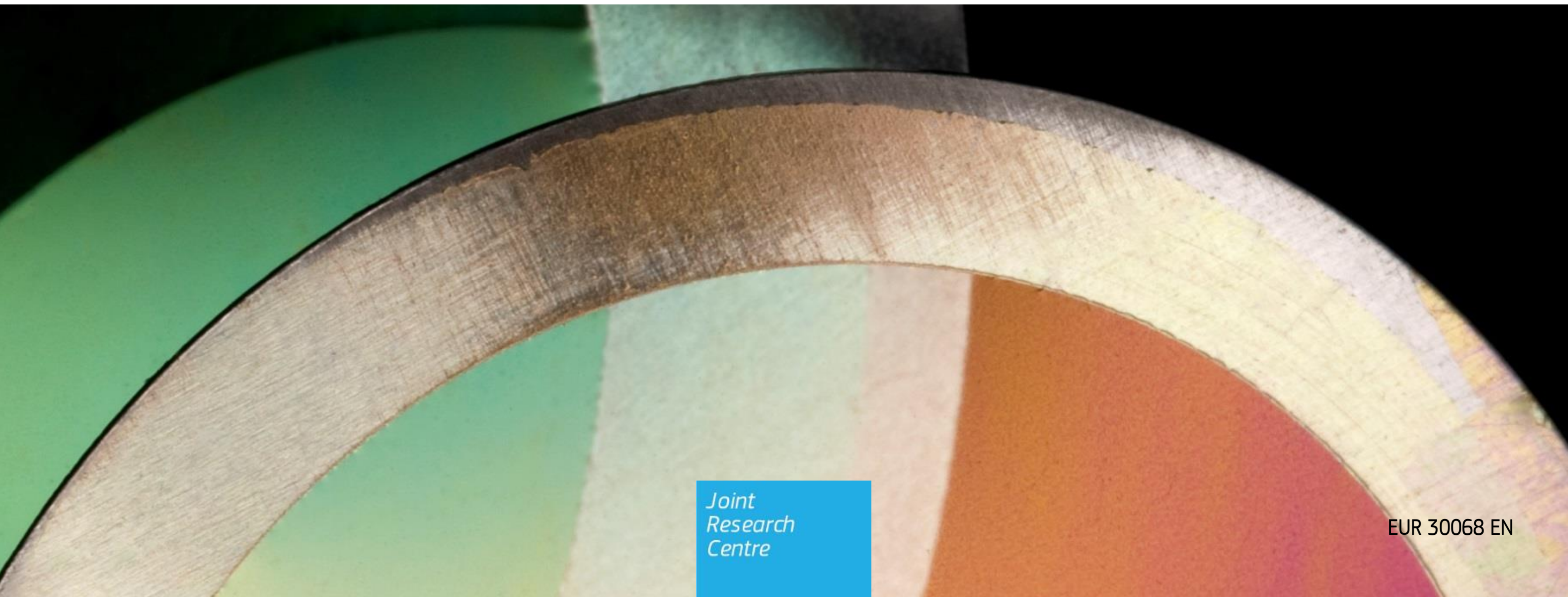
JRC TECHNICAL REPORT

Guidance for the Assessment of Material Efficiency: Application to Smartphones

Final report for Task 2 of the AA N. 070201/2015/SI2.719458/ENV.A.1

Mauro Cordella, Felice Alfieri, Javier Sanfelix (European Commission, Joint Research Centre, Seville, Spain)

2020



Joint Research Centre

EUR 30068 EN

Contact information
Name: Mauro Cordella
Address: Joint Research Centre, Edificio Expo. c/ Inca Garcilaso, 3. E-41092 Seville (Spain)
Email: JRC-B5-E4C@ec.europa.eu
Tel.: +34 954 488 424

EU Science Hub
https://ec.europa.eu/jrc

JRC116106

EUR 30068 EN

PDF ISBN 978-92-76-15411-2 ISSN 1831-9424 doi:10.2760/037522

Luxembourg: Publications Office of the European Union, 2020

How to cite this report: Cordella, M., Alfieri, F. and Sanfelix Forner, J., Guidance for the Assessment of Material Efficiency: Application to Smartphones, EUR 30068 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-15411-2, doi:10.2760/037522, JRC116106.

Contents

List of figures

List of tables

List of Acronyms

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	3rd Generation Partnership Project
3TG	Tungsten, Tantalum, Tin, and Gold
4G	Fourth Generation
5G	Fifth Generation
AC	Alternating Current
AMOLED	Active Matrix OLED
AMPS	Advanced Mobile Phone System
ASM	Artisanal small-scale mining
BBP	Butyl benzyl phthalate
BFR	Brominated flame retardants
BS	Base Station
BoM	Bill of Materials
C&L	Classification & Labelling
CBD	Chronic Beryllium Disease
CDMA	Code division multiple access
CEPN	Clean Electronics Production Network
CF	Carbon Footprint
CFC	Chlorofluorocarbons
CLP	Classification, Labelling and Packaging
CoC	Code of Conduct
CMR	Carcinogenic, Mutagenic or toxic for Reproduction
CPU	Central Processing Unit
CRM	Critical Raw Materials
DBP	Dibutyl phthalate
DC	Direct Current
DEHP	Bis(2-ethylhexyl) phthalate
DIBP	Diisobutyl phthalate
DINP	di-isononyl phthalate
DIY	Do It Yourself
DNOP	di-n-octyl phthalate
DRC	Democratic Republic of Congo
EC	European Commission
ECHA	European Chemical Agency
EDGE	Enhanced Data rates for GSM Evolution
EEE	Electrical and Electronic Equipment

ELV	End-of-Life Vehicles
EoL	End of Life
EPR	Extended Product Responsibility
EPS	External Power Supplies
	Evolved Packet System
ErP	Energy-related Product
ESD	Electrostatic Discharges
EU	European Union
EUTRAN	evolved UMTS terrestrial radio access network
E-UTRA	evolved UMTS terrestrial radio access
GAME	Guidance for the Assessment of Material Efficiency
GB	Gigabyte
GGSN	Gateway GPRS Support Node
GHG	Greenhouse gas
GPP	Green Public Procurement
GPRS	General Packet Radio Service
GPS	Global Positioning System
GPSD	General Product Safety Directive
GPU	Graphics Processing Unit
GSH	Globally Harmonised System
GSM	Global Systems for Mobile Communications
GWP	Global Warming Potential
HBCDD	Hexabromocyclododecane
HC	Hydrocarbons
HCFC	Hydrochlorofluorocarbons
HD	High Definition
HDSPA	High-Speed Downlink Packet Access
HFC	Hydrofluorocarbons
IC	Integrated Circuit
ICT	Information and Communications Technology
IEC	International Electrotechnical Commission
IPXX	Ingress Protection XX
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCD	Liquid Cristal Display
LCI	Life Cycle Inventory
LED	Light Emitting Diode
LP	Low Power
LPDDR	Low-Power Double Data Rate
LTE	Long Term Evolution

MIMO	Multi Input Multi Output
MoU	Memorandum of Understanding
MP	Mega Pixels
NFC	Near Field Communication
NGO	Non-Governmental Organisation
NIB	Neodymium
NMT	Nordic Mobile Telephone
OEM	Original Equipment Manufacturer
OS	Operating System
PA	Power Amplifiers
PBB	Polybrominated biphenyls
PBDE	Polybrominated diphenyl ethers
PBT	Persistent, Bio-accumulative and Toxic
PC	Personal Computer
PCB	Polychlorinated biphenyls
PCT	Polychlorinated terphenyls
	Projected Capacitive Touch
PRO	Producer Responsibility Organisation
PSA	Pressure Sensitive Adhesive
PVC	Poly Vinyl chloride
RAM	Random-Access Memory
RAPEX	Rapid Alert System for non-food dangerous products
REAPRO	Resource Efficiency Assessment of Energy-related PROducts
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RCI	Responsible Cobalt Initiative
RED	Radio Equipment Directive
REE	Rare Earth Elements
RNC	Radio Network Controller
ROHS	Restriction of Hazardous Substances Directive
SD	Storage Device
SGSN	Serving GPRS Support Node
SIM	Subscriber Identity Module
SMD	Surface Mount Device
SoC	State of Charge
	System on a Chip
SVHC	Substance of Very High Concern
TACS	Total Access Communication System
TBBPA	Tetrabromobisphenol A
TCPP	Phosphoric acid tris (2-chloro-1-methylethyl) ester
TDCPP	tris (1,3-dichloro-2-propyl) phosphate

TDMA	Time Division Multiple Access
TD-CDMA	Time Division Synchronous Code Division Multiple Access
TD-SCDMA	Time Division Synchronous Code Division Multiple Access
TWG	Technical Working Group
UMTS	Universal Mobile Telephone System
UN	United Nations
UPA	Universal Power Adaptor
USB	Universal Serial Bus
vPvB	very Persistent and very Bio-accumulative
WEEE	Waste Electrical and Electronic Equipment
WiFi	Wireless Fidelity
WMSC	Wideband CDMA Mobile Switching Centre
W-CDMA	Wideband CDMA Mobile Switching Centre

EXECUTIVE SUMMARY

Improving the material efficiency of products has the potential of bringing benefits to the environment and to the economy, by saving resources and avoiding production of waste. However, improved design of products needs to be assisted by appropriate assessment methods.

In this context, the Joint Research Centre Directorate B, Circular Economy & Industrial Leadership unit (JRC B.5), prepared a guidance for the assessment of material efficiency of products (GAME) addressing two practical targets:

- The identification of key material efficiency aspects of products;
- The definition of tangible improvement measures.

The guidance, which is described in this report in parallel to its application to smartphones, is based on the analysis of technical and functional aspects of products, as well as on the definition of life cycle assessment scenarios targeting environmental and economic impacts. The product group "smartphones" is used as an illustrative case study to show how to implement this guidance for the analysis. Possible actions for improving the performance of smartphones with respect to material efficiency are investigated. Aspects like durability, reparability, upgradability, recyclability and use of materials are analysed.

Resembling the methodology for the ecodesign of energy-related product (MEErP), the analysis was carried out in the following steps:

1. Product group definition - The scope of the analysis is defined, legislative references identified as well as relevant testing methods;
2. Market - The market of the product is characterised, particularly in relation with practices promoting a more circular economy;
3. User behaviour - How consumers use and interact with the product is analysed;
4. Technical aspects - Technical elements for the analysis of material efficiency and system aspects are provided;
5. Material efficiency hotspots - Life Cycle Assessment and Life Cycle Cost impacts are quantified for alternative scenarios based on the information gathered;
6. Definition of possible design measures for improving material efficiency - Possible measures that could improve the material efficiency of the analysed product are defined.

Main findings related to the application of the guidance to smartphones are provided below.

Different organisations have been working worldwide for the development of standards and labels on smartphones (Section 1) which can be used as a starting point for improving the material efficiency and the sustainability of the product.

The market sales of new smartphones globally appear to have slowed down in recent years, while the 2nd-hand market has slightly increased in size (Section 2). Two main business strategies of manufacturers and service providers can be outlined: i) focusing on the upgrade of models and the integration of new technological features; and ii) contributing to the development of circular business models that can allow retaining the product's value (e.g. via more durable/reparable designs).

Smartphones are on average replaced by users every two years (Section 3). In more than half of the cases, the replacement was found to be due to the user wanting a new model/software (in absence of failures). Results may differ from one country to another. The technical lifetime of smartphones could be reasonably extended.

From a technological point of view, functionality of smartphones has been increasing over time, with consequent increase of power demand, storage capacity and materials needed (Sections 4.1 and 2).

Smartphones are made of a variety of materials, some of them used in very small quantities but of global concern because of their social, economic and geopolitical impacts (CRM and minerals from conflict-affected and high-risk areas). At the end of life, smartphones are typically left unused at home (one out of two). This diverts resources from processes aimed at the reuse, recycling and recovery of materials (Sections 4.2 and 4.4.).

Limiting states of smartphones are often associated to a failure of screens and batteries. The upgradability of Operating System, firmware and software (i.e. security updates/patches) are also important aspects to ensure the longevity of smartphones (Section 4.3). Design strategies followed by manufacturers to extend the lifetime of smartphones focus on reliability and resistance of the device and/or on their reparability/upgradability.

A broad variety of products is available on the market that presents different functionalities, characteristics and impacts. Life Cycle Thinking can be used to better understand trade-offs and investigate if any material efficiency strategy can be prioritised over the others (Section 5). In the case of smartphones, it was found that remanufacturing and reuse should come first, followed by extending the years of use of the device, especially in absence of repair interventions. The impact of replacing a battery appears in particular low if compared to the benefits achievable with an extension of the product lifetime. It should also be observed that benefits from the use of second-hand devices could be partially offset by an increase of the global purchase of smartphones. Recycling can be then considered as a complementary strategy to recover precious metals and critical materials.

Significant impacts from the life cycle of smartphones are associated to data consumption and related communication infrastructures, which constitute an "invisible" source of impact of which to make consumers, operators and policy makers more aware. On the other hand, energy consumption due to the recharge of the battery seems to play only a secondary role. Moreover, service contracts appear the most important cost for consumers along the life cycle of the product (Section 5).

A series of possible measures to improve the material efficiency of smartphones has been presented based on the information gathered (Section 6). These cover both technical and behavioural aspects of smartphones since also consumers can play a dramatic role in determining the life cycle impact of their devices.

Results of the study could be used for the integration of material efficiency aspects in decision-making processes targeting the design, manufacture and purchase of smartphones.

It should be remarked that results are general in nature, so that do not take into account the characteristics of specific models on the market, and should not be extended directly to other product categories. However, these can serve as an information basis for broader discussion about the possible regulation and standardisation of ICT products.

The guidance could be moreover adapted to the specificities of any product on the market, and integrated in ecodesign, energy labelling and eco-labelling studies aimed at identifying measures to improve the sustainability of product groups. In this respect, the guidance is considered compatible with the MEErP. The integration in MEErP of the aspects described in this study is recommended to handle material efficiency aspects in Ecodesign.

The study also highlights that the discussion on material efficiency is complex and can be limited by lack of quantitative information and data. As remedy to such limitation, the study was conducted through a structured consultation process involving stakeholders with different backgrounds and interests (e.g. representatives of manufacturers, repairers, recyclers, NGOs and testing organisations, Member States and scientific institutions). From the one hand, this has allowed access to best available information from alternative sources; from the other hand, this has allowed a quality check of the information reported. As a general rule it is thus remarked the importance of engaging with a comprehensive and heterogeneous pool of stakeholders, as well as to interpret, analyse critically and report transparently the information processed and any result proceeding from modelling activities.

INTRODUCTION

The Communications from the Commission COM(2015) 614 "Closing the loop – An EU action plan for the Circular Economy" and COM(2016) 773 "Ecodesign Working Plan 2016-2019" point out the increased importance of improving the resource efficiency of products in order to promote a transition towards a more circular economy in the EU. This can be for instance supported through a series of measures aiming to make products more durable, easier to repair, reuse or recycle.

Improving the material efficiency of products has the potential of bringing benefits to the environment and to the economy, by saving resources and avoiding production of waste. However, improved design of products needs to be assisted by appropriate assessment methods. The importance of assessment and verification procedures is also confirmed by the recent creation of the CEN/CENELEC JTC10 "Energy-related products – Material Efficiency Aspects for Ecodesign", which is working on the development of general standards on material efficiency aspects for Energy-related Products (ErP).

In this context, the Commission has launched a research study focused on the assessment of material efficiency aspects for smartphones, and aimed at compiling a list of possible measures for improving their performance with respect to circular economy aspects such as durability, reparability and upgradability, use of materials and recyclability. The study, entrusted by DG ENV to the Joint Research Centre Directorate B, Circular Economy & Industrial Leadership unit (JRC B.5), will follow a guidance for the assessment of material efficiency (GAME), which is described in the present document while applied to the analysis of smartphones.

GAME was prepared by JRC B.5 to support the assessment of material efficiency of products and the definition of possible improvement measures in those areas. The guidance is targeted at the achievement of two practical goals:

1. Identification of key material efficiency aspects of products;
2. Proposal of tangible improvement measures.

The guidance builds on in-house knowledge about the application of Life Cycle Assessment (LCA) to product policy (Cordella et al. 2015; Cordella and Hidalgo 2016), the analysis of material efficiency aspects of energy-related products (Alfieri et al. 2018a; Cordella et al. 2018a; Cordella et al. 2019a), the analysis, development and implementation of regulations on products (Cordella et al. 2018b, 2019b), as well as on former methodological work carried out in the JRC (Ardente and Mathieux 2014).

The following steps were defined resembling the methodology for the ecodesign of energy-related product (MEErP)[1]:

1. Product group definition (scope, legislation and testing methods of interest);
2. Market characterisation;
3. Information on user behaviour;
4. Analysis of technical and system aspects;
5. Definition of a framework for the life cycle assessment of material efficiency hotspots;
6. Definition of improvement measures.

As described in the respective chapters, these are based on the analysis of technical and functional aspects of products, as well as on the definition of life cycle scenarios and the further assessment of environmental and economic impacts.

A Technical Working Group (TWG) of experts, consisting of manufacturers, retailers, repairers, recyclers, academia, environmental and consumer NGOs, as well as experts working in relevant authorities of Member States, was

[1] https://ec.europa.eu/growth/industry/sustainability/ecodesign_en (accessed on 12 November 2019)

created to provide input to the study. Two written consultations were planned to get technical input and feedback from stakeholders:

- The first consultation took place from 23 April to 21 May 2018;
- The second consultation took place from 6 May to 3 June 2019.

Background information about the study are available on a dedicate website (http://susproc.jrc.ec.europa.eu/E4C/index.html). It is anticipated that results of the study could feed into work on actions covered under the Circular Economy Action Plan and related to product policy[2] and the Ecodesign task force for ICT products[3].

[2] COM(2015) 614
[3] COM(2016) 773

1 PRODUCT GROUP DEFINITION

The first step of the guidance for the assessment of material efficiency is

1. To define the product group to be analysed (i.e. smartphones, in this case), and
2. To identify reference legislation and relevant testing methods with which to shape possible improvement measures.

1.1 Scoping

1.1.1 Key definitions

Some general definitions were found in a few voluntary labelling and certification schemes, as described in the table below. As apparent, no standard definition is used internationally for this fast developing product group.

Table 1: Definitions provided in different labelling and certification schemes

Reference	Scope	Definition
RAL-UZ 106 (2017) - Blue Angel Eco-Label for Mobile Phones	Mobile phones	Mobile phones, i.e. portable, cordless phones that transmit telephone calls via mobile phone networks. The mobile phone is equipped with a module (SIM card) which allows the identification of the individual subscriber. In addition to the telephony function the mobile phone can provide several other functions, such as, for example, transmission of text messages, mobile use of Internet services, execution of programmes or recording and replay of video and audio signals. Mobile phones are also called cellular phone, cell phone, or smartphone - and many Germans call their mobile phone "handy"[4].
TCO Certified Smartphones 2.0	Smart-phones (display sizes ≥ 3" to ≤ 6")	The intended use of a Smartphone is portable computing and mobile communication. A Smartphone is an electronic device used for long-range communication over a cellular network of specialized base stations known as cell sites. It must also have functionality similar to a wireless, portable computer that is primarily for battery mode usage and has a touch screen interface. Connection to mains via an external power supply is considered to be mainly for battery charging purposes and an onscreen virtual keyboard or a digital pen is in place of a physical keyboard.
UL Standard 110, Edition 2 - Standard for Sustainability for Mobile Phones (2017)	Mobile phones	A wireless handheld device that is designed to send and receive transmissions through a cellular radiotelephone service including only the device itself and not packaging or accessories. Slates/tablets, as defined in the most recent applicable version of Energy Star specification, are excluded from this definition.

1.1.2 Product classification

Some characteristics to classify smartphones are reported in Table 2 (OCU 2018a).

[4] The former definition, used in 2013 version of RAL-UZ 106 was "Mobile phones include "Handys" (as the Germans call mobile phones) and smart phones using the LTE (often also called 4G), HSDPA (3G+), UMTS (3G) or GSM standard (2G). The devices shall be primarily designed for making phone calls, text messaging and/or the mobile use of internet services. The size of the visible display is used to distinguish mobile phones from mobile computers (e.g. tablet PCs). Thus, devices with a maximum visible display size of 100 cm^2 are considered as mobile phones, provided that they meet the above requirements"

Table 2: Examples of key characteristics that can be used to classify smartphones (OCU 2018a)

Part	Characteristics
Display	> 5.5" (Phablets) 5-5.5" (Medium-size smartphones) < 5" (Small-size smartphones)
Operating System (OS)	iOS (Apple) vs. Android
Memory	> 11-17 GB (iOS), > 8-13 GB (Android), external micro SD
Battery	2000-5000 mAh (theoretical vs. real)[5]
Camera	5-23 MP (back), 1-16 MP (front) Hardware (e.g. 1 vs. 2 back cameras) and software 4K, full HD, HD (video)

1.1.3 Scope of the study

For the purposes of this study, a smartphone is described as follows:

- A smartphone is a handheld electronic device designed for mobile communication (making phone calls, text messaging), internet connection and other uses (e.g. multimedia, gaming).
- It can be used for long-range communication over a cellular network of specialized base stations known as cell sites[6].
- It is functionally similar to tablets and other wireless, portable computers, since

  - designed for battery mode usage, and connection to mains via an external power supply is mainly for battery charging purposes,

  - presenting an operating system[7], WiFi connectivity, web browsing capability, and ability to accept original and third-party applications (Apps),
- It has a display size between 4 and 6.5 inches, a high-resolution touch screen interface in place of a physical keyboard, a fissure for a Subscriber Identity Module (SIM), and usually a camera.

In particular, the following functions and technical specifications seem to be important for consumers:

- Size of the screen, camera, quality aspects as reliability and screen resolution (Kantar World Panel 2017),
- Longevity of battery, internet access, and high specification camera (Benton et al. 2015).
- Availability of operating system updates, which do not decrease the operating speed of the device (also known as "software obsolescence").

Basic mobile phones, feature phones[8] and smart-watch phones are not considered in the scope of this study. Tablets are also not investigated in this study, although they can be considered similar to smartphones[9].

[5] Main sources of energy consumption: display, web browsing, watching videos, GPS
[6] These include GSM standard (2G), UMTS (3G), HSDPA (3G+), LTE (often also called 4G), 5G, or similar
[7] For examples: Google's Android, BlackBerry OS, Apple's iOS, Nokia's Symbian, Microsoft's Windows Phone, or similar
[8] A feature phone is a mobile phone that incorporates features such as the ability to access the Internet and store and play music but lacks the advanced functionality of a smartphone.
[9] Compared to smartphones, it can be considered that tablets: i) typically use the same operating system (e.g. iOS or Android) and interaction techniques; ii) use similar processors, cameras, loudspeakers and internal circuits, although display, batteries and few other components are bigger; iii) use similar form-factor, construction and assembly techniques and materials; iv) normally do not provide the capability of using the mobile network for "voice conversation", although voice capabilities are anyhow possible using VoIP applications (e.g. Facetime, Messenger, Telegram, Viber).

1.2 Legislative context and testing methods

This section describes legislative aspects that can influence material efficiency of the product (e.g. repair and/or upgrade, use of materials). Testing methods and standards used worldwide to assess and verify material efficiency of the product are also presented.

1.2.1 Safety

1.2.1.1 General Product Safety Directive

The General Product Safety Directive (GPSD) 2001/95/EC aims to ensure that only safe products are made available on the market. The GPSD applies in the absence of other EU legislation, national standards, Commission recommendations or codes of practice relating to safety of products. It also complements sector specific legislation. Specific rules exist for the safety of toys, electrical and electronic goods, cosmetics, chemicals and other specific product groups[10]. The GPSD establishes obligations to both businesses and Member States' authorities:

- Businesses should place only products that are safe on the market, inform consumers of any risks associated with the products they supply. They also have to make sure any dangerous products present on the market can be traced so they can be removed to avoid any risks to consumers.
- Member States, through their appointed national authorities, are responsible for market surveillance to check that products on the market are safe. Information about dangerous products found on the market has to be reported to the Rapid Alert System for non-food dangerous products (RAPEX).

1.2.1.2 Radio Equipment Directive

The Radio Equipment Directive 2014/53/EU (RED) ensures a Single Market for radio equipment by setting essential requirements for safety and health, electromagnetic compatibility, and the efficient use of the radio spectrum. It applies to all products using the radio frequency spectrum, including smartphones.

The Radio Equipment Directive requires that manufacturers ensure that the radio equipment is accompanied by instructions and safety information. Such information has to include, where applicable, a clear description of accessories and components, including software, which allow the radio equipment to operate as intended.

In the recital of the Radio Equipment Directive there is moreover a clear reference to mobile phones and their compatibility with a common charger.

