …… 5
7. Cost
    a. Reasonable cost …… 5
8. Life expectancy
    a. High …… 4
9. Hardware
    a. Correct operation of apps …… 5
    b. Fast …… 5
    c. Large storage capacity …… 4
10. Hardware
11. Screen
    a. Fast touch answer rate …… 4
    b. High resistance to breakage …… 3

b. Design Requirements and Direction for Improvement

Once the customer requirements are set, it is necessary to translate these into Design Requirements, and determine the Target Value, Direction for Improvement, and the other sections of the “house of quality”. Considering all the customer requirements, the following design requirements are established:

- Weight (g)

The user wants and ergonomic design and a reduced weight is one of the most important design requirements to achieve this.

- Target Value: 120 grams
- Direction for Improvement: ▼
- Difficulty: 2

- Length (mm), Width (mm), and Height (mm)

These measurements are very important for achieving an aesthetic, ergonomic design, as well as for having enough space to house all the components of the phone.

- Target Value: 141, 71, 8.7 mm
- Direction for Improvement: x
- Difficulty: 2

- Cost (€)

The price of this phone is quite reasonable given its performance. However, users are always looking for the best affordable phone.

- Target Value: 199 €
- Direction for Improvement: ▼
- Difficulty: 9

- Life Span (years)

Users want to spend money on a phone that has the characteristics they want, but they want it to be worth it, with a phone that will last enough time.

- Target Value: 5 years
- Direction for Improvement: ▲
- Difficulty: 10

- Camera Resolution (MP)

In order to have a high-quality camera, increasing the camera resolution is very important. Users find it a priority to have a good camera. Newer models have focused on this aspect and it is the biggest difference with previous models.

- Target Value: 20 MP
- Direction for Improvement: ▲
- Difficulty: 9

- Battery Duration (hours)

Increasing the battery duration satisfies one of the biggest customer requirements. If the battery lasts a short time, the user will have to be charging the phone constantly. A bigger battery would be beneficial to meet this requirement. However, the size is another requirement that needs to be taken care of, so there is a trade-off between battery duration and size.

  - Target Value: 48 hours in total
  - Direction for Improvement: ▲
  - Difficulty: 9

- Battery Life (years)

The battery life plays an important role when it comes to the phone's lifespan; especially in this case where the battery is nonremovable. The goal in this design requirement is to increase the battery life.

  - Target Value: 5 years
  - Direction for Improvement: ▲
  - Difficulty: 9

- Screen Time Response (ms)

Screen time response measures how much time the screen takes to respond when the user interacts with the phone. Attaining a value below 5 ms for this design requirement will ensure the correct the operation of the apps.

  - Target Value: 5 ms
  - Direction for Improvement: x
  - Difficulty: 4

- Screen size (")

The screen size has influence in many of the aspects involved in the user's experience, as well as the aesthetics of the phone. A larger screen will get better reviews when it comes to aesthetics and use of the screen. However, this will increase the probability of its breakage. In this case, the screen size is acceptable

  - Target Value: 5"
  - Direction for Improvement: x
  - Difficulty: 2

- Internal Memory (GB)

Many customers reported having issues while transferring files from the internal memory to the SD Card. Increasing the Internal Memory would avoid this problem, since an external memory device would not be necessary, and it would meet other customer requirements since phones are a tool used for telecommunication, social media, leisure, taking pictures, etc., which require a lot of storage.

  - Target Value: 128 GB
  - Direction for Improvement: ▲

- Difficulty: 7

- Aesthetic Design (% of likeability)

Although an ugly design can be hidden using a phone case, users prefer it when the phone has an elegant design.

- Target Value: 80%
- Direction for Improvement: ▲
- Difficulty: 4

- High RAM (GB)

Having a high RAM has great impact on the performance of the phone. The higher the RAM, the better the phone will work

- Target Value: 8 GB
- Direction for Improvement: ▲
- Difficulty: 6

- Repair Time (hours)

By decreasing the repair time, the user will be happier with the technical support.

- Target Value: 5 hours
- Direction for Improvement: ▼
- Difficulty: 8

c. QFD Diagram

The whole "house of quality" is shown in Image 4.6.2:

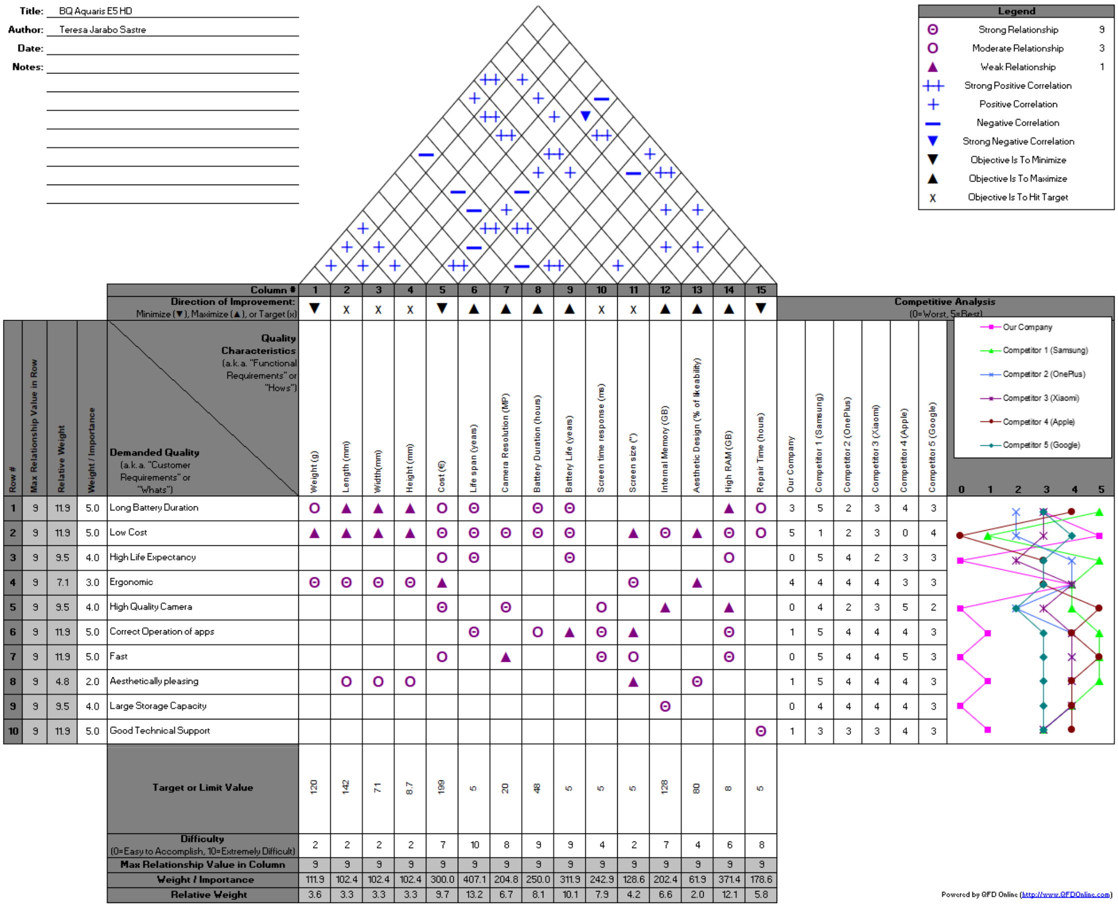


Image 4.6.2. "House of Quality"

d. QFD findings and Areas to Concentrate Design Efforts

Table 4.6.1 shows the weight or importance each of the Design Requirements has, and it can be analyzed to determine which design requirements are the most important, so that most time and effort are invested on them.

Table 4.6.1. Design Requirement Importance

Weight/ Importance														
Weight	Length	Width	Height	Cost	Life span	Camera resolution	Battery duration	Battery life	Screen time response	Screen size	Internal memory	Aesthetic design	RAM	Repair time
111.9	102.4	102.4	102.4	300.0	407.1	204.8	250.0	311.9	242.9	128.6	202.4	61.9	371.4	178.6

As it can be observed from the table, life span is the most important design requirement with a weight of 407.1, followed by battery life and RAM, with a weight of 311.9 and 371.4, respectively.

Increasing the RAM will help with the general performance of the phone. 1 GB is not enough memory, especially since more and more is expected from the phones; they are used for taking pictures, for playing music, for playing games, for learning, etc. If the highest performance is expected of the phone when using several apps at the same time, a phone must have at least 8 GB of RAM.

The battery life is a key aspect when the product lifetime is considered. If the battery stops working, it does not matter how good the other components are, the phone will not work. Phones use rechargeable batteries that have a useful life, after which they have to be replaced. New batteries are worth investigating. In fact, it is very important that more durable, less toxic batteries are developed, in order to increase the product lifetime and reduce the technological waste.

Increasing the life span of the phone is one of the most complex design requirements since it involves a combination of the improvement of all of them. Nevertheless, it is the one that better addresses the customer requirements.

There are several ways of concentrating on increasing the life span of the phone. For example, investigating on new batteries, trying new materials, or reducing the number of components. The three of them can be considered as part of Design for Recyclability. So, it can be concluded that in order to achieve what the customer wants, Design for Recyclability is necessary.

4.7. Design for Manufacture and Assembly (DFMA) analysis

Design for Manufacture and Assembly is the combination of two methods that focus on ease of manufacture and efficiency of assembly, minimizing time and cost.

Traditionally, these two have been separated, but the combination of both yields the greatest benefit. New and improved products are designed and manufactured in a shorter period of time, since it avoids revisions and design modifications. Companies are starting to make the two areas work together. Design for Manufacture focuses on the individual components, studying ways to reduce the number of components, and to eliminate intricate features that increase the difficulty of manufacture. Design for Assembly focuses on the reduction and the standardization of parts and assemblies, aiming to reduce the total assembly time and cost. As it can be seen, these areas are mutually dependent.

The **main principles** of DFMA are (QUAL20):

- <u>Reduce the quantity of component parts and simplify part design</u>

The designer must review the assembly design and decide if any of the parts can be eliminated or combined. When the number of parts is reduced, the number of steps in the assembly also decreases.

- <u>Design parts for ease of fabrication</u>

The designer has to consider the fabrication method of all of the parts, the material, and the required production volume. The following guidelines help achieve this:

  - List commonly used materials that are compatible with the design and the existing production processes that will minimize processing time.
  - Analyze each of the parts and eliminate unnecessary details that will increase steps in the process.

- <u>Design within known process capabilities and avoid tight tolerances</u>

The designer must know the equipment needed for manufacturing the parts and avoid tighter tolerances than what the machine can reach.

- <u>Use common parts and materials</u>

Incorporating common parts in similar products can help minimize inventory levels and will yield a lower cost and higher quality.

- <u>Mistake-proof design and assembly</u>

A fail-safe design is an efficient way of making sure the design is error free. To mistake-proof the designs, the designer needs to make sure the assembly of the parts is instantly recognizable, without room for doing it the wrong way. This is achieved by adding tabs, slots, asymmetrical holes, and interference features that make it impossible to assemble incorrectly.

- Handling requirements and part orientation

This must be observed since the machines have motion constraints. Some basic principles are:

  - Drawings should always indicate the orientation the part is fed into the process.
  - Parts that can easily tangle or that are difficult to pick up should be avoided.
  - If it is feasible, design symmetrical parts along both axes.
  - Parts should be grasped, oriented, and placed with ease.
  - Sharp edges must be avoided. They must be rounded, or a chamfer must be used.
  - Always consider the assembler and operator safety. Do not include heavy parts that require lifting operations.
  - Plan for minimum worker travel time.

- Design for ease of assembly

The simpler the design, the easier it is to assemble. Some guidelines to achieve this are:

  - Incorporate simple movements in the assembly line and minimize steps or take into consideration breaking into sub-assemblies.
  - Prevent reorientation during the assembly process.
  - Use gravity to the advantage of the assembly process: assembly from the bottom up.
  - Consider tool clearance and ensure there are no hidden attachment points.

- Reduce/eliminate flexible parts and interconnectors

Many products fail because, during the design, the environment in which it was going to work was not duly considered.

  - Use robust connectors.
  - Minimize wire harnesses. If used, error-proof the connectors.
  - Take advantage of direct drive rather than using pulleys or belts

- Incorporate easy and efficient fastening methods

Instead of using nuts and bolts, which take a long time to assemble, use alternative methods of attachment.

  - Use weld nuts.
  - Minimize the variety of hardware (e.g. use one screw size throughout the whole design).
  - Use integrated connectors such as snap fits and slots.
  - Use adhesives
  - Contemplate ease of disassembly for repairing.

- Modular product design
  - Modules reduce cost since the number of different parts in a family of products is decreased.
  - The manufacturer can balance production, based on projected sales.
  - The manufacturer can easily answer to the high demand of a product, delivering the required modules to the plant.
  - Modular assemblies can be modified without affecting the rest of modules.

- Design for automation

The product must be designed to be handled by automated equipment. Some advantages are the increase in the process efficiency, a more predictable output, consistency during the process, and reduced labor cost.

a. Manufacturing Analysis

Design for Manufacture focuses on designing for ease of manufacture of the different parts, selecting the most cost-effective materials and manufacturing processes.

In this section, each of the parts of the cell phone is analyzed in order to determine its Manufacturing Process & Material.

- Part 1: Back-cover (case)

The back-cover is made of polycarbonate (PC) and 10% of glass fiber (GF) and it was Plastic Injection Molded. The properties of PC + 10% GF can be found in the annex PC + 10% GF properties.

- Part 2: Front frame

The front frame is made of polycarbonate (PC) and 10% glass fiber, and it was Plastic Injection Molded.

- Part 3: Phone Body

The phone body is made of two materials. The black part is polycarbonate (PC) and the light part is made of magnesium. Each part was Plastic Injection Molded and joined by Solvent Bonding. In Solvent Bonding, plastics are softened with a solvent and then pressed together, resulting in the interdiffusion of the polymer chain, at the bonding junction. Image 4.7.1 shows a detail of how these two parts were joined.

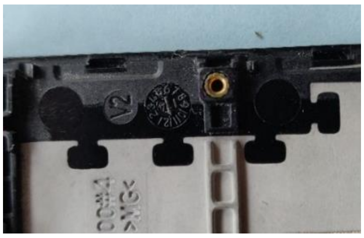


Image 4.7.1. Phone body detail

- <u>Part 4&5: PN Screw (3 mm) & (4 mm)</u>

Pan Screws are typically made of Stainless Steel to prevent them from rusting. It is an off-the-shelf item.

- <u>Part 6: Circuit Board and Circuitry</u>

An epoxy-fiberglass composite is used for the circuit board. It is copper clad, and the copper pattern is plated onto the board. The components on the board are usually made of platinum and tungsten. The SIM card and SD card slots are welded to the PCB.

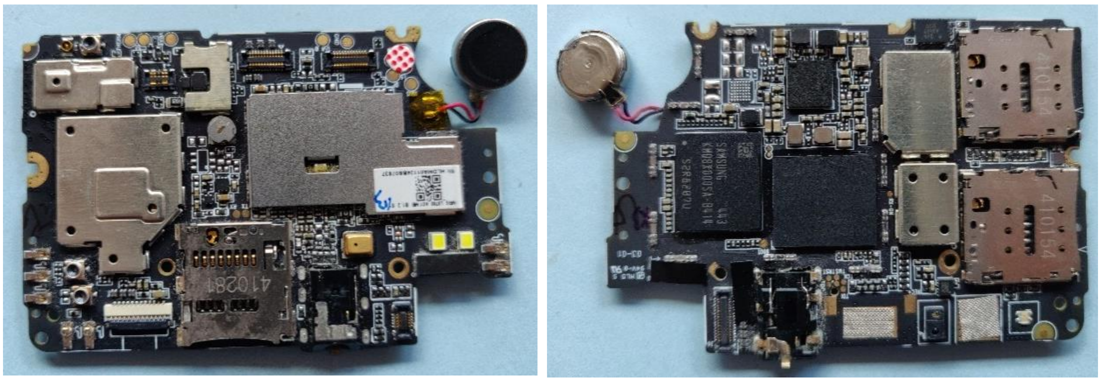


Image 4.7.2. PCB

- <u>Part 7: Circuit Board Cover</u>

The cover is made of two parts. The first one is made of aluminum that was sheet metal formed and pressed. The second one is made of PC and was plastic injection molded onto the aluminum sheet.

Image 4.7.3. Circuit Cover

- <u>Part 8: SD Card Holder</u>

The SD Card Holder is made of two different materials. The top part, which is seen, is made out of the same material as the back-cover and the front frame: PC and 10% Fiber Glass. It is done using plastic injection molding. The frame on which the SD Card is placed is made out of aluminum and it can be machined, or sheet metal pressed.

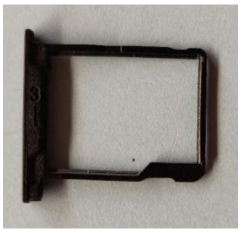


Image 4.7.4. SD Card Holder

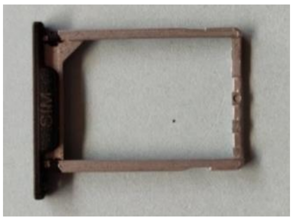


Image 4.7.5. SIM Card Holder

- <u>Part 9: SIM Card Holder</u>

The SIM Card Holder is also done with two materials. The black part is PC with 10% Fiber Glass, which is plastic injection molded, and the grey part is aluminum that was either machined or sheet metal pressed.

- <u>Part 10: Battery</u>

The battery on this phone is a Lithium Polymer (LiPo) battery and is an off-the-shelf product.

Image 4.7.6. Battery

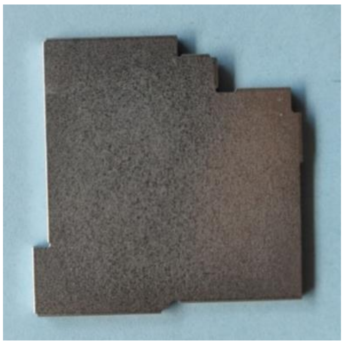


Image 4.7.7. Metal Circuit Cover

- <u>Part 11: Metal Circuit Cover</u>

These two parts are made of steel and were sheet metal stretch formed. They click onto the circuit board to protect some of the components.

- <u>Part 12: Camera</u>

The cameras are made of PC, aluminum and glass and is an off-the-shelf product.

Image 4.7.8. Phone Cameras

- Part 13: Microphone

The microphone is a silicon wafer and is an off-the-shelf product.