1.2.1.3 Main standards and testing methods

Main standards and testing methods on safety include:

- IEC 60065:2014 - Audio, video and similar electronic apparatus - Safety requirements.
- IEC 60950-1:2005+AMD1:2009+AMD2:2013 CSV - Information technology equipment - Safety - Part 1: General requirements.
- IEC 62209-1:2016 - Measurement procedure for the assessment of specific absorption rate of human exposure to radio frequency fields from hand-held and body-mounted wireless communication devices. Devices used next to the ear (Frequency range of 300 MHz to 6 GHz).
- IEC 62368-1:2014 - Audio/video, information and communication technology equipment - Part 1: Safety requirements.

[10] https://ec.europa.eu/info/business-economy-euro/product-safety-and-requirements/consumer-product-safety/standards-and-risks-specific-products_en (accessed on 27 February 2019)

1.2.2 Chemicals

1.2.2.1 CLP Regulation

The Classification, Labelling and Packaging (CLP) Regulation (EC) No 1272/2008 is based on the UN's Globally Harmonised System (GHS) and its purpose is to ensure a high level of protection of health and the environment, as well as the free movement of substances, mixtures and articles.

Since 1 June 2015, CLP is the only legislation in force in the EU for classification and labelling of substances and mixtures. CLP is legally binding across the Member States and directly applicable to all industrial sectors. It requires manufacturers, importers or downstream users of substances or mixtures to classify label and package their hazardous chemicals appropriately before placing them on the market. Hazard classes used in CLP cover physical, health, environmental and additional hazards.

CLP is also the basis for many legislative provisions on the risk management of chemicals. In addition, the notification obligation under CLP requires manufacturers and importers to submit classification and labelling information for the substances they are placing on the market to a database (the "C&L Inventory") held by the European Chemical Agency (ECHA).

1.2.2.2 REACH Regulation

The Regulation (EC) No 1907/2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) aims to improve the protection of human health and the environment from the risks that can be posed by chemicals because of their intrinsic properties. REACH establishes procedures for collecting and assessing information on the properties and hazards of substances.

Companies are responsible for collecting and communicating information on the properties and uses of the substances they manufacture, import or use in their products above one tonne a year. Depending on the volume of the substance, different rules apply. The Regulation also calls for the progressive substitution of the most dangerous chemicals (referred to as "Substances of Very High Concern") when suitable alternatives have been identified. SHVCs are defined as:

1. Substances meeting the criteria for classification as carcinogenic, mutagenic or toxic for reproduction (CMR) category 1A or 1B in accordance with the CLP Regulation.
2. Substances which are persistent, bio-accumulative and toxic (PBT) or very persistent and very bio-accumulative (vPvB) according to REACH Annex XIII.
3. Substances on a case-by-case basis, which cause an equivalent level of concern as CMR or PBT/vPvB substances.

Once a substance is identified as an SVHC, it is included in the Candidate List. ECHA regularly assesses the substances from the Candidate List to determine which ones should be included in the Authorisation List (Annex XIV). Once a substance is included in an Authorisation List, this can be used/produced only if

a. The risk to human health or the environment is adequately controlled, or
b. It can be demonstrated that the socio-economic benefits compensate the impacts, also taking into account possible alternatives

A Restrictions List (Annex XVII) is also periodically revised. Once a substance is included in the Restrictions List, specific or general uses of such substance are prohibited.

Article 33 of REACH establishes the right of consumers to be able to obtain information from suppliers on substances in articles and suppliers of articles are obliged to provide industrial/professional users or distributors with certain pieces of information on articles containing substances with irreversible effects on human health or the environment.

1.2.2.3 ROHS Directive

Smartphones are in the scope of the Restriction of Hazardous Substances Directive 2011/65/EU (ROHS), included as "IT and telecommunications equipment". The legislation restricts the use of certain hazardous substances used in electrical and electronic equipment, which have to be substituted by safer alternatives. As listed in the amended Annex II of the Commission Delegated Directive (EU) 2015/863, restricted substances are:

- Lead (0.1 %)
- Mercury (0.1 %)
- Cadmium (0.01 %)
- Hexavalent chromium (0.1 %)
- Polybrominated biphenyls (PBB) (0.1 %)
- Polybrominated diphenyl ethers (PBDE) (0.1 %)
- Bis(2-ethylhexyl) phthalate (DEHP) (0.1 %)
- Butyl benzyl phthalate (BBP) (0.1 %)
- Dibutyl phthalate (DBP) (0.1 %)
- Diisobutyl phthalate (DIBP) (0.1 %)

The restriction of DEHP, BBP, DBP and DIBP does not apply to cables or spare parts for the repair, the reuse, the updating of functionalities or upgrading of capacity of Electrical and Electronic Equipment (EEE) placed on the market before 22 July 2019. Further exemptions are provided in Annex III and Annex IV.

1.2.3 Materials

1.2.3.1 EU list of Critical Raw Materials (CRM)

The Commission's communication COM(2017) 490 indicates 27 raw materials that can be defined as "critical" because risks of supply shortage and their impacts on the economy are higher than those of most of the other raw materials (see Table 3).

Table 3: EU list of Critical Raw Materials on 13 September 2017

Raw Material		
1. Antimony	10. Germanium	19. Phosphorus
2. Baryte	11. Hafnium	20. Scandium
3. Beryllium	12. Helium	21. Silicon metal
4. Bismuth	13. Indium	22. Tantalum
5. Borate	14. Magnesium	23. Tungsten
6. Cobalt	15. Natural graphite	24. Vanadium
7. Coking coal	16. Natural rubber	25. Platinum Group Metals
8. Fluorspar	17. Niobium	26. Heavy Rare Earth Elements
9. Gallium	18. Phosphate rock	27. Light Rare Earth Elements

1.2.3.2 Import of minerals from conflict-affected and high-risk areas

The EU Regulation 2017/821 establishes a Union system for supply chain due diligence in order to curtail opportunities for armed groups and security forces to trade in tin, tantalum and tungsten, their ores, and gold. Minerals and metals covered by the EU Regulation 2017/821 are listed in Table 4.

Table 4: Conflict minerals and metals covered by the EU Regulation 2017/821

Description	Volume threshold (kg)
Tin ores and concentrates	5 000
Tungsten ores and concentrates	250 000
Tantalum or niobium ores and concentrates	To be adopted no later than 1 July 2020
Gold ores and concentrates	To be adopted no later than 1 July 2020
Gold, unwrought or in semi-manufactured forms, or in powder with a gold concentration lower than 99,5 % that has not passed the refining stage	100
Tungsten oxides and hydroxides	100 000
Tin oxides and hydroxides	To be adopted no later than 1 July 2020
Tin chlorides	10 000
Tungstates	100 000
Tantalates	To be adopted no later than 1 July 2020
Carbides of tungsten	10 000
Carbides of tantalum	To be adopted no later than 1 July 2020
Gold, unwrought or in semi-manufactured forms, or in powder form with a gold concentration of 99,5 % or higher that has passed the refining stage	100
Ferrotungsten and ferro-silico-tungsten	25 000
Tin, unwrought	100 000
Tin bars, rods, profiles and wires	1 400
Tin, other articles	2 100
Tungsten, powders	2 500
Tungsten, unwrought, including bars and rods obtained simply by sintering	500
Tungsten wire	250
Tungsten bars and rods, other than those obtained simply by sintering, profiles, plates, sheets, strip and foil, and other	350
Tantalum, unwrought including bars and rods, obtained simply by sintering; powders	2 500
Tantalum bars and rods, other than those obtained simply by sintering, profiles, wire, plates, sheets, strip and foil, and other	150

This Regulation, which took effect on 1 January 2012, was designed to provide transparency and certainty as regards the supply practices of Union importers, and of smelters and refiners sourcing minerals and metals from conflict-affected and high-risk areas. Union importers of these minerals or metals have disclosure obligations:

- Make available to Member State competent authorities the reports of any third-party audit carried out or evidence of conformity with a supply chain due diligence scheme recognised by the Commission;
- Make available to their immediate downstream purchasers all information gained and maintained pursuant to their supply chain due diligence with due regard for business confidentiality and other competitive concerns;
- Publicly report as widely as possible, including on the internet, on their supply chain due diligence policies and practices for responsible sourcing.

Where a Union importer can reasonably conclude that metals are derived only from recycled or scrap sources, it has to disclose publicly its conclusion and describe in detail the supply chain due diligence measures exercised. With the exception of this disclosure requirement, this Regulation does not apply to recycled metals.

1.2.3.3 Main standards and testing methods

Main standards and testing methods on materials have been identified only for plastics:

- ISO 1043-1:2011 - Plastics - Symbols and abbreviated terms - Part 1: Basic polymers and their special characteristics. The standard defines abbreviated terms for the basic polymers used in plastics, symbols for components of these terms, and symbols for special characteristics of plastics.
- ISO 1043-2:2011- Plastics - Symbols and abbreviated terms - Part 2: Fillers and reinforcing materials. The standard specifies uniform symbols for terms referring to fillers and reinforcing materials.
- ISO 1043-3:2016 - Plastics - Symbols and abbreviated terms - Part 3: Plasticizers. The standard provides uniform symbols for components of terms relating to plasticizers to form abbreviated terms.
- ISO 1043-4:1998 - Plastics - Symbols and abbreviated terms - Part 4: Flame retardants. The standard provides uniform symbols for flame retardants added to plastics materials.
- ISO 11469:2016 - Plastics - Generic identification and marking of plastics products. The standard specifies a system of uniform marking of products that have been fabricated from plastics materials. Provision for the process or processes to be used for marking is outside the scope of this International Standard.

1.2.4 Functional and performance aspects

1.2.4.1 External power supply

External Power Supplies (EPS) are subject to the EU ecodesign regulation (EC) No 278/2009. They convert power input from the mains into lower voltage output for smartphones and a large variety of other electric and electronic products.

Ecodesign requirements for EPS are mandatory for all manufacturers and suppliers wishing to sell their products in the EU. These requirements cover both the "active" efficiency, i.e. the average efficiency when power is supplied to, and the "no-load" power consumption, i.e. the power that the supply still uses when connected to the power mains but not supplying electricity to any device.

An EU Code of Conduct (CoC) on Energy efficiency of EPS is also available, the version 5 being released in 2013. The Code of Conduct is a voluntary initiative targeting single voltage external AC/DC and AC/AC power supplies for electronic and electrical appliances, which also include mobile phone chargers. The initiative aims to minimise the energy consumption of external power supplies both under no-load and load conditions in the output power range 0.3W to 250W.

At international level, the U.S. EPA developed an international efficiency marking protocol for EPS. This provides a system to designate the minimum efficiency performance of an EPS, so that finished product manufacturers and government representatives can easily determine a unit's efficiency. This mark demonstrates the performance of the EPS when tested to the internationally supported test methods (U.S. Department of Energy 2013).

In June 2009, a campaign[11] for the introduction of a voluntary agreement for a common charger for mobile phones was launched. many of the world's largest mobile phone manufacturers signed an EC-sponsored Memorandum of Understanding (MoU), agreeing to make most new data-enabled mobile phones marketed in the European Union compatible with a to-be-specified common EPS. All signatories agreed to develop a common specification for the EPS to allow for full compatibility and safety of chargers and mobile phones. The standard was published in December 2010 as EN 62684:2010 "Interoperability specifications of common EPS for use with data-enabled mobile telephones" and in January 2011 as IEC 62684:2011. Vencovsky et al. (2014) found that 99% of data-enabled phones sold in Europe in 2013 were compliant with the MoU. An updated version of IEC 62684:2018 has been published this year that makes it clearer that compliance with the MoU is equivalent to compliance with the standard. This standard specifies the interoperability based on Micro USB-B technologies. According to this standard, the EPS must operate in the following ranges:

- 100-230 V
- 50-60 Hz
- 0 to 35 °C
- Up to 90% of relative humidity.

USB Micro-B is currently giving way to USB Type-C. Many manufacturers (Apple, Google, Lenovo, LG, Motorola, Samsung, and Sony) have signed a new MoU[12] committing that new smartphone models will be chargeable through a USB Type-C connector or cable assembly. For these purposes, the relevant standard is IEC 63002:2016 "Identification and Communication Interoperability Method for External Power Supplies Used with Portable Computing Devices". The objective of this International Standard is to support interoperability of external power supplies used with the increasing variety of portable computing devices that implement the IEC 62680-1-2 "USB Power Delivery" with the IEC 62680-1-3 "USB Type-C" connector standards. Broad market adoption of this International Standard is expected to make a significant contribution to the global goals of consumer convenience and re-usability of power supplies by building a global market system of IEC 62680 compliant devices and facilitating interoperability across different product categories. However, the new agreement still allows manufacturers to use also vendor-specific connectors.

1.2.4.2 Packaging and Packaging Waste Directive

The Packaging and Packaging Waste Directive 2004/12/EC seeks to reduce the impact of packaging and packaging waste on the environment by introducing recovery and recycling targets for packaging waste, and by encouraging minimisation and reuse of packaging. A scheme of symbols, currently voluntary, has been prepared through Commission Decision 97/129/EC. Manufacturers can use them on the packaging of products so that different materials can be identified to assist end-of-life recycling. The latest revision of the Packaging and Packaging Waste Directive was published on 29 April 2015 with the adoption of Directive (EU) 2015/720 of the European Parliament and of the Council amending Directive 94/62/EC as regards the consumption of lightweight plastic carrier bags.

1.2.4.3 Guarantees for consumers

The Consumer Sales Directive 1999/44/EC regulates aspects of the sale of consumer goods and associated legal guarantees. According to the 1999/44/EC Directive, the term guarantee shall mean any undertaking by a seller or producer to the consumer, given without extra charge, to reimburse the price paid or to replace, repair or handle

[11] http://ec.europa.eu/growth/sectors/electrical-engineering/red-directive/common-charger_en (accessed on 9 October 2018)

[12] https://www.digitaleurope.org/wp/wp-content/uploads/2019/01/2018.03.20-MoU%20on%20the%20future%20of%20Common%20Charging%20Solutions%20(1)%20(1)%202.pdf (accessed on 22 February 2019)

consumer goods in any way if they do not meet the specifications set out in the guarantee statement or in the relevant advertising.

The duration of the guarantee for new products must be at least 2 years. The minimum duration is applied in the majority of EU-countries. Longer durations are applied in some countries (e.g. Sweden, Ireland, the Netherlands and Finland) depending on the expected lifespan of the item sold. The duration of the guarantee for second hand goods can be lower (minimum 1 year).

The seller must deliver goods to the consumer, which are in conformity with the contract of sale, and then further specifies presumption of conformity of a number of conditions. All Member States introduced in their national law a "reversal of burden of proof" of at least 1 year. This is the period within which the lack of conformity is presumed to have existed at the time of delivery and the seller is thus liable to the consumer, i.e. the seller must prove that the item was not defective. After six months the burden of proof shifts to the consumer, i.e. the consumer must prove that the product was defective.

Article 3 of the Consumer Sales Directive indicates a list of remedies that should be provided to the consumer in the case of a defect (i.e. repair, replacement, reduction in price and rescission of contract). In the first place, the consumer may require the seller to repair the goods or he may require the seller to replace them.

In addition, Directive 2011/83/EU on consumer rights defines the concept of "commercial guarantee" (also known as "warranty"), which can be offered by sellers or producers in addition to the legal guarantee obligation. This can either be included in the price of the product or at an extra cost.

The average consumer does not seem to be aware of the provisions set by legal guarantees. At EU level, awareness of commercial guarantees lies at 67% while only 35% are also aware of the legal guarantee period in their country: the majority of consumers in half of EU Member States think that the legal guarantee period is a single year. Additional coverage over a wider range of cases (e.g. accidental damage, water damage) is increasingly being offered to consumers as a complimentary service, in sales campaigns or in return for additional payment (Watson et al. 2017).

The European Commission proposed "A New Deal for Consumers" package in 2018[13] consisting of

1. The revision of the Injunctions Directive 2009/22/EC ('Representative Actions Proposal'), with a view of fully exploiting the potential of injunctions by addressing the main problems faced by consumers in obtaining redress, and by diminishing significant disparities among Member States in the level of the use of the injunction procedure and its effectiveness.
2. A proposal to amend Directive 93/13/EEC on unfair terms in consumer contracts, Directive 98/6/EC on consumer protection in the indication of the prices of products offered to consumers, Directive 2005/29/EC concerning unfair business-to-consumer commercial practices and Directive 2011/83/EU on consumer rights ('Proposal on better enforcement and modernisation).

The European Parliament and the Council adopted the Directive (EU) 2019/2161 on better enforcement and modernisation of EU consumer protection. The work on the Representative Actions Proposal continues in the European Parliament and Council[14]. The main improvements will be more transparency for consumers when buying online, effective penalties and clear rules to tackle the issue of dual quality of products in the EU[15].

[13] http://www.europarl.europa.eu/legislative-train/theme-area-of-justice-and-fundamental-rights/file-new-deal-for-consumers (accessed on 18 April 2018)

[14] https://ec.europa.eu/info/law/law-topic/consumers/review-eu-consumer-law-new-deal-consumers_en (accessed on 7 January 2020)

[15] https://ec.europa.eu/commission/presscorner/detail/en/IP_19_1755 (accessed on 7 January 2020)

1.2.4.4 Durability and reparability

The European Parliament[16] called the EU Commission, Member States and producers to take measures to ensure consumers can enjoy durable, high-quality products that can be repaired and upgraded. Recommendations include:

- "Minimum resistance criteria" to be established for each product category from the design stage
- Extension of guarantees to fully cover periods of time in which repair is expected
- Promotion of repairs and second-hand sales
- Avoidance of technical, safety or software solutions which prevent repairs from being performed, other than by approved firms or bodies
- Ease of disassembly of essential components (such as batteries and displays), unless for safety reasons
- Availability of spare parts which are indispensable for the proper and safe functioning of the goods "at a price commensurate with the nature and life-time of the product"
- Introduction of an EU-wide definition of "planned obsolescence" and of a system that could test and detect the "built-in obsolescence", as well as "appropriate dissuasive measures for producers".
- Development of an EU label to inform consumers better about product's durability, ecodesign features, upgradeability in line with technical progress and reparability.

At Member State level, the French decree 2014-1482 published in December 2014[17] put new requirements on retailers to inform consumers about the durability of their products and the availability of spare parts, under the threat of fine of 15000 EUR. Manufacturers are required to deliver the parts needed for repairs within two months. The French decree also extends the burden of proof on the seller in the case of a fault within 24 months. Planned obsolescence is also a legal offence punishable by 300000 EUR. Planned obsolescence is defined by the French decree as "all techniques by which a producer seeks to deliberately limit product life in order to increase the replacement rate" (Transform Together 2018).

In addition, the VAT on the repair of certain products has been lowered in Sweden, where repair costs are also tax deductible to further stimulate repairs. In Belgium, VAT is set at 6% for the repair of bicycles, shoes and clothes[18]. However, ICT products are not yet covered in these countries (Transform Together 2018).

Out of the legislative context, some manufacturers claim to meet specific standards and certifications to ensure a more durable smartphone:

- The Galaxy S8 Active claims to be tested to achieve both MIL-STD-810G[19] specification and IP68 certification[20]. This MIL-STD (also called MIL-SPEC, military standard, or MilSpecs) was developed by the U.S. Defense Department to test the resistance of devices under harsh conditions of use. Phones meet MIL-SPEC by undergoing a range of trials, among which a Transit Drop Test (Method 516.6 Procedure IV).
- A specific test method is also proposed by CTIA Certification, with a Device Hardware Reliability Test Plan (version 1.1) published in August 2017[21]. CTIA Hardware Reliability Certification is a voluntary initiative run by a trade association for the American market.
- IEC 60529 - Degrees of protection provided by enclosures (IP Code) (Table 5) is an important standard to classify products based on the degrees of protection provided against the intrusion of solid objects (including body parts like hands and fingers), dust, accidental contact, and water in electrical enclosures. The standard aims to provide users more detailed information than vague marketing terms such as waterproof. This standard defines the IP codes, which are designed as a "system for classifying the degrees of protection provided by the enclosures of electrical equipment". The IP Code (or International Protection Rating, sometimes also interpreted as Ingress Protection Rating) consists of the letters IP

[16] http://www.europarl.europa.eu/doceo/document/A-8-2017-0214_EN.pdf (accessed on 7 January 2020)
[17] Decree No. 2014-1482 of 9 December 2014 concerning Disclosure Requirements and Supply of Spare Parts
[18] https://www.unizo.be/advies/welke-btw-tarieven-moet-u-toepassen (accessed on 30 May 2018)
[19] MIL-STD-810G available at http://everyspec.com/MIL-STD/MIL-STD-0800-0899/MIL-STD-810G_12306/ (accessed on 12 March 2019)
[20] https://insights.samsung.com/2017/08/11/drop-testing-samsungs-most-durable-smartphone-2/ (accessed on 13 February 2018)
[21] https://api.ctia.org/docs/default-source/certification/ctia-device-hardware-reliability-test-plan-ver-1-1.pdf (accessed on 7 June 2018)

followed by two digits and an optional letter. The first number (from 0 to 6) in the rating code represents the degree of protection provided against the entry of foreign solid objects, such as fingers or dust (Table 6). The second number (from 0 to 8) represents the degree of protection against the entry of moisture (Table 7). IP67 and IP68 are the highest level of protection claimed by some manufacturers. An IP code with an "X" in place of the first or second number means that a device has not been tested with respect to the corresponding type of protection. Devices are not required to pass every test below the claimed rating, although many companies test their smartphones at various protection levels. Examples of how some devices are rated by manufacturers:

- The iPhone 8 and 8 Plus are rated with an IP67 rating, which means that they are fully protected from dust (6) and can also withstand being submerged in 1m of static water for up to 30 minutes (7).

- The Samsung Galaxy S8 is rated IP68. This means that, like the iPhone 8 (and 8 Plus), the Galaxy S8 can withstand being submerged in static water, but the specific depth and duration must be disclosed by the company, which in this case is 1.5 meters for up to 30 minutes.

- The Sony Xperia XZ is rated with an IP65 and IP68 rating, meaning that it is protected from dust and against low-pressure water jets, such as a faucet, when all ports are closed. The company also specifies that the Z5 can be submerged in 1.5 meters of fresh water for up to 30 minutes.

Table 5: meaning of IP codes used to claim the Smartphone's level of protection

IP codes	First Digit - SOLIDS	Second Digit - LIQUIDS
IP67	Protected from total dust ingress.	Protected from immersion between 15 centimetres and 1 meter in depth.
IP68	Protected from total dust ingress.	Protected from long-term immersion up to a specified pressure.

Table 6: Solid protection levels set by the IEC 60529[22]

Level	Effective against	Description
0	-	No protection against contact and ingress of objects
1	>50 mm	Any large surface of the body, such as the back of a hand, but no protection against deliberate contact with a body part
2	>12.5 mm	Fingers or similar objects
3	>2.5 mm	Tools, thick wires, etc.
4	>1 mm	Most wires, slender screws, large ants etc.
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
6	Dust tight	No ingress of dust; complete protection against contact (dust tight). A vacuum must be applied. Test duration of up to 8 hours based on air flow

[22] https://www.cnet.com/how-to/how-waterproof-are-the-new-iphones-heres-what-all-the-ratings-mean/ (accessed on 13 February 2018)

Table 7: Moisture protection levels set by the IEC 60529[23]

Level	Protection against	Effective against	Details
0	None	-	-
1	Dripping water	Dripping water (vertically falling drops) shall have no harmful effect on the specimen when mounted in an upright position onto a turntable and rotated at 1 RPM.	Test duration: 10 minutes Water equivalent to 1 mm rainfall per minute
2	Dripping water when tilted at 15°	Vertically dripping water shall have no harmful effect when the enclosure is tilted at an angle of 15° from its normal position. Four positions are tested within two axes.	Test duration: 2.5 minutes for every direction of tilt (10 minutes total) Water equivalent to 3 mm rainfall per minute
3	Spraying water	Water falling as a spray at any angle up to 60° from the vertical shall have no harmful effect, utilizing either: a) an oscillating fixture, or b) A spray nozzle with a counterbalanced shield. Test a) is conducted for 5 minutes, and then repeated with the specimen rotated horizontally by 90° for the second 5-minute test. Test b) is conducted (with shield in place) for 5 minutes minimum.	For a Spray Nozzle: Test duration: 1 minute per square meter for at least 5 minutes Water volume: 10 litres per minute Pressure: 50–150 kPa For an oscillating tube: Test duration: 10 minutes Water Volume: 0.07 l/min per hole
4	Splashing of water	Water splashing against the enclosure from any direction shall have no harmful effect, utilizing either: a) an oscillating fixture, or b) A spray nozzle with no shield. Test a) is conducted for 10 minutes. Test b) is conducted (without shield) for 5 minutes minimum.	Oscillating tube: Test duration: 10 minutes, or spray nozzle (same as IPX3 spray nozzle with the shield removed)
5	Water jets	Water projected by a nozzle (6.3 mm) against enclosure from any direction shall have no harmful effects.	Test duration: 1 minute per square meter for at least 15 minutes Water volume: 12.5 litres per minute Pressure: 30 kPa at distance of 3 m
6	Powerful water jets	Water projected in powerful jets (12.5 mm nozzle) against the enclosure from any direction shall have no harmful effects.	Test duration: 1 minute per square meter for at least 3 minutes Water volume: 100 litres per minute Pressure: 100 kPa at distance of 3 m
6K	Powerful water jets with increased pressure	Water projected in powerful jets (6.3 mm nozzle) against the enclosure from any direction, under elevated pressure, shall have no harmful effects. Found in DIN 40050, and not IEC 60529.	Test duration: at least 3 minutes Water volume: 75 litres per minute Pressure: 1000 kPa at distance of 3 m

[23] https://www.cnet.com/how-to/how-waterproof-are-the-new-iphones-heres-what-all-the-ratings-mean/ (accessed on 13 February 2018)

Level	Protection against	Effective against	Details
7	Immersion, up to 1 m depth	Ingress of water in harmful quantity shall not be possible when the enclosure is immersed in water under defined conditions of pressure and time (up to 1 m of submersion).	Test duration: 30 minutes - ref IEC 60529, table 8. Tested with the lowest point of the enclosure 1000 mm below the surface of the water, or the highest point 150 mm below the surface, whichever is deeper.
8	Immersion, 1 m or more depth	The equipment is suitable for continuous immersion in water under conditions that shall be specified by the manufacturer. However, with certain types of equipment, it can mean that water can enter but only in such a manner that it produces no harmful effects. The test depth and duration is expected to be greater than the requirements for IPx7, and other environmental effects may be added, such as temperature cycling before immersion.	Test duration: Agreement with Manufacturer Depth specified by manufacturer, generally up to 3 m
9K	Powerful high temperature water jets	Protected against close-range high pressure, high temperature spray downs. Smaller specimens rotate slowly on a turntable, from 4 specific angles. Larger specimens are mounted upright, no turntable required, and are tested freehand for at least 3 minutes at distance of 0.15–0.2 m. There are specific requirements for the nozzle used for the testing. This test is identified as IPx9 in IEC 60529.	Test duration: 30 seconds in each of 4 angles (2 minutes total) Water volume: 14–16 litres per minute Pressure: 8–10 MPa (80–100 bar) at distance of 0.10–0.15 m Water temperature: 80°C

Test methods are developed and used also by consumers testing organizations (Table 8) in order to test and inform consumers about different performance aspects and durability of their products (e.g. battery performance, resistance to specific stresses as rain, water submersion, shocks).

Table 8: Examples of durability tests carried out by Consumer Testing Organizations[24]

Test Type	Description
Running time test	The running time test is performed by a robot, which repeats a list of common tasks until the battery is empty. This includes voice calls, standby, playback of on-line videos, taking of pictures, scrolling on digital maps.
Rain test	The mobile phones are switched on and connected to a network. A measurement according to EN 60529 - 2000-09 is performed. A raining appliance is used to give an even rain distribution according to IPx1 (7.2 l/h). The phones lie horizontally on a rotary table and are irrigated for 5 minutes. The correct function is assessed immediately, after one day, after 2 days and after 3 days.
Water resistance submersion	Only devices that are claimed to be waterproof (IPxx) are tested. They are submerged into water tube at the stated maximum depth for 30 minutes to verify the waterproofness. The correct functioning is assessed immediately, after one day, after 2 days and after 3 days.
Shock resistance tumble test	The durability against mechanical shocks (e.g. drops) is tested with a tumbling barrel to simulate an 80 cm fall against a stone surface, as described in EN 60065. Handsets are switched on and set into operation (call) and are put into a tumbling drum (tumbling height of 80 cm) for 50 rotations (100 drops) and the damages are checked after each 25 and 50 rotations.
Scratch resistance test	The scratch resistance of the phones' displays and their bodies is examined. Therefore, a hardness test pencil (ERICHSEN, Model 318 S) is used. A rating for the display is generated depending on the maximum load that does not lead to permanent scratches on the device under test.

1.2.4.5 Other standards and testing methods

In response to the Commission's Mandate 543[25], the CEN/CENELEC JTC10 "Energy-related products – Material Efficiency Aspects for Ecodesign"[26] has been created. The CEN/CENELEC JTC10 aims to develop general standards on material efficiency aspects for Energy-related Products, which can be used to support the policy making process. The standards, published in 2019 and 2020, will be followed, wherever needed, by vertical implementation (i.e. product-specific standards). Six working groups have been formed:

- WG1: Terminology
- WG2: Durability
- WG3: Reparability, upgradability and reusability
- WG4: Ability to Remanufacture
- WG5: Recyclability, recoverability and recycled content (including critical raw materials)
- WG6: Provision of information (including critical raw materials).

Other standards and testing methods on functional and performance include:

- IEC 61960-3:2017 - Secondary cells and batteries containing alkaline or other non-acid electrolytes. Secondary lithium cells and batteries for portable applications. Prismatic and cylindrical lithium secondary cells, and batteries made from them
- IEC 61966-2-1:1999 - Multimedia systems and equipment - Colour measurement and management - Part 2-1: Colour management - Default RGB colour space – sRGB.

[24] Based on input from Consumers Testing Organisations

[25] M/543 COMMISSION IMPLEMENTING DECISION C(2015)9096 of 17.12.2015 on a standardisation request to the European standardisation organisations as regards ecodesign requirements on material efficiency aspects for energy-related products in support of the implementation of Directive 2009/125/EC of the European Parliament and of the Council

[26] https://www.cenelec.eu/dyn/www/f?p=104:7:1299206399119101::::FSP_ORG_ID:2240017 (accessed on 1 June 2018)

- IEC 62133-1:2017 - Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications – Part 1: Nickel systems
- IEC 62133-2:2017 - Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications – Part 2: Lithium systems
- ISO 3664:2009 - Graphic technology and photography – Viewing conditions
- ISO 3741:2010 - Acoustics -- Determination of sound power levels and sound energy levels of noise sources using sound pressure -- Precision methods for reverberation test rooms
- ISO 3744:2010 - Acoustics -- Determination of sound power levels and sound energy levels of noise sources using sound pressure -- Engineering methods for an essentially free field over a reflecting plane
- ISO 3745:2003 - Acoustics -- Determination of sound power levels of noise sources using sound pressure -- Precision methods for anechoic and hemi-anechoic rooms
- ISO 7779:2010 - Acoustics -- Measurement of airborne noise emitted by information technology and telecommunications equipment
- ISO 9241-400:2007 - Ergonomics of human--system interaction -- Part 400: Principles and requirements for physical input devices.
- ISO 9296:2017 - Acoustics -- Declared noise emission values of information technology and telecommunications equipment
- ISO 11201:2010 - Acoustics -- Noise emitted by machinery and equipment -- Determination of emission sound pressure levels at a work station and at other specified positions in an essentially free field over a reflecting plane with negligible environmental corrections
- ISO 12646:2015 - Graphic technology -- Displays for colour proofing -- Characteristics
- Standard ECMA-74- Measurement of Airborne Noise emitted by Information Technology and Telecommunications Equipment

1.2.5 End-of-Life of the product

1.2.5.1 Waste Directive

Directive 2008/98/EC, amended by Directive (EU) 2018/851, sets the basic concepts and definitions related to waste management, such as definitions of waste, recycling, recovery. It explains when waste ceases to be waste and becomes a secondary raw material (so called end-of-waste criteria), and how to distinguish between waste and by-products. The Directive lays down some basic waste management principles: it requires that waste is managed without endangering human health and harming the environment, and in particular without risk to water, air, soil, plants or animals, without causing a nuisance through noise or odours, and without adversely affecting the countryside or places of special interest. Waste legislation and policy of the EU Member States shall apply as a priority order the following waste management hierarchy:

1. Prevention
2. Preparation for reuse
3. Recycling
4. Recovery
5. Disposal.

The Directive introduces the "polluter pays principle" and the "extended producer responsibility". It incorporates provisions on hazardous waste and waste oils, and includes two new recycling and recovery targets to be achieved by 2020: 50% preparing for re-use and recycling of certain waste materials from households and other origins similar to households, and 70% preparing for re-use, recycling and other recovery of construction and demolition waste. The Directive requires that Member States adopt waste management plans and waste prevention programmes. These also include measures to encourage the design of safer, more durable, re-usable and recyclable products. Annex III of the Waste Framework Directive 2008/98/EC also defines which properties render waste hazardous.

1.2.5.2 Waste Electrical and Electronic Equipment (WEEE) Directive

Smartphones fall in the scope of the WEEE Directive 2012/19/EU as "small IT and telecommunication equipment (no external dimension more than 50 cm)".

According to Article 4, Member States shall encourage cooperation between producers and recyclers and measures to promote the design and production of EEE, notably in view of facilitating re-use, dismantling and recovery of WEEE.

Annex VII of WEEE lists a series of materials and components to remove and collect separately for depollution at the EOL of products:

- Polychlorinated biphenyls (PCB) containing capacitors in accordance with Council Directive 96/59/EC of 16 September 1996 on the disposal of polychlorinated biphenyls and polychlorinated terphenyls (PCB/PCT),
- Mercury containing components, such as switches or backlighting lamps,
- Batteries,
- Printed circuit boards of mobile phones generally, and of other devices if the surface of the printed circuit board is greater than 10 square centimetres,
- Toner cartridges, liquid and paste, as well as colour toner,
- Plastic containing brominated flame retardants,
- Asbestos waste and components which contain asbestos,
- Cathode ray tubes (the fluorescent coating has to be removed),
- Chlorofluorocarbons (CFC), hydrochlorofluorocarbons (HCFC) or hydrofluorocarbons (HFC), hydrocarbons (HC). Equipment containing gases that are ozone depleting or have a global warming potential (GWP) above 15, such as those contained in foams and refrigeration circuits: the gases must be properly extracted and properly treated. Ozone-depleting gases must be treated in accordance with Regulation (EC) No 1005/2009,
- Gas discharge lamps,
- Liquid crystal displays (together with their casing where appropriate) of a surface greater than 100 square centimetres and all those back-lighted with gas discharge lamps,
- External electric cables (the mercury shall be removed),
- Components containing refractory ceramic fibres as described in Commission Directive 97/69/EC of 5 December 1997 adapting to technical progress for the 23rd time Council Directive 67/548/EEC on the approximation of the laws, regulations and administrative provisions relating to the classification, packaging and labelling of dangerous substances,
- Components containing radioactive substances with the exception of components that are below the exemption thresholds set in Article 3 of and Annex I to Council Directive 96/29/Euratom of 13 May 1996 laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation,
- Electrolyte capacitors containing substances of concern (height > 25 mm, diameter > 25 mm or proportionately similar volume)[27]

[27] Substance of concern could be defined based on Annex II of RoHS Directive 2011/65EU (+ exemptions in Annex III and Annex IV); Annex XVII (restriction list) and Annex XIV (authorisation list) of REACH; Annex III of the Waste Framework Directive 2008/98/EC

- These substances, mixtures and components shall be disposed of or recovered in compliance with Directive 2008/98/EC.

Article 14 allows Member States to require producers to show purchasers, at the time of sale of new products, information on collection, treatment and disposal of EEE. These can include: (a) the requirement not to dispose of WEEE as unsorted municipal waste and to collect such WEEE separately; (b) the return and collection systems available to them, encouraging the coordination of information on the available collection points irrespective of the producers or other operators which have set them up; (c) their role in contributing to re-use, recycling and other forms of recovery of WEEE; (d) the potential effects on the environment and human health as a result of the presence of hazardous substances in EEE; (e) the meaning of the symbol shown in Annex IX, which must be applied to each EEE placed on the market. Moreover, article 15 establishes that in order to facilitate the preparation for re-use and the correct and environmentally sound treatment of WEEE, including maintenance, upgrade, refurbishment and recycling, Member States must take necessary steps to ensure that producers provide information free of charge about preparation for re-use and treatment in respect of each type of new EEE placed for the first time on the market within one year after the equipment is placed on the market.

1.2.5.3 Extended Product Responsibility

To raise levels of high quality recycling, improvements are needed in waste collection and sorting. Collection and sorting systems are often financed in part by extended producer responsibility (EPR) schemes, in which manufacturers contribute to product collection and treatment costs[28].

All Member States of the EU have implemented EPR schemes on the four waste streams for which EU Directives recommend the use of EPR policies: packaging, batteries, End-of-Life Vehicles (ELVs), Electrical and Electronic Equipment (WEEE). In addition, a number of Member States have put in place additional schemes for products that are not directly addressed in EU-wide legislation (e.g. for tyres, graphic paper, oil and medical waste) (OECD 2014).

In order to recycle waste electrical and electronic equipment (WEEE) properly and in environmentally sound manner, it is necessary that old equipment is collected separately from other waste. Smartphones are generally included in EPR systems together with other EEE and covered as part of a larger collection and treatment ICT group. Collection networks have been established at point of sales and through public waste management authorities. In Germany, it has been reported by stakeholders involved in the development of this study that consumers can use an "eSchrott" (WEEE) app since 2013 to display the nearest collection point for old electrical appliances.

Producers share costs for collection and treatment according to market share. In countries like Germany, producers must provide an insolvency-proof guarantee upon registration in order to ensure e-waste is being properly treated and recovered even if the original producer is no longer in the market. In Belgium, EUR 0.05-0.09 (incl. VAT) are charged for the purchase of a new smartphone with the aim to fund collection schemes for used smartphones. E-waste recyclers in Belgium have to place bids on appliances collected through Recupel. The winning bidder has a right to purchase 50% of the lot and others can purchase the rest by aligning to the winning price. Stakeholders involved in the development of this study reported that the collection scheme is highly profitable since purchase prices for high-value WEEE are considerably higher than the taxes to be paid for the same amount of products, at least in the case of smartphones.

Moreover, article 15 of the WEEE Directive requires producers to provide information free of charge about preparation for re-use and treatment for each type of EEE placed on the market. To this purpose, APPLIA and DIGITALEUROPE developed an online database where recyclers can access all recycling information for EEE: the I4R platform[29].

Any seller of electrical or electronic appliances is obliged to take back old appliances upon sales of new ones, whilst large distributors of electrical and electronic equipment are obliged to take back WEEE free of charge and to inform consumers about the created return facilities. That means that stationary/online shops with EEE sales/shipment areas of at least 400 m^2:

[28] COM(2015) 614 final
[29] https://i4r-platform.eu (accessed on 4 June 2018)

- Have to take back WEEE in exchange for a new product, as long as the WEEE is of equivalent type and has fulfilled the same functions (1:1 Take-back) and
- Have to take back small WEEE (no external dimension more than 25 cm) without the obligation to buy any new EEE (0:1 Take-back).

However, many waste smartphones from private households are collected also by:

- Public waste management authorities;
- Manufacturers, telecom operators, charities, NGOs and other parties.

In the latter case, smartphones are typically collected for refurbishment or direct resale in Europe or abroad. Some companies also established individual return systems by mail. There are some programmes to mail EOL smartphones back free of charge[30] [31].

1.2.5.4 Batteries

The Batteries Directive 2006/66/EC intends to contribute to the protection, preservation and improvement of the quality of the environment by minimising the negative impact of batteries and accumulators and waste batteries and accumulators. It also ensures the smooth functioning of the internal market by harmonising requirements as regards the placing on the market of batteries and accumulators. With some exceptions, it applies to all batteries and accumulators, no matter their chemical nature, size or design.

The Directive:

- Prohibits the marketing of batteries containing some hazardous substances (Batteries and accumulators must not have a lead, mercury or cadmium content above the fixed threshold limits of 0.004%, 0.0005% and 0.002% by weight, respectively, unless labelled in accordance with the Directive. Specific labelling requirements are outlined in the directive where these thresholds are exceeded);
- Defines measures to establish schemes aiming at high level of collection and recycling;
- Fixes targets to Member States for collection and recycling activities;
- Sets out provisions on labelling of batteries (in particular, all batteries have to be marked with the crossed-out wheeled bin symbol indicating "separate collection");
- Sets out provision on their removability from equipment: Member States have to ensure that manufacturers design appliances in such a way that waste batteries and accumulators can be readily removed, either by end-users or by independent qualified professionals.

Producers of batteries and accumulators and producers of other products incorporating a battery or accumulator are moreover given responsibility for the waste management of the batteries and accumulators that they place on the market.

1.2.6 Ecolabels and Green Public Procurement

Environmental Labelling and green public procurement criteria have been developed to help customers and public authorities to identify and purchase smartphones that meet environmental criteria. Criteria typically cover energy use, sustainable sourcing of materials, product life extension, restrictions in the use of hazardous materials and conflict minerals, as well as social aspects. However, the market uptake of ecolabelled products appears so far limited.

[30] https://www.deutschepost.de/de/e/electroreturn.html (accessed on 30 May 2018)
[31] https://www.apple.com/de/trade-in/ (accessed on 30 May 2018)

According to stakeholders involved in the development of this study, sustainability criteria for smartphones should also cover the provision of software updates. When a smartphone manufacture stops providing software updates, older phones automatically become obsolete due to security issues, although they can be still usable.

1.2.6.1 Blue Angel

Criteria for the award of the Blue Angel ecolabel to mobile phones have been setup in Germany. The last version of the criteria is dated July 2017. To the knowledge of the authors of this report, for the time being the label has been awarded only to Fairphone 2.

The Blue Ange for mobile phones considers climate protection, reduction of energy consumption, increased resource efficiency and the avoidance of harmful substances and waste as key objectives of environmental protection. The ecolabel may be awarded to devices featuring the following environmental properties:

- Product longevity Low user exposure to electromagnetic radiation;
- Design that supports maintenance and recycling;
- High-value (secondary) batteries;
- Compliance with fundamental social standards.

Besides, the Blue Angel distinguishes a product whose manufacturer actively supports an improved take-back and recycling scheme. Requirements are summarised in Annex I.

1.2.6.2 TCO

TCO Certified is an international third party sustainability certification scheme for IT products. Although covering mobile phones, no model is awarded with this standard.

TCO is a type-1 label certifying that products fulfil requirements along its life cycle:

- Manufacturing (social responsible manufacturing, environmental management system)
- Use phase (climate, ergonomics, health and safety, extended product life and emissions)
- End of life (reduction of hazardous content and chemicals, design for recycling)

The second and last version of criteria for smartphones is the TCO Certified Smartphones 2.0, which has been released in November 2015. Requirements needed to be met by TCO Certified Smartphones are summarised in Annex I. At the moment there are no models awarded and registered as TCO Certified[32].

The last generation of TCO Certified ("Generation 8") was released in December 2018[33]. The new criteria include resource efficiency aspects such as the availability of spare parts for critical components (e.g. battery and display).

1.2.6.3 EPEAT

EPEAT is a free source of environmental product ratings allowing the selection of high-performance electronics. The system began in 2003 with a stakeholder process convened by the U.S. Environmental Protection Agency and has grown to become a global environmental rating system for electronics. Managed by the Green Electronics Council, EPEAT currently tracks more than 4400 products from more than 60 manufacturers across 43 countries.

[32] http://tcocertified.com/product-finder/ (accessed on 11 July 2018)
[33] http://tcocertified.com/new-generation-tco-certified/#draftcriteria (accessed on 30 May 2018)

Manufacturers register products in EPEAT based on the devices' ability to meet certain required and optional criteria that address the full product lifecycle, from design and production to energy use and recycling:

- Bronze-rated products meet all of the required criteria in their category.
- Silver-rated products meet all of the required criteria and at least 50% of the optional criteria,
- Gold-rated products meet all of the required criteria and at least 75% of the optional criteria.

The U.S EPEAT registry uses a lifecycle based sustainability standard developed by UL (Underwriter Laboratories). In particular, UL 110 addresses mobile phones[34]. Requirements applied to smartphones are listed in Annex I. The EPEAT, with 33 registered mobile phone models from four different manufacturers (i.e. Apple, Google, LG, Samsung)[35], seems the most popular eco-label for mobile phones.

1.2.6.4 iFixit

iFixit has developed a Reparability Score for smartphones[36] (see Annex II). Points are gained based on the ease of opening the device, the types of fasteners and tools used, the complexity of replacing key components, and the upgradability and modularity of the device.

As part of the Horizon 2020 project Sustainably Smart, which focuses on material efficiency of smart devices[37], iFixit is working to upgrade the scoring system and create a more objective and robust methodology that can allow the assessment at part level.

1.2.6.5 Green public procurement

There are examples of green public procurement requirements for smartphones in the EU and worldwide:

- The Scottish Procurement established a new suite of frameworks for the supply of ICT client devices in 2016, which included mobile phones[38]. In the framework contract for Information and Communications Technology (ICT), client devices bidders must meet or exceed the EPEAT Gold or Silver compliance requirements (depending on the product category), as well as reduce packaging and extend the lifetime of their products. Award criteria also cover social aspects (e.g. work conditions and supply chain control).
- In the U.S., Federal government agencies and many states, provincial, and local governments are required to buy greener electronics (including mobile phones) included in the EPEAT registry, where manufacturers register their products stating the environmental performance of their products.
- In Japan, the Law on Promoting Green Purchasing sets out criteria including provisions for material efficiency and it specifically covers mobile phones.

[34] epeat.net/...round/UL%20110%20Verification%20Requirements%20-%20FINAL.pdf (accessed on 23 March 2018)
[35] https://ww2.epeat.net/Companies.aspx?stdid=0&epeatcountryid=0 (accessed on 30 May 2018)
[36] https://www.ifixit.com/smartphone_repairability (accessed on 8 April 2019)
[37] https://www.sustainably-smart.eu/ (accessed on 11 July 2018)
[38] http://ec.europa.eu/environment/gpp/pdf/news_alert/Issue69_Case_Study_139_Scotland.pdf (accessed on 18 April 2018)

2 MARKET

The second step of the guidance is to collect background information about the market of the product in order to better understand sales and penetration of product, life cycle costs, business practices, trends and associated consequences at material efficiency level. Examples of information to collect include prices of new and second hand products; costs and frequencies of repair/refurbishment; market failures and circular business models.

2.1 Basic market data

2.1.1 Market sales

Smartphones came onto the consumer market in the late 90s but only gained mainstream popularity with the introduction of Apple's iPhone in 2007 (Statista, 2018a). Smartphones have rapidly overtaken basic mobile phones and feature phones (Figure 1), as well as other small electronics as digital cameras, GPS, MP3 players, calculators, voice recorders. Every two out of three mobile phones that were shipped globally in 2014 were smartphones: the introduction of smartphones on the market has changed the behaviour of both consumers and businesses (Watson et al. 2017).

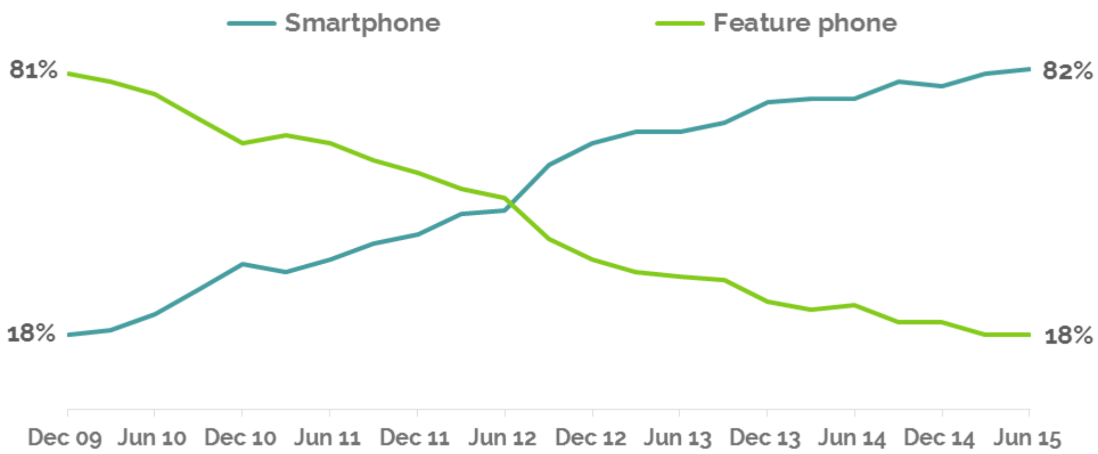


Figure 1: Smartphone and feature phone ownership in the UK (Source: Farmer 2015)

The smartphone industry has been steadily developing and growing, both in market size, as well as in models and suppliers. Almost 1.5 billion smartphones were sold to end users in 2016, an increase from less than 300 million units in 2010 (Statista 2018b).

The smartphone market has been reported to stop its growth in 2016. Smartphone sales between 2015 and 2016 dropped by 2% in US, Great Britain, Germany, France, Italy, Spain, China, Australia, and Japan. As the smartphone industry matures, fewer consumers are moving between brands and market growth has increasingly relied on replacing existing devices (Kantar World Panel 2017). No market data has been found to confirm this trend also for 2017-2018. Smartphone shipments worldwide are projected to add up to 1.71 billion in 2020 (Statista, 2018a), a tenfold increase from 2009 although an asymptotic limit appears approached (Figure 2).

Sales of smartphones in Western Europe increased from 115.4 million units in 2013 to 125.6 million units in 2017 (+9%). Sales reached a peak of 135 million units in 2015, after which they decreased by 3-4% (Statista 2018c). Sales are instead increasing in Central and Eastern Europe, from 50.9 million units in 2013 to 85.2 million units in 2017 (+67%) (Statista 2018d). The overall picture for Europe results in an increase of shipments from 166.3 million units in 2013 to 210.8 units in 2018 (+27%). Sales in Europe represent around 15% of the global sales of smartphones (Figure 3).