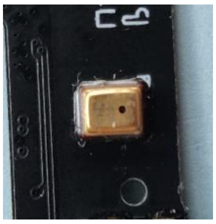


Image 4.7.9. Microphone

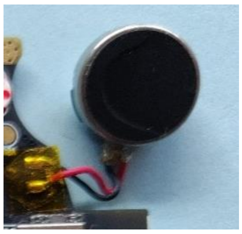


Image 4.7.10. Speaker

- Part 14: Speaker

The speaker is composed of piezoceramics and shim (metal materials) and is an off-the-shelf product.

- Part 15: Receiver

The receiver is made of plastic, copper and aluminum and is an off-the-shelf product.

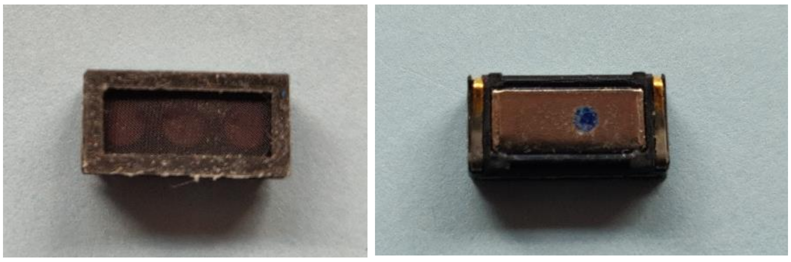


Image 4.7.11. Receiver

- Part 16: Screen

The screen is made of glass and is an off-the-shelf product.

- Part 17: Wiring

Typical materials for wiring are gold, copper and silver and they are an off-the-shelf product.

- Part 18: Insulating Tape

The insulating tape can be made of vinyl or plastic and is an off-the-shelf product.

b. Design for Assembly (DFA) Analysis

Design for Assembly focuses on ease of assembly, minimizing the cost and the number of operations.

These guidelines must be considered (PHIL19):

- The design of the product with a view to overall ease of assembly
- The design of each component for ease of assembly to its neighbors
- The means by which the parts are joined or assembled

The following questions taken from Mike Philpott's (PHIL19) eBook help analyze the existing product design, and each of the parts are run through them.

1. Can the part potentially be combined with any of the previously assembled parts because it can be made from the **same material**.
2. Can the part potentially be combined with any of the previously assembled parts because it **does not move** with respect to any other part.
3. Can the part potentially be combined with any of the previously assembled parts because it is **not required to be separate** to allow assembly of an internal part or parts.
4. Can the part potentially be combined with any of the previously assembled parts because there is an **alternative fabrication process** that could be feasibly or economically adopted.

Table 4.7.1. DFA analysis

	Part Name	**Q1**	**Q2**	**Q3**	**Q4**	**Opportunity to combine or eliminate**	**Notes**
1	Back-cover	N	N	N	N	N	
2	Front Frame	N	N	N	N	N	
3	Phone body	N	N	N	N	N	
4	PN screw (3 mm)	Y	Y	Y	Y	Y	Could use other mechanisms such as adhesives
5	PN screw (4 mm)	Y	Y	Y	Y	Y	Could use other mechanisms such as adhesives
6	Circuit Board & Circuitry	N	Y	N	N	N	
7	Circuit Board Cover	Y	Y	Y	Y	Y	Could be eliminated
8	SD Card Holder	N	N	N	Y	N	
9	SIM Card Holder	N	N	N	Y	N	
10	Battery	N	Y	N	N	N	

	Part Name	Q1	Q2	Q3	Q4	Opportunity to combine or eliminate	Notes
11	Metal Circuit Cover	Y	Y	N	Y	N	
12	Camera	N	Y	Y	N	N	
13	Microphone	N	Y	Y	N	N	
14	Speaker	N	Y	Y	N	N	
15	Receiver	N	Y	Y	N	N	
16	Screen	N	Y	Y	N	N	
17	Wiring	N	N	N	N	N	
18	Insulating tape	N	N	N	N	N	

Number of Parts in the assembly: 33

Theoretical Minimum Number of Parts: 15

Originally, the number of parts was 33, but after the DFA analysis, the number of parts can potentially be reduced to 15.

This can be achieved by eliminating some parts and using different joining mechanisms.

In the case of the screws, other mechanisms could be used such as adhesive bonding, reducing the assembly time. However, using adhesive can contaminate potentially recyclable parts if it cannot be removed easily. Another option is to use snap fits as the design can integrate molded-in plastic hinges. Also, considering DFA, a single size could be used for the screws, as a way of reducing the number of hardware parts, and of proof-designing, so that the screws are not misplaced.

Finally, the circuit board cover could be removed altogether, or it could be integrated with the back-cover.

Assembly Time

DFA is also used to estimate the time of assembly. The Handling and Alignment time refers to the time it takes to get the part, orientate it, and align it so that it is ready to be combined. The Insertion and Secure Time is the time it takes to join the part to the assembly. The α symmetry refers to the symmetry about the axis perpendicular to the insertion axis. The β symmetry refers to the symmetry about the axis of insertion. The Aspect Ratio is the ratio between length and thickness. The size refers to the longest size of the smallest rectangular prism while the thickness is the smallest length (the radius if it is a diameter) (LIEB20).

In order to calculate the Assembly Time, the following tabulation approximations are used:

- Handling and Alignment:
  - Part Fetch Time: 0.5s / 0.5m distance (0.5s minimum)
  - Symmetry: add $(\alpha + \beta) / 360$ seconds
  - Par size: small (L < 2 cm) add 0.5s, large (L > 20 cm) add 0.3s
  - Each handling difficulty (sharp, tangle, flexible) add 0.4s
  - Aspect ratio > 20 add 0.1s, aspect ratio > 40 add 0.3s
- Insert and Secure
  - General placement: 0.5s
  - Align to small hole (< 2mm) add 0.4s, medium (2 < pin diameter < 4mm) add 0.1s
  - Requiring a grasping aid (tweezer, special gloves, magnifying glass) add 1.4s
  - Turning insertion (screw) add 1s
  - Snap: add 0.3s, Crimp: add 0.8s
  - Final screw tightening: add 2s (for one sided, e.g. screw) or 7s (for two sided, e.g. nut on a bolt)
  - For each insertion difficulty (view, force, spring, hold, tight tolerance) add 0.4s
  - Rotate base (i.e. turning the assembly over): 1.8s

Assembly Table												
							Handling and Alignement		Insert and Secure			
Operation Number	Times Operation is Carried Out	Part Description	Alpha (deg)	Beta (deg)	Size (mm)	Thickness (mm)	Description	Time (s)	Description	Time (sec)	Total Time (sec)	Opportunity to Combine or Eliminate?
1	1	Back Cover	360	360	71	7	No extra time	2.5	General Placement (GP)	0.5	3	1
2	1	Front Frame	360	360	71	3	Aspect ratio > 20	2.6	GP; Snap; Tight tolerance	1.2	3.8	1
3	1	Phone body	360	360	71	5	No extra time	2.5	GP; insertion difficulty (force); tight tolerance	1.3	3.8	1
4	12	PN screw (3 mm)	360	0	3	0.5	Part size: small	2	GP; align to small hole; turning insertion; final screw tightening; insertion difficulty (hold)	4.6	79.2	0
5	2	PN screw (4 mm)	360	0	4	0.5	Part size: small	2	GP; align to small hole; turning insertion; final screw tightening; insertion difficulty (hold)	4.6	13.2	0
6	1	Circuit Board & Circuitry	360	360	45	4	No extra time	2.5	GP; Align to small pin	0.9	3.4	1
7	1	Circuit Board Cover	360	360	47	3	No extra time	2.5	GP; Snap	0.8	3.3	0
8	1	SD Card Holder	360	360	12	1	No extra time	2.5	GP; Align to hole	0.6	3.1	1
9	2	SIM Card Holder	360	360	13	1	No extra time	2.5	GP; Align to hole	0.6	6.2	1
10	1	Battery	360	360	63	4	No extra time	2.5	GP	0.5	3	1
11	2	Metal Circuit Cover	360	360	33	1.6	Handling difficulty: sharp Aspect ratio > 20	3	GP; Snap	0.8	7.6	1
12	2	Camera	360	360	9	6	Part size: small	3	GP; Align to medium hole; Snap	1.1	8.2	1
13	1	Microphone	360	360	3	1	Part size: small	3	GP; Align to medium hole; Snap	1.1	4.1	1
14	1	Speaker	360	360	5	3	No extra time	2.5	GP; Align to medium hole; Snap	1.1	3.6	1
15	1	Receiver	360	360	6	3	Part size: small	3	GP; Align to medium hole; Snap	1.1	4.1	1
16	1	Screen	360	360	68	0.8	Handling difficulty: sharp Aspect ratio > 40	3.2	GP; Use of gloves; Tight tolerance	2.3	5.5	1
17	1	Wiring	0	180	3	0.5	Flexible	1.4	GP; Insertion difficulty (hold)	0.9	2.3	1
18	1	Insulating tape	360	180	8	0.1	Flexible	2.4	GP; Insertion difficulty (hold)	0.9	3.3	1
											160.7	15
							DFA Index =	0.28002			Total Time	Minimum number of parts
							N_m*t_m/t_a					
					N_m = Theoretical minimum number of parts			15				
					t_m = Minimum assembly time per part			3				
					t_a = Estimated total assembly time			160.7				

Image 4.7.12. Assembly Time

Image 4.7.12 shows the Assembly Time calculation using the tabulation approximations. The Total estimated assembly time is of **160.7 seconds**, that is, 3 minutes approximately.

The DFA Efficiency can be computed suing the following equation:

$$DFA\ Efficiency = \frac{3 \cdot NM}{TM}$$

Where NM is the theoretical minimum number of parts, TM is the calculated assembly time, and 3 is the minimum assembly time per part.

$$DFA\ Efficiency = \frac{3 \cdot 15}{160.7} = 0.28$$

Using the obtained assembly time, 160.7 seconds, the DFA Efficiency is found out to be 0.28.

In the assembly time calculations, it can be seen that the parts that need more time to be assembled are the screws, with a total time of 92.4 seconds (more than half the time). In the previous section, the theoretical minimum number of parts is 15, as opposed to 33 initial parts. The theoretical minimum of parts is obtained by substituting the screws with snap fits or adhesives, so it is only reasonable that the DFA Efficiency is as low as 28%.

If snap fits were to be used instead, the assembly process would no longer include the 92.4 seconds. The Snap fits would be used in the three different parts were the screws were placed in the original design, adding three times 0.3 second to the total time.

$$New\ Total\ Time = 160.7 - 92.4 + 3 * 0.3 = 69.2\ seconds$$

$$New\ DFA\ Efficiency = \frac{3 \cdot 15}{69.2} = 0.65$$

The new efficiency, 65%, is higher than the original efficiency, as expected. If the DFA Efficiency is higher than 90%, this means all the components are essential. So, it can be concluded that there is still room for improvement and that not all the parts are essential.

4.8. Generation and Evaluation of New Concepts

In the previous sections we have stressed the importance of considering ease of disassembly in electronic devices. QFD has shown that the best way to fulfill the customer's requirements is by increasing the product's life span. One way of doing this is by increasing the battery life. DFMA showed that the number of original parts can be decreased by pursuing other joining mechanisms. With all this in mind, and focusing on Design for Recyclability, three different concepts are developed: redesign of the chassis assembly, redesign of the battery, and redesign of the chassis material.

a. New Concepts

- **Concept 1: redesign of chassis assembly**

As it has been discussed in previous chapters, one of the most important problems with electronic devices is the difficulty to recycle them. It was explained that facilitating the disassembly would make it easier to reach the inside of the product for inspection and repair, and reuse and recycling. This is achieved by **redesigning the way the two parts of the chassis** (the back-cover and the phone body) **are assembled**.

This concept focuses on Design for Disassembly as means for increasing the recyclability of the phone.

During the disassembly of the phone it was observed that it was very difficult to separate these two parts. There are several reasons for this. The first one is that the components inside the phone must be protected from the outside. The second reason is that the manufacturer does not want the user to take the battery out, since it is not considered to be safe. Finally, it is not convenient for dust and dirt to get inside the phone so, ensuring the back-cover does not come off will prevent this from happening.

So, it is important that the new design considers this and focuses on the back-cover not opening spontaneously. Image 4.8.1 shows a sketch of the new design.

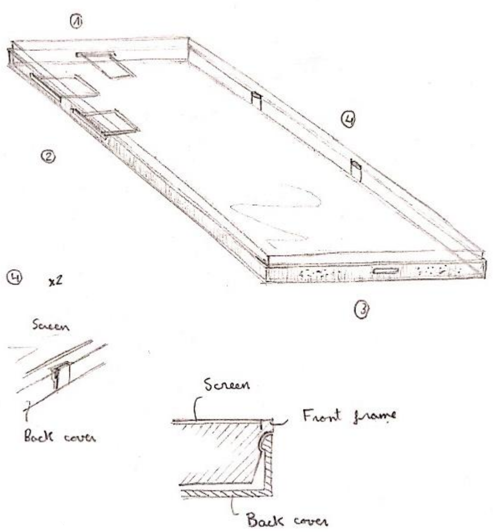


Image 4.8.1. Sketch

- **Concept 2: redesign of battery**

Another issue with electronic device disposal is that many times, they end up in the same waste stream as domestic waste. This should be avoided because electronic devices contain hazardous components that are bad for the environment and for human health, such as the Lithium Polymer Battery of the phone studied in this project.

Image 4.8.2. Battery

The Lithium Polymer Battery is a rechargeable battery of lithium-ion technology that uses a polymer electrolyte. LiPo batteries are widely used in portable electronics because of their light weight, their ability to take any desired shape, the small space requirement, and the low self-discharge rate. The estimated life of a LiPo battery is about two to three years or 300 to 500 charge cycles.

There exist some issues regarding the environmental impact of LiPo batteries (MURR19). River pollution has led to the death of fish and livestock near the Ganzizhou Rongda lithium mine in Tibet. There are environmental problems in South America as well. Chile is the second largest lithium mine in the world. The way the lithium is obtained is that holes are drilled in salt flats to pump salty, mineral-rich brine to the surface and they are left there for over 18 months so the liquid can evaporate. After that, the lithium carbonate is left, and it is turned into metallic lithium. But, similarly to what happens in Tibet, local habitats are destroyed, and nearby grasslands and rivers are polluted with the hydrochloric acid used in the lithium process. Another issue is that the process requires 500,000 gallons of water for every ton of lithium. For example, in Salar de Atacama, mining activities consumed up to 65% of the region's water, causing havoc for local farmers (MURR19). Lithium operations have also been damaging soil which farmers use to herd livestock.

The Friends of the Earth Europe charity reported the following on lithium (MURR19): "The extraction of lithium has significant environmental and social impacts, especially due to water pollution and depletion. In addition, toxic chemicals are needed to process lithium. The release of such chemicals through leaching, spills or air emissions can harm communities, ecosystems, and food production. Moreover, lithium extraction inevitably harms the soil and also causes air contamination."

When it comes to recycling these batteries, there is still a long way to go. Researchers are still working on this. In Australia, a study showed that only 2% of the 3,300 tons of lithium waste is recycled (MURR19). This increases the probability of leakage of the liquid from the batteries into landfills, and their release into the environment. On top of that, it is difficult to recycle these batteries because manufacturers are secretive about what goes into the batteries. The batteries are recycled by shredding the lithium cells, creating a mixture of metals that can be separated using burning techniques (MURR19). However, a lot of the lithium is not recovered.

Research is going into using an aluminum battery instead of a LiPo battery, as a greener alternative. Researchers in Sweden and Slovenia say it has twice the energy density of the older aluminum batteries, and that it could reduce the production cost and the environmental impact, compared to lithium-ion rechargeable batteries (MURR19).

- **Concept 3: redesign of chassis material**

Lastly, the phone chassis is made of polycarbonate (PC) and 10% glass fiber. This plastic has high impact resistance, good temperature resistance and high flexibility. PC is 100% recyclable, with high demands in China. However, an option would be to investigate the use of bioplastics. Sometimes, these plastics do not meet the physical or mechanical requirements, but they can be reinforced with fiber, as it was done with PLA bioplastic reinforced with kenaf.

The use of bioplastics significantly reduces the CO_2 emissions. In particular, a ton of bioplastics generates 0.8 to 3.2 less tons of carbon dioxide than a ton of petroleum-based plastics (PRAM15). Additionally, the instability in oil prices has urged the designers to think of new sustainable ways of getting plastics. A benefit of using bioplastics is that they reduce the toxic excess generated by petroleum-based plastics and they are often biodegradable. Its biodegradability has a drawback and it is that when they decompose, they release methane, which is a powerful greenhouse effect gas. Enhanced properties can be obtained from the bioplastics if they are reinforced with other materials such as kenaf. In electronic devices, a kenaf-reinforced casing has been used, made with 90% PLA, which helps reduce overheating by conducting the heat, and yields high temperature resistance and increased strength.

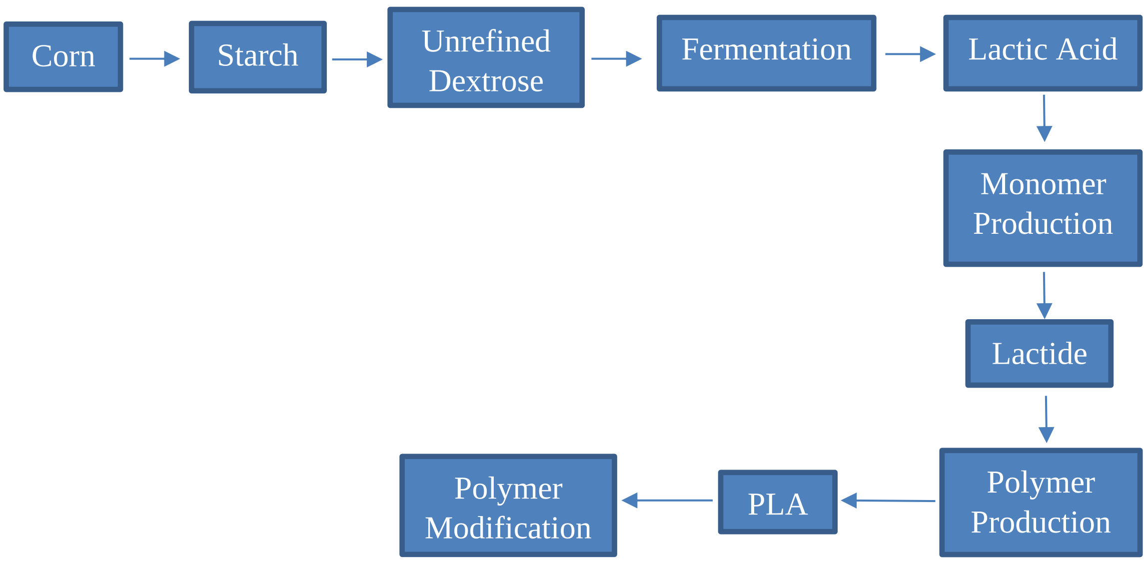


Figure 4.8.1. Polylactic acid (PLA) for plastics production

b. Pugh Matrix

A Pugh Matrix can be created to select one of the concepts. The Pugh Matrix is a Controlled Convergence method that uses a matrix to compare and evaluate different concepts, converging onto the best concept.