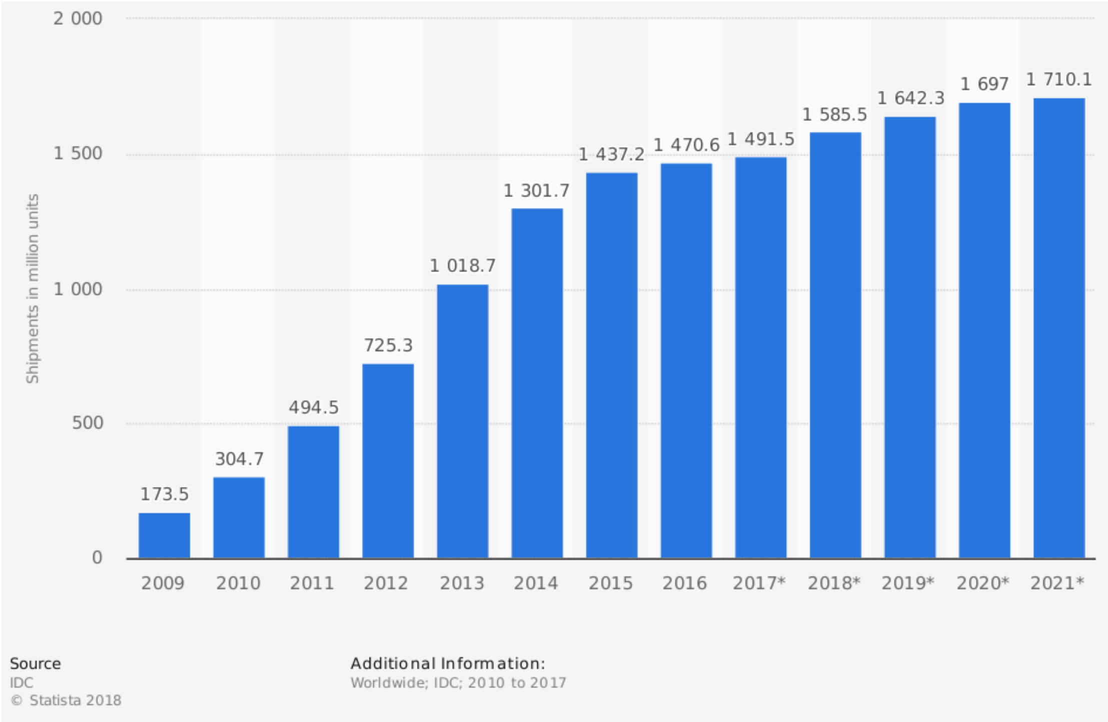


Figure 2: Global smartphone shipment forecast from 2010 to 2021 (million units) (Statista 2018e)

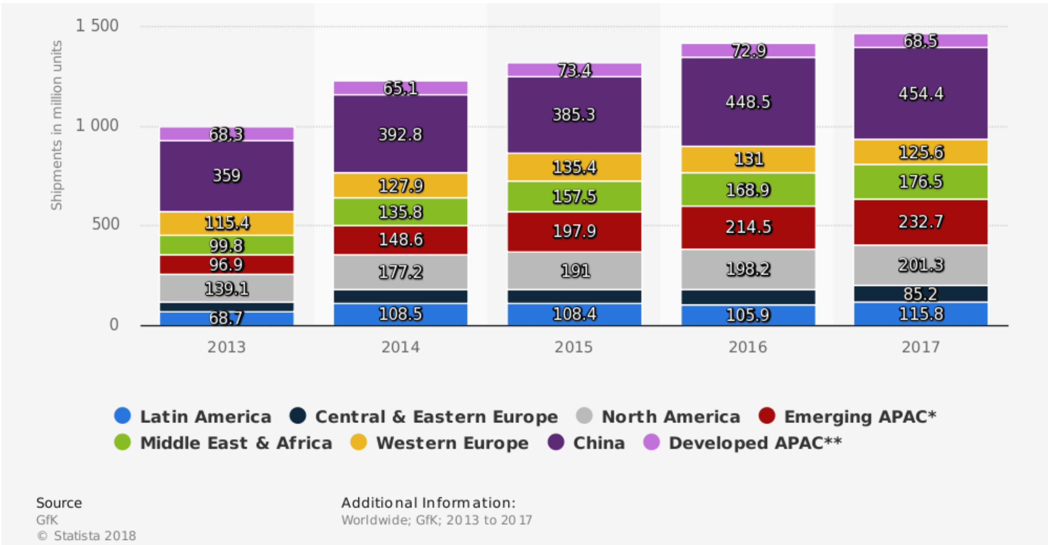


Figure 3: Smartphone unit shipments worldwide from 2013 to 2017 (in million units), by region (Statista 2018f)

In terms of total value, sales of smartphones in 2017 were 56 billion USD in Western Europe (Statista 2018g) and 21.2 billion USD in Central and Eastern Europe Statista 2018h), which add to 77.2 billion USD. Total value of sales has increased constantly since 2013.

Values of single units in 2017 for Western Europe and for Central and Eastern Europe would correspond to 446 and 249 USD, respectively. Compared to 2013, the single unit value has decreased by 16% in Eastern Europe while it has remained almost constant in Western Europe. The European average is 366 USD, 10% less than in 2013.

2.1.2 Market penetration

The number of smartphone users is forecast to grow from 2.1 billion in 2016 to around 2.5 billion in 2018 (Figure 4), with smartphone penetration rates increasing as well. Over 36% of the world's population is projected to use a smartphone by 2018, up from about 10% in 2011 (Statista 2018i) and 21.6% in 2014 (Statista 2018b). Higher penetration levels are achieved in some markets and saturation may be reached soon in developed countries (e.g. in Japan 97% of mobile subscribers have smartphones) (Benton et al. 2015).

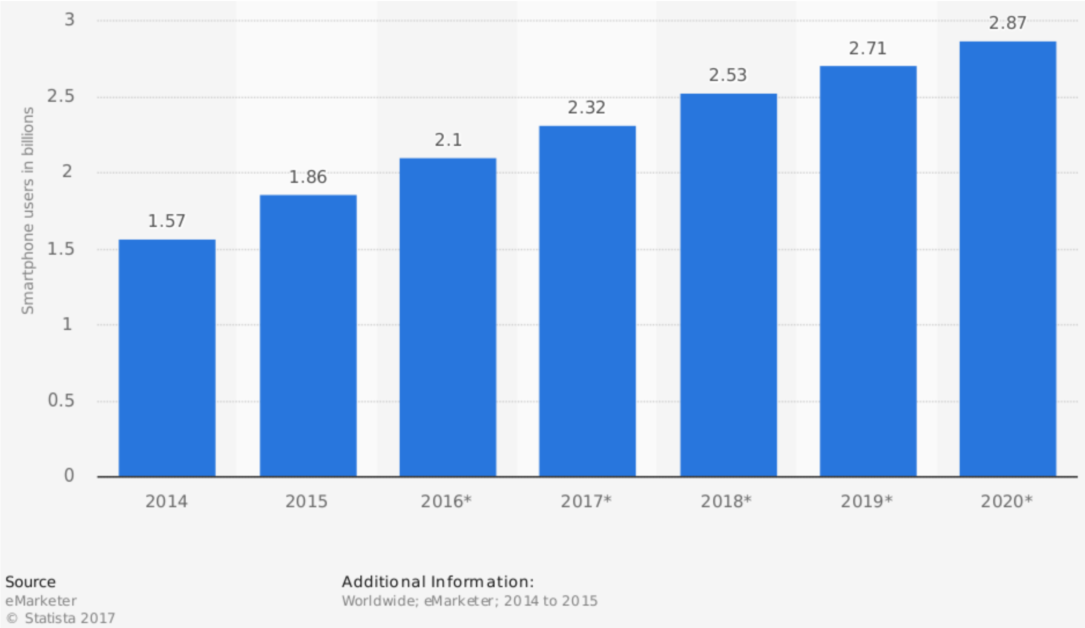


Figure 4: Number of smartphone users worldwide from 2014 to 2020 (in billions) (Statista 2018i)

China, the most populous country in the world, leads the smartphone industry. The number of smartphone users in China is forecast to grow from around 563 million in 2016 to almost 675 million in 2019. Around half of the Chinese population is projected to use a smartphone by 2020 (Statista 2018i). This would correspond to about a quarter of all smartphone users in the world (Statista 2018a).

The smallest regional market for smartphones is the Middle East and Africa, where smartphone penetration will stand at an estimated 13.6% (Statista 2018b). The highest penetration rates are instead registered in Western Europe and North America. It is estimated that in 2018 about 64% of the population of those regions will own a smartphone. Market penetration has increased significantly in the last years in both regions: from 22.7% in 2011 in Western Europe, and from 51% in 2014 for North America (Statista 2018b, 2018j). Smartphone penetration per capita in Central & Eastern Europe has been estimated to increase from 13.3% in 2011 to 58.2% in 2017. Penetration rates appear significant in the most populated countries of Europe:

- The number of smartphone users in France was estimated to reach 43.35 million in 2017. From 2015 to 2022, the number of smartphone users is expected to grow by 17.68 million users (+26%). Most individuals without a smartphone still own a regular mobile phone and only 7% of the population own no type of phones (Statista 2018k). In relative terms, the share of monthly active smartphone users is projected to increase from 59% of the total population in 2016 to 78.5% in 2022 (Statista 2018k).
- The number of smartphone users in Germany was estimated to reach 55.46 million in 2017 (Statista 2018l). In relative terms, the share of monthly active smartphone users is projected to increase from 61% of the total population in 2016 to 78.5% in 2022 (Statista 2018m).
- The number of smartphone users in Italy was estimated to increase from 26.8 million in 2015 to 31.5 million in 2017 (Statista 2018n). In relative terms, the share of monthly active smartphone users is projected to increase from 46% of the population in 2014 to 65% in 2021 (Statista 2018o).

- The number of smartphone users in Spain was estimated to reach 30.3 million in 2017. From 2015 and 2021, the number of user is expected to grow by 7.7 million to 34.3 million users (+16%) (Statista 2018p). In relative terms, the share of monthly active smartphone users is projected to increase from 59% of the population in 2016 to 72% in 2022 (Statista 2018q).
- The number of monthly active smartphone users in the United Kingdom (UK) is projected to grow steadily from 41.09 million in 2015 to 53.96 million in 2022 (Statista 2018r). In relative terms, the share of monthly active smartphone users is projected to increase from 62% of the population in 2014 to 78% in 2022 (Statista 2018s).

However, ownership differs across age groups. For example, 88% of 16-24 year olds owned smartphones in 2014 in the UK, compared to 14% of those over 65 (Benton et al. 2015).

2.1.3 Market shares by vendor

Until the first quarter of 2011, Nokia was the leading smartphone vendor worldwide with a 24% market share (Statista 2018a). As represented in Figure 5, the leading smartphone vendors in 2016 were Samsung and Apple, with about 20-25% and 15% of the share respectively, followed by Huawei, OPPO and Vivo (IDC, Statista 2018i). Other prominent smartphone vendors include Lenovo and Xiaomi (IDC, Statista 2018a). At the end of 2017, Apple had a worldwide market share of 19%, surpassing Samsung (Statista 2018t).

China is not only home of three of the top smartphone vendors (Huawei, Lenovo and Xiaomi), but it is also the largest smartphone market in the world (Statista 2018u). Shares vary depending on the country and the year considered. For example, in the UK the most popular mobile device vendor has been Apple since 2010, which had a total market share of 49% in the first eight months of 2017. In January 2017, the total market share of the Apple iPhone 7 Plus in terms of total smartphone sales in the UK was higher than all others (Statista 2018s).

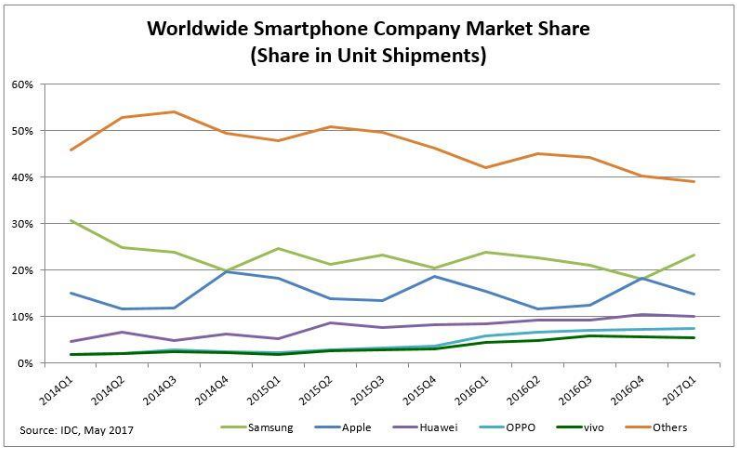


Figure 5: Worldwide Smartphone Company Market Share from 2014 to first quarter of 2017 (Share in Unit Shipments) (IDC)

2.1.4 Market shares by operating system

Google's Android is the clear leader among operating systems with a global market share of more than 80%. Apple's operating system iOS is its main competitor, accounting for about 15% of the share (Statista 2018a). The two operating systems amounted to 352.67 million Android units and 77.04 million iOS units being shipped in the final quarter of 2016 (Statista 2018e) (see also Figure 6, Figure 7, Figure 8). There are however differences between regional markets; in the United States for example, the market is almost equally divided between Android and iOS (Statista 2018v).

Microsoft's Windows Phone is another smartphone operating systems on the market. Symbian, which was used extensively on mobile phones and early generations of smartphones by leading manufacturers, such as Samsung, LG, Motorola and Nokia, was a dominant player on the market in 2009 and 2010. Due to the growing popularity of Android, which most major smartphone manufacturers adopted as their OS of choice, and Nokia's partnership with Windows Phone, which began in 2011, Symbian was pushed off the market in 2014 (Statista 2018v). It has been also reported by stakeholders involved in the development of this study that Blackberry stopped shipping products with Blackberry 10 in 2015 and switched to Android.

Although the main producers of operating systems are based in the U.S., the Chinese smartphone industry may dominate the market in the future: China could control about a third of the smartphone market in 2017 (Statista 2018e).

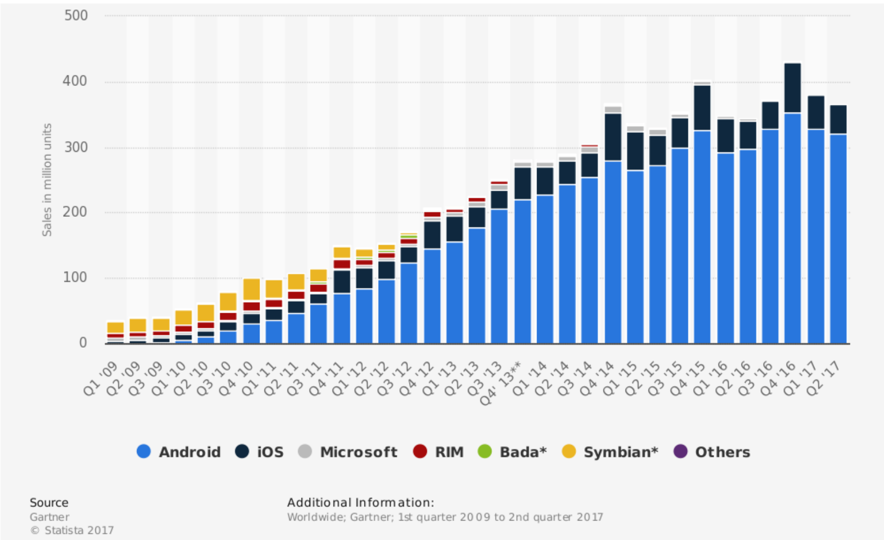


Figure 6: Global smartphone sales to end users by operating system from 1st quarter 2009 to 2nd quarter 2017 (in million units) (Statista 2018w)

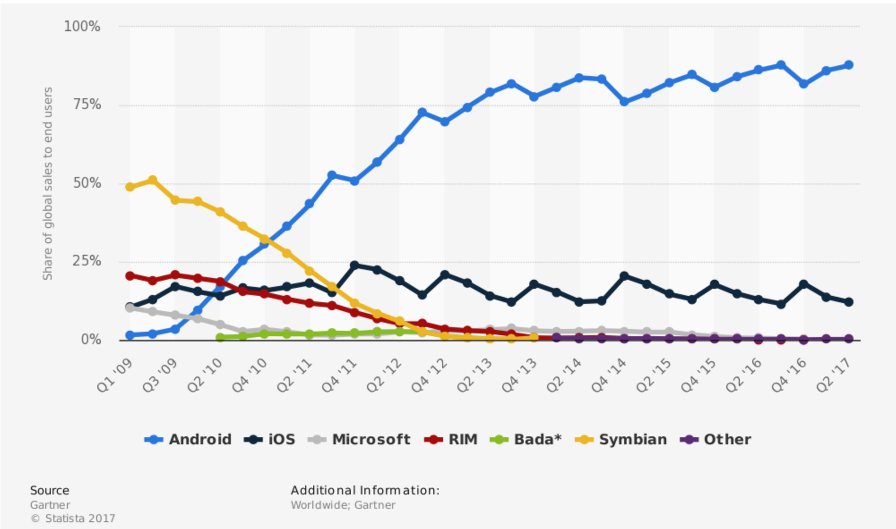


Figure 7: Global market share held by the leading smartphone operating systems in sales to end users (Statista 2018z)

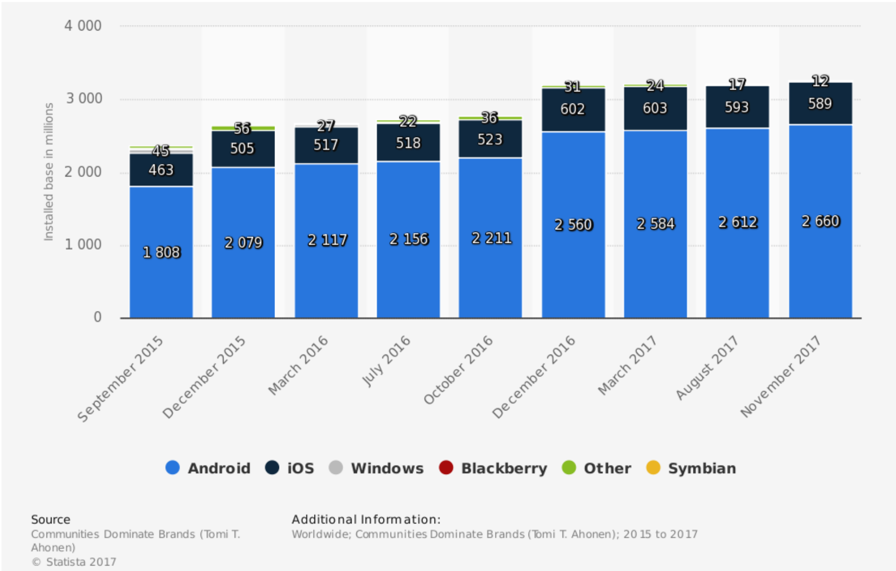


Figure 8: Installed base of smartphones by operating system from 2015 to 2017 (in million units) (Statista 2018aa)

2.2 Key actors

Different actors play an important role in the smartphone business:

- Mobile phone producers, which have a direct influence on the design and servicing of smartphones (Watson et al. 2017). The landscape of producers is characterised by the large established global companies such as Apple, Samsung, Sony and Nokia[39]. Start-up companies, such as Fairphone, that have sustainability as a core element of their business, are gaining popularity although their market share is still quite small.

- Software producers, which make business through the use of a device (e.g. Google, Apple, and other digital services and app developers) and have interest in securing agreements with hardware providers and providing up-to-date software along the lifetime of smartphones to avoid the installation of a different operating system (Benton et al. 2015).

- Retailers, which are among the biggest providers of mobile phones, which can influence customers towards certain business models, and which can enter 2nd-hand markets (Watson et al. 2017). Many EU countries also oblige retailers under specific conditions (e.g. size of shop) to provide a collection point for WEEE[40]. For large retail chains of electronics and white goods, sales of mobile phones represent a minor element of total turnover; however, these sales are growing in importance. For more specialised retailers the share of turnover represented by phone sales can be as high as 80%, with the remaining 20% represented by reparations, tablets or accessories.

- Network service providers, which are large sellers/providers of mobile phones, which they sell via subscriptions of network services to attract and keep customers (Watson et al. 2017). They can have a strong influence over how often customers upgrade their telephones, but also have relevance to warranties, repair and refurbishment processes. The range of models via which network service providers are offering mobile phone upgrades have been diversifying rapidly over the past few years in global markets and now can include leasing and buy-back upgrades. Sales of phones do not directly generate profits for the service providers (some service providers even claim it is a cost). The providers' main turnover is via data and network services and subscriptions for these.

[39] Nokia's mobile phone section was bought by Microsoft and ran on a Microsoft operating system, but announced that production would seize in summer 2017. Meanwhile, Finnish company HMD began production of Nokia-branded Android phones in 2014

[40] For instance, in Spain, shops with a surface larger than 400 m^2 must accept small electronic devices (as smartphones) with no burden for customers (https://www.ecolec.es/sociedad/que-hago-con-el-raee/, accessed on 21 March 2018)

- Mobile phone repairers, which can be found frequently in cities and towns. Phone producers/electronics retailers increasingly demand that repair shops are certified in order to activate product warranties. There is also a wide range of professional and amateur repairers that are not official but independent. For repair companies, repair of mobile phones is in general a large part of their business (up to 95% of the total turnover). However, also selling accessories is becoming a relevant part of the business for repair companies (Watson et al. 2017).
- Refurbishers and 2nd-hand sellers, which commercialise 2nd-hand IT with warranties (Watson et al. 2017). These can be single shops, as well as chains. Market is expanding as smartphone prices increase. There is also an overlap between companies involved in mobile phone repair and 2nd-hand sales.

2.3 Costs

2.3.1 Purchase price

Statistics available online (Statista 2018ab) indicate that the average selling price for smartphones in Europe was 366 USD in 2017 (310 USD as worldwide average in 2014). This would correspond to about 320 EUR[41].

Over the last few years, mid-range smartphones accounted for about 40-50% of all smartphone shipments, while low-end's share varied between 26-34% and high-end held from 20-28% of the share. Smartphones that cost less than 150 USD (about 130 EUR) are considered low-end models. Mid-range smartphone retail prices vary from 150 USD to 550 USD. Any smartphone above 550 USD (about 480 EUR) fits in the high-end category (Statista 2018ab).

Since 2010, the average selling prices of smartphones worldwide has varied within the mid-range category. In 2010, customers paid, on average, 440 USD for a smartphone, the highest price over the last six years. The average selling price of smartphones worldwide was 333 USD in 2013, 310 USD in 2014, and 305 USD in 2015, with further reductions predicted for the future years (Statista 2018ab), as also shown in Figure 9.

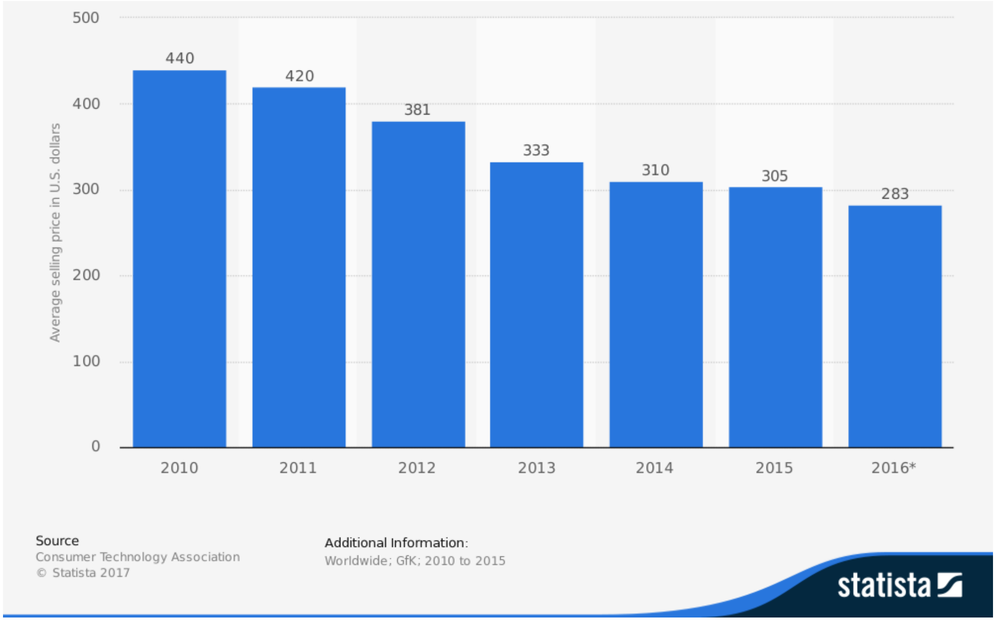


Figure 9: Average selling price of smartphones worldwide from 2010 to 2016 (in USD) (Statista 2018ab)

[41] Considering an exchange rate of 0.8712 EUR / USD on 9 October 2018 (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

The average selling price for an Android smartphone was 231 USD in 2015. In comparison, Blackberry smartphones costed about 348 USD and Windows Phones had an average selling price of 247 USD in the same year. By 2018, Windows Phones are projected to become the most affordable smartphones, with an average selling price of 195 USD. Android smartphones are forecast to cost 202 USD by 2018. iPhones have the highest average selling price: the average cost of an iPhone in 2015 was 652 USD. A decline in the average selling price of Android smartphones (202 USD) and iPhones (610 USD) is expected by 2018 (Statista 2018ab).