First, a set of criteria is considered, such as Impact on recycling, Manufacturing cost, Mechanical durability, etc., to compare and evaluate the different concepts.

Second, a weight value from 1 to 5 is assigned to each criterion, depending on its importance, being 5 the most important criterion and 1 the least important.

Third, the criteria are evaluated for each of the concepts and the following signs are assigned:

(+) if the criterion for that concept is met

(-) if the criterion for that concept is not met

(S) if the criterion does not change for that concept

Finally, the total number is computed for the three different concepts using the weight and the assigned sign, as can be seen in the following table. Obviously, the concept with a higher value is chosen.

Table 4.8.1. Pugh Matrix

Criteria	Weight	Concept 1	Concept 2	Concept 3
Impact on Recycling	5	+	+	+
Manufacturing Cost	4	S	-	-
Ease of Assembly	4	S	S	S
Safety and reliability	3	-	S	S
Structural integrity	3	-	S	-
Heat resistance	2	S	S	-
Mechanical Durability	1	S	S	-
Design Complexity	3	+	-	S
Aesthetics	3	S	S	+
Total		**+2**	**-2**	**-2**

As it can be seen in Table 4.8.1, Concept 1, redesigning the chassis assembly, has a positive impact on recycling since the phone is easier to disassemble. From the sketch it can be seen that there are no major changes on the amount of material used nor the general design, so the manufacturing cost stays the same. The ease of assembly stays the same as well. In terms of safety and reliability, this concept has a negative impact. If disassembly is made easier, there exists a higher probability of the back-cover separating from the phone body, compromising the structural integrity at the same time. Heat resistance and mechanical durability stay the same. The design complexity is reduced, which is good, and the aesthetic stays the same.

Concept 2, redesign of battery, also has a positive impact on recycling. However, the manufacturing cost increases because new requirements need to be met with the use of aluminum batteries (e.g. weight, size…). Ease of assembly, safety and reliability, structural integrity, heat resistance, mechanical durability and aesthetics stay the same. Design complexity increases since more time is needed to investigate new battery alternatives, and the design needs to be changed to integrate the new battery requirements.

Concept 3, redesign of chassis material, has a positive impact on recycling, whether it is using a more expensive material that has a smaller impact on the environment, or the use of recycled materials. The manufacturing cost can increase, depending on how easy to handle the new material is, but the ease of assembly and the safety and reliability stay the same. Using recycled materials can have a negative effect on structural integrity. They may present issues with heat resistance or mechanical durability. The design complexity stays the same, but the aesthetic can be improved with different textures, colors, surface finish, etc.

Based on the Pugh Matrix, **Concept 1** was chosen as it provides the largest advantage (+2) compared to the original product, and to the other concepts.

4.9. Redesign of the Chassis Assembly

Using the Pugh Matrix, Concept 1 was chosen. In this section, the redesign of the chassis assembly is studied in depth. First, the new idea is explained, using the sketch, and then, the CAD models are shown.

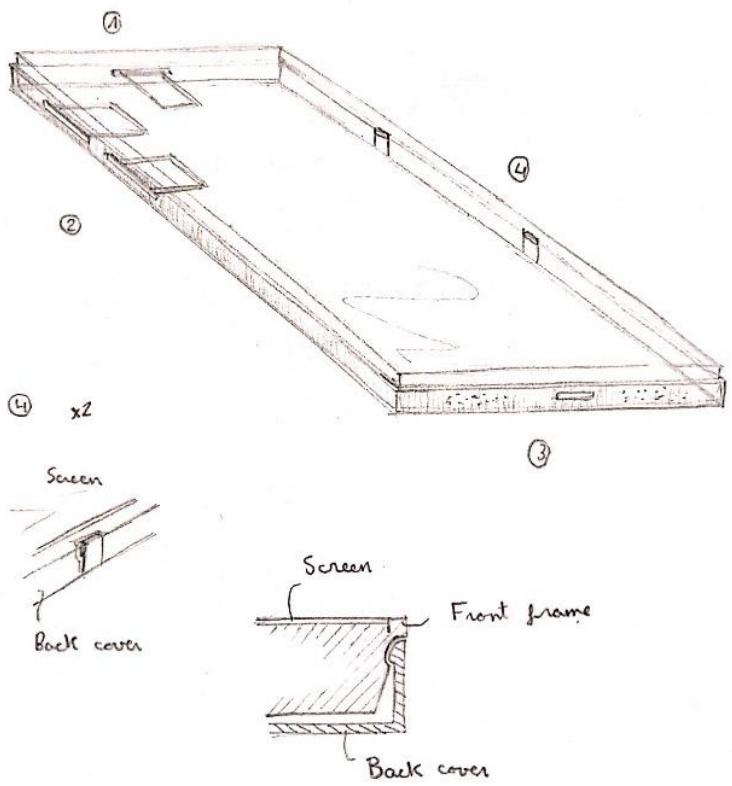


Image 4.9.1. Sketch

The idea of this design is to ease the disassembly of the phone, so as to make it more recyclable and to facilitate the inspection and repair of the components. In the original design, the four sides of the phone have snap fits that make it really hard to separate the back-cover from the phone body. The proposed design will decrease the difficulty of disassembly as well as the design complexity.

One of the biggest concerns is that the back-cover and the phone body must stay together. This can be achieved by making sure the new design meets this condition. Therefore, the new design focuses on how the phone back-cover and body stay together, while using the minimum amount of fastening methods on each side.

As it can be seen on the sketch, the back-cover is bigger than the phone body, and the phone body is fitted into the back-cover.

Side 1 of the phone has a slot to fit the SD card holder tray. This tray goes into the phone body, but it first goes through the slot on the back-cover, "locking" the back-cover in place with the phone body.

Side 2 has two slots to fit the two SIM card trays and follows the same principle as side 1. Once the phone body is fitted into the back-cover, the SIM car holders go through the back-cover and into the phone body.

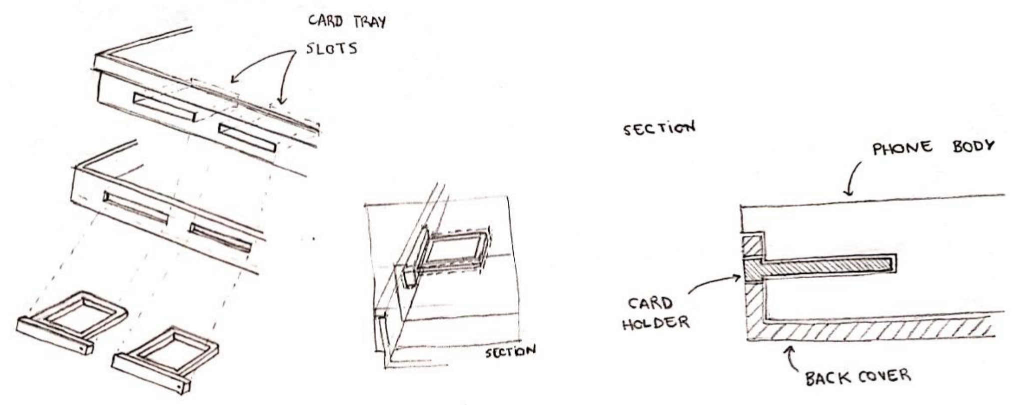


Image 4.9.2. Sketch

The argument of this design is that the card holder trays provide enough resistance to make the back-cover stay in place, on sides 1 and 2.

On **side 4**, there are two snap fits, following the design from the sketch. The back-cover has an extrusion towards the inside, at its edge. The phone body has an extrusion towards the inside, in the same place where the back-cover extrusion is. Additionally, the phone body side has an angle, where the slips are, that creates a slope on which the back-cover extrusion can slide. That is, if the card holders are removed, when the two snaps are put out of place using a slot on side 4, the back-cover extrusion will allow no other option than to slide downwards, helping with the disassembly of the phone.

Side 3 is left without any locking mechanisms, for the following two reasons. First, there is not enough space for adding the snap fits; the charging inlet, the microphone and the speaker are already there. Second, it is not necessary since the other locking mechanisms are believed to be sufficient to hold the back-cover in place.

So, the new disassembly process would be as follows:

1. Using the ejection tool, the SIM card trays, and the SD card tray are taken out.
2. The extrusions on the back-cover from the snap fits are pushed outwards and downwards, and the back-cover slides out thanks to the inclination of the fit on the phone body.

a. CAD Models

The following images show the new CAD models. The measurements are in millimeters.

- Back-cover: two extrusions are added on the right side (side 4). The changes are circled in red.

Image 4.9.3. Back-cover re-design

Image 4.9.4 and Image 4.9.5 show the extrusion, in green, and its measurements.

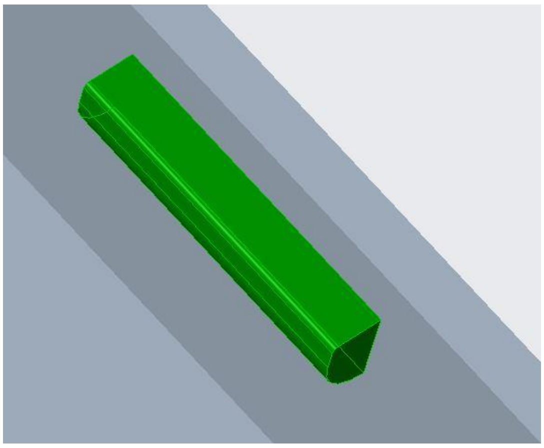


Image 4.9.4. Back-cover re-design detail

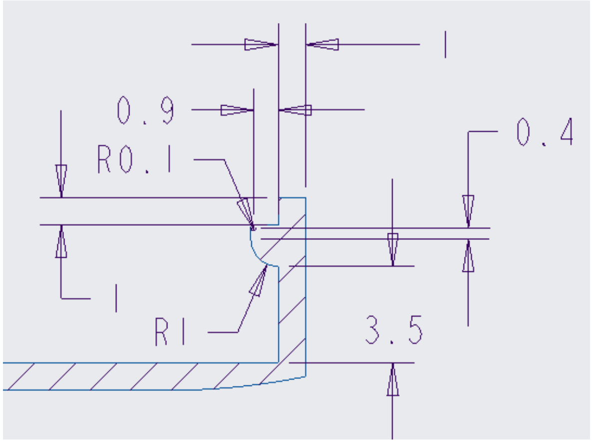


Image 4.9.5. Back-cover re-design Measurements

- <u>Front frame + phone body</u>: there are two changes on these parts. First, an extrusion removing material is done to match where the back-cover extrusions are. Second, a slope is added to the phone body. The changes are circled in red.

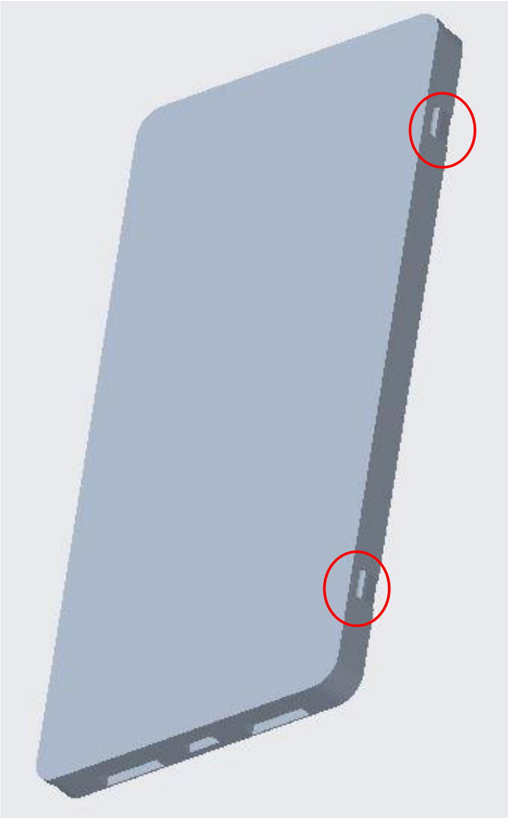


Image 4.9.6. Phone Body re-design

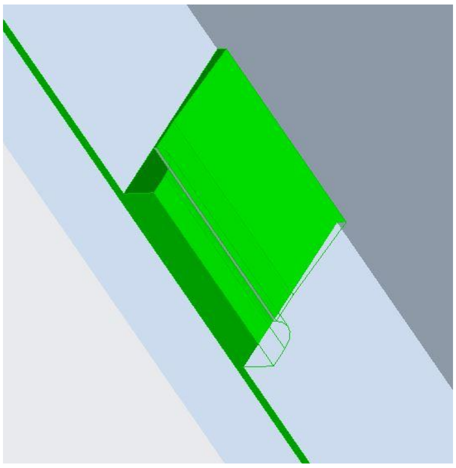


Image 4.9.7. Phone Body re-design detail

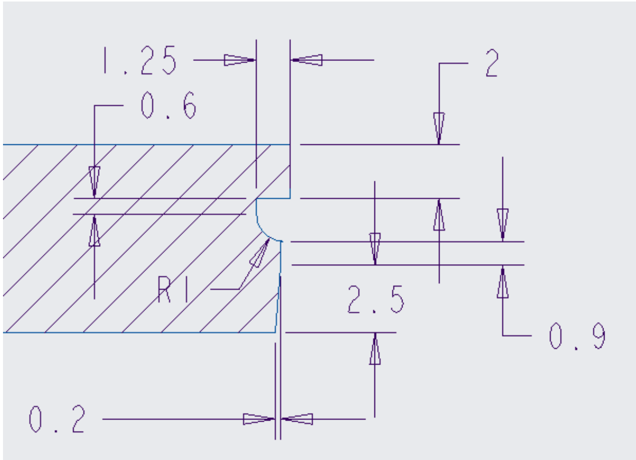
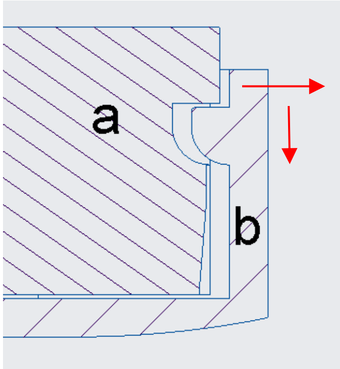


Image 4.9.8. Phone Body re-design Measurements

Image 4.9.7 shows, in green, the shape of the new snap fit. The measurements are included in Image 4.9.8. The angle of the slope can be computed:

$$\alpha = \operatorname{atan}\left(\frac{0.2}{2.5}\right) = 4.57°$$

- Section: the section of the assembly shows the snap fit. Part **a** represents the phone body and part **b** is the back-cover.



It can be seen that, in order to disassemble the chassis, part **b** is pushed outwards and downwards, as the arrows show, taking advantage of the flexibility of polycarbonate. The slope in the phone body will help the back-cover slide down. The extrusion on **b** has a flat surface to limit how far the phone cover goes.

Image 4.9.9. Section

- Assembly: the next images show the assembly of the phone body, the back-cover, and the card holders.

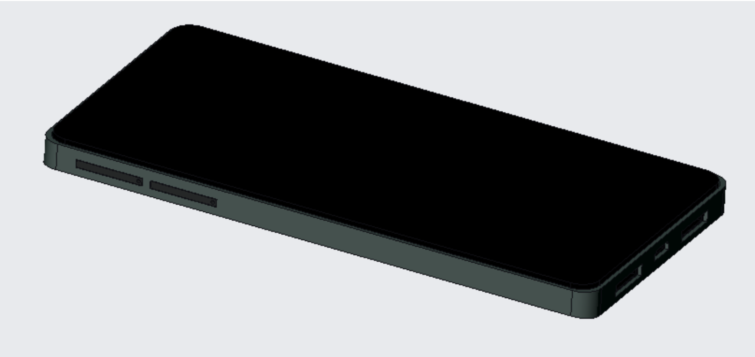


Image 4.9.10. Assembly

In Image 4.9.11, the shape of the card trays can be seen in green. As it was explained, these trays first go through the back-cover, and then they go into the corresponding slots in the phone body.

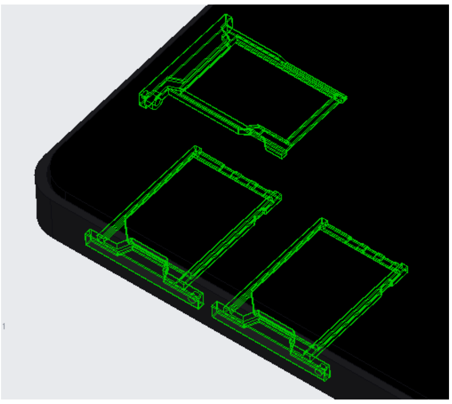


Image 4.9.11. Assembly of the card holders

The new disassembly process is as follows:

1. The card holders are removed.

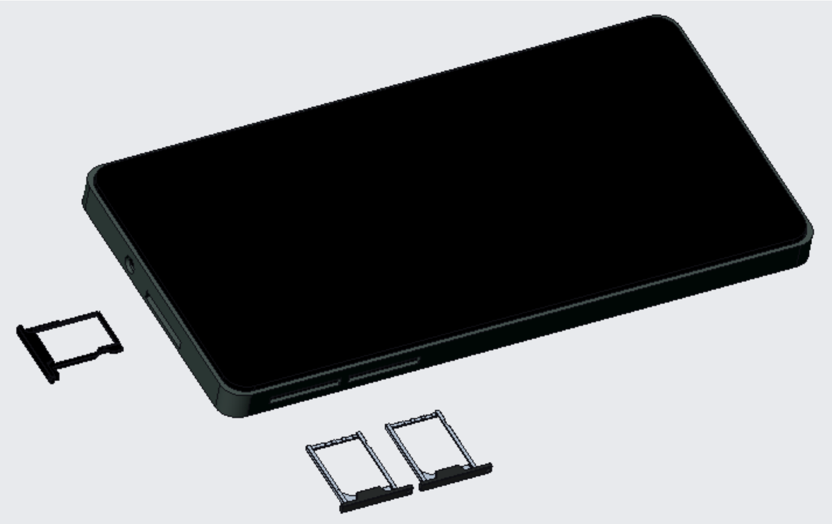


Image 4.9.12. The card trays are removed

2. The snap fit is taken out of place and the back-cover slides downwards.

Image 4.9.13. The back-cover slides downwards

b. Manufacturing Cost Analysis of Redesigned Product

The redesign only entails the change of the housing design to make it easier to disassemble. Therefore, there is no significant change in the manufacturing cost. The volume of the parts is practically the same and so is the material. The direct overhead, the labor cost, and the amortized investment stay the same.

Table 4.9.1. Estimated Costs

Part	Estimated Cost ($)
Back-cover	1.385
Front Frame	0.035

In any case, the cost would increase in the first stages of the Design Process. Changing the design implies that there is background research that justifies this change. Following that, the product design specifications are developed, after which the prototype is built and tested.

Image 4.9.14. Redesigned Back-cover

This new design reduces the time needed to disassemble the phone. Less time means less money, so recycling will be easier and cheaper than with the previous design. Another positive aspect is that if the phone breaks, it can be easily opened for inspection and repair, which is good for the environment, since less phones would be discarded as useless before their end of life.

4.10. Injection Molding of the Redesigned Back-cover

Using Autodesk MoldFlow Adviser, the injection molding of the back-cover can be simulated.

The first step is the selection of material injection. The back-cover is made of PC and 10% Glass Fiber. The material used in the simulation is Makrolon 9415: Covestro. Its properties are included in the annex Injection Molding Material Properties.

After that, the process settings are set to the recommended values, given the material. The mold temperature is set to 100ºC, the melt temperature to 310ºC, and the maximum machine injection pressure to 180 MPa.

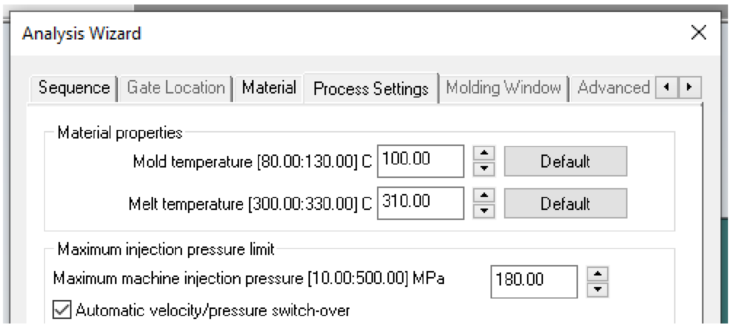


Image 4.10.1. Process Settings

The next step is to select the injection location, which can be done with the help of the Gate Locator Analysis Wizard. This tool helps find the region that will yield the best fill. As it can be seen in Image 4.10.2, the best gate location is in the middle of the back-cover, and the worst locations are the corners.

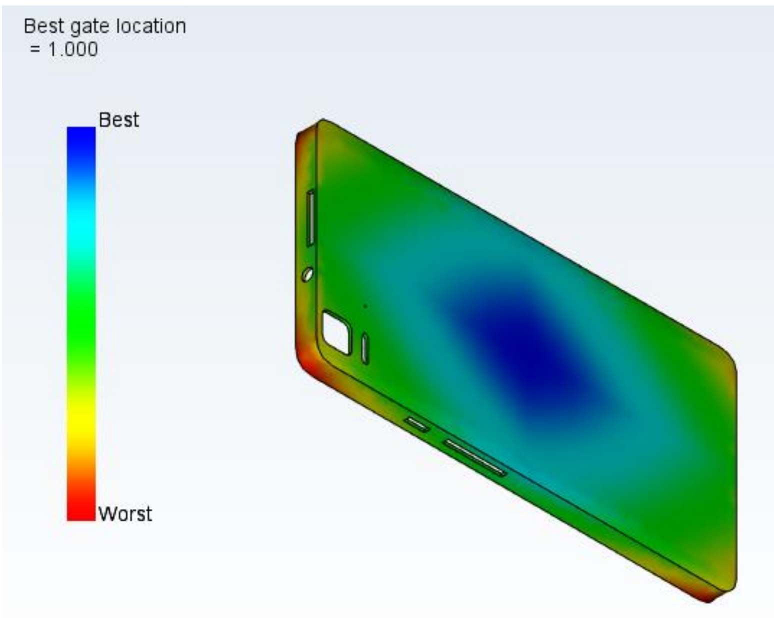


Image 4.10.2. Gate Locator Analysis

Using one injection location placed in the middle of the back-cover, as it can be seen in the images as a yellow cone, the Fill analysis is run. Several interesting results are obtained.

The Fill time shows how much time was needed in the injection process. The total fill time is 0.8155 seconds. From Image 4.10.3 it can be seen that most of the part was filled within the first 0.6 seconds, which makes sense since the part is very thin. Additionally, the flow path of the plastic through the mold can be seen.

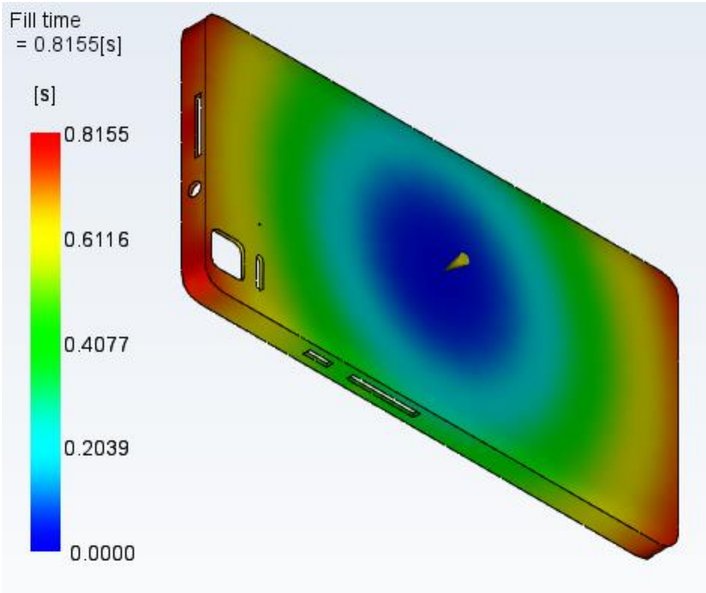


Image 4.10.3. Fill Time

The Plastic Flow shows how much of the part is filled at the end of the simulation. In this case, the plastic flows to every part of the back-cover.

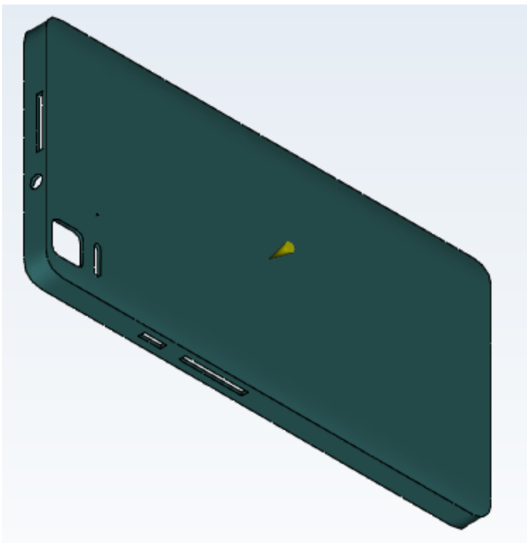


Image 4.10.4. Plastic Flow

The Confidence of Fill shows what percentage of the part is filled with different levels of confidence. The analysis shows that the whole part has 100% confidence of fill, indicating that the process settings were well chosen.

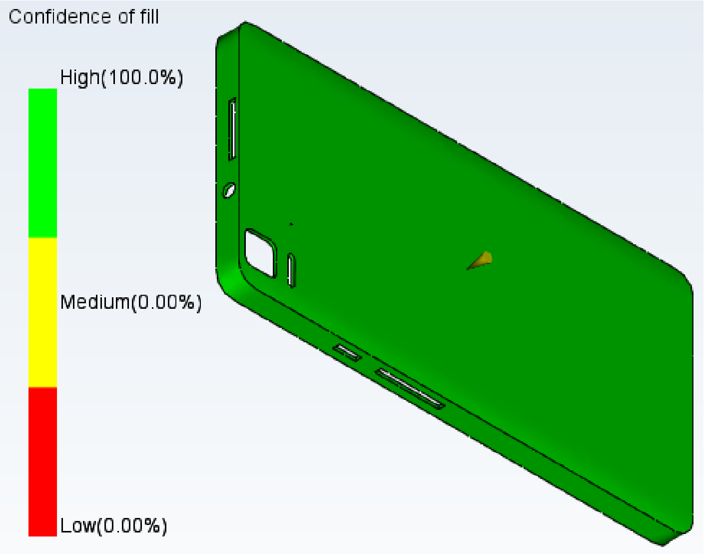


Image 4.10.5. Confidence of Fill

The Quality Prediction measures the expected quality of the back-cover's appearance and its mechanical properties. Most of the part, 94.7%, has medium quality prediction. One reason for these might be that the part is very thin, consequentially not having the best mechanical properties. For the sake of the phone's integrity it would be better to have a high-quality prediction in order to make sure the part does not break when it falls. However, this result might be referring to the appearance, in which case it is not a big issue since it can go through an additional coating process that will solve it.

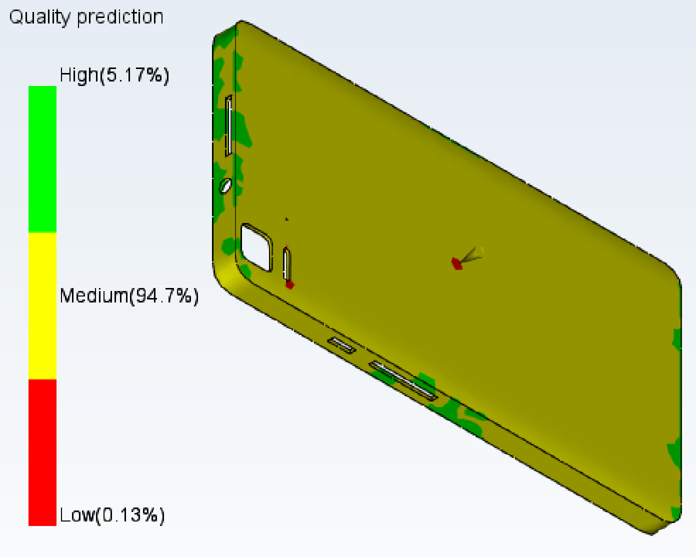


Image 4.10.6. Quality Prediction

The Injection Pressure shows the pressure of the plastic as it flows through the mold. When the plastic flow reaches the edges of the back-cover, the pressure drops to zero. Initially, the maximum injection pressure is set to 180 MPa, and the highest pressure is reached at the gate location, at 122.9 MPa.

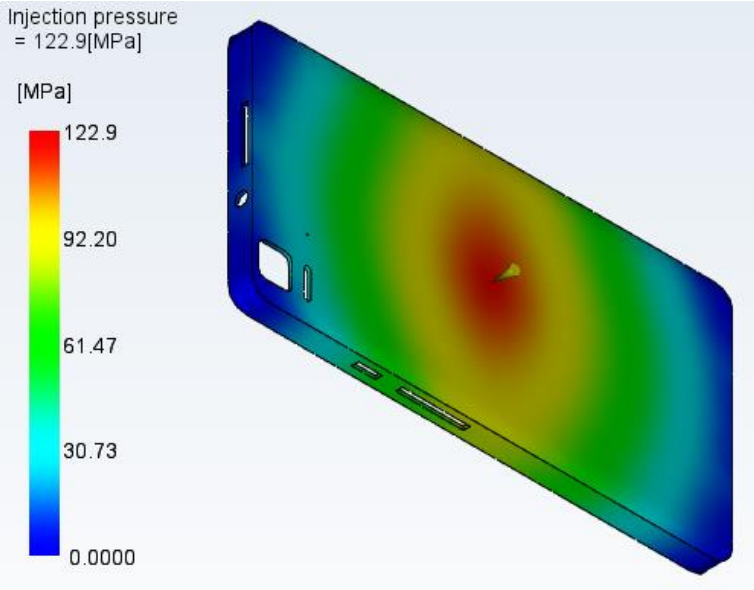


Image 4.10.7. Injection Pressure

The Pressure Drop displays the drop in pressure from the injection point to the selected point, at the moment that point is filled.

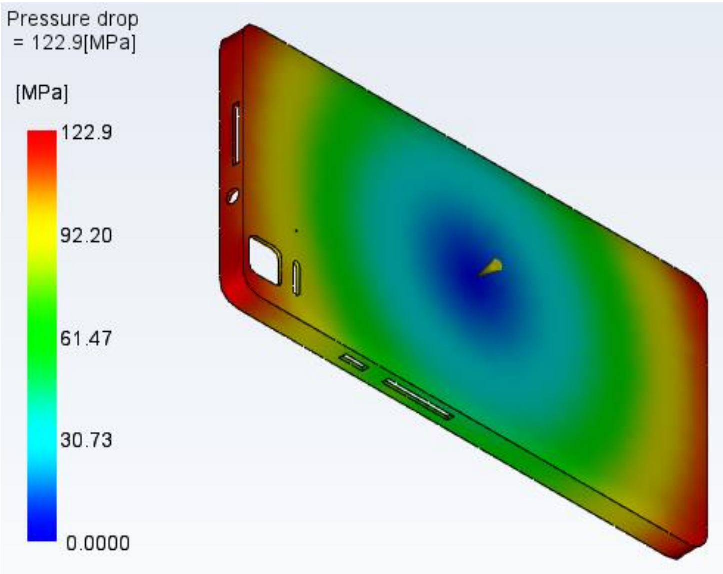


Image 4.10.8. Pressure Drop

The Temperature at Flow Front shows the material melt temperature at each point, the moment it is filled. The first points that are filled will be closer to the established melt temperature, around 310 ºC. However, as the plastic flows through the mold, its temperature decreases, as it is in contact with the mold which initially is at 100 ºC. Due to heat transfer, the melted plastic cools down whilst the mold temperature rises. At the end of the process, the plastic's temperature is 293.4ºC. The temperature does not change drastically because the injection time is very small (0.8 seconds). If the process took longer, the temperature would drop more.

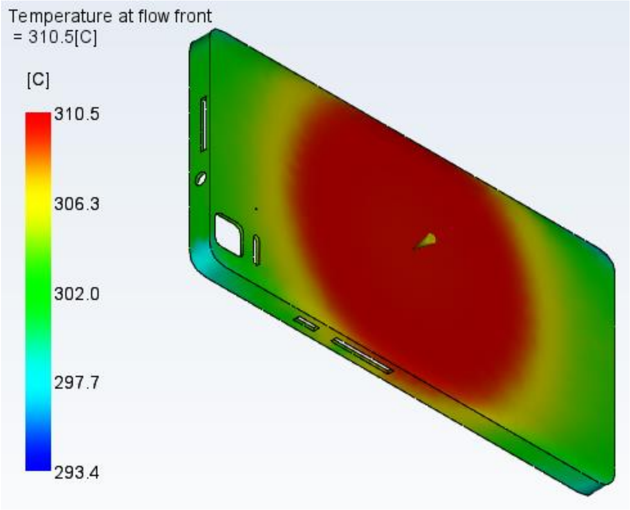


Image 4.10.9. Temperature at Flow Front

The Air Traps are shown in pink and show potential places where the melt stops because of two or more flow fronts of the plastic converging. Image 4.10.10 shows that this happens especially on the top and the bottom of the back-cover. A solution to avoid this is to include two air gates in these two places, so that the air can exit the mold.

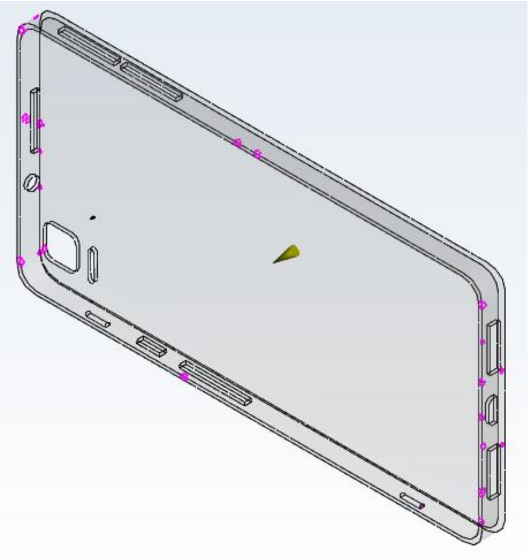


Image 4.10.10. Air Traps

The cycle time is estimated to be 9.09 seconds. Image 4.10.11 shows the cycle breakdown. As it can be seen, the injection of plastic takes the least amount of time in the whole process, the cooling time is 3.31 second, and the handling of the part, that is, opening the mold and getting the part, takes 5 seconds.

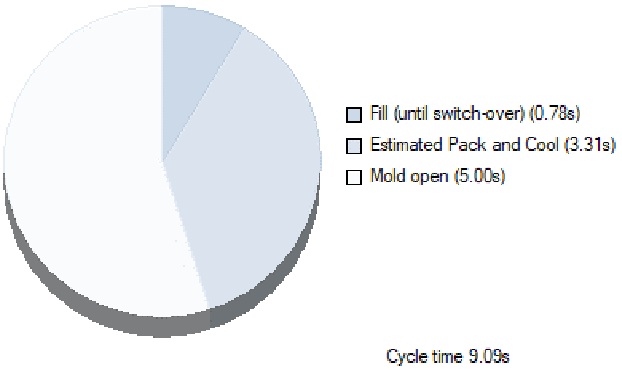


Image 4.10.11. Cycle Time

Further investigation can be done regarding the Quality Prediction. The quality prediction is high, medium, or low. If three points in different quality areas are compared, it can be concluded that as the quality increases, both the shear stress and the shear rate decrease. In fact, the issue with the back-cover is that the shear stress exceeds the recommended limit of 0.5 MPa.