According to Counterpoint Research (2016), more than half of the Australian, Chinese, German and Saudi smartphone users revealed that they would be willing to spend more than 400 USD to replace their current device. More than one third of German and Australian users would be willing to spend more than 500 USD in their next smartphone purchase. Apple dominates the installed base in both countries, and more than 85% of the Apple users would not switch brands. Willingness to pay more than 400 USD significantly decreases in the other countries investigated in the survey (30% in Thailand, 27% in South Africa, 23% in Malaysia, 13% in Japan, 5% in India).

Globally, the average value of 2nd hand smartphones could be estimated to be around 140 USD per device (Watson et al. 2017). A study financed by WRAP (Culligan and Menzies 2013) investigated more in detail the value of electronics for trade-in and re-sale. Although not covering smartphones, the WRAP study analysed tablets. The study also provides indication about the depreciation of electronic devices (Table 9). Like most new consumer items, most value is lost in the first year with depreciation slowing over subsequent years. For example, the residual value could be on average:

- 54% of the original price for 1 year old product
- 32% after 2 years
- 20% after 3 years.

Trade-in could be no longer economic after 4-5 years. However, lifetime and residual value of smartphones can vary depending on the manufacturer and the quality of the models. In particular, high-end smartphones have a higher residual value (Makov, 2018).

Table 9: Depreciation of tablets from year to year (Culligan and Menzies 2013)

Product Types	Year 2010	2011	2012	2013
Kindle Fire 7"			129	60
Galaxy Tab 2 7.0			160	65
iPad Mini			279	180
Galaxy Tab 2 10.1			279	160
Ipad 4th Gen			460	275
Asus Nexus 7			160	90
Acer Icona W700			600	365
Galaxy tab 10.1			300	100
Ipad 2		499	275	150
Acer Icona tab A200		210	125	70
Kindle 4			80	40
TF101		300	170	100
Ipad 1	499	275	150	100
Average refurb, repair & logistical cost A GBP	43.22	43.22	43.22	43.22
Average refurb/repair & logistical cost B GBP	29.19	29.19	29.19	29.19

2.3.2 Margins

The purchase price (PP) of products is given by the manufacturing costs (MC) plus the margins added, which could be simplified as follows (adapted from Boyano et al. 2017):

PP = MC x (1+MM) x (1 + RM) x (1+VAT)

Where:

- MC = material costs, considered to include the cost of the smartphone's parts
- MM = manufacturing margins, considered to include additional costs (e.g. investment and operational costs associated with manufacturing, product design, software, Intellectual Property, certifications)
- RM = aggregated sale margin
- VAT = value-added tax (e.g. 21.6% as average in the EU in 2015)

PP of Fairphone 2 was reported to be about 1.5 times MC, and MM to be about 20% of MC (Fairphone 2015). MC of Galaxy S has been indicated to increase from 213 USD for the S3 to 375 USD for the S9+ (+76%). Since PP would have increased instead from 599 USD for the S3 to 840 USD for the S9+ (+40%), it means that the ratio of PP to MC has decreased from 2.8 to 2.2[42]. The same source indicates that MC and PP of iPhones have increased from 174 USD and 599 USD (about 3.5 times the MC) for the iPhone 3G to 370 USD and 999 USD (about 2.7 times the MC) for the iPhone X. MM could be up to 40% of MC in the case of the iPhone 5[43].

In terms of manufacturing costs (see Table 10, made from data reported in Statista 2018ac):

- Display is the most important part (~20% of the total manufacturing cost), followed by apps/baseband processor (~17%) and mechanicals (~12%). These 3 components make together up to 50% of the manufacturing costs;
- ~80% of the total manufacturing cost is reached by adding four components (memory (~9%), electro-mechanicals (~8%), radio frequency power amplifier (RF/PA) (~7%) and cameras (~6%));
- ~90% of the total manufacturing cost is reached by further including two additional components (user interface (~5%) and power management (~4%));
- The remaining 10% of the manufacturing costs is made by other components (box contents, conversion costs, blue tooth and wireless local-area network (BT/WLAN), battery, glue logic & micro-controller units (MCU)).

Such orders of magnitude find some level of confirmation on the web[44] [45]. However, manufacturing costs do not include environmental externalities (for instance related to the extraction of raw materials) which can make the product price different from the "real" costs for society.

[42] https://hipertextual.com/2018/06/precio-smartphones (Accessed on 6 March 2019)
[43] https://www.digitaltrends.com/mobile/iphone-cost-what-apple-is-paying/ (Accessed on 6 March 2019)
[44] https://www.digitaltrends.com/mobile/iphone-cost-what-apple-is-paying/ (Accessed on 6 March 2019)
[45] https://technology.ihs.com/601100/galaxy-s9-materials-cost-43-more-than-previous-versions-ihs-markit-teardown-shows (Accessed on 6 March 2019)

Table 10: Bill of materials cost for Google Pixel XL by component in 2016 (in USD) (Statista 2018ac)

Part	Cost (USD)	%
Display	58.0	20.3%
Apps/baseband processor	50.0	17.5%
Mechanicals	35.0	12.2%
Memory	26.5	9.3%
Electro-mechanicals	24.0	8.4%
RF/PA	19.5	6.8%
Cameras	17.5	6.1%
User interface	15.5	5.4%
Power management	11.0	3.8%
Box contents	10.0	3.5%
Conversion costs	7.8	2.7%
BT/WLAN	5.0	1.7%
Battery	4.0	1.4%
Glue logic & MCU	2.0	0.7%
Total	285.8	

2.3.3 Operative costs

The main operative costs for consumers are:

- The consumption of electricity to recharge the battery of the smartphone: 0.2113 EUR per kWh[46];
- The mobile service contract: 31.8 EUR per month[47] (DG CONNECT 2018).

2.3.4 Repair/refurbishment costs

Some smartphone manufacturers publish repair and/or spare part costs on their website. For example, Fairphone publishes on its website the price of smartphone's module as spare parts and claims that each module can be replaced without the need to return the entire device. Spare part price of each module, expressed as percentage of the purchase price of the Fairphone 2, is reported in Table 11. Apple instead publishes on its website the repair prices in different countries (e.g. Spain, as reported in Table 12

Table 12).

According to Bullitt (2017), 34% of the EU consumers had suffered a damage of their devices in a three-year period of observation. 24% of users in the UK had a screen breakage in a two-year period of observation[48]. Even higher frequencies are reported for the US[49].

The most frequent failure types, related to the screen, are usually not covered by legal guarantee, generating in case of breakage or failure a repair cost of 15-40% of the purchase price, as showed in Table 11, Table 12 and

[46] https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics (accessed on 6 august 2019)

[47] As average in the EU28 in 2017 for a service contract including 5 GB of data and 100 calls. The average cost would decrease to 14.11 EUR for 100 MB and 30 calls.

[48] https://www.mintel.com/press-centre/technology-press-centre/smashing-times-24-of-uk-smartphone-owners-have-broken-their-screen-in-the-past-two-years (accessed on 5 April 2019)

[49] https://bgr.com/2018/11/20/smartphone-screen-repair-data/ (accessed on 5 April 2019)

Table 13. The replacement of the battery can be also needed after 2-3 years of use and cost about 5-10% of the purchase price based on Table 11 and Table 12.

Table 11: Indicative price of spare parts, reported as percentage of the Fairphone 2 purchase price[50]

Spare part	Price (EUR)	Relative price (as % of the product's purchase price)[51]
Display	87	16%
Back cover	30	6%
Charging port module + speaker, vibration motor, microphone	25	5%
Battery	20	4%

Table 12: iPhone's repair service pricing applied by Apple in Spain[52]

iPhone model	Screen repair only (EUR)[53]	Battery (EUR)
iPhone XS Max	361.10	75
iPhone XS	311.10	75
iPhone XR	221.10	75
iPhone X	311.10	75
iPhone 8 Plus	191.10	55
iPhone 8	171.10	55
iPhone 7 Plus	191.10	55
iPhone 7	171.10	55
iPhone 6s Plus	191.10	55
iPhone 6s	171.10	55
iPhone 6 Plus	171.10	55
iPhone 6	151.10	55
iPhone SE iPhone 5s, iPhone 5c, iPhone 5	151.10	55

Also for independent professional repairers, the cost of repair can vary depending on the brand and model to repair. Examples are reported in Table 13. The cost of repair for the display can reach in some cases almost 50% of the price for a new unit of the same model.

[50] Calculated based on the information available on https://shop.fairphone.com/en/spare-parts and https://shop.fairphone.com/en/buy-fairphone2-2/ (accessed on 11 June 2019)

[51] Considering a purchase price of 529 EUR based on https://www.connexing.fr/fairphone-2-smartphone-ecologique.html (accessed on 11 June 2019)

[52] https://support.apple.com/es-es/iphone/repair/service/pricing (accessed on 11 June 2019)

[53] Based on the prices reported in https://www.elcorteingles.es/electronica/moviles-y-smartphones/?f=brand::Apple (accessed on 11 June 2019), it is estimated that screen repair costs could roughly account for 25-33% of the purchase price for models more recent than iPhone 7 and above 33% for older models

Table 13: Smartphone's repair service pricing applied by an independent professional repairer in Germany[54]

Apple	Display repair (EUR)	Samsung	Display repair (EUR)	Huawei	Display repair (EUR)
iPhone 5,5C	60	Galaxy S5	160	Huawei P8	180
iPhone 5S,SE	70	Galaxy S6	180	Huawei P9	140
iPhone 6	80	Galaxy S6 edge	220	Huawei P9 Lite	120
iPhone 6+	100	Galaxy S7	180	Huawei P10	140
iPhone 6S	100	Galaxy S7edge	280	Huawei P20	140
iPhone 6S+	120	Galaxy S8	250	Huawei P20 Pro	250
iPhone 7	140	Galaxy S9	260	Huawei Mate 20	200
iPhone 7 Plus	160	Galaxy S9+	320	HuaweiMate 20 Pro	350
iPhone 8	180				
iPhone 8 Plus	200				

In addition, Culligan and Menzies (2013) provide indication about the impact that average refurbishment and repair costs have on the life cycle value of tablets (which could be considered as alternative proxies for smartphones) (Table 14).

Table 14: Breakdown of refurbishment cost for PC Tablets (Culligan and Menzies 2013)

Product Type	Logistic cost from a single user GBP (A)	Logistic cost - regional depot GBP (B)	Standard refurb cost GBP	Cleaning, storage and dispatch cost GBP	Re-packaging cost material GBP	Recycle Cost Avg GBP	Total GBP
Kindle Fire 7"	14.5		12.11	2.5	2.75	1.52	33.38
Kindle Fire 7"		0.47	12.11	2.5	2.75	1.52	19.35
Galaxy Tab 2 7.0	14.5		12.11	2.5	2.75	1.52	33.38
Galaxy Tab 2 7.0		0.47	12.11	2.5	2.75	1.52	19.35
iPad Mini	14.5		12.11	2.5	2.75	1.52	33.38
iPad Mini		0.47	12.11	2.5	2.75	1.52	19.35
Galaxy Tab 2 10.1	14.5		12.11	2.5	2.75	1.52	33.38
Galaxy Tab 2 10.1		0.47	12.11	2.5	2.75	1.52	19.35
Ipad 4th Gen	14.5		12.11	2.5	2.75	1.52	33.38
Ipad 4th Gen		0.47	12.11	2.5	2.75	1.52	19.35
Asus Nexus 7	14.5		12.11	2.5	2.75	1.52	33.38
Asus Nexus 7		0.47	12.11	2.5	2.75	1.52	19.35
Acer Icona W700	14.5		12.11	2.5	2.75	1.52	33.38
Acer Icona W700		0.47	12.11	2.5	2.75	1.52	19.35
Galaxy tab 10.1	14.5		12.11	2.5	2.75	1.52	33.38
Galaxy tab 10.1		0.47	12.11	2.5	2.75	1.52	19.35
Ipad 2	14.5		12.11	2.5	2.75	1.52	33.38
Ipad 2		0.47	12.11	2.5	2.75	1.52	19.35
Acer Icona tab A200	14.5		12.11	2.5	2.75	1.52	33.38
Acer Icona tab A200		0.47	12.11	2.5	2.75	1.52	19.35
Kindle 4	14.5		12.11	2.5	2.75	1.52	33.38
Kindle 4		0.47	12.11	2.5	2.75	1.52	19.35
TF101	14.5		12.11	2.5	2.75	1.52	33.38
TF101		0.47	12.11	2.5	2.75	1.52	19.35
Ipad 2	14.5		12.11	2.5	2.75	1.52	33.38
Ipad 2		0.47	12.11	2.5	2.75	1.52	19.35

[54] https://phone-service-center.de/en/ (accessed on 24 October 2019)

2.3.5 Overview of costs

The cost information collected for smartphones and presented in the sections above is summarised in Table 15.

Table 15: Summary of information on product costs for smartphones

Cost category	Average value (1) (2)
Purchase price • Low-end • Medium • High-end Value of the product	 < 130 EUR/product 320 EUR/product > 480 EUR/product 54% of original price after 1 year, 32% of original price after 2 years, 20% of original price after 3 years (3)
Installation and maintenance costs	Not relevant
Operative costs	Consumption of electricity to recharge the battery of the smartphone: 0.2113 EUR per kWh; Mobile service contract: 31.8 EUR per month.
Repair/refurbishment costs (4)	About 15-40% of the product price for display; usually above 10% of the product price for other repairs
Disposal costs (EUR/product)	In accordance to the WEEE directive provisions, producers fulfil their responsibility of financing the costs of collection, treatment, recovery and environmentally sound disposal of domestic WEEE deposited at collection facilities. These costs are passed over to the consumer in the final purchase price (5).
Note: (1) VAT included (2) Costs are quantified on the basis of the information collected in Section 1.3 and considered representative for 2018 (3) As average; lifetime and residual value of smartphones can vary depending on the manufacturer and the quality of the models (4) Where relevant (5) WEEE financing is a part of selling price, with relevant differences across the EU. In UK, the fee is not visible; in Italy, the fee is visible to trade partners, but not to consumers, in France the fee is visible also to final consumer. Costs also vary from country to country; logistic costs are a main source of variability. Manufacturers can leverage on economies of scale to ensure that collection and treatment costs are optimised.	

2.4 Market drivers, trends and circular business models

2.4.1 Drivers, trends and business strategies

The following market drivers and trends have been identified for smartphones:

- Quality of screen and camera are leading drivers of purchase (Kantar World Panel 2017). However, also the longevity of the battery is an important feature (Benton et al. 2015, Priya et al. 2016). According to some manufacturers, customers are demanding highly portable devices with batteries that can last all day, which requires successful products to be highly integrated, thin, light, and durable to withstand the rigours of everyday use.

- Internet sales continue to increase in total market share, along with shopping through websites like Amazon and eBay. In the US, a third of smartphone sales were made online in 2016, up from 27% in 2014, while 34% of purchases in Urban China were transacted online. Global trade and the rise of online retail make it easier to buy cheaper smartphones from abroad, which do not necessarily need to comply with European standards and regulations, e.g. regarding hazardous substances, potentially causing health risks to the consumers (Transform Together 2018).

- Smartwatches were expected to become as popular as phones. These wearable smartphones have achieved good levels of penetration only in some markets (e.g. 16% in the US, 9% in Europe). The brands experiencing significant success are those that focused on individual needs through niche products, rather than on a fit-all-purposes device. Wearables appear to be appealing to consumers interested in monitoring health parameters and track their performance, but do not have gained much application beyond that (Kantar World Panel 2017). The use of fingerprint readers and other biometric identifiers (e.g. eye, face recognition) is instead expected to continue increasing (Deloitte 2016). A more disruptive technology could be the introduction on the market of foldable phones with flexible displays[55].

- Virtual reality (VR), augmented reality (AR), artificial intelligence (AI), and virtual assistants may produce a big impact and several companies are investing in this direction (e.g. Google's Daydream VR and Project Tango, Facebook's Oculus, Samsung's Gear VR, Asus' Zenfone AR, Microsoft's HoloLens, HTC's Vive VR, Apple's AR) (Kantar World Panel 2017). If VR/AR grows, screen size will remain one of the most important features of smartphones. This fits with the current market trend towards the sales of screens above 5". Delivering the most realistic experience for users relies on devices with large AMOLED screens. However, high-resolution requirements and AMOLED screens can be a challenge in terms of costs for some manufacturers (Kantar World Panel 2017).

- Services may play a more important role in particular those related to multimedia streaming (e.g. music, videos, TV) (Kantar World Panel 2017). Moreover, there is a recent trend towards storing and processing information remotely in the cloud (e.g. Dropbox, Google Docs). Older hardware could be used if tasks are offloaded to the cloud. More durable hardware would be beneficial and performance diagnosis software should be integrated to ensure the fulfilment of technical requirements necessary for the service (e.g. speed to load webpages) (Benton et al. 2015).

- In June 2016, the first 500 megabit per second (Mbit/s) mobile broadband services were launched in South Korea, with a gigabit per second (Gbit/s, equivalent to 1,000 Mbit/s) service planned for 2019. Delivering 1 Gbit/s connection over a mobile network is a significant technological achievement. However, this can come with questions over the actual need, and commercial viability, of such high speeds. Over half of UK adults have a 4G connection, and this already offers peak headline speeds of over 300 Mbit/s across parts of the UK. This headline speed is higher than the maximum speeds available from the majority of active fixed broadband connections. A 2 Mbit/s connection is sufficient to deliver a high-definition television image to a 40 inch screen, and even a 20 Mbit/s connection is more than sufficient to download high-definition videos to a five-inch smartphone screen. Although a large household might have many bandwidth-consuming devices (e.g. multiple TV sets) which might have an aggregate demand close to 1 Gbit/s at peak times, smartphones are owned and used by individuals, and typical usage does not need for 1 Gbit/s. At the moment there is no application that requires 1 Gbit/s connection and there is no website that can transfer data at 1 Gbit/s (Deloitte 2016). On the other hand, the fast development of mobile broadband services is a critical factor for determining the obsolescence of devices. Vodafone, for

[55] https://www.androidauthority.com/best-foldable-phones-922793/ (Accessed on 6 March 2019)

example, is planning to shut off its 3G network in 2020, with the potential cut-off of many smartphones from data services[56].

- Sales of new smartphones could stop to increase, especially in developed economies, also because of the relatively high price of new smartphones, compared to the technological innovation brought by new models. This could result in lower replacement/upgrade rates or longer times of use of the device from the other side (Watson et al. 2017).

- Early upgrade programmes were designed by retailers to convince consumers to upgrade their devices on a frequent basis – usually every 12 months – improving revenues and keeping customers locked into a specific smartphone vendor and carrier. However, these programmes did not result being attractive to consumers, also because the market is saturated and offering no disruptive but similarity competitive technologies. Some manufacturers (e.g. Apple and Samsung) now offer branded upgrade plans directly to consumers, but sales from these channels remain a small part of the overall smartphone business (Kantar World Panel 2017). This is now being challenged by rising demand for SIM-only services and reluctance to accept long binding periods (Watson et al. 2017).

- Businesses increasingly have to compete on price and user experience rather than impressive features to attract and retain customers (Benton et al. 2015). Quality of materials and design has become an important area of innovation also for low and mid-range devices, where full metal and glass designs can be now found (Kantar World Panel 2017). The apparent tendency to all-glass, bezel-free smartphones could increase the area of the phone that is susceptible to cracks and breakages[57].

- Premium market saturation and slowing pace of technology change can also be an opportunity for the 2nd-hand market (Benton et al. 2015). Repair, refurbishment and 2nd-hand sales are growing in association with take-back/buy-back schemes operated by producers/retailers/network service providers (Watson et al. 2017). 2nd-hand premium devices from developed countries can compete with low-end and mid-tier devices in developing countries, where there is still only 10% smartphone penetration of the mobile market, and projections indicate rapid growth rates will continue, especially in urban areas. Penetration may be further boosted by prices falling, e.g. smartphones costing less than 100 USD or even less than 50 USD (Benton et al. 2015).

- Due to consumers' increasing dependence on smartphones, a strong demand for rapid repair services (under one hour) has developed in recent years. Fast-repairers are experiencing significant growth and require physical repair shops. Phones could be borrowed to consumers for longer repairs. This could be enabled by increasing reliance on "cloud off-loading" to allow easy transfer of data to a temporary borrowed phone.

- More attention is paid by manufacturers on durability and reparability aspects in the design stage also to reduce the warranty costs (Watson et al. 2017).

2.4.2 Circular business models

In the market context depicted above, business strategies undertaken by manufacturers of smartphones and service providers can be divided in two main groups (Watson et al. 2017):

1. Some are focusing their R&D and marketing efforts on the upgrade of models and the integration of new technological features;

2. Others are contributing to the development of circular business models that can allow increasing / retaining / recovering the product's value (e.g. by extending the longevity of the smartphone and/or facilitating its take-back, repair, refurbishment and resale).

Circular business models can in general cover:

- Design of the product and provision of extended support and accessories:

- Reuse-promoting activities and markets:

[56] https://www.gsmarena.com/vodafone_netherlands_will_kill_its_3g_network_in_2020-news-28762.php (accessed on 6 June 2018)
[57] https://www.theverge.com/2017/3/29/15104372/glass-screen-smartphone-design-lg-g6-samsung-galaxy-s8 (accessed on 18 April 2018)

The growth in circular businesses is leading to partnerships and interactions across the value chain between sellers of phones (producers, retailers, and network service providers), repairers, 2nd-hand sellers and refurbishers. At the same time, some service providers are developing in-house refurbishment and repair services (Watson et al. 2017). No model can be considered as the best one, being all options potentially contributing to improve the resource efficiency of smartphones.

2.4.2.1 Design of the product and provision of extended support and accessories

The design of smartphones can potentially integrate the use of more sustainable materials and the consideration of durability, reparability and upgradeability aspects (for hardware, software and firmware). The selection of more sustainable materials can contribute to mitigate the environmental impacts of smartphones[58]. However, consumers seem more interested in the reliability of electronic products and in saving costs (Watson et al. 2017). This calls for design approaches aimed at ensuring a satisfactory use of smartphones over time (by reducing the likelihood of failures) and facilitating their disassembly, repair and upgrade.

Some companies have advertised their smartphones showing how their products are tested and remanufactured. However, there are currently no minimum quality standards available at EU or national level. Other companies have explored the concept of modular phone (e.g. Google, ZTE, Puzzlephone, Fairphone) (Watson et al. 2017), although only Fairphone and Shiftphone[59, 60, 61] seem to have been able to bring it to the market.

The lifetime of smartphones can be extended also through accessories (e.g. new covers) which can protect the device from damages and/or give them a new look (which could possibly reduce the likelihood to replace the phone with a new model).

Apart from hardware considerations, design of smartphones also concerns firmware and software issues (Watson et al. 2017). The availability of extended support is an essential condition for ensuring the functionality of smartphones over time and reducing the risk of replacing prematurely the device. This can include the provision of spare parts, firmware/software updates, and online support, as well as the availability of features facilitating the transfer and deletion of data, and the restoration of passwords and settings. Such characteristics can also have an influence over the resale value of smartphones (Benton et al. 2015).

The implementation of design approaches aimed at promoting the use of smartphones over time could be stimulated also through extended guarantee policies (Watson et al. 2017).

A more detailed description of key design aspects is provided in section 4.

2.4.2.2 Reuse-promoting activities and markets

In case of breakage or failure, smartphones can be repaired and re-used by the same or a new user. The same occur when discarded devices are collected. In both cases a smartphone can be either refurbished, to make it again fully functional, or remanufactured, to restore it to original "as new" conditions (Cordella et al. 2019b)[62]. In any case, reuse of products and recovery of parts avoid the production of new parts.

Repair activities are attractive for smartphones because of the relatively high price of the product. In recent times, several examples of small, independent services can be found, besides officially authorised networks, which can offer repair training and services, used devices and parts. Access to repair manuals, diagnostic tools, original components, and specialised repair equipment is in some cases restricted to authorised centres only. Cooperation

[58] More sustainable materials generally refer to material options that are assessed as being less critical with respect to environmental, economic and social issues. In practice, these can for instance include, if supported by evidence: recycled or bio-based materials, materials that do not pose any social or chemical concerns, materials characterised by a lower embodied carbon/energy.

[59] https://www.theverge.com/2016/9/2/12775922/google-project-ara-modular-phone-suspended-confirm (accessed on 6 June 2018)

[60] https://www.techradar.com/news/they-were-supposed-to-be-the-future-so-why-havent-modular-phones-taken-off (accessed on 6 June 2018)

[61] https://www.shiftphones.com/en/ (accessed on 8 April 2019)

[62] When the product is considered a waste, these operations are referred to as "preparation for reuse"

between manufacturers and independent repairers can be limited by factors such as safety, guarantee and quality issues related to customer satisfaction and producer liability, intellectual property rights, competition in the repair market. The unavailability of original spare parts can in particular result in the purchase of 2nd hand smartphones to cannibalise for components, or in the use of compatible parts, of the same or lower quality, from other sources. By not issuing original parts, producers could be undermining the quality of repairs made through independent channels and losing a potential source of income (Watson et al. 2017). However, manufacturers pointed that other important elements to take into account include the training of repairers and the control over the quality of the repair operation, as well as contractual issues.

Repair operations undertaken by independent repairers could compromise the guarantee/warranty. However, from another perspective, they can avoid the return of functional products to manufacturers and retailers (Benton et al. 2015). The possibility to apply a warranty on repaired products would be important to build trust and deliver a good service, especially for repairers that are not certified by manufacturers. Repair services are also challenged by the cost of work, which could be counter balanced through the implementation of lower VAT or tax breaks (Watson et al. 2017).

The circular business model that seems to be most widely implemented is the take-back and buy-back of used phones for their remanufacturing/refurbishment and resale and/or for the reuse of parts (Watson et al. 2017). The value of devices lies more in their highly engineered parts rather than in the raw materials of which they are made (Figure 10). This means that revalorisation of parts can be much more valuable than material recycling. Opportunities for the revalorisation of parts include for example the use of old screens and cameras in low cost devices, and the use of batteries to power LED lighting (Benton et al. 2015).

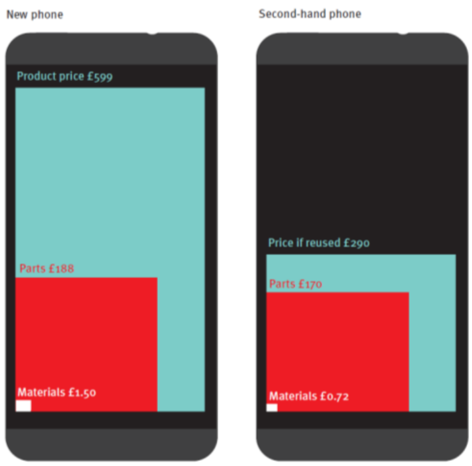


Figure 10: Contribution of materials and parts to the total product price for new and 2nd hand phones (Benton et al. 2015)

Manufacturers can remanufacture devices that are relatively new. Older devices can be sold in 2nd hand markets (Benton et al. 2015). The market for 2nd hand mobile phones has been growing since the early 2000s in developing countries. It is only more recently with smartphones that 2nd hand markets have become more important also in developed countries (Watson et al. 2017). The 2nd hand market of smartphones is expected to rise globally from 53 million in 2013 to 257 million in 2018. However, only 12% of smartphone replacements involved the old device being sold or traded. The reuse of smartphones in 2018 could account for about 8% of the global market (Benton et al. 2015).

Mugge et al. (2017) suggest a positive attitude of consumers towards reused smartphones because of the perceived environmental benefits. However, the growth in the 2nd hand market can be correlated also with the higher price of new devices. Nearly two thirds of smartphones live a 2nd life in Germany and in the U.S., either as new sale or exchange between users. When a new high-end smartphone model is introduced, previous models become available on 2nd hand markets. Best quality used goods are re-circulated in domestic markets, while lower quality goods go to markets with lower purchasing power (Watson et al. 2017). 2nd hand smartphones can be competitive with mid-to-low end devices (see Figure 11). Makov et al. (2019) highlight that depreciation can vary depending on the brand and the perceived quality.

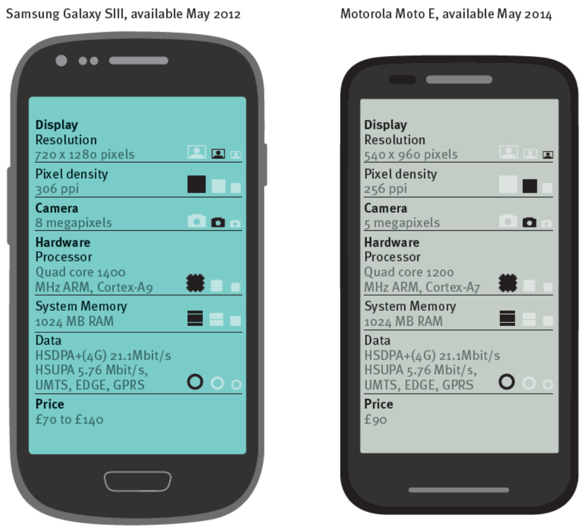


Figure 11: Specifications of two similar smartphones sold in the UK in 2012 and 2014 (Benton et al. 2015)

While some producers are fully engaged with refurbishment and resale companies, others fear that the resale of devices could damage their image if low-quality 2nd hand versions of their phones are sold without their control. Some refurbishers find that the supply of take-back phones is too limited and that better methods for incentivising consumers to return their phones should be developed. A retailer can act both as an official WEEE collector for discarded mobile phones, and in a separate take-back-and-buy channel, where they purchase used phones from consumers (in the understanding that they are not waste since intended for reuse) (Watson et al. 2017). Collaboration between carriers, retailers, software providers and consumers could facilitate the recovery of devices that would be otherwise scrapped or stored away. However, it is reported that many phones in developed countries are kept at home unused (e.g. in US and UK, where unused devices make up to 58 billion USD). Between 27% and 36% of US consumers said they keep an old phone because they "don't know what to do with it"; 17% were "too lazy" to get rid of them. Consumers could be incentivised to sell their old devices by being made aware of the value the devices still have and the availability of platforms to sell them (Benton et al. 2015). Device deposits have been also introduced to promote the return of used phones to the original manufacturer either for refurbishing or for recycling[63].

Take-back services can allow the recovery of parts and materials, and the proper recycle / final disposal of the device. For example, remade[64] is a French organization specialised in the remanufacturing of a specific brand of smartphone (iPhones). The entire process is conducted in France and includes the repair of screens (often only the glass needs replacement), motherboards and covers. In 2017, Remade refurbished more than 600000 smartphones. These are mainly 1-year-old phones supplied from leasing programmes for iPhones in the US[65].

However, 2nd hand phones shipped to developing countries typically end in open landfills once they are disposed, with negative consequences for human health and the environment, at least until modern e-waste recycling facilities will be deployed there. Closing the loop[66] collects client's phones for reuse/recycle purposes. For each phone, a waste phone is collected from developing countries and brought back to countries with appropriate recycling infrastructures. The programme also allows manufacturers to buy and recycle old phones from developing countries for each new phone put on the market (Transform Together 2018).

[63] www.shiftphones.com/en/deposit/ (accessed on 7 June 2018)
[64] https://www.remade.com/ (accessed on 12 March 2019)
[65] http://trendnomad.com/refurbished-phone-smarter-than-the-latest-model/ (accessed on 12 March 2019)
[66] http://www.closingtheloop.eu/ (last accessed on 01/02/19)

Refurbishment and 2nd hand businesses are also affected by the Consumer Sales Directive. For example, sellers of 2nd hand phones in Nordic Countries have the same minimum guarantee obligations as sellers of new phones. In practice, however, only a six-month guarantee period is effectively applied in most cases. Enforcing the full guarantee period could have both negative (increase of costs) and positive (increase of consumer confidence) effects (Watson et al. 2017).

Sustainable Product Service Systems (SPSS) could be an additional strategy of interest within the circular economy. The core concept of these models is that businesses retain ownership on the product and rather sell a service to consumers. SPSS can be broadly classified as (Hobson et al. 2018):

1. Product-Oriented (selling a good with additional services);
2. Use-Oriented (leasing or renting goods with attached services); and
3. Result-Oriented (providing a service rather than just material goods).

The offer of products as services provides an incentive, to the actor offering the service, to optimise their products in terms of material efficiency aspects such as their durability, reparability, upgradability, and suitability for remanufacturing. However, it should be pointed out that this does not represent by default an improvement of the material efficiency of the product (for example in case newer, upgraded devices are frequently offered by providers to replace the old ones).

3 USER BEHAVIOUR

The third step of the guidance is to collect background information about how consumers use and interact with the product. This is fundamental to understand up to which point the impacts of products are influenced by users and/or inherent design and performance characteristics. Examples of information to collect include consumer expectations and conditions of use of the product, indications about the technical and functional lifetimes and main causes of replacement.

3.1 Conditions of use and behavioural aspects

Smartphones have changed the world in a relatively short period (around a decade) and have become an essential tool and accessory for users. Over 36% of the world's population was estimated to use a smartphone in 2018, while penetration per capita in Central & Eastern Europe was estimated to be almost 60% in 2017 (Statista 2018i).

The devices are used for many different purposes, and as a result have made many other small electronic devices (e.g. digital cameras) unnecessary (Watson et al. 2013). Smartphones are multifunctional devices and they need mobile telecommunication (telco) networks and the internet in order to deliver all their functions. Popularity of smartphones also increases the overall data traffic in networks.

3.1.1 Type of phone and age of users

A majority of consumers in both developed and high-growth economies owns a mobile phone, although there are some differences in the types of mobile devices owned (Figure 12). In general, younger users are more likely to own a smartphone than older users, although there can be some exceptions (Nielsen 2013).

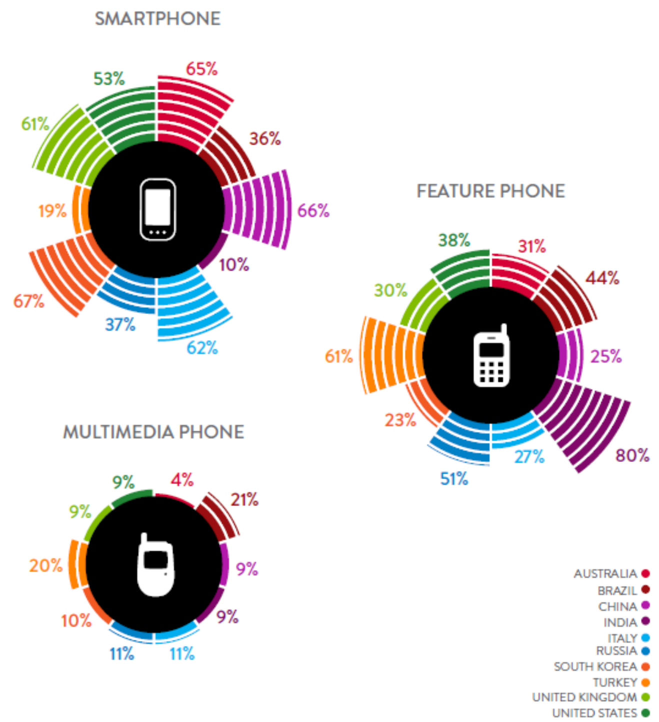


Figure 12: Use of mobile phones in different countries (Nielsen 2013)

3.1.2 Functionalities

Browsing the internet and gaming are among the most popular uses of a smartphone in different countries (Figure 13). Voice calls are the preferred choice of communication in some markets (e.g. Germany and Japan), although messaging is more and more popular especially in Asian and African markets. Watching videos and spending time on social networks are the fifth and sixth most popular activities on a smartphone (Counterpoint Research 2016).

It is reported that on average, a consumer in the US spends about 644 minutes per month in voice calls (164.5 voice call per month) and exchanges about 764 text messages (Nielsen 2013).

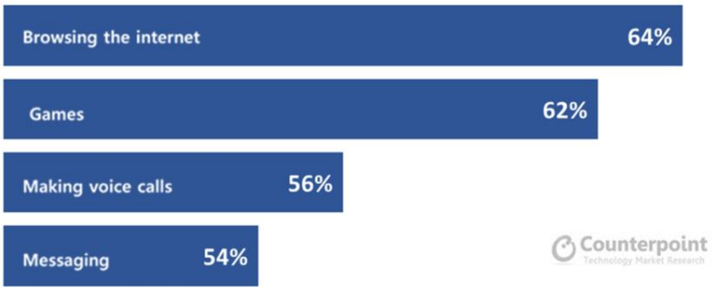


Figure 13: Global daily use behaviour (Counterpoint Research 2016)

The use of internet in smartphones is mainly associated with search engines, checking of email accounts and visiting social networks. These are the most common activities carried out weekly with a smartphone in countries like France, Spain, and the UK (Statista 2018k, 2018p, 2018s). As shown in Figure 14, the use of these services is increasing over time, as well as the use of data communication services (Deloitte 2016).

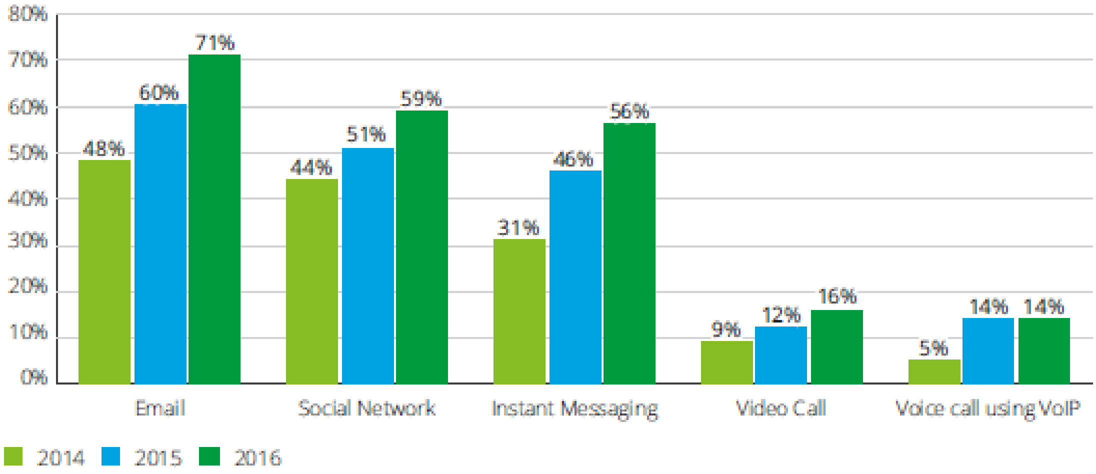


Figure 14: Smartphone users who use data communication services weekly in the UK (Deloitte 2016)

Interestingly, as shown in Figure 15, the use of smartphones for voice calls, which is the primary function of phones, seems to be decreasing over time (Deloitte 2016).

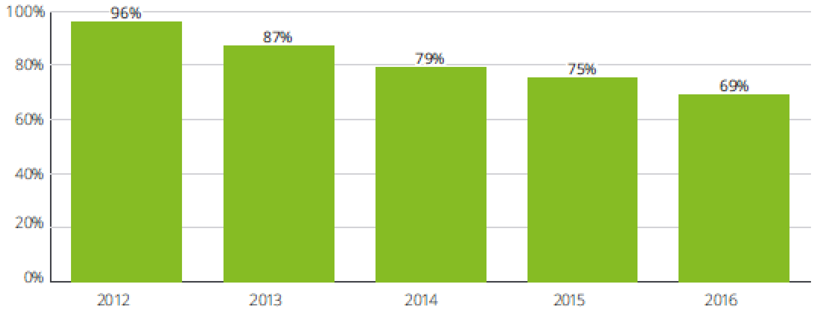


Figure 15: Use of smartphones for standard phone calls in the UK from 2012 to 2016 (Deloitte 2016)

Applications are one of the most disruptive innovations of the last decade and have played a core role for the commercial success of smartphones (Figure 16). Apps tend to be most successful for tasks that are undertaken regularly (Deloitte 2016).

Applications installed on smartphones devices often track user's location, contributing to higher battery drain, as well as to privacy concerns, which could be limited by disabling features when not needed. However, smartphones can also offer the opportunity to drive sustainable development with certain apps. For example, applications facilitating sharing economy practices and providing information about products (e.g. environmental impacts, energy-efficiency) are becoming increasingly popular and can represent an efficient way of using a smartphone (Transform Together 2018).

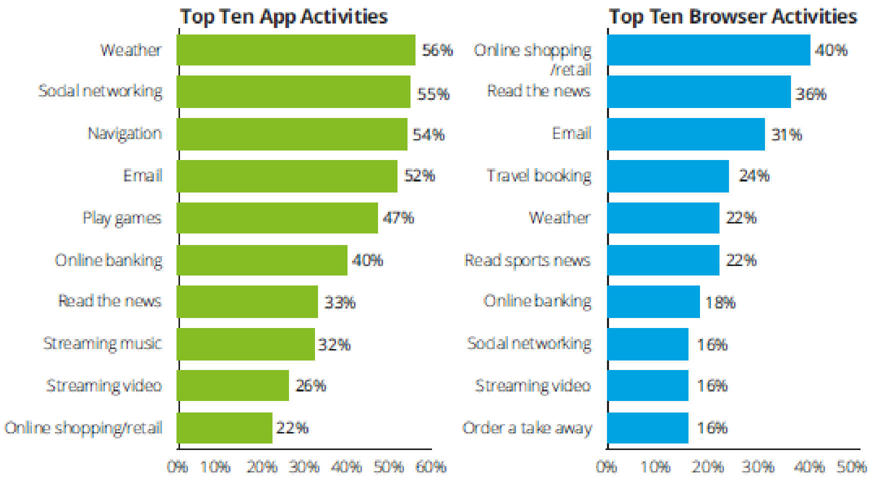


Figure 16: Top ten activities accessed in the UK when using an app or a browser (Deloitte 2016)

Another important functionality of smartphones is their ability to take pictures (Figure 17). In the UK, for instance, it has been observed that photo taking and sharing has increased in the last years. 27% of people took photos on a daily basis in 2016, more than double than in 2015. At the same time, there has been a corresponding increase in daily photo posting to social media and sharing via instant messaging, from 5% to 12%. Videos are also becoming more and more popular, also because of faster connectivity speeds and the availability of sharing applications and social media platforms (Deloitte 2016). However, video viewing is not considered universally a full replacement of TV (Nielsen 2013).

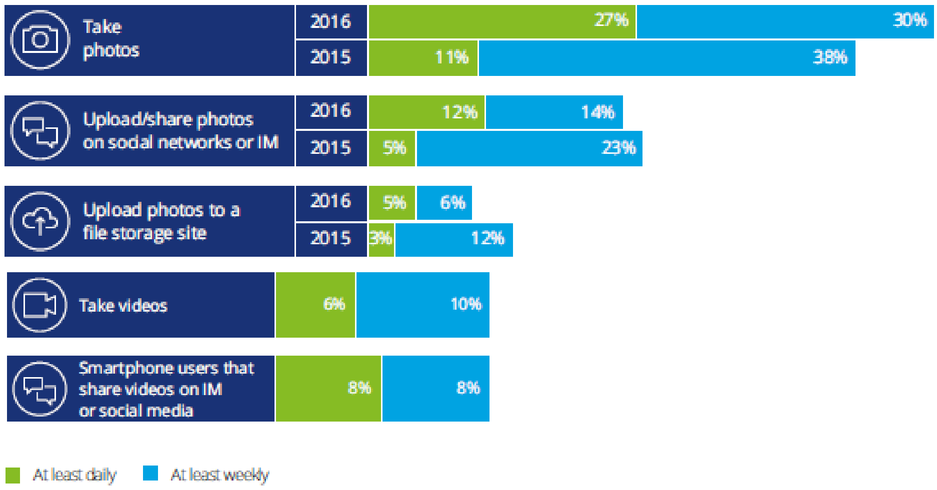


Figure 17: Photo and video taking and sharing in the UK in 2015 and 2016 (Deloitte 2016)

With respect to other features, only 12% of users were reported to use the voice assistant in the UK in 2016, and another 21% were using the fingerprint identity verification method to log into their devices (Statista 2018r). However, more recent data for the UK market seems to indicate that the frequency of use of such services has increased significantly in the recent period (Deloitte 2018). Moreover, it has been reported by stakeholders involved in the development of this study that also other forms of identifications, as face identification, are available since 2017.

Smartphones compete with other devices such as laptops and tablets for a range of applications. According to a survey conducted in the UK (Deloitte 2016), smartphones would be the preferred device for checking social networks, calling using internet, playing games, taking photos and recording videos.

3.1.3 Time and place of use

People spend more time on their smartphones than any other device: smartphones are taking a central stage of consumer life (Figure 18). Almost half of respondents to a global survey spent more than 5 hours per day on their smartphone. Additionally, one in four users spent more than 7 hours every day on their smartphone (Counterpoint Research 2016).

Figure 18: Time Spent on Smartphones Daily (Counterpoint Research 2016)

The use of smartphones can enhance social lives, but also comes with risks (e.g. dependency, distraction, arguments). In the UK, a tenth of smartphone owners instinctively reach for their phones as soon as they wake up, and not just to turn off their alarm. A third reaches for their phones within five minutes of waking, and half within a quarter of an hour. A similar pattern takes place at night. Two thirds of smartphone owners do not check their phones at night, however, over three quarters of smartphone owners check their phones within one hour before going to sleep; half within 30 minutes; a quarter within five minutes; and a tenth immediately before. Exposure to light, including that from a screen just before going to sleep, can confuse the brain into thinking it is still day-time, and inhibit the process of falling asleep. Screens should be turned off at least an hour before turning out the lights. Alternatively, night-time modes should be used that make screens with warmer and yellower tones instead of standard blue lights. As with most emerging technologies, consumers need to find a balance between usefulness and overuse of smartphones (Deloitte 2016).

3.1.4 Purchasing behaviour

The main factor consumers in the UK are taking into consideration when making a decision about purchasing a new smartphone is the price, while the main reason for purchasing a new smartphone is that the consumer's current device is out of date (Statista 2018r).

Environmental concerns do not seem to be a key driver of purchase for most consumers. Retailers do not report any increased interest in smartphones made from materials that embed lower environmental impacts, or modular devices that can facilitate the repair and/or upgrade of their parts. This is confirmed also by some manufacturers, who indicate that the user experience with the phone and the value for money are what really matter for most consumers (Nielsen 2013; Watson et al. 2017).

3.2 Causes of replacement

- According to a recent study (Watson et al. 2017), discarded or replaced phones are often replaced because of functional obsolescence driven by launching of new models and features, and by social expectations. However, loss of performance, failures and breakages of smartphones can still be important reasons for replacing the product in Europe.

The decision on whether to repair or replace the device may depend on a number of factors, such as type and value of the product, lifetime considerations, functionality of new/alternative products and technologies, emotional attachment. The decision can also be influenced by sociodemographic factors (e.g. age, relationship with technology, attitude towards new vs. conserving the old, social pressures).

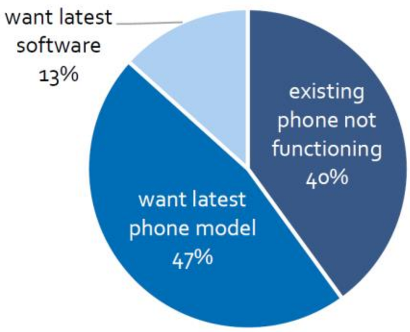


Figure 19: Reasons for smartphone replacement (Watson et al. 2017)

3.3 Product's lifetime

According to the results of a global consumer survey (2016), the average global smartphone replacement cycle was 21 months in 2016 (Figure 20). Emerging market consumers seem more assertive in replacing their device than consumers in developed markets. This could be triggered by the growth of Chinese brands as well as by the rise of 2nd hand and refurbished smartphones (Counterpoint Research 2016). In alignment with the figure just provided, another survey (Kantar World Panel 2017) indicates that the average time of first use of smartphones increased from 18.3 months in 2013 to 21.6 months in 2016 in the five most populated countries of Europe (Figure 21). The available evidence suggests that consumers of developed countries are holding their phones longer than in the last years, which could be in part explained by a decrease in the speed of innovation.

Figure 20: Average replacement cycle for smartphones in 2016 (Counterpoint Research 2016)

	USA	China	EU5	France	Germany	Great Britain	Italy	Spain
2016	22.7	20.2	21.6	22.2	20.3	23.4	21.6	20.5
2015	21.6	19.5	20.4	21.6	18.8	23.5	17.7	20.0
2014	20.9	21.8	19.5	19.4	18.2	22.0	18.7	18.2
2013	20.5	18.6	18.3	18.0	17.1	20.0	18.6	16.6

Figure 21: Average time of first use of smartphones by country (number of months) (Kantar World Panel 2017)

A review study for the German context (Prakash et al. 2015) also reports that the time of first use is 2 years for new mobile phones (2.5 years considering 2nd hand use). This could be due to the fact that mobile phone contracts in Germany usually run over 2 years. With the conclusion of a contract, a new model is often purchased and the old device taken out of service. Such outcomes are aligned with indications from Stiftung Warentest, according to which 42% of users in Germany exchange their mobile phone within 2 years. Around 16% of users change phones every 3 years, with another 12% every 4 years. Only about 20% of respondents exchange their mobile phone less frequently than every 5 years (Prakash et al. 2015).