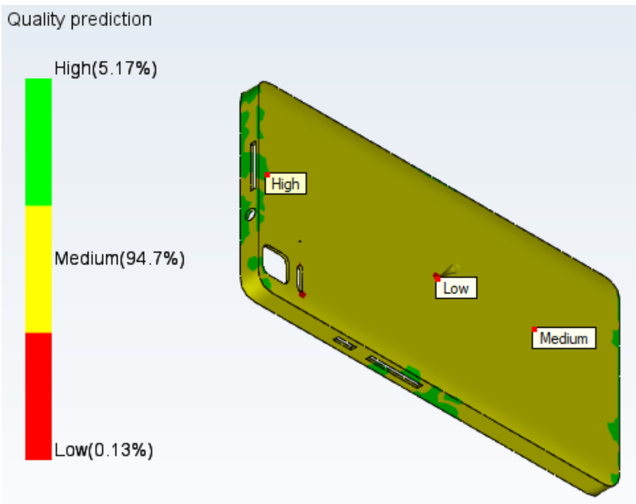


Image 4.10.12. Quality prediction in three different points

Table 4.10.1. Quality Prediction

	Low quality	**Medium quality**	**High quality**
Shear stress	1.185 MPa	0.8816 MPa	0.3490 MPa
Shear rate	15921 1/s	1204.9 1/s	454.6 1/s
	Shear stress greatly exceeds the recommended limit	Shear stress exceeds the recommended limit	Quality is high

The recommended shear stress limit for this material is 0.5 MPa, and the maximum shear stress is 40,000 1/s.

A study of how the process settings affect the final result yielded the following insights.

- Maximum machine injection pressure: increasing the maximum pressure does not have an effect on the process. However, if the maximum pressure is lowered, the plastic does not fill the whole part.
- Melt temperature: the maximum melt temperature is 330ºC. Above this temperature, the quality prediction decreases significantly throughout the whole part. The same thing happens if the temperature is lowered.
- Mold temperature: the ideal limit is 130ºC. If the mold temperature is lowered, the quality of the part decreases. If the mold temperature is set to a higher value, the predicted quality rises in all the structure.

After several simulations, the following conclusion is obtained. Setting the Mold temperature to 290ºC and the Melt temperature to 330ºC, yields a high-quality prediction of 98.8% of the part and 1.24% of medium quality. This result is very favorable since the integrity of the back-cover is crucial. However, the increase of the mold temperature leads to a longer fill time of 3.184 seconds, and a longer cooling time of 603.18 seconds. So, there is a trade-off between time and quality. Also, the actual injection pressure is 20.56 MPa, which is a lower pressure than the first simulation. This happens because the flow front's cooling rate as the plastic travels through the mold is lower, because the mold temperature is higher.

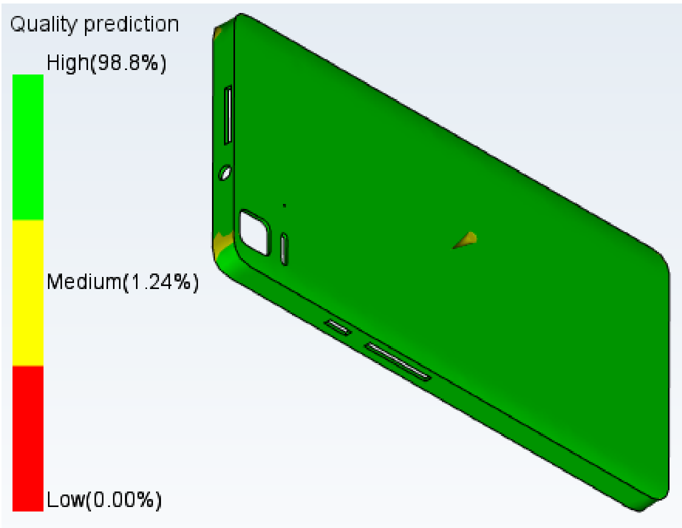


Image 4.10.13. New Quality Prediction

Although the time increase is quite significant (66 times higher), it can be concluded that it is better to have a longer cycle with higher quality.

4.11. Design of Experiment

Design of Experiments is the design of any information-gathering exercise where variation is present, and the subsequent use of factorial design statistical techniques is used to help identify the source(s) of variation (PHIL19).

The objectives of an experiment are the following:

- Determine which input variables (x_i) are the most influential on the output (y).
- Determine where to set the influential x-values so that the y-value is near the nominal requirement.
- Determine where to set the influential x-values so that variability of y is small.
- Determine where to set the influential x-values so that the effects of uncontrollable variables z are minimized.

So, an experiment studies the effects of input variables, called factors, on a response. The factors can have different levels. The design of the experiment involves choosing the factors, selecting the levels, and determining the combinations. The design regulates the number of times each combination is done. The 2^k Factorial Design only considers two levels for the k factors.

a. Problem statement

A Design of Experiment can be performed to test the redesigned product. Two measured inputs are chosen as factors. First, the **angle of the slope on a**. Second, the **length of the extrusion on b**. Each of these variables has two levels, high (+1) and low (-1).

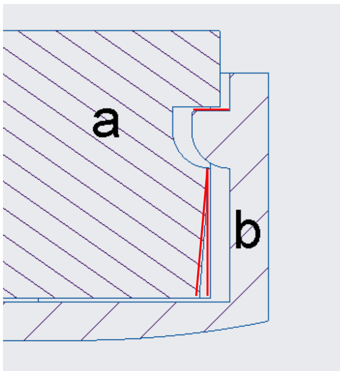


Image 4.11.1. New Design Section

Table 4.11.1. Variable Levels

Variable	**Variable description**	**Low (-1)**	**High (+1)**
x1	Angle (º)	4.57	6.84
x2	Extrusion (mm)	0.9	1.1

Having 2 factors with 2 levels each yields 2^2 combinations, i.e. 4 combinations.

With this Design of Experiment, the **number of times the phone case opens when it is subjected to a test of ten 4-meter falls** is measured.

Table 4.11.2 shows the four possible combinations and the resulting number of times the phone case opens in three tests. These data have been estimated in order to perform a statistical analysis on the redesigned component.

Table 4.11.2. Design Matrix

Treatment combination	**Angle (º) x1**	**Extrusion (mm) x2**	**Number of times the back-cover opens**			
			Test 1	**Test 2**	**Test 3**	**Average**
1	-	-	2	3	2	2.33
2	+	-	4	4	6	4.67
3	-	+	0	3	1	1.33
4	+	+	1	3	2	2.00

b. Contrast and Effect computation

Table 4.11.2 can be used to compute the effect of the individual factors and interactions among the factors. The results are included in Table 4.11.3, as "Contrast" and "Effect", where row (1) indicates both factors are at low level, 'a' indicates that the angle is high and the extrusion is low, 'b' indicates the angle is low and the extrusion high, and 'ab' indicates both factors are at high level.

Table 4.11.3. Contrast and Effect

	Design Columns		**Calculation column**				
Treatment combination	**Angle (º) x1**	**Extrusion (mm) x2**	**Interaction**	**Number of times the back-cover opens**			
				Test 1	**Test 2**	**Test 3**	**Average**
(1)	-	-	+	2	3	2	2.33
a	+	-	-	4	4	6	4.67
b	-	+	-	0	3	1	1.33
ab	+	+	+	1	3	2	2.00
Contrast	3	-3.667	-1.667				
Effect	1.5	-1.833	-0.833				

The contrast of a factor is calculated using the following equation:

$$Contrast = \sum column\ of treatment\ combination\ codes \times column\ of\ signs\ under\ any\ factor$$

$$Contrast\ of\ angle = -(1) + a - b + ab = -2.33 + 4.67 - 1.33 + 2.00 = 3$$

$$Contrast\ of\ extrusion = -(1) - a + b + ab = -2.33 - 4.67 + 1.33 + 2.00$$
$$= -3.667$$

$$Contrast\ of\ interaction = (1) - a - b + ab = 2.33 - 4.67 - 1.33 + 2.00$$
$$= -1.667$$

The contrast of the factors and interactions is included in Table 4.11.3.

The effect of the factors can then be computed as follows:

$$Effect = \frac{Contrast}{2^{k-1}}$$

Where k is 2 because there are two factors.

$$Effect\ of\ angle = \frac{Contrast\ of\ angle}{2^{2-1}} = \frac{3}{2} = 1.5$$

$$Effect\ of\ extrusion = \frac{Contrast\ of\ extrusion}{2^{2-1}} = \frac{-3.667}{2} = -1.833$$

$$Effect\ of\ interaction = \frac{Contrast\ of\ interaction}{2^{2-1}} = \frac{-1.667}{2} = -0.833$$

The results in Table 4.11.3 indicate that when the angle goes from low to high, the number of times the phone's back-cover opens increases by 1.5 times. When the extrusion goes from low to high, it decreases 1.833 times. And when both factors change from low to high, the number of times the back-cover opens decreases 0.833 times.

Additionally, since the effect of the interaction is smaller than the sum of the other two factor's effects, it can be concluded that the interaction between the two factors is low.

$$Interaction < Angle + Extrusion \rightarrow -0.833 < -0.333$$

c. Analysis of Variance

The next step is to determine whether the effects are truly significant, and this is done applying the analysis of variance (ANOVA) with confidence intervals (CI). The first step is the computation of the standard deviation and the standard error. Then, 95% CI are established for each effect using the standard error. If any CI includes 0, then the corresponding effect is not significant. If any CI does not include 0, then the corresponding effect is significant.

$$S^2 = \frac{1}{4(n-1)} \sum_{1=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{n} \left(y_{ijk} - \overline{y_{ij}}\right)^2$$

$$S^2 = \frac{1}{4(3-1)} [(2-2.33)^2 + (3-2.33)^2 + (2-2.33)^2 + (4-4.67)^2$$
$$+ (4-4.67)^2 + (6-4.67)^2 + (0-1.33)^2 + (3-1.33)^2$$
$$+ (1-1.33)^2 + (1-2)^2 + (3-2)^2 + (2-2)^2] = 1.25$$

$$s.e. = \sqrt{\frac{S^2}{2^{k-2}n}} = \sqrt{\frac{1.25}{2^{2-2}3}} = 0.645$$

The approximate 95% CI is:

$$CI = Effect \pm 2 \times s.e.$$

Then, the CI for the factors is:

$$CI\ of\ angle = 1.5 \pm 2 \times 0.645 \rightarrow [0.209, 2.791]$$

$$CI\ of\ extrusion = -1.833 \pm 2 \times 0.645 \rightarrow [-3.124, -0.542]$$

$$CI\ of\ interaction = -1.5 \pm 2 \times 0.645 \rightarrow [-2.124, 0.457]$$

The CI of the angle and the extrusion do not include 0. Therefore, they are significant. However, the CI for the interaction does include 0, so it is not significant. This result is in line with the previous discovery where it was stated that the interaction between the two factors is low.

Table 4.11.4. Relationship between factors

		Extrusion	
		-	+
Angle	-	2.33	1.33
	+	4.67	2.00

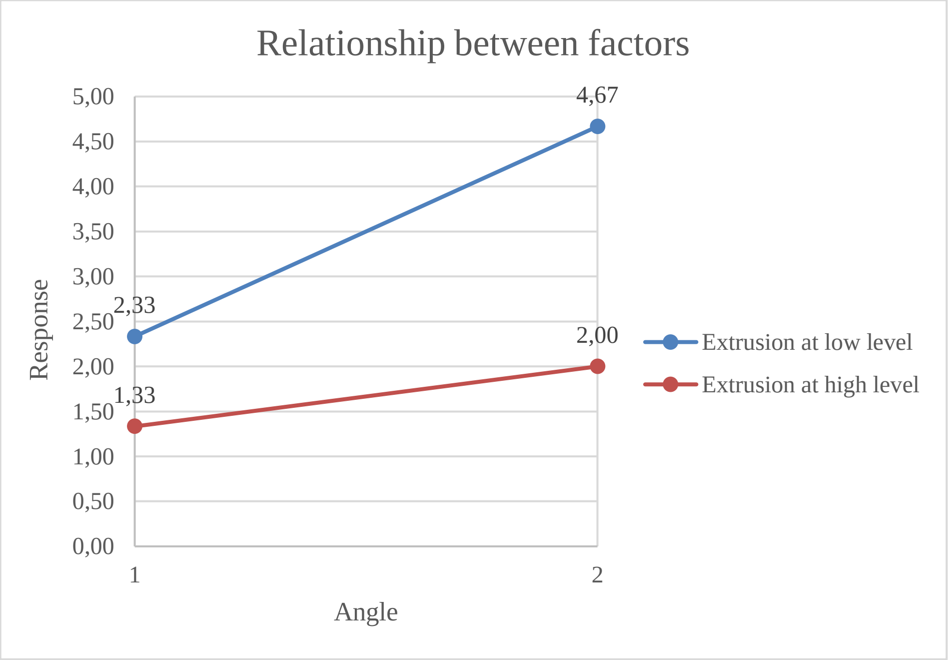


Figure 4.11.1. Relationship between factors

Again, since the two lines do not cross each other, it can be concluded that the interaction is not significant, as it had been obtained with the confidence interval method.

The following insights can be obtained from the previous figure. In both a high and a low level for the extrusion, the response increases when the angle is changed from low to high. That is, increasing the angle is bad for the design and it will yield a higher number of times where the phone's back-cover opens.

Finally, the scenario that yields the least number of times where the back-cover opens is when the angle is set to low and the extrusion is set to high, that is, 4.57º and 1.1 mm respectively.

d. System Characteristic Equation

From the results obtained with the analysis of variance, the system characteristic equation can be obtained. This equation is a mathematical model that summarizes the results obtained in the analysis of variance. It is used to predict the output of an experiment, using the significant factors of the model.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2$$

Where β_0 is the overall mean, that is, the mean of the means of each combination, and β_1, β_2, and β_{12} are half the value of the effects.

$$\beta_0 = \frac{2.33 + 4.67 + 1.33 + 2}{4} = 2.583$$

In the analysis of variance, it was seen that the angle and the extrusion are significant because their confidence interval does not contain 0, while the interaction between the factors is not significant. Setting the insignificant values to zero, the characteristic equation is determined.

$$\hat{Y} = \bar{Y} + \frac{M_1}{2} x_1 + \frac{M_2}{2} x_2 + \frac{M_{12}}{2} x_1 x_2$$

$$\boldsymbol{\hat{Y} = 2.583 + \frac{1.5}{2} x_1 - \frac{0.833}{2} x_2}$$

So, knowing that the redesign used an angle of 4.57º and an extrusion of 0.9 mm, which is low level in both factors, the expected number of times the back-cover will open in a ten 4-meter fall experiment can be obtained.

$$\boldsymbol{\hat{Y}} = 2.583 + \frac{1.5}{2}(-1) - \frac{0.833}{2}(-1) = \mathbf{2.75} \approx \mathbf{3\ times}$$

The least output value is obtained when the angle is low, 4.57º, and the extrusion is high, 1.1 mm. these conditions give the following estimated time:

$$\boldsymbol{\hat{Y}} = 2.583 + \frac{1.5}{2}(-1) - \frac{0.833}{2}(1) = \mathbf{0.92} \approx \mathbf{1\ time}$$

In conclusion, DOE helped with the analysis of the redesigned product, and it was obtained that the best values for the factors are an angle of 4.57º and an extrusion 1.1 mm long, in an experiment where the phone was thrown ten times from a 4-meter fall.

5. CONCLUSION

In every design process there is a trade-off between Function, Quality, and Cost.

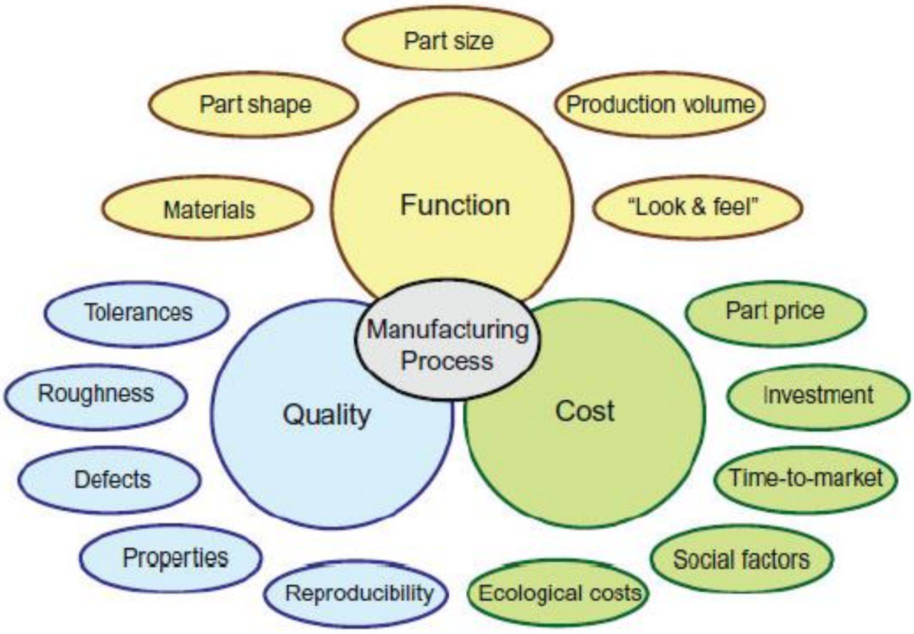


Image 4.11.1. Cost, Function and Quality

In terms of Cost, the part price is the same in both designs, but the ecological costs are lower for the redesigned product since a lot is invested in the Design for End of Life and for Recycling.

In terms of Function, both designs perform similarly. The part sizes are the same, and so are the materials and the "look & feel".

In terms of Quality, the performance is similar too. The main difference is that the back-cover of the phone can be opened more easily. As studied in the Design of Experiment, the possibility of the phone back-cover opening when the phone falls is analyzed. However, this does not mean it will happen, and it can be said with confidence that the quality of both products, the original one and the redesigned one, is comparable.

Introducing Design for Recyclability is often not very complex, and it can have so many benefits. It can be done by being careful in the selection of the materials, or by easing the disassembly of the product so that the interior is more accessible. This project has shown the importance of recycling electronics and how designers and manufacturers can work on the product's disposal since the conception of the product. In fact, it has been shown with an example how design for recyclability can be applied to a cell phone.

The following conclusions can be drawn from the Case Study.

Estimating the material cost, the labor cost, the direct overhead and the amortized investment, the total cost of the different parts that were modeled in CAD is found out to be:

Table 4.11.1. Estimated Cost

Part	**Estimated Cost ($)**
Back-cover	1.385
Front Frame	0.035
Metal Circuit Cover	0.285
SIM Card Holder	0.193
SD Card Holder	0.193

From the Quality Function Deployment matrix, it was found out that the lifespan of the product is the most important design requirement, followed by battery life and a high RAM. It is important to realize that most of the design requirements, if met, will contribute to the increase of the product lifespan.

DFMA analysis showed that the number of parts can go from 33 to 15, if adhesives or snap fits are used instead of two types of screws, and if the circuit cover is integrated with the phone's back-cover. Additionally, the Assembly Time is estimated to be 160.7 seconds, which yields a DFA Efficiency of 28%. This efficiency indicates that there are parts of the product that are not essential, such as the screws.

From the three proposed concepts, the Pugh Matrix method concludes that the concept that will yield a higher improvement with respect to the original design is the first one: the redesign of the chassis assembly. This concept is based on the belief that the SIM and SD card holders provide enough resistance to the back-cover opening, in two of the sides. Another side does not have any locking mechanism. The last side has two snap fits.

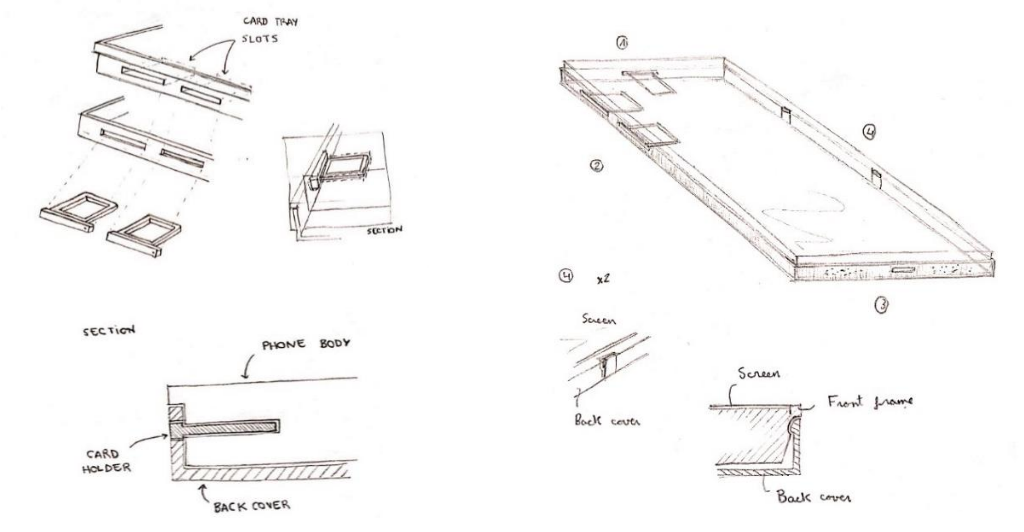


Image 4.11.2. Concept 1

Ease of disassembly was the main criterion of this concept. Image 4.11.3 shows the new disassembly process. First, the SIM and SD card holders are taken out. Second, the snap fits are opened by pulling outwards the extrusion on the back-cover. Using the slope on the phone body, the snap fits will slide downwards, contributing to the disassembly of the chassis. Thus, the objective of the redesign is met.

Image 4.11.3. New disassembly process

The analysis from MoldFlow shows that using the standard process settings, mold temperature 100ºC, melt temperature 310ºC, and maximum machine injection pressure 180 MPa, the predicted quality is unacceptable, but if the mold temperature is increased to 290ºC, the predicted quality is high in 98.8% of the part. The drawback of increasing the mold temperature is that the cycle time increases 66 times (603.18 seconds) because the cooling time is longer.

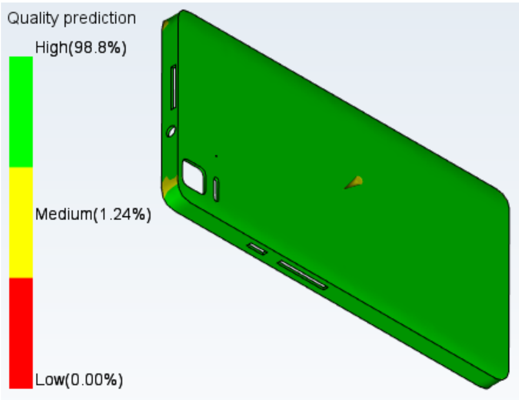


Image 4.11.4. Quality Prediction

Finally, from the Design of Experiments it can be concluded that both the angle and the extrusion length are significant when determining the number of times the back-cover will open, but their interaction is not significant. With the system characteristic equation, an estimate of the number of times the back-cover opens can be calculated. The combination that gives the lowest output, one time throughout the whole experiment, is a high extrusion length (1.1 mm), and a low angle (4.57º).

$$\hat{Y} = 2.583 + \frac{1.5}{2}x_1 - \frac{0.833}{2}x_2$$

All in all, this project has taught me several things. The first one is I have become aware that the amount of technological waste is alarmingly high. This can be attributed to the incorrect recycling of devices and the speed at which these devices become obsolete. It has become a need for everybody to have the latest cell phone model in the industry. This leads to many cell phones that end up forgotten in drawers, that still have some useful life. I have learnt that these cell phones can be put to good use, either by giving them to someone that might need them, or by recycling them. These devices can still be used to recover materials or components that can be used in other products.

I have also learnt that there is a trade-off between sustainability and functionality. The batteries in cell phones are hazardous and can harm the environment if they are not correctly eliminated. Usually, the plastics used in cell phones contain substances that make it impossible to recycle them but are necessary to avoid the flammability of the cell phone. There are many researchers looking for greener materials and new solutions. But, until the best one is found, the user has to choose between sustainability and functionality.

On a more constructive note, I take comfort in the thought that the electronics industry is concerned about this and is making some changes to encourage recycling. It is slowly transitioning to a circular economy. It was interesting to see how simple ideas such as introducing Design for Disassembly in the design process can help in this transition.

Any change, even if it is small, contributes towards a circular economy. One solution for the technological waste problem is to change the materialistic and consumeristic mentality into a sustainable mindset, in order to build a better future.

6. BIBLIOGRAPHY

[PHIL19] Philpott, M., N. Dornik, B. Ellis, P. Hong, C. Warning, "Design for Manufacture", aPriori Education, 2019.

[QUAL20] Quality One, "Design for Manufacturing/Assembly (DFM/A)", Quality One, 2020. https://quality-one.com/dfm-dfa/

[PERE18] Pérez, E., "Los laboratorios de BQ por dentro", Xataka, December 2018, https://www.xataka.com/moviles/fabrica-bq-dentro-asi-se-disenan-moviles-espana-estas-pruebas-que-deben-pasar-antes-poder-venderse

[CRES20] Crespo Ballester, J., "What does IP Code mean?", Crespo printing group, http://jcrespo.com/index.php?s=g3.php&sel=&gal=3&codseccion=22&tit=&idioma=gb

[MURR19] Murray, J., "Is the Nobel Prize-winning lithium-ion battery really having a positive impact on the environment?", NS Energy. https://www.nsenergybusiness.com/features/lithium-ion-battery-environmental-impact/

[LIND92] Lindhqvist, T., "Towards an [EPR]- analysis of experiences and proposals", April 1992.

[SMOC11] Smock, D. "Design for Recyclability". Design News. July 12, 2011. https://www.designnews.com/content/design-recyclability

[ACOS18] Acosta, Y. "Solo el 37% de los españoles ha reciclado alguna vez su móvil viejo", Ciencias Ambientales. November 23, 2018. https://www.google.com/amp/s/www.cienciasambientales.com/es/noticias-ambientales/certideal-37-espanoles-ha-reciclado-alguna-vez-su-movil-viejo-17028/amp

[UN__19] United Nations, "Sustainable Development Goal 12". United Nations. 2019. https://sustainabledevelopment.un.org/sdg12

[ELLE20] Ellen MacArthur Foundation "Circular Economy", Ellen MacArthur Foundation, 2020. https://www.ellenmacarthurfoundation.org/circular-economy/concept

[GARC18] García Nieto, J., "¿De qué está hecho tu móvil?", andro4all, September 2018.

[LEVO10] Levonas, E., "What's in my cell phone?", Minerals Education Coalition, 2010.

[VANE17] Vanegas, P., J.R. Peeters, D. Cattrysse, P. Tecchio, F. Ardente, F. Mathieux, W. Dewulf, J.R. Duflou, "Ease of disassembly of products to support circular economy strategies", Resources, Conservation and

Recycling, January 2017. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5989810/

[SODH01] Sodhi, M. S., B. Reimer, “Models for Recycling Electronics End-of-Life Products”, ResearchGate, February 2001. https://www.researchgate.net/publication/227170486_Models_for_Recycling_Electronics_End-of-Life_Products

[ROSE99] Rose, C. M., K. Ishii, “Product End-of-Life Strategy Categorization Design Tool”, Stanford University, 1999.

[PRAM15] Pramanik, P., U. Mina, N. Sharma, “Bioplastic: Sustainable Green Plastic”, ResearchGate, December 2015. https://www.researchgate.net/publication/313315235_Bioplastic_Sustainable_Green_Plastic

[HEST09] Hestler, R. E., R. M. Harrison, “Electronic Waste Management”, The RoyalSociety of Chemistry, 2009.

[LIEB20] Liebenberg, L., “Design for Manufacturability”, University of Illinois, Spring 2020.

[MEDI20] Sims Media, “Sustainable Electronics: Best Practices for Circular Design”, Sims Lifecycle Services, April 2020.

Other links:

All Answers ltd, “Quality Function Deployment in the Mobile Phone Industry” (allanswers.co.uk, June 2020) https://ukdiss.com/examples/quality-function-deployment-mobile-phone-industry.php?vref=1

Amazon reviews: https://www.amazon.es/BQ-Aquaris-E5-Smartphone-Quad-Core/product-reviews/B00KLZAQF8/ref=cm_cr_getr_d_paging_btm_next_5?ie=UTF8&reviewerType=all_reviews&filterByStar=critical&pageNumber=5

https://www.ellenmacarthurfoundation.org/circular-economy/concept

https://www.google.com/amp/s/andro4all.com/2018/09/de-que-estan-hechos-moviles/amp

https://www.google.com/amp/s/ecoembesdudasreciclaje.es/donde-tirar-moviles/amp/

https://www.techwalla.com/articles/what-materials-are-used-to-make-cell-phones

https://www.anandtech.com/show/7984/discussion-on-material-choices-in-mobile

https://www.recycledplastic.com/index.html%3Fp=10197.html

https://mynewmicrophone.com/what-kind-of-microphones-are-used-in-cell-phones/

https://www.machinedesign.com/fastening-joining/article/21834668/joining-plastic

https://www.plasticstoday.com/packaging/project-gets-funding-invisible-markers-improve-plastics-recycling-quality/8630306024196

https://www.plasticstoday.com/packaging/new-fluorescent-tech-can-light-food-packaging-recycling-rates/168540508662231

https://www.google.com/amp/s/www.cienciasambientales.com/es/noticias-ambientales/certideal-37-espanoles-ha-reciclado-alguna-vez-su-movil-viejo-17028/amp

https://www.google.com/amp/s/marketing4ecommerce.net/tienda-de-telefonia-movil-certideal-opiniones-analisis-y-valoracion/amp/

https://www.certideal.es/concepto-certideal

https://en.m.wikipedia.org/wiki/European_Week_for_Waste_Reduction

https://en.m.wikipedia.org/wiki/Extended_producer_responsibility

https://www.designnews.com/content/design-recyclability

https://www.designingbuildings.co.uk/wiki/Design_for_Manufacture_and_Assembly_(DfMA)

https://andro4all.com/2017/01/temperatura-maxima-minima-smartphones

https://www.cnet.com/how-to/how-waterproof-is-your-android-phone-or-iphone-heres-what-ip68-and-ip67-ratings-mean/

https://www.xataka.com/moviles/fabrica-bq-dentro-asi-se-disenan-moviles-espana-estas-pruebas-que-deben-pasar-antes-poder-venderse

https://www.yoandroideo.com/2019/08/05/ip68-ip52-moviles-resistentes-al-agua-y-al-polvo/

http://www.matweb.com/search/DataSheet.aspx?MatGUID=532e15cdf26f4b609596da4a0adac610

https://en.wikipedia.org/wiki/Lithium_polymer_battery

http://www.matweb.com/search/DataSheet.aspx?MatGUID=532e15cdf26f4b609596da4a0adac610

https://computerhoy.com/fichas/bq-aquaris-e5-hd

https://books.google.es/books?id=9Oj49a2aDPsC&pg=PA155&lpg=PA155&dq=using+adhesive+instead+of+screws+in+electronics&source=bl&ots=zAloJE0GUr&sig=ACfU3U0mAZGzM1XWK0Y-QD9L157tDTUCfw&hl=en&sa=X&ved=2ahUKEwja97KWydTpAhVbDWMBHRUaAfEQ6AEwAHoECAEQAQ#v=onepage&q=using%20adhesive%20instead%20of%20screws%20in%20electronics&f=false

https://ukdiss.com/examples/quality-function-deployment-mobile-phone-industry.php

https://www.google.com/amp/s/www.elconfidencial.com/amp/tecnologia/2014-10-14/bq-en-un-smartphone-de-800-euros-la-mayor-parte-es-margen-de-beneficio_238885/

https://www.amazon.es/Placas-Laminas-Aluminio/b?ie=UTF8&node=10229786031&ref_=d6k_applink_bb_marketplace

https://m.alibaba.com/product/60832344592/Thin-7075-T6-Aluminium-Sheet-Plate.html?s=p

https://www.google.com/search?client=ms-unknown&ei=eWXnXuLiIKmalwSznY6YBg&q=sheet+metal+press+machine+price+in+dollars&oq=sheet+metal+press+machine+price+in+dollars&gs_lcp=ChNtb2JpbGUtZ3dzLXdpei1zZXJwEAM6BAgAEBM6BggAEB4QEzoICAAQFhAeEBM6BQghEKABOggIIRAWEB0QHlCCDljcH2CNIWgAcAB4AIABpgGIAbMMkgEEMC4xMpgBAKABAQ&sclient=mobile-gws-wiz-serp

https://rexplastics.com/plastic-injection-molds/how-much-do-plastic-injection-molds-cost

https://mineralseducationcoalition.org/wp-content/uploads/mec_fact_sheet_cell_phone_0.pdf

https://www.simsrecycling.com/2020/04/21/sustainable-electronics-best-practices-for-circular-design/

7. ANNEX

Annex A. BQ Aquaris E5 HD Technical characteristics

https://computerhoy.com/fichas/bq-aquaris-e5-hd

Design

Length: 142 mm

Width: 71 mm

Height: 8.7 mm

Weight: 134 g

Screen

Size: 5”

Screen type: IPS

Resolution: 1280 x 720

Pixel density: 294 ppp

Protection type: Dragontrail

Software

Operating system: Android

SO version: 4.4

Hardware

Processor: Mediatek Cortex A7

Cores: 4

Speed: 1.30 Mhz

Storage:

RAM: 1 GB

Internal memory: 16 GB

MicroSD magnification: YES

Until 32 GB

Camera

Main camera:

Resolution: 13 MP

Flash: Flash LED Dual

Video: Full HD 1080p

Frontal camera:

Resolution: 5.0

Battery

Capacity: 2,500 mAh

Wireless charging: NO

Connectivity

NFC: NO

Bluetooth: v4.0

WiFi: 802.11 b/g/n

USB: microUSB v2.0

SIM card:

- SIM card type: microsim
- Dual SIM: YES
- Dual SIM 4G: NO

Compatible networks:

- 2G networks (GSM): 850 / 900 / 1800 / 1900 MHz
- 3G networks (HSDPA): 900 / 2100 MHz
- Compatible 3G Spain: YES
- Compatible 4G Spain: NO

Sound

FM radio: YES

Annex B. Sustainable Development Goals

This project targets the following SDGs:

Table 4.11.1. SDGs

SDG Dimension	SDG Identified	Role	Goal
Biosphere	SDG 13: Take urgent action to combat climate change and its impacts	Secondary	Reduce the material footprint
Society	-	-	-
Economy	SDG 12: Responsible consumption and production patterns	Primary	Include Design for Recyclability in the design process of electronic components so the technology waste will be reduced

This project is about Design for Recyclability of electronic devices, which is directly related with the Sustainable Development Goal number 12, that addresses the implementation of **responsible consumption and production patterns**.

The project's main goal is to show how easy it is to include Design for Recyclability in the design process and the benefit of doing so. As it was taught during the ME 270 course by Professor Liebenberg, the product design is the most important part of a production line since it is in that stage when the possible problems are addressed and solved. The benefit of introducing Design for Recyclability is that it makes producers consider the recycling and disposal of their products. In fact, there is an initiative called Extended Producer Responsibility (EPR) that makes the producers responsible for the costs of a product throughout its lifecycle. The goal of this strategy is to increase product recovery and minimize the environmental impact of waste materials (Johnson, Michael R; "Product recovery decisions within the context of Extended Producer Responsibility"). This is the best way to make sure that producers focus on high environmental standards in product design.

The concept was first used in Sweden in 1990 by Thomas Lindhqvist, about which he states that "[EPR] is an environmental protection strategy to reach an environmental objective of a decreased total environmental impact of a product, by making the manufacturer of the product responsible for the entire life-cycle of the product and especially for the take-back, recycling, and final disposal." (LIND92)

Thus, EPR often uses financial incentives to encourage producers to design environmentally friendly products. Producers often have control over product design, being able to reduce toxicity and waste.

As it was mentioned in the Introduction, technological waste has greatly increased in the past years, making it one of the biggest problems that urgently needs a solution. Electronic devices contain materials that cannot be thrown away with domestic waste since they contain materials that are dangerous for the human health and for the environment, such as lead, cadmium, and mercury. Many countries have included EPR to address this problem, implementing laws that require recycling electronic waste, building recycling infrastructure for technological waste disposal, and restricting the use of harmful substances. If producers are financially or physically responsible of the electronic devices after their use, they may shift towards a more sustainable design that is easier to recycle.

Design for Recyclability is a method that works very well with the concept behind EPR. This method can take different shapes. Design for disassembly, for instance, is a good way to recover materials and reuse most of them after the devices reach the end of their useful life. Design engineers believe this is possible. However, this initiative has slowed down due to strong pressure among producers because they do not want to bear higher costs or because they lack the recycling infrastructure to reuse the materials. Nevertheless, design engineers consider using two strategies to reduce disassembly time: component reduction through modular designs and fastener standardization. (SMOC11)

As for the progress of Goal 12 in 2019 (UN__19), “Worldwide material consumption has expanded rapidly, as has material footprint per capita. (…) Urgent action is needed to ensure that current material needs do not lead to the over extraction of resources or to the degradation of environmental resources, and should include policies that improve resource efficiency, reduce waste and mainstream sustainability practices across all sectors of the economy.” It is clear that Design for Recyclability is important to achieve this goal.