However, the lifespan of a mobile phone can range from 1.7 up to 7.99 years[67], with the median reported to decrease from 4.8 to 4.6 years (-3%) between 2000 and 2005 (Bakker et al. 2014). According to data available on the website of the German WEEE registry (EAR), 6 years would instead be the average time before a mobile phone reaches the end-of-life[68], probably due to reuse of mobile phones and/or the storage of unused devices at home.

[67] Encyclopedia of mobile phone behavior / Zheng Yan, editor. Information Science Reference (an imprint of IGI Global), Hershey PA (USA). ISBN 978-1-4666-8239-9 (hardcover) -- ISBN 978-1-4666-8240-5 (ebook)

[68] German register for waste electric (WEEE registry), https://www.stiftung-ear.de/hersteller/produktbereiche-regelsetzung-und-regeln/produktuebergreifende-arbeitsgruppe-pbue/regelsetzung-garantiehoehe (accessed on 13 June 2018)

4 TECHNICAL ASPECTS

The fourth step of the guidance is to gather technical information enabling the analysis of material efficiency aspects such as durability, reparability and recyclability. This include the analysis of functionalities, parts, technologies and materials used in the product; typical limiting states, frequencies, causes and strategies to avoid/overcome them; EOL practices. Trade-offs and system aspects (e.g. infrastructures) are also discussed. The goal is to set the basis:

1. For the preliminary identification of design measures which could contribute to improve the material efficiency of the analysed product;
2. For the definition of product design option(s) that can be representative for average performance conditions and for the assessment of scenarios associated to different material efficiency aspects.

4.1 Technological aspects

4.1.1 Design and innovation

Decisions taken during the design of a product can have consequences over its entire life cycle. These can for instance address functionalities and target levels of performance, aesthetic considerations, type and quality of parts, their durability and disassemblability, supply, safety and recyclability of materials. The design phase plays a key role in determining the impacts of a product. Trade-offs can be in particular associated to different design strategies addressing material efficiency aspects as durability, reparability and recyclability, as discussed in Section 4.5.

Mobile phones are changing every subsequent generation in terms of quality, computational power, size of parts, and materials. The Moore's law (doubling of computational power every two years) could be less relevant than in the past for estimating the progressive increase of computational power. This is another reason why life extension of hardware is relevant. However, mobile phones are becoming more powerful and the energy consumption of their parts (e.g. chipsets and screens) is increasing (Transform Together 2018). Miniaturisation is also leading to use fewer resources, expressed as overall mass, although some of them can be precious and/or critical.

Smartphones on the market can be considered to belong to the fourth generations of mobile communication systems (Agrawal et al. 2015), while the fifth generation is going to be available shortly. The main features of each generation are described below:

1. The first generation of mobile communication networks was introduced in 1980s and was based on the analog 1G system. The most popular were the Advanced Mobile Phone System (AMPS) in the US and the Nordic Mobile Telephone (NMT) and the Total Access Communication System (TACS) in Europe. Analog systems were based on circuit switching technology, which supported transfer speed of up to 2.4kbps and offered only voice communication.
2. The second generation, conceived as 2G technology, was introduced in late 1980s and was based on low-band digital data signalling. Analog technology was replaced by Digital Access techniques such as TDMA (Time Division Multiple Access) and CDMA (Code Division Multiple Access). The most popular 2G wireless technology is known as Global Systems for Mobile Communications (GSM). The CDMA breaks down voice and data transmission on a signal by codes, whereas TDMA breaks them down by time slots. The result in both cases is an increased network capacity for the wireless carrier and a lack of interference. Transfer speeds of 64 kbps were provided.
3. The third generation (3G) was introduced at the end of 1990s. The 3G brought disruptive transformation in the mobile communication by providing peak data rates of at least 200 kbit/s. The most important technology was the Universal Mobile Telecommunications System (UMTS). The UMTS uses the W-CDMA, TD-CDMA, or TD-SCDMA air interfaces. The main components includes BS (Base Station) or nod B, RNC (Radio Network Controller), apart from WMSC (Wideband CDMA Mobile Switching Centre) and SGSN/GGSN. The W-CDMA gave additional advantages of high transfer rate, and increased system capacity and communication quality. In the W-CDMA system, the data is split into separate packets, which are then transmitted and reassembled in the correct sequence at the receiver by using the code that is sent with each packet. The UMTS systems are designed to provide a range of data rates (up to 144 kbps for moving vehicles, up to 384 kbps for pedestrians and up to 2 Mbps for indoor or stationary users). The 3G allowed multimedia applications such as video and photography, and the provision of services like mobile television, GPS (global positioning system), video call and conferencing, high speed mobile internet access.
4. The fourth generation (4G) was introduced at the end of 2000s, also due to an increased demand of data transfer. Better modulation techniques were used to improve the upload and download rate of data. The Long Term

Evolution (LTE) was the evolution of universal mobile telephone system (UMTS). Its components are named "evolved UMTS terrestrial radio access" (E-UTRA) and "evolved UMTS terrestrial radio access network" (EUTRAN). The basic architecture of LTE contains a separate IP connectivity layer for all the IP based services and Evolved Packet System (EPS) which handles the overall communication procedure. Since LTE allows for inter-operation with existing systems, there are various paths available to connect to LTE: both an operator with a GPRS/EDGE network or a Non-3GPP systems can connect to a LTE network. LTE can have download rates of about 100 Mbps in update rate of 50 Mbps. Higher rates can be achieved if multiple-input multiple-output (MIMO), i.e. antenna arrays, are used. Moreover, it provides better quality of communication, easy access to internet, streaming media, video calling services.

- 5G is the fifth and latest generation of wireless technology for digital cellular networks, which can provide high data transfer rate (1-2 Gbps), reduced latency, energy saving, cost reduction, higher system capacity, and massive device connectivity. The worldwide deployment of 5G began in 2019[69].

When smartphones were introduced on the market, products were innovating rapidly: the average time new models spent on the market was 6-9 months in 2010, whilst the average shelf time was about three years prior to 2007[70]. However, longer update cycles could be adopted now (Watson et al 2017).

4.1.2 Manufacture

Smartphones are complex products for which there are increasing demands on computing power, display and device size, and use of high-grade materials. Electronics are required in a smartphone (e.g. integrated circuits (IC), printed wiring boards (PWB), batteries, or displays) which production is a very energy intensive and pollutant process (Transform Together 2018). Environmental concerns are also due to the high consumption of water, including ultrapure water, for the cleaning and rinsing phases required in the production of smartphones, as well as the use of hazardous materials (Transform Together 2018).

The majority of smartphones are produced in Asia, mainly in China (e.g. Apple, Nokia, Xiaomi, and Huawei), South Korea (Samsung), Japan (Sony), India (LG), or Taiwan (HTC). The production deployment in some of these countries raises also some social concerns about the working conditions associated to exposure to harmful chemicals, child labour exploitation, work overload and low wages (Transform Together 2018).

Some manufacturers are committing to reduce the impact of the production stage. For instance, Apple's supplier facilities have committed to Zero Waste to landfill and Apple's facilities in the 2018 were reported to use 100% of their electricity from renewables. However, overall energy consumption, water consumption and waste generation seem to have increased in absolute terms in the last five years (Apple 2018a), probably due to an increased market volume.

Selecting, monitoring and working closely with suppliers are also important to improve working conditions during manufacturing and assembly of parts. Companies are committed to improve working conditions along the product's supply chain, as for instance is the case of Fairphone (Transform Together 2018) and Apple[71]. The majority of the smartphone manufacturers have a supplier management and audit programme in place, although their efforts in this area can vary. Many of the big manufacturers are part of The Responsible Business Coalition (formerly known as Electronic Industry Citizenship Coalition), which requires its members to adhere to a Code of Conduct that sets standards on social, ethical and environmental issues. Apple and Fairphone are also part of the Clean Electronics Production Network (CEPN), which has the goal to move toward zero exposure of workers to toxic chemicals in the electronics manufacturing process (Transform Together 2018).

[69] https://en.wikipedia.org/wiki/5G (accessed on 7 January 2020)
[70] http://money.cnn.com/2011/01/31/technology/new_smartphone/index.htm (accessed on 1 March 2018)
[71] https://www.apple.com/supplier-responsibility/ (accessed on 8 April 2019)

4.1.3 Functions

Products are conceived to deliver certain functions. The analysis of functions (also referred to as functional analysis in this report) is fundamental to understand the purpose of a product, identify the parts needed and define their technical specifications. Functions of a product and their relative importance can be analysed following the principles of the standard EN 12973:2000 – Value Management[72].

A smartphone is described in section 1.1.3 as follows:

- It is an electronic device primarily designed for mobile communication (making phone calls, text messaging) and use of internet services;
- It can be used for long-range communication over a cellular network of specialized base stations known as cell sites, including the new 5G network, LTE (often also called 4G), HSDPA (3G+), UMTS (3G) or GSM standard (2G);
- It is functionally similar to wireless, portable computers (e.g. tablet PCs), since

  - designed for battery mode usage, and connection to mains via an external power supply is mainly for battery charging purposes,

  - presenting an operating system (Google's Android, BlackBerry OS, Apple's iOS, Nokia's Symbian, Microsoft's Windows Phone), WiFi connectivity, web browsing capability, and ability to accept sophisticated applications;
- It has a display size between 3 and 6 inches and a high-resolution touch screen interface, in place of a physical keyboard.

Functions of a smartphone could be classified as:

- Communication functions (phone calls making, text messaging, access to web services, keyboard, touch-screen interface);
- Portable operability (rechargeable battery, longevity and ease of replacement of the battery, computational features);
- Multimedia functions (camera features, audio/video recording, audio/video reproduction, screen size and resolution).

According to the information collected in the former sections 2 and 3, the following functions seem particularly important for consumers:

- Size of the screen, camera, quality aspects as reliability and screen resolution (Kantar World Panel, 2017)
- Longevity of battery, internet access, and high specification camera (Benton et al. 2015).

A classification of smartphone's functions is reported in Table 16.

[72] 5 steps are defined: 1) Identification and list of functions; 2) Organisation of the functions; 3) Characterisation of the functions; 4) Setting the functions in a hierarchical order; 5) Evaluation of the functions

Table 16: Smartphone's functions and related characteristics

Function	User needs	Required characteristics
Secure access	- Security of access / access restriction - Ease of access	- Access recognition / restriction (e.g. passcode, fingerprint sensors, face ID)
Connectivity	- Reliable and fast voice / data connection - Internet access - Availability of different connection options (including ability to provide network access to another device and ability to connect with other devices)	- Cellular Band communication - Wi-Fi Network connection - Infrared/blue-tooth connection - NFC (near-field communication) connection - GPS connection - Tethering - USB/cable connection
Communication, user interface and multimedia reproduction	- Ability to communicate (send and receive information) via audio, photo and video, and keyboard / touch - Ability to receive/provide notifications via screen / audio / vibration - Ability to take quality photo/video in a wide range of lighting conditions - Ability to support communication apps (such as for video calling, messaging, email) - Ability to adapt display / touchscreen for different phone orientations	- Microphone - Speaker - Audio jack - Keyboard and/or touch-screen - Functional display and touch screen (size, resolution, color and luminance) - Integrated photo and video-camera (rear and front) - Vibration motor - Accelerometer / gyroscope / proximity sensor
Data storage and processing	- Adequate capacities for storage and processing of data (including media)	- RAM and HD capacities
Portable operability	- Ability to connect to mains for charging - Ability to connect to other devices for charging and data transfer (e.g. laptop) - Battery that holds charge for a certain time	- Rechargeable battery - External power supply unit - Connector(s) - Duration cycle of the battery
Longevity	- Software that is freely updated and maintained for security updates - O/S that supports users' applications - Product that is reliable (electronics) and resistant to typical stresses (e.g. scratches, drops) - Battery that is functional (measured as capacity) over time and replaceable - Product that can be easily repaired and upgraded	- Updatable operating system and software - Resistance to stresses - Longevity of battery - Ease of repair and upgrade

4.1.4 Parts

The delivery of functions is done in an interplay between physical parts (hardware) and software. Smartphones is composed of between 500 to 1000 different components, many of which are extremely small (Wiens 2014). The main parts of a smartphones are described in the next sections.

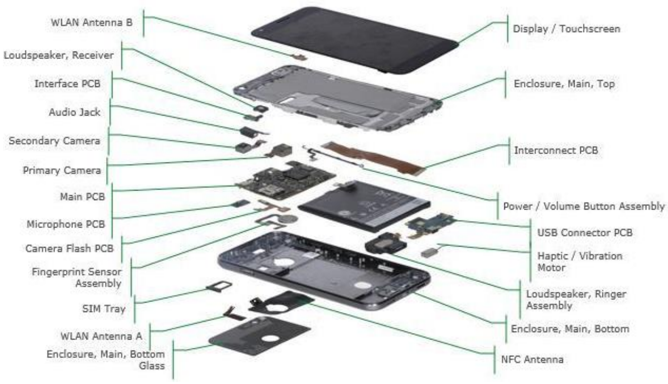


Figure 22: Parts of a smartphone: exploded view based of the Google Pixel XL[73]

4.1.4.1 Frame and back cover

The phone is typically designed to find a balance between aesthetics, durability and an increasing number of functionalities". Frame and back cover are the endo- and exo-skeleton of smartphones and are typically made of metals (mainly aluminium, copper and iron/steel alloys), plastics, glass and ceramics (Andrae 2016; Manhart et al. 2016; Proske et al. 2016).

4.1.4.2 Display assembly

The display assembly of smartphones is the interface that allows users to visualise information on their devices. A standard three-part display assembly consists of a display, a capacitive layer (touch screen) and a glass cover. For several models on the market, such parts are glued together and form one unit.

In terms of size, the majority of displays sold in 2016 were larger than 5" (Kantar World Panel 2018). Alternative technologies can be applied for the visualisation of information (Fossbytes 2017):

1. Liquid Crystal Displays (LCDs), where a backlight is transmitted through some polarizers and filters and result in different colours in the display. The light is not being generated by the display itself. When the display is black, no light gets through its crystal. However, the light behind the display is still being generated meaning that the smartphone is still using a bit of battery;
2. Light-Emitting Diodes (LEDs), where pixels are illuminated by light emitting diodes (also known as LEDs) which produce red, green, and blue colours. The display itself is generating the different colours. This means that no energy is used when a pixel is off and colour is black, which is beneficial for the battery life;
3. OLED (Organic Light-Emitting Diode), where pixels actually produce their own light. These pixels are called "emissive". OLED are typically used in high-end phones although they are is becoming popular since they have a very fast response time and allow making curved and flexible screens, good view angles and an always-on display mode[74];
4. AMOLED (Active Matrix OLED) is a type of OLED technology used in smartphones, which is more energy efficient thanks to the use of at least two thin-film transistors that control the current flowing of each pixel.

[73] https://www.businesswire.com/news/home/20161025005551/en/Google-Pixel-XL-Manufacturing-Cost-Line-Rival (accessed on 6 March 2019)

[74] http://www.displaymate.com/Galaxy_S10_ShootOut_1S.htm#Table (accessed on 4 April 2019)

Manufacturing costs of different display panels are reported in Figure 23. The cost of OLED displays is relatively higher than other types of displays; however, smartphones with OLED displays are more expensive also because they generally include also other high-end parts (e.g. camera, chip)[75].

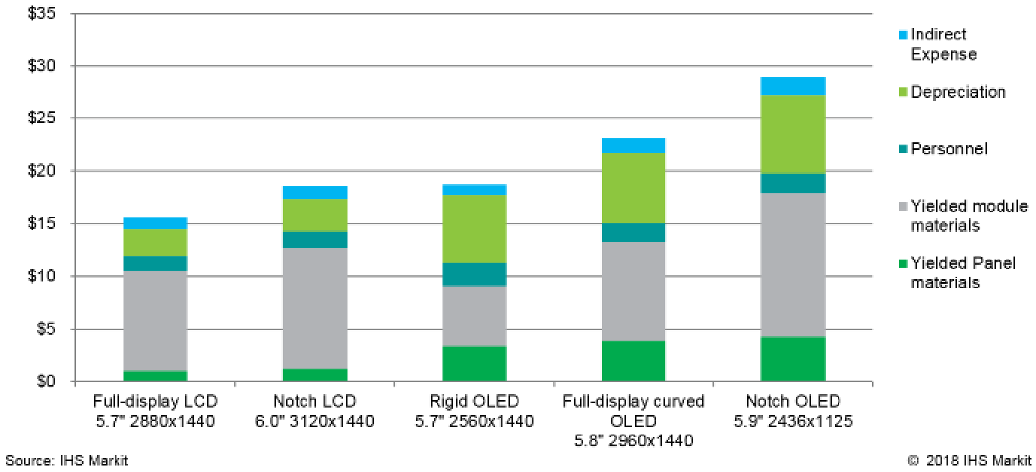


Figure 23: Manufacturing cost of different display panels[76]

The touch screen consists of a capacitive layer typically based on Projected Capacitive Touch (PCT) technology. A voltage is applied to a grid to create a uniform electrostatic field. When a conductive object touches the PCT panel, it distorts the electrostatic field of the electrodes that are nearby the touch point. This is measurable as a change in the electrode capacitance. If a finger bridges the gap between two of the electrodes, the charge field is further affected. The capacitance can be changed and measured at every individual point on the grid. Therefore, this system is able to accurately estimate the touch position (Li Du 2016).

The glass cover is the outer part of a screen. Modern smartphones feature a toughened glass (commonly an alkali-aluminosilicate glass)[77]. This increases the durability of the display in terms of scratch- and drop-resistance and ensures a clear visualisation of images. Strengthened glass panels are getting more and more durable. Corning's Gorilla Glass 4, for example, offers twice the protection of its predecessor (Gorilla Glass 3). Both Gorilla Glass and Apple's ion-strengthened glass have been chemically altered via ion exchange to improve their strength. The process involves the exchange of sodium ions in the glass material with larger potassium ions under high temperature. The result is a material that is more impact resistant and scratch-proof than regular glass[78].

Recently, a new type of glass that can heal itself from cracks and breaks has been developed. This is made from a low weight polymer called "polyether-thioureas" and can heal breaks when pressed together by hand without the need for high heat to melt the material[79].

[75] http://www.displaymate.com/iPhoneXS_ShootOut_1s.htm (accessed on 10 April 2019)

[76] https://technology.ihs.com/603423/smartphone-display-with-notch-design-estimated-to-cost-about-20-percent-more-ihs-markit-says (accessed on 10 April 2019)

[77] https://www.androidguys.com/tips-tools/types-of-smartphone-glass/ (accessed on 27 March 2019)

[78] https://smartphones.gadgethacks.com/how-to/4-most-durable-premium-smartphones-for-clumsy-people-0175454/#jump-comparisonchart (accessed on 23 March 2018)

[79] https://www.theguardian.com/technology/2017/dec/18/smashed-cracked-phone-screen-self-healing-glass-university-of-tokyo (accessed on 23 March 2018)

4.1.4.3 Battery

Batteries of phones are normally based on lithium-ion (Li-ion) technology (Fossbytes 2017) and can be removable either by end-users or only by professionals.

Lithium polymer (Li-poly) is the latest technology commercially available for smartphones where a polymer electrolyte is used, instead of a liquid one. Li-ion and Li-poly batteries have the same chemical composition, but one of their differences is that Li-ion batteries have a tendency to overheat and need to have an active protection circuit to prevent overheating. Since Li-poly batteries do not require such protection circuit, they allow thinner formats of cells. Another characteristic of the Li-poly batteries is that they do not suffer from memory effect[80, 81]. Li-ion batteries have a higher energy density and cost less for their manufacturing[82].

The energy accumulated in a battery (battery capacity) is normally expressed in terms of milliAmpere hours (mAh) and it is usually in the 2000-4000 mAh range for smartphone on the market. The actual battery duration (in hours) is influenced by factors relating to the design of smartphones, their energy management systems, and how devices are used. The battery endurance can be expressed in terms of charging and discharging cycles.

The battery can affect the durability of the device. Some manufacturers argued that integrated batteries are compatible with water-proof designs and require less space to deliver the same level of performance of removable-by-user batteries. However, information collected and reported in Table 17[83] shows that there is not any evident correlation between smartphone modularity (e.g. Fairphone, Shift) and battery capacity. Durability of batteries is further discussed in section 4.3.1 of this report.

Table 17: Battery capacity associated to different modular and not modular devices

Model	Capacity (in mAh)
iPhone 7	1960
iPhone 8	1821
Fairphone 2	2440
SHIFT5me	2450
Galaxy J5	2600
iPhone 10	2716
Fairphone 3	3060
Xiaomi Mi 9	3300
Huawei P30 Pro	4200
SHIFT6m	4200
Galaxy Note10+	4300

Solid-state lithium batteries could represent one of the main evolutions of Li-ion batteries for the future (Science for Environment Policy 2018), as well as silicon anode batteries, energy-harvesting nano-generators, durable nanowire batteries and organic "flash" batteries[84].

[80] The "memory effect" happens when rechargeable batteries are not fully discharged between charge cycles; as a result the battery "remembers" the shortened cycle and is thus reduces its capacity

[81] https://www.themobileindian.com/news/understanding-cell-phone-batteries-5168 (accessed on 8 April 2019)

[82] https://www.quora.com/Which-type-of-battery-for-smartphone-is-better-Li-Ion-or-Li-Po (accessed on 8 April 2019)

[83] https://www.gsmarena.com/ (accessed on 24 October 2019)

[84] https://enterprisersproject.com/article/2018/10/5-mobile-phone-battery-breakthroughs-watch (accessed on 10 April 2019

4.1.4.4 Electronics

The "System-on-a-Chip" or SoC (also known as an IC chip) is one the most important parts of a smartphone. This comprises the CPU (Central Processing Unit), the GPU (Graphics Processing Unit), the modem, the display and video processors, and other electronics that turn the product into a functional system. Most of smartphones use the same architecture from ARM[85]. Some companies instead make their proprietary processors but these are compatible with ARM's system architecture (Fossbytes 2017).

With respect to modems (Fossbytes 2017), these are communication components used in smartphones to receive and send information. Every SoC manufacturer has its own brand of modems. The fastest one is the Cat. 16 LTE modem. However, this can be used at its full potentiality only if the level of speed is supported in the cellular network.

4.1.4.5 Memory and storage

No smartphone can function without a RAM and an internal memory storage system (Fossbytes 2017). The internal memory storage system ranges typically from 32GB to 256GB.

With respect to the RAM, most mobile devices are shipped with LPDDR3 or LPDDR4, while some high-end smartphones are shipped with LPDDR4X RAM. LP stands for "Low-Power" and reduces the total voltage of these chips, making them highly efficient and giving mobile phones an extended battery life. LPDDR4 is more efficient and powerful than LPDDR3, while the LPDDR4X is the fastest, most efficient, but expensive. Newer generations of RAM are going to be introduced, such as LPDDR5. In terms of capacity, the current RAM usually ranges between 2 GB and 8 GB.

Terminating or uninstalling unused apps can result in the availability of more RAM and can improve the performance of a smartphone.

4.1.4.6 Firmware and software

Smartphones are run through an Operating System (OS) and firmware. An operating system allows the device to run applications and programs, therefore, bringing advanced functions that were previously restricted to computers only (Statista 2018z). The firmware is a kind of software that serves for specific purposes related to hardware parts. Updates can determine the performance of essential hardware as battery and CPU; this can determine the overall performance of the smartphone. In this sense, updates as well as a lack of updates can make a smartphone obsolete.

Manufacturers provide updates on a regular basis to fix problems and security issues. Updates are as important as the physical elements of a smartphone to ensure a longer life of the device and to reduce phone replacement rates. A lack of updates might indeed make smartphones obsolete while its hardware is still fully functioning (Watson et al. 2017).

Security updates, even though do not significantly affect the performance of a device, are considered crucial and should be ensured for much longer time (e.g. 5/7 years), irrespective of other software updates according to some stakeholders. Not receiving security updates during 2 years can lead to less secure devices and to potential conditions of obsolescence (e.g. in case of malfunctioning of apps).

4.1.4.7 Multimedia and connections

Multimedia-related parts include the camera and audio components as microphone, speakers, headset connector. In particular, all smartphones come with rear-facing and front-shooting cameras. The camera comprises up of three main parts: the sensor (which detects light), the lens (the component in which light comes through), and the image processor. While the megapixels on the smartphone are still an important part of the camera, they carry less importance than in the past. Instead, the primary limiting factor is the camera sensor of the phone and how sensitive it is when light passes through the lens. Each sensor behaves differently from smartphone to smartphone. Since smartphones have small sensor sizes, they tend to perform badly in low-light areas. This is an area where camera sensor manufacturers have been working to improve the performance of the device (Fossbytes 2017). Interactivity with the user is also possible through USB ports.

[85] https://www.arm.com/ (accessed on 8 March 2019)

4.1.4.8 Other functional parts

Smartphones come with a vibration mechanism and with sensors that provide specific functionalities (Fossbytes 2017):

- Accelerometer, which is used by apps to detect the orientation of the device and its movements, as well as allows the phone to react to the shaking of the device (e.g. to change music);
- Gyroscope, which works with the Accelerometer to detect the rotation of the device, for features like tilting the phone to play racing games or to watch a movie;
- Digital Compass, which helps the device to find the North direction, for map/navigation purposes;
- Ambient Light Sensor, which automatically sets the screen brightness based on the surrounding light, thus helping to reduce the eyes strain and to preserve the battery life;
- Proximity Sensor, which detects the proximity of the device with the body, so that the screen is automatically locked when brought near the ears to prevent unwanted touch commands.

4.1.4.9 Accessories

A smartphone can include a set of accessories in the sale package:

1. Headset;
2. Transfer cable;
3. External Power Supply (charger);

Instead of including a captive charger and data transfer cable, it could be more efficient to use a detachable charger (RPA 2014). Interoperability of chargers can be ensured by the compliance with the IEC 62684:2018 "Interoperability specifications of common external power supply (EPS) for use with data-enabled mobile telephones" that is based on the common use of USB 2.0 Micro B interfaces. However, in March 2018 several manufacturers have signed a MoU committing, by three years from the signature date, to produce smartphones that will be chargeable through a USB Type-C connector or cable assembly [86]. For these purposes, the relevant EPS interoperability standard is IEC 63002:2016 "Identification and Communication Interoperability Method for External Power Supplies Used with Portable Computing Devices". However, an effective saving of materials can be achieved only if the sale of EPSs is decoupled from the sales of the smartphones (RPA 2014; Sustainably SMART 2019).

Others accessories generally not sold by the OEM but necessary for a smartphone to function properly over time include:

- Micro SD cards and micro SIMs;
- Protection accessories: protective cases (also called bumpers) and screen protectors.

4.2 Materials

4.2.1 Bill of Materials

Compiling a precise list of materials contained in a smartphone is difficult due to tightly protected Intellectual Property and variations between models and manufacturers over time.

Prunel et al. (2015) indicate that the weight of mobile communication appliances can range from 60 g (when the display size is 1.5", for a surface of 7 cm^2) to 200 g (when the display size is 6.5", for a surface of 120 cm^2). However, this is beyond the scope of this study, which focuses on 4-6.5" smartphones.

[86] https://www.digitaleurope.org/wp/wp-content/uploads/2019/01/2018.03.20-MoU%20on%20the%20future%20of%20Common%20Charging%20Solutions%20(1)%20(1)%202.pdf (accessed on 22 February 2019)

Data available for 32 models of smartphones produced by Huawei[87] shows a range in weight from 142.4 g to 232 g. Battery represents around 25-30% of the product weight and together with glass and ceramic materials represent more than 50% of the smartphone mass.

Weight of 15 models of smartphones produced by Apple[88] instead ranges from 112 g to 208 g, with an apparently higher weight for newer models. The relative weight of batteries has passed from about 25% for older models to about 40% for the newest ones. Stainless steel is reported to be used more than aluminium and plastics. However, a variation in the use of different materials over time can be observed.

The weights of smartphone models from Fairphone (170 g for a size of 75.5 cm^2) (Proske et al. 2016) and Samsung[89] are also included in the range described above.

Based on the available data, the weight of a smartphone could be estimated approximately as 29 g per display size inch (+/-15%). A smartphone has been reported (Manhart et al. 2016) to have, on average, a display size of 75.53 cm^2 and a weight of 160 grams, including 39 g for the battery, and excluding accessories and packaging.

The mass of a smartphone in general consists of metals (mainly aluminium, copper and iron/steel alloys, but also minor quantities of other elements used for specific applications because of their properties, including rare earth elements and conflict minerals), glass and ceramics, plastics, and other materials (Andrae A. 2016; Manhart et al. 2016; Proske et al. 2016).

Screens are manufactured mainly from aluminosilicate glass, a mixture of aluminium oxide and silicon dioxide, which is then placed in a hot bath of molten salt. These are pressed together when the glass cools, producing a layer of compressive stress on the glass and increasing its strength and resistance to mechanical damage. A thin, transparent, conductive layer of indium tin oxide is deposited on the glass in order to allow it to function as a touch screen. Several rare earth elements are also present in very small quantities to produce the colours displayed on the screen (Compoundchem 2014).

The majority of smartphones use lithium ion batteries. These batteries tend to use lithium cobalt oxide as the positive electrode in the battery (though other transition metals are sometimes used in place of cobalt), whilst the negative electrode is formed from carbon in the form of graphite. Batteries also have an organic solvent that acts as the electrolytic fluid. The lithium in the positive electrode is ionised during charging of the battery, and moves into the layers of the graphite electrode. During discharge, the ions move back to the positive electrode. The battery is usually housed in an aluminium casing (Compoundchem 2014).

A wide range of elements and compounds are used in the electronics of a phone. The main processor of the phone is made from pure silicon, which is then exposed to oxygen and heat in order to produce a film of silicon dioxide on its surface. Parts of this silicon dioxide layer are then removed where current is required to flow. Silicon does not conduct electricity without being doped with other elements; this process involves the silicon being bombarded with a variety of different elements, which can include phosphorus, antimony, arsenic, boron, indium or gallium. Different types of semiconductor (P or N) are produced depending on the element used, with boron being the most common type of P-type dopant (Compoundchem 2014). The micro-electrical components and wiring in the phone are composed mainly of copper, gold, and silver. Tantalum is also used, being the main component of micro-capacitors. A range of other elements, including platinum and palladium are also used. Solder is used to join electrical components together. This was usually composed of tin and lead but in recent years lead-free alternatives have been developed, many of which use a combination of tin, silver and copper (Compoundchem 2014).

The microphone and speaker of the phone both contain magnets, which are usually neodymium-iron-boron alloys, though dysprosium and praseodymium are often also present in the alloy. These are also found in the vibration unit of the phone (Compoundchem 2014).

[87] https://consumer.huawei.com/en/support/product-environmental-information/ (accessed on 31 January 2019)

[88] https://www.apple.com/lae/environment/reports/ (accessed on 31 January 2019)

[89] https://images.samsung.com/is/content/samsung/p5/sec/aboutsamsung/sustainability/pdf/2018/2018Life-CycleAssessmentforHHPandDisplay_180831.pdf (accessed on 8 March 2019)

The casing can be made of metal or plastic, or a mix of the two. Metal casings can be made of magnesium alloys, whilst plastic casings are carbon based. The casing can often contain flame retardant compounds. Efforts have been being made to minimise the use of brominated flame-retardants beyond RoHS (Compoundchem 2014).

The current trend in smartphone body design seems to be towards the use of high-grade materials (as aluminium, stainless steel or even titanium) instead of commonly used plastics and also specialty ceramics and toughened glass are used increasingly (Triggs 2019). Environmental impacts embedded in materials, can be higher for smartphones that have larger size and functionalities, use more advanced chips and/or higher-grade materials.

A list of the most common materials used in smartphones is provided in Table 18. The Bill of Materials is in general represented at elemental level, so that compounds as alumina silicates used in display's glass, PVC and flame-retardants are not addressed. Another illustrative Bill of Materials at compound level is provided in Table 19.

Additional materials are necessary for packaging, documentation and accessories (Ercan et al. 2016) such as headset, USB-cable, charger, including a quite relevant amount of plastic materials. Packaging (Proske et al. 2016) is typically made of fibre and, to a lower extent, plastic materials[90] (e.g. 110 grams of cardboard and 20 grams of LDPE film).

With respect to the origin of materials, many smartphone materials are sourced in China, via companies that have traditionally been reticent to reveal details about their environmental and social impacts (Nield 2015). Nevertheless, some companies like Fairphone are committed to provide transparency about their supply chain[91].

Both the type and the processing of materials used in smartphones are key factors for determining the environmental impacts of devices. For example, it has been reported that the impact on climate change of primary aluminium is about 20 kg $CO_{2,eq}$ per kg of materials when produced from coal-based electricity, and this drops to about 5 kg $CO_{2,eq}$ per kg of materials when produced using hydro-based electricity. Recycled aluminium has an even lower impact on climate change. The carbon footprint of most plastics is instead about 4-5 kg $CO_{2,eq}$ per kg of material.

[90] https://www.apple.com/lae/environment/reports/ (accessed on 31 January 2019)
[91] http://open.sourcemap.com/maps/57bd640851c05c0a5b5a8be1

Table 18: Bill of Materials at elemental level for an average smartphone (Manhart et al. 2016)

Material	Common Use	Content per smartphone (g)	Content in all smartphones made since 2007 (t)	CRM listed (Y/N)	Minerals from conflict-affected and high-risk areas (Y/N)
Aluminium (Al)	Case	22.18	157 478	N	N
Copper (Cu)	Wires, alloys, electromagnetic shielding, PCB, speakers, vibration alarm	15.12	107 352	N	N
Plastics	Case	9.53	67 663	N	N
Magnesium (Mg)	Case	5.54	39 334	N	N
Cobalt (Co)	Lithium-ion battery	5.38	38 198	Y	N
Tin (Sn)	Solder paste	1.21	8 591	N	Y
Iron (steel) (Fe)	Case	0.88	6 248	N	N
Tungsten (W)	Vibration alert module	0.44	3 124	Y	Y
Silver (Ag)	Solder, PCB	0.31	2 201	N	N
Gold (Au)	PCB	0.03	213	N	Y
Neodymium (Nd)	Speakers Magnets	0.05	355	Y	N
Praseodymium (Pr)	Speakers Magnets	0.01	71	Y	N
Tantalum (Ta)	Capacitors	0.02	142	N	Y
Indium (In)	Display	0.01	71	Y	N
Palladium (Pd)	PCB	0.01	71	N	N
Gallium (Ga)	LED-backlights	0.0004	3	Y	N
Gadolinium (Gd)	LED-backlights	0.0002	1	Y	N
Europium (Eu)	LED-backlights	0.0001	-	Y	N
Cerium (Ce)	LED-backlights	0.00003	-	Y	N
Others	(glass, ceramic, semiconductors)	99.29	-		

Table 19: Illustrative Bill of Materials at compound level for a smartphone (Andrae 2016)

Raw material	Content per smartphone	
	(g)	(%)
Iron/steel alloys (primary)	16.250	7%
Aluminium alloys (primary)	8.690	4%
Copper alloys (primary)	36.250	16%
Gold (primary)	0.121	0%
Silver (primary)	0.198	0%
Nickel	1.500	1%
Tin	2.000	1%
Palladium	0.034	0%
Zinc	1.213	1%
Acrylonitrile butadiene styrene	22.500	10%
Poly(methy methacrylate)	1.875	1%
PA (Nylon)	1.625	1%
PVC	18.750	8%
Polyethylene-high-density	8.625	4%
Polyester (e.g. polyethylene terephthalate)	2.875	1%
Polycarbonate	2.625	1%
Polypropylene	1.313	1%
Polyurethane	1.625	1%
Epoxy	20.000	9%
Fiberglass	43.750	19%
Glass	33.750	15%
Total	225.569	

4.2.2 Critical Raw Materials and minerals from conflict-affected and high-risk areas

Of the 83 stable and non-radioactive elements in the periodic table, more than 60 can be found in smartphones (Manhart et al. 2016). Most of them are metals, with some of them like iron and aluminium, available in large quantities. For others, there are potential supply concerns and risks. For instance, some of these materials are included in the EU list of critical raw materials[92]:

- Cobalt is used as cathode material in Li-on battery chemistries with extended lifetime, on average 5.38 g per device (Manhart et al. 2016). A large portion of the mined cobalt production (around 50%) is in the DRC, where a significant amount of cobalt is mined by unregulated artisanal and small-scale mining practices (ASM).
- Tungsten is used in the vibration alert module, on average 0.44 g per device (Manhart et al. 2016).
- Indium is used in displays, on average 0.01 g per device (Manhart et al. 2016).
- Gallium is used in Power Amplifiers (PAs) to amplify voice and data signals to the appropriate power level allowing their transmission to the network base-station and in LED-backlights. The use of Gallium is on average 0.0004 g per device (Manhart et al. 2016).
- 16 (out of 17) rare earth elements (REE) are of relevance for smartphones. Neodymium, praseodymium and dysprosium are used to allow smartphones to vibrate through permanent magnet motors (also called NIB magnets); terbium and dysprosium are used in tiny quantities in touchscreens to produce the colours of a phone display (Nield 2015). The majority of REE production takes place in China.

[92] COM(2017) 490 (see section 1.2.3)

Furthermore, smartphones also require conflict minerals (also referred to as 3TG = Tungsten, Tantalum, Tin, and Gold). These materials come from areas where they are mined in conditions of armed conflict and in which human rights abuses are common. They are then sold or traded by armed groups. This is an issue particularly associated with the DRC[93]. As described in section 1.2.3, the EU Regulation 2017/821 establishes a Union system for supply chain due diligence of 3TG minerals and ores that will be mandatory from 2021 for the EU importers.

Some manufacturers are currently committed in supply chain transparency and/or due-diligence on conflict minerals. For example, Fairphone (2016) sources fair trade certified gold for its phones and has extended its supply chain due-diligence programmes beyond 3TG to include cobalt, as well as Apple did (Apple 2018a). Currently 9 out of every 10 smelters in Apple's supply chain are reported to have been verified as conflict-free or are undergoing audits. Manufacturers like Samsung, Sony, Apple and Huawei are also members of the Responsible Cobalt Initiative (RCI)[94], which is driving the supply chain due diligence system and standards for cobalt (Transform Together 2018). Other responsible mining initiatives have been developed by NGOs and/or mining companies (e.g. Alliance for Responsible Mining[95], Responsible Minerals Initiative[96], Enough Project[97], Initiative for Responsible Mining Assurance[98], Towards Sustainable Mining Initiative[99], The Finnish Network for Sustainable Mining[100], European Partnership for Responsible Materials[101], Global e-Sustainability Initiative[102]).

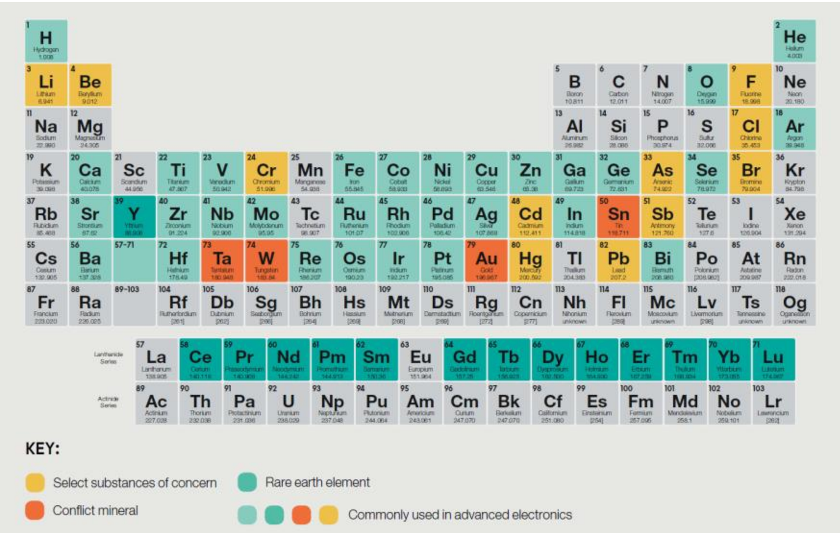


Figure 24: Chemical elements in smartphones (Jardim 2017)

4.2.3 Recycled materials

Smartphones contain a wide variety of materials, often speciality metals. Recycled materials could be used in smartphones, especially those presenting a high recycling rate like precious metals (gold and silver), base metals and alloys (copper and steel). Unfortunately, this is not the case of REE and other priority materials such as Indium, Gallium, Lithium and Tantalum (Compoundchem 2015).

Some companies have started to pay attention on the use of recycled materials (Jardim 2017). However, the recycled content of smartphones, and particularly of high-grade materials, remains relatively low (Transform Together 2018).

---

93 http://ec.europa.eu/trade/policy/in-focus/conflict-minerals-regulation/ (accessed on 8 March 2019)
94 https://www.firstcobalt.com/responsibility/responsible-cobalt-initiative/ (accessed on 8 March 2019)
95 http://www.responsiblemines.org/en/# (accessed on 18 October 2018)
96 www.responsiblemineralsinitiative.org/ (accessed on 18 October 2018)
97 https://enoughproject.org/products/reports/conflict-minerals (accessed on 18 October 2018)
98 https://responsiblemining.net/ (accessed on 18 October 2018)
99 http://mining.ca/towards-sustainable-mining (accessed on 18 October 2018)
100 https://www.kaivosvastuu.fi/finnish-sustainability-standard-for-mining-translated-into-english/ (accessed on 18 October 2018)
101 https://europeanpartnership-responsibleminerals.eu/ (accessed on 18 October 2018)
102 https://gesi.org/ (accessed on 18 October 2018)

For most manufacturers the secondary materials use is mainly limited to plastic. Samsung uses recycled plastic in travel adaptors (20% content of recycle plastics), in ear phone cases and in packaging trays. The use of recycled plastic is not feasible for electrical parts of the phone according to stakeholders of this study.

Fairphone has reported to use recycled copper and tungsten in its devices. To prioritize which materials to tackle first, Apple has instead created Material Impact Profiles for 45 elements and raw materials, which combine environmental, social, and supply risk factors along the value chain (Apple 2018a).

Aluminium, tin, and cobalt have been identified as priority materials for the supply of secondary sources of materials. Regarding aluminium, Apple claims that the quality level requested in their products can be achieved only with clean material streams. For this reason, recycled aluminium is not mixed with other grades of scrap aluminium (Apple 2018a).

Apple has also reported to use 100% recycled tin for soldering the main logic board (Apple 2018a). Apple finally announced its target to create a closed- loop supply chain, where products are made using recycled or renewable materials only, and where Apple returns an equivalent amount of material back to the global market (Apple 2018a).

Despite some progress made in closing the loop on materials, smartphone manufacturers are still reliant on virgin materials (Transform Together 2018). Sourcing and supply of recycled materials of adequate quality are the main constrains.

Although EOL smartphones can be a source of high value secondary materials, recovery of some of the materials becomes challenging when mixed with other WEEE. According to some manufactures, another barrier to the use of recycled material can be the perception that primary materials have a higher quality. The validity of this perception is variable depending on the material (e.g. paperboard, plastic, glass) and the application for which it is intended (Manhart et al. 2016).

Moreover, for materials for which there is not sufficient market availability, a higher recycled content in products does not necessarily have positive effects as it will likely lead to a situation where lower amounts of secondary materials are used for other products (Manhart et al. 2016). Where the market of certain recycled materials needs to be stimulated, it could be more appropriate to set quantitative targets in terms of recyclability (Cordella et al. 2019b).

4.2.4 Other substances of concern

Substances of concern are defined here as those chemicals that may have significant impact on both humans and the global environment, independently whether they are controlled by law or not. The use of these substances on the EU market is prohibited/restricted or gradually phased out through ROHS directive and REACH regulation (See section 1.2.2).

The smartphone industry is currently committed to limit the use of certain substances (Jardim 2017):

1. PVC: Due to possible formation of hazardous substances from the incineration of this type of plastic, some manufacturers have been reducing the content of PVC in the product. For instance, Sony (2018), Fairphone[103] and Apple (2018a) declared to have banned the use of PVC in their devices.

- Halogenated and other flame-retardants: these compounds can result in the release of highly toxic dioxins, among other hazardous chemicals, when scrap is burned (especially in case of rudimentary e-waste recycling operations). Polybrominated biphenyls (PBB) and Polybrominated diphenyl ethers (PBDE) are restricted under RoHS. Plastics containing brominated flame-retardants (BFRs) have to be separated according to WEEE. Industry is also working to limit the use of parts and materials containing BFRs. Sony (2018) for instance claims not to use polybrominated diphenyl ethers, polybrominated biphenyls, hexabromocyclododecanes, in a progressive effort of phasing out BFRs. Sony has developed a bromine-free flame retardant for the manufacture of a polycarbonate plastic. Moreover, Sony has banned the use of tris(2-chloroethyl) phosphate, a chlorinated flame retardant identified to carry similar risks to those associated with brominated flame retardants, as well as phosphoric acid tris (2-chloro-1-methylethyl) ester (TCPP) and tris (1,3-dichloro-2-propyl) phosphate (TDCPP). Apple, LGE and Samsung have also eliminated the

[103] https://support.fairphone.com/hc/en-us/articles/215392683-How-about-hazardous-materials- (accessed on 19 April 2018)

use of BFRs (Jardim 2017). Moreover, other flame-retardants such as hexabromocyclododecane (HBCDD) and tetrabromobisphenol A (TBBPA) have not been detected when specific parts of Fairphone 2 were tested[104].

2. Beryllium: Beryllium copper[105] is used in electronic and electrical connectors, battery, undersea fibre optic cables, chips (consumer electronics and telecommunications infrastructure). Beryllium is used as an alloying element in copper to improve its mechanical properties without impairing the electric conductivity. Scrap generated during manufacturing in the EU are typically sent back to suppliers outside Europe for recycling. However, beryllium contained in the waste can end up in landfill or be down-cycled so that there is actually no post-consumer functional recycling of beryllium neither in Europe nor in the world (Jardim 2017). Beryllium and beryllium compounds are recognized as carcinogens and they can be released as dusts or fumes during processing and recycling. Exposure to these chemicals, even at very low levels and for short periods, can cause chronic beryllium disease (CBD), an incurable and debilitating lung disease. Beryllium is moreover included in the EU List of Critical Raw Materials. Industry is working to avoid the use of such substances: Sony (2018) for instance is using no beryllium compounds, and also Apple (2018a) reported to have eliminated Beryllium from all new product designs.

3. Antimony: this element is alloyed with lead or other metals to improve their hardness and strength and is used in the electronics industry to make some semiconductor devices, such as infrared detectors and diodes. Other uses include batteries, metal printing, cable sheathing. Antimony compounds are moreover used to make flame-retardant materials, paints, enamels, glass and pottery (CRM Alliance 2019). Antimony trioxide is recognized as a possible human carcinogen and exposure to high levels in the workplace, as dusts or fumes, can lead to severe skin problems and other health effects (Transform Together 2018). Antimony is also included in the EU List of Critical Raw Materials (COM(2017) 490). Several manufacturers (e.g. Apple, LGE, Sony, Samsung, and Fairphone) have eliminated the use of Antimony (Jardim 2017).

4. Phthalates: used as softeners for plastics, some of these substances are classified as "toxic to reproduction" and are known to be hormone disrupters. Industry is working to eliminate specific phthalates. Sony (2018) for instance reported to have eliminated the phthalates DEHP, DBP, BBP, DIDP, DNOP and DINP. Fairphone[106] and Apple (2018a) also reported to have eliminated these substances across their product portfolio. DEHP, DBP, BBP and DIBP are restricted under RoHS since July 2019. According to the ECHA (2013), in the specific case of DINP and DIDP, dermal exposure is not anticipated to result in a risk for the adult population, whereas a risk from the mouthing of toys and childcare articles with DINP and DIDP cannot be excluded.

5. Arsenic compounds: Sony (2018) reported to have banned the use of LCD panels containing diarsenic trioxide and diarsenic pentoxide. Apple (2018b) also claims to have restricted the use of Arsenic (50 ppm thresholds are set for LCD display glass, camera lens, trackpad glass, display cover glass, antifouling agents).

6. 1,3-propanesultone: used in the battery cell electrolyte, this is a SVHC. According to the harmonised classification and labelling approved by the European Union, this substance may cause cancer, is harmful if swallowed and is harmful in contact with skin[107].

7. Cadmium: this element can bio-accumulate in the environment and is highly toxic. The availability of cadmium-free substitutes for batteries (e.g. lithium-ion battery technologies) has reduced the risk of contamination by cadmium. Cadmium could be also present in pigment stabilizer, copper alloys in electronic contacts (Apple, 2018b). Cadmium is restricted under RoHS.

Manufacturers implement a substance control system for "environment-related substances to be controlled" (also referred to as "controlled substances") or "restricted substances" (Sony 2019, Apple 2018b).

[104] https://support.fairphone.com/hc/en-us/articles/215392683-How-about-hazardous-materials- (accessed on 19 April 2018)

[105] Beryllium copper (BeCu), also known as copper beryllium (CuBe), beryllium bronze and spring copper, is a copper alloy with 0.5—3% beryllium and sometimes other elements

[106] https://support.fairphone.com/hc/en-us/articles/215392683-How-about-hazardous-materials- (accessed on 19 April 2018)

[107] https://echa.europa.eu/substance-information/-/substanceinfo/100.013.017 (accessed on 13 June 2018)

4.2.5 Reducing the impacts of materials

As described above smartphones are made of a broad and heterogeneous list of materials, also including critical raw materials, minerals that could come from conflicting areas, and hazardous substances. Sustainability of the product could be improved by:

- Reducing and/or optimising the amount of materials used in the product, for example through the application of lean designs[108] and the avoidance of unnecessary accessories (as could be the case of external power supplies supplied with new products[109]);
- Increasing the amount of recycled and renewables-based materials. The recycled