Around 50 million tons of electronic waste is produced every year of which only 20% is recycled. At this rate, electronic waste is estimated to reach 120 million tons annually by 2050 (MEDI20). Fortunately, companies are starting to take action, opting for more sustainable products, working towards a circular economy. The following practices in product design work towards responsible consumption and production patterns.

The first practice is to use environmentally **sustainable materials**. Designers often have to choose between circular design and functionality. For example, the use of plastic containing brominated flame-retardant chemical compound is used to reduce the flammability of heat generated from electronic devices, but it makes this material impossible to recycle. Other hazardous materials such as batteries, need to be appropriately labeled so recyclers become aware of their presence. Metals such as gold, aluminum, and steel have a high recoverable value and are easy to recycle.

Another practice is to create more **opportunities for reuse and resale**. The Consumer Electronics Association estimated that the average life of a smartphone is 4.7 years but that it usually is replaced after 21 months (MEDI20). Measures to support the reuse of these devices, still in working condition, should be taken, to give these devices to people who need them.

The next practice is that time is very important since the value and desirability of electronic devices decreases at a very high rate.

Standardization of processes is essential to reduce production costs. Designing features in the product that help in the disassembly makes the process more efficient. For example, these features might be standardized screw types, snap fits, and universal parts that ease the disassembly of a product for its repair, reuse, or recycling.

Another practice is to avoid using adhesives. In cell phones, adhesive is often used to seal the battery in place, making it more difficult to disassemble. Some designs use bonded or molded together materials, preventing the recycling of the materials, as it is the case of the body of the phone studied in this project, where two plastics were solvent bonded.

Lastly, devices are sometimes replaced to add a feature that the old device sometimes has, but that the user did not know about. Including instructions or other resources to teach the user how to better use the device will help the users take full advantage of their device.

In summary, Design for Recyclability helps achieve the SDG 12 by chasing the following targets (MEDI20):

- Sustainable management
- Efficient use of natural resources
- Environmentally sound management of chemicals and all wastes
- Reduction of waste generation
- Sustainable practices and reporting

This project indirectly targets Sustainable Development Goal number 13: Take urgent action to combat climate change and its impacts. Using Design for Recyclability reduces the exploitation of resources since more materials are reused and electronic devices have a longer lifetime. Thus, less technological waste is generated, having a positive impact on the environment.

The electronics market is estimated to reach $1.7 billion by 2014 (MEDI20). In an industry of this size, any change, even if it is small, will have a positive effect in the transition to a circular economy.

Annex C. PC + 10% GF properties

Physical Properties	Metric	English	Comments
Density	1.18 - 1.41 g/cc	0.0426 - 0.0509 lb/in³	Average value: 1.27 g/cc Grade Count:201
	1.08 - 1.08 g/cc @Temperature 300 - 300 °C	0.0390 - 0.0390 lb/in³ @Temperature 572 - 572 °F	Average value: 1.08 g/cc Grade Count:2
Filler Content	5.00 - 10.0 %	5.00 - 10.0 %	Average value: 9.22 % Grade Count:32
Water Absorption	0.0500 - 0.320 %	0.0500 - 0.320 %	Average value: 0.168 % Grade Count:66
Moisture Absorption at Equilibrium	0.100 - 0.310 %	0.100 - 0.310 %	Average value: 0.158 % Grade Count:23
Water Absorption at Saturation	0.120 - 0.310 %	0.120 - 0.310 %	Average value: 0.227 % Grade Count:6
Viscosity Number	42.0 - 56.0 cm³/g	0.420 - 0.560 dl/g	Average value: 49.5 cm³/g Grade Count:4
Maximum Moisture Content	0.0200	0.0200	Average value: 0.0200 Grade Count:6
Linear Mold Shrinkage	0.000300 - 0.0150 cm/cm	0.000300 - 0.0150 in/in	Average value: 0.00402 cm/cm Grade Count:168
	0.00600 - 0.00600 cm/cm @Temperature 80.0 - 80.0 °C	0.00600 - 0.00600 in/in @Temperature 176 - 176 °F	Average value: 0.00600 cm/cm Grade Count:1
Linear Mold Shrinkage, Transverse	0.00100 - 0.00800 cm/cm	0.00100 - 0.00800 in/in	Average value: 0.00478 cm/cm Grade Count:51
	0.00500 - 0.00500 cm/cm @Temperature 80.0 - 80.0 °C	0.00500 - 0.00500 in/in @Temperature 176 - 176 °F	Average value: 0.00500 cm/cm Grade Count:1
Melt Flow	5.00 - 36.0 g/10 min	5.00 - 36.0 g/10 min	Average value: 13.1 g/10 min Grade Count:117
Ash	10.0 - 10.5 %	10.0 - 10.5 %	Average value: 10.1 % Grade Count:6

Mechanical Properties	Metric	English	Comments
Hardness, Rockwell M	70.0 - 90.0	70.0 - 90.0	Average value: 83.8 Grade Count:22
Hardness, Rockwell R	89.0 - 124	89.0 - 124	Average value: 117 Grade Count:38
Ball Indentation Hardness	50.0 - 128 MPa	7250 - 18600 psi	Average value: 106 MPa Grade Count:3
Tensile Strength, Ultimate	35.0 - 120 MPa	5080 - 17400 psi	Average value: 66.6 MPa Grade Count:137
	25.0 - 25.0 MPa @Temperature 60.0 - 60.0 °C	3630 - 3630 psi @Temperature 140 - 140 °F	Average value: 25.0 MPa Grade Count:1
Tensile Strength, Yield	44.1 - 125 MPa	6400 - 18100 psi	Average value: 68.5 MPa Grade Count:104
Elongation at Break	1.80 - 110 %	1.80 - 110 %	Average value: 13.0 % Grade Count:164
	28.0 - 28.0 % @Temperature 60.0 - 120 °C	28.0 - 28.0 % @Temperature 140 - 248 °F	Average value: 76.0 % Grade Count:1
Elongation at Yield	4.00 - 13.0 %	4.00 - 13.0 %	Average value: 5.72 % Grade Count:25
	2.20 - 3.00 % @Temperature 60.0 - 120 °C	2.20 - 3.00 % @Temperature 140 - 248 °F	Average value: 2.67 % Grade Count:1
Modulus of Elasticity	1.80 - 10.7 GPa	261 - 1550 ksi	Average value: 3.77 GPa Grade Count:85
	2.20 - 2.90 GPa @Temperature 60.0 - 120 °C	319 - 421 ksi @Temperature 140 - 248 °F	Average value: 2.63 GPa Grade Count:1
Flexural Yield Strength	55.0 - 190 MPa	7980 - 27600 psi	Average value: 111 MPa Grade Count:164
Flexural Modulus	1.80 - 10.4 GPa	261 - 1510 ksi	Average value: 3.56 GPa Grade Count:184
Flexural Strain at Yield	5.00 - 5.80 %	5.00 - 5.80 %	Average value: 5.64 % Grade Count:5
Compressive Yield Strength	89.6 - 97.0 MPa	13000 - 14100 psi	Average value: 94.9 MPa Grade Count:8
Izod Impact, Notched	0.392 - 8.01 J/cm	0.735 - 15.0 ft-lb/in	Average value: 1.28 J/cm Grade Count:130
	1.00 - 1.00 J/cm @Temperature 0.000 - 0.000 °C	1.87 - 1.87 ft-lb/in @Temperature 32.0 - 32.0 °F	Average value: 0.945 J/cm Grade Count:3
	0.700 - 1.10 J/cm @Temperature -40.0 - 0.000 °C	1.31 - 2.06 ft-lb/in @Temperature -40.0 - 32.0 °F	Average value: 0.945 J/cm Grade Count:2
	0.700 - 1.10 J/cm @Thickness 3.20 - 3.20 mm	1.31 - 2.06 ft-lb/in @Thickness 0.126 - 0.126 in	Average value: 0.945 J/cm Grade Count:2
Izod Impact, Unnotched	0.785 J/cm - NB	1.47 ft-lb/in - NB	Average value: 11.9 J/cm Grade Count:25
Izod Impact, Notched (ISO)	6.00 - 25.0 kJ/m²	2.86 - 11.9 ft-lb/in²	Average value: 10.5 kJ/m² Grade Count:31
	5.00 - 9.00 kJ/m² @Temperature -30.0 - -30.0 °C	2.38 - 4.28 ft-lb/in² @Temperature -22.0 - -22.0 °F	Average value: 7.75 kJ/m² Grade Count:4
Charpy Impact Unnotched	2.50 - 1000 J/cm²	11.9 - 4760 ft-lb/in²	Average value: 6.67 J/cm² Grade Count:35
	2.50 - 999.9 J/cm² @Temperature -60.0 - -20.0 °C	11.9 - 4759 ft-lb/in² @Temperature -76.0 - -4.00 °F	Average value: 8.86 J/cm² Grade Count:8
Charpy Impact, Notched	0.100 - 1.50 J/cm²	0.476 - 7.14 ft-lb/in²	Average value: 0.830 J/cm² Grade Count:35
	0.600 - 0.900 J/cm² @Temperature -40.0 - -20.0 °C	2.86 - 4.28 ft-lb/in² @Temperature -40.0 - -4.00 °F	Average value: 0.743 J/cm² Grade Count:7
Puncture Energy	16.0 - 50.0 J	11.8 - 36.9 ft-lb	Average value: 32.2 J Grade Count:9
	10.0 - 30.0 J @Temperature -30.0 - -30.0 °C	7.38 - 22.1 ft-lb @Temperature -22.0 - -22.0 °F	Average value: 19.0 J Grade Count:5

Electrical Properties	Metric	English	Comments
Electrical Resistivity	500 - 1.00e+17 ohm-cm	500 - 1.00e+17 ohm-cm	Average value: 1.43e+16 ohm-cm Grade Count:67
Surface Resistance	300 - 1.00e+16 ohm	300 - 1.00e+16 ohm	Average value: 1.73e+15 ohm Grade Count:47
Dielectric Constant	2.80 - 3.30	2.80 - 3.30	Average value: 3.12 Grade Count:42
Dielectric Strength	16.1 - 70.0 kV/mm	410 - 1780 kV/in	Average value: 28.7 kV/mm Grade Count:52
Dissipation Factor	0.000800 - 0.0160	0.000800 - 0.0160	Average value: 0.00584 Grade Count:33
Arc Resistance	0.000 - 125 sec	0.000 - 125 sec	Average value: 109 sec Grade Count:17
Comparative Tracking Index	100 - 250 V	100 - 250 V	Average value: 186 V Grade Count:45
Hot Wire Ignition, HWI	30.0 - 120 sec	30.0 - 120 sec	Average value: 75.0 sec Grade Count:5
High Amp Arc Ignition, HAI	15.0 - 120 arcs	15.0 - 120 arcs	Average value: 89.1 arcs Grade Count:5
High Voltage Arc-Tracking Rate, HVTR	0.000 - 150 mm/min	0.000 - 5.91 in/min	Average value: 41.7 mm/min Grade Count:3

Thermal Properties	Metric	English	Comments
CTE, linear	3.24 - 88.0 µm/m-°C	1.80 - 48.9 µin/in-°F	Average value: 40.7 µm/m-°C Grade Count:47
CTE, linear, Transverse to Flow	55.0 - 74.0 µm/m-°C	30.6 - 41.1 µin/in-°F	Average value: 62.8 µm/m-°C Grade Count:27
Specific Heat Capacity	1.21 - 1.60 J/g-°C	0.290 - 0.382 BTU/lb-°F	Average value: 1.50 J/g-°C Grade Count:4
Thermal Conductivity	0.191 - 0.663 W/m-K	1.33 - 4.60 BTU-in/hr-ft²-°F	Average value: 0.243 W/m-K Grade Count:15
Maximum Service Temperature, Air	80.0 - 150 °C	176 - 302 °F	Average value: 126 °C Grade Count:19
Hot Ball Pressure Test	125 - 140 °C	257 - 284 °F	Average value: 135 °C Grade Count:10
Deflection Temperature at 0.46 MPa (66 psi)	124 - 155 °C	255 - 311 °F	Average value: 142 °C Grade Count:125
Deflection Temperature at 1.8 MPa (264 psi)	92.8 - 203 °C	199 - 397 °F	Average value: 136 °C Grade Count:175
Vicat Softening Point	100 - 160 °C	212 - 320 °F	Average value: 145 °C Grade Count:65
Minimum Service Temperature, Air	-40.0 °C	-40.0 °F	Average value: -40.0 °C Grade Count:11
UL RTI, Electrical	80.0 - 130 °C	176 - 266 °F	Average value: 108 °C Grade Count:36
UL RTI, Mechanical with Impact	80.0 - 130 °C	176 - 266 °F	Average value: 101 °C Grade Count:36
UL RTI, Mechanical without Impact	80.0 - 130 °C	176 - 266 °F	Average value: 106 °C Grade Count:36
Flammability, UL94	HB - 5VA	HB - 5VA	Grade Count:143
Oxygen Index	27.0 - 37.1 %	27.0 - 37.1 %	Average value: 33.7 % Grade Count:17
Glow Wire Test	800 - 960 °C	1470 - 1760 °F	Average value: 914 °C Grade Count:36

Optical Properties	Metric	English	Comments
Transmission, Visible	90.0 - 97.0 %	90.0 - 97.0 %	Average value: 94.9 % Grade Count:4

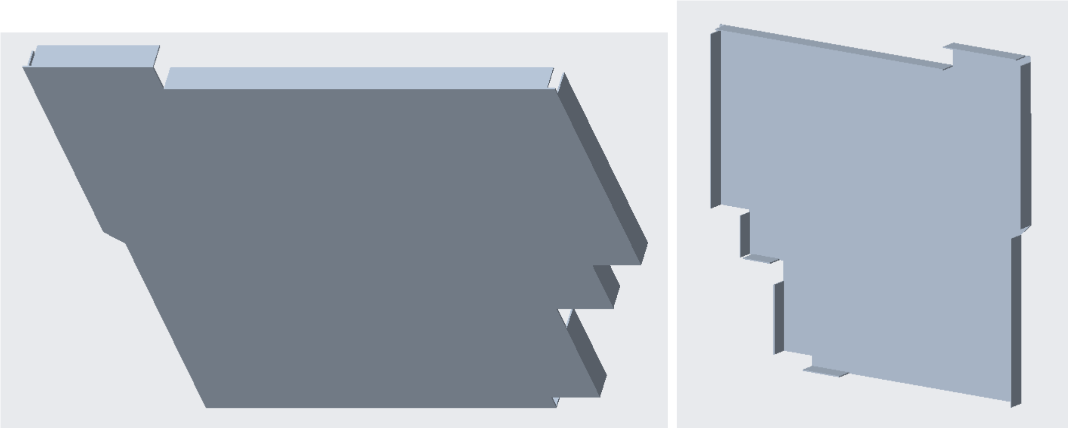
Processing Properties	Metric	English	Comments
Processing Temperature	249 - 330 °C	480 - 626 °F	Average value: 279 °C Grade Count:20
Nozzle Temperature	250 - 343 °C	482 - 650 °F	Average value: 296 °C Grade Count:33
Melt Temperature	221 - 343 °C	430 - 650 °F	Average value: 296 °C Grade Count:77
Mold Temperature	10.0 - 130 °C	50.0 - 266 °F	Average value: 94.6 °C Grade Count:90
Injection Velocity	200 mm/sec	7.87 in/sec	Average value: 200 mm/sec Grade Count:8
Drying Temperature	70.0 - 130 °C	158 - 266 °F	Average value: 116 °C Grade Count:69
Moisture Content	0.0100 - 0.200 %	0.0100 - 0.200 %	Average value: 0.0474 % Grade Count:31
Dew Point	-40.0 - -17.8 °C	-40.0 - 0.000 °F	Average value: -29.7 °C Grade Count:14
Drying Air Flow Rate	22.7 - 28.3 l/min	0.800 - 1.00 ft³/min (CFM)	Average value: 25.5 l/min Grade Count:3
Injection Pressure	8.27 - 138 MPa	1200 - 20000 psi	Average value: 87.2 MPa Grade Count:25
Vent Depth	0.00250 - 0.00762 cm	0.000984 - 0.00300 in	Average value: 0.00528 cm Grade Count:3
Cushion	0.635 cm	0.250 in	Average value: 0.635 cm Grade Count:3

Annex D. Additional CAD Views

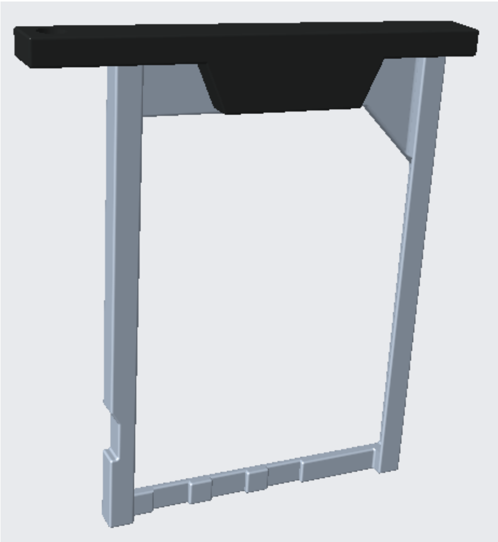
1- Phone Cover (case)

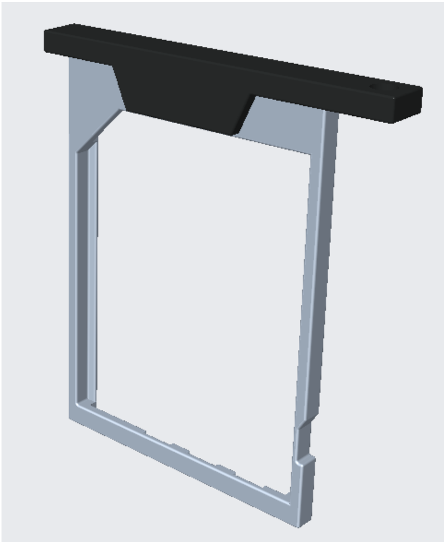
2- Front frame

3- Metal Circuit Cover



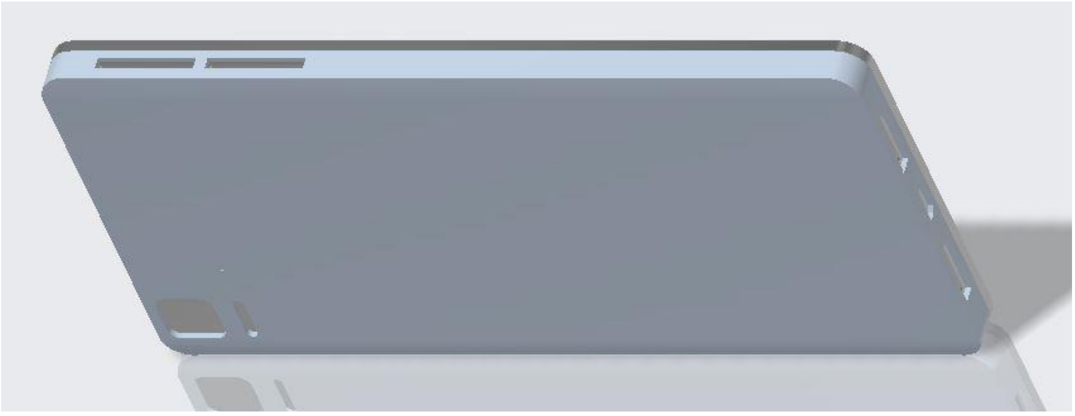
4- SIM Card Holder



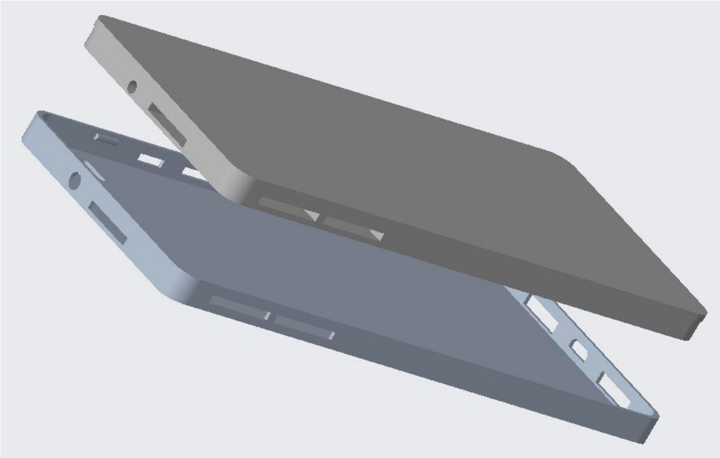


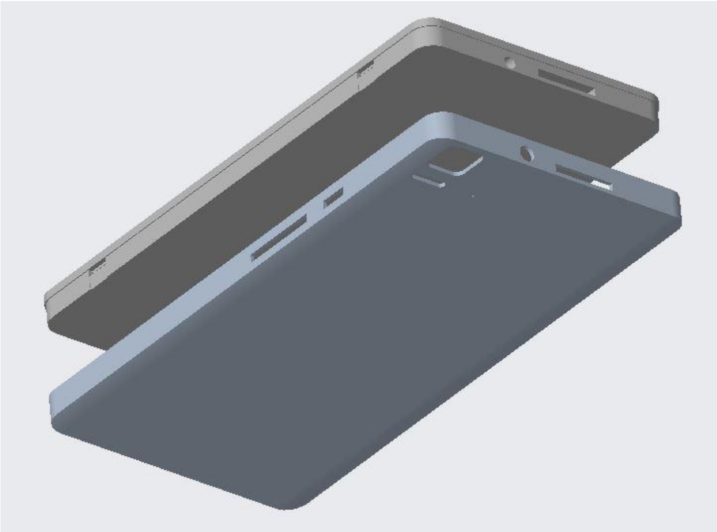
5- SD Card Holder

Assembly

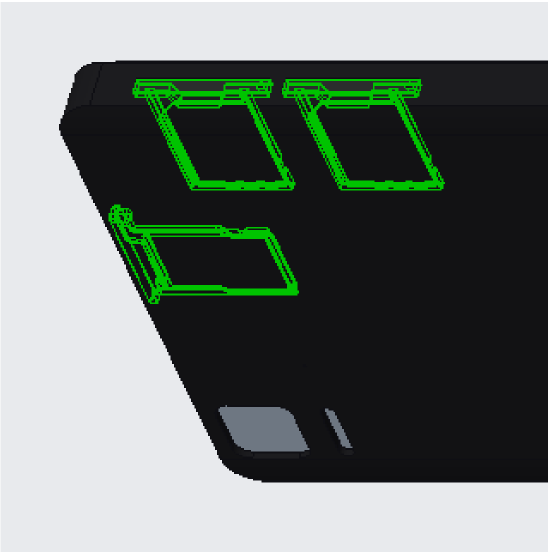


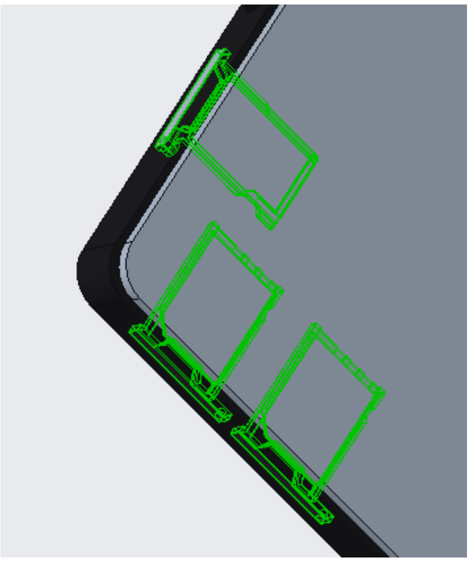
Exploded View





Card Holder Detail





Annex E. Injection Molding Material Properties

Material Data Method Report:

Manufacturer	Covestro
Trade Name	Makrolon 9415
Family Abbreviation	PC
Fibers / Fillers	10% Glass Fiber Filled
Autodesk Moldflow Material ID	14653
Moldflow Grade Code	CM14653

The material was tested by the manufacturer. Data was last updated on 12-OCT-11.

This data is Non-Confidential.

SUMMARY:

Data Type	Date	Method
Rheology	12-OCT-11	Unknown
Thermal	12-OCT-11	Unknown
Specific Heat	12-OCT-11	Unknown
pvT	12-OCT-11	Unknown
Shrinkage	26-MAR-2018	Uncorrected Residual Stress

RHEOLOGY:

The material's rheological behavior was tested by the manufacturer (unspecified test method). Data was last updated on 12-OCT-11.

THERMAL:

The material's thermal conductivity was tested by the manufacturer (unspecified method). Data was last updated on 12-OCT-11. Thermal conductivity was established at a single temperature.

SPECIFIC HEAT:

The material's specific heat was tested by the manufacturer (unspecified method). Data was last updated on 12-OCT-11. Specific heat was established at a single temperature.

pvT:

The material's pvT data was tested by the manufacturer (unspecified method). Data was last updated on 12-OCT-11.

SHRINKAGE (MIDPLANE & DUAL DOMAIN MODELS ONLY):

For this material, shrinkage and warpage predictions will be based on an uncorrected residual stress model with generic estimates of material mechanical properties. Data was last updated on 26-MAR-2018.

You can achieve more accurate shrinkage predictions by using measured shrinkage data and Autodesk Moldflow's CRIMS model.

ENVIRONMENTAL IMPACT

The material's Resin identification code is 7.

The material's Energy usage indicator is 5.

MATERIAL QUALITY INDICATORS

The material's Filling Indicator is Silver.

The material's Packing Indicator is Silver.

The material's Warpage Indicator is Bronze.

DISCLAIMER:

The information contained in this report has been prepared by Autodesk, Inc. based on data and other information received from third parties. No representations or warranties are provided regarding this report or its conclusions and Autodesk, Inc. specifically disclaims any liability that may result from reliance on these results.

Annex F. Injection Molding Results Summary

° Release version: 2019
° Study name: back_cover_re_design_study_(copy).sdy
° Study location:
D:\back_cover\back_cover_redesign\back_cover_re_design_study_(copy).sdy
° Part name: back_cover_re_design.stl
° Model suitability: The imported model is thin walled, and is appropriate for Dual-Domain analysis.
° Analysis resolution: Level 0 (Standard)
° Material manufacturer: Covestro
° Material trade name: Makrolon 9415
° Material Resin identification code: 7
° Material Energy usage indicator: 5
° Melt temperature: 310.0 (C)
° Mold temperature: 100.0 (C)
° Injection locations: 1
° Max. machine injection pressure: 180.000 (MPa)
° Injection time selected: Automatic
° Velocity/pressure switch-over: Automatic

Model warnings
None

Your part can be filled easily but part quality may be unacceptable.

View the Quality Prediction plot and use the Results Adviser to get help on how to improve quality of the part.

° Actual filling time: 0.82 (s)
° Actual injection pressure: 122.932 (MPa)
° Clamp force area: 100.7716 (cm^2)
° Max. clamp force during filling: 63.609 (tonne)
° Velocity/pressure switch-over at % volume: 97.18 (%)
° Velocity/pressure switch-over at time: 0.78 (s)
° Estimated cycle time: 9.09 (s)
° Total part weight: 14.303 (g)
° Shot volume: 11.9559 (cm^3)

Clamp force estimate during packing using:
° 20% of the injection pressure: 25.257 (tonne)
° 80% of the injection pressure: 101.027 (tonne)
° 120% of the injection pressure: 151.540 (tonne)

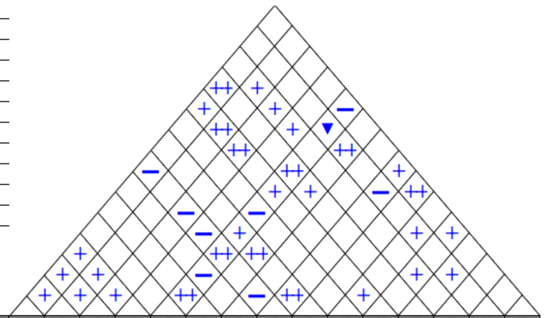
Annex G. BOM and DFMA Table

	Part Name	Qty	Dimension (mm)	Material	Manufacturing Process	Function	Opportunity to combine or eliminate	Notes
1	Back Cover (case)	1	142 x 71 x 6	PC	Plastic Injection Molding	Covers the phone body that supports the circuit board, battery and electronic components	N	
2	Front Frame	1	142 x 71 x	PC	Plastic Injection Molding	Supports the screen	N	
3	Phone body	1	140 x 69 x 4	PC	Plastic Injection Molding + Solvent Bonding	Supports the phone body that supports the circuit board, the battery and other electronic	N	
4	PN screw (3 mm)	12	3 mm	Stainless Steel	purchased	Give structural support	Y	Could use other mechanisms like adhesives
5	PN screw (4	2	4 mm	Stainless Steel	purchased	Give structural support	Y	Could use other mechanisms like adhesives
6	Circuit Board & Circuitry	1	67 x 45 x 4	Epoxy-fiberglass composite + Platinum +	purchased	Support for circuitry	N	
7	Circuit Board Cover	1	69 x 47 x 4	PC + aluminum	Sheet Metal Forming & Pressing + Plastic Injection Molding	Protects circuit	Y	Could be eliminated
8	SD Card Holder	1	19 x 16 x 2	PC + aluminum	Sheet Metal Forming + Plastic Injection Molding	Supports the SD card	N	
9	SIM Card Holder	2	19 x 17 x 2	PC + stainless steel	Sheet Metal Forming + Plastic Injection Molding	Supports the SIM card	N	
10	Battery	1	67 x 63 x 4	Lithium Polymer	purchased	Powers the phone	N	
11	Metal Circuit Cover	2	32 x 32 x 2	Steel	Sheet Metal Stretch Forming	Protects circuit	Y	Could be welded to the circuit board
12	Camera	2	9 x 9 x 5	Glass + aluminum + PC	purchased	Used to take pictures and videos	N	
13	Microphone	1	20 x 14 x 2	Silicon wafer	purchased	Used to record the voice	N	
14	Speaker	1	7 x 4 x 2	Piezoceramics + shim (metal materials)	purchased	Used to play sound	N	
15	Receiver	1	12 x 6 x 3	Plastic + Copper + Aluminum	purchased	Used to hear the phone calls	N	
16	Screen	1	141 x 69 x	Glass	purchased	Used to display and interact with the phone	N	
17	Wiring	1		Gold + copper + silver	purchased	Electrical connection	N	
18	Insulating tape	1		Vinyl + Plastic	purchased	Provides physical and electrical insulation	N	

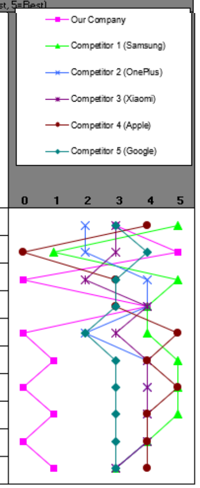
Annex H. House of Quality

Title: BQ Aquaris E5 HD
Author: Teresa Jarabo Sastre
Date:
Notes:

Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
—	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	



Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Weight (g)	Length (mm)	Width(mm)	Height (mm)	Cost (€)	Life span (years)	Camera Resolution (MP)	Battery Duration (hours)	Battery Life (years)	Screen time response (ms)	Screen size (")	Internal Memory (GB)	Aesthetic Design (% of likeability)	High RAM (GB)	Repair Time (hours)	Our Company	Competitor 1 (Samsung)	Competitor 2 (OnePlus)	Competitor 3 (Xiaomi)	Competitor 4 (Apple)	Competitor 5 (Google)
				Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Competitive Analysis (0=Worst, 5=Best)					
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▼	x	x	x	▼	▲	▲	▲	▲	x	x	▲	▲	▲	▼						
1	9	11.9	5.0	Long Battery Duration	O	▲	▲	▲	O	Θ		Θ	Θ					▲	O	3	5	2	3	4	3
2	9	11.9	5.0	Low Cost	▲	▲	▲	▲	Θ	Θ	Θ	Θ	Θ		▲	Θ	▲	Θ	O	5	1	2	3	0	4
3	9	9.5	4.0	High Life Expectancy					O	Θ			Θ					O		0	5	4	2	3	3
4	9	7.1	3.0	Ergonomic	Θ	Θ	Θ	Θ	▲						Θ		▲			4	4	4	4	3	3
5	9	9.5	4.0	High Quality Camera					Θ		Θ			O		▲		▲		0	4	2	3	5	2
6	9	11.9	5.0	Correct Operation of apps						Θ		O	▲	Θ	▲			Θ		1	5	4	4	4	3
7	9	11.9	5.0	Fast					O		▲			Θ	O			Θ		0	5	4	4	5	3
8	9	4.8	2.0	Aesthetically pleasing		O	O	O							▲		Θ			1	5	4	4	4	3
9	9	9.5	4.0	Large Storage Capacity												Θ				0	4	4	4	4	3
10	9	11.9	5.0	Good Technical Support															Θ	1	3	3	3	4	3



Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Target or Limit Value	120	142	71	8.7	199	5	20	48	5	5	5	128	80	8	5
Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	2	2	2	2	7	10	8	9	9	4	2	7	4	6	8
Max Relationship Value in Column	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Weight / Importance	111.9	102.4	102.4	102.4	300.0	407.1	204.8	250.0	311.9	242.9	128.6	202.4	61.9	371.4	178.6
Relative Weight	3.6	3.3	3.3	3.3	9.7	13.2	6.7	8.1	10.1	7.9	4.2	6.6	2.0	12.1	5.8

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Annex I. Assembly Time

Assembly Table												
							Handling and Alignement		Insert and Secure			
Operation Number	Times Operation is Carried Out	Part Description	Alpha (deg)	Beta (deg)	Size (mm)	Thickness (mm)	Description	Time (s)	Description	Time (sec)	Total Time (sec)	Opportunity to Combine or Eliminate?
1	1	Back Cover	360	360	71	7	No extra time	2.5	General Placement (GP)	0.5	3	1
2	1	Front Frame	360	360	71	3	Aspect ratio > 20	2.6	GP; Snap; Tight tolerance	1.2	3.8	1
3	1	Phone body	360	360	71	5	No extra time	2.5	GP; insertion difficulty (force); tight tolerance	1.3	3.8	1
4	12	PN screw (3 mm)	360	0	3	0.5	Part size: small	2	GP; align to small hole; turning insertion; final screw tightening; insertion difficulty (hold)	4.6	79.2	0
5	2	PN screw (4 mm)	360	0	4	0.5	Part size: small	2	GP; align to small hole; turning insertion; final screw tightening; insertion difficulty (hold)	4.6	13.2	0
6	1	Circuit Board & Circuitry	360	360	45	4	No extra time	2.5	GP; Align to small pin	0.9	3.4	1
7	1	Circuit Board Cover	360	360	47	3	No extra time	2.5	GP; Snap	0.8	3.3	0
8	1	SD Card Holder	360	360	12	1	No extra time	2.5	GP; Align to hole	0.6	3.1	1
9	2	SIM Card Holder	360	360	13	1	No extra time	2.5	GP; Align to hole	0.6	6.2	1
10	1	Battery	360	360	63	4	No extra time	2.5	GP	0.5	3	1
11	2	Metal Circuit Cover	360	360	33	1.6	Handling difficulty: sharp Aspect ratio > 20	3	GP; Snap	0.8	7.6	1
12	2	Camera	360	360	9	6	Part size: small	3	GP; Align to medium hole; Snap	1.1	8.2	1
13	1	Microphone	360	360	3	1	Part size: small	3	GP; Align to medium hole; Snap	1.1	4.1	1
14	1	Speaker	360	360	5	3	No extra time	2.5	GP; Align to medium hole; Snap	1.1	3.6	1
15	1	Receiver	360	360	6	3	Part size: small	3	GP; Align to medium hole; Snap	1.1	4.1	1
16	1	Screen	360	360	68	0.8	Handling difficulty: sharp Aspect ratio > 40	3.2	GP; Use of gloves; Tight tolerance	2.3	5.5	1
17	1	Wiring	0	180	3	0.5	Flexible	1.4	GP; Insertion difficulty (hold)	0.9	2.3	1
18	1	Insulating tape	360	180	8	0.1	Flexible	2.4	GP; Insertion difficulty (hold)	0.9	3.3	1
											160.7	15
							DFA Index =	0.28002			Total Time	Minimum number of parts
							N_m*t_m/t_a					
					N_m = Theoretical minimum number of parts			15				
					t_m = Minimum assembly time per part			3				
					t_a = Estimated total assembly time			160.7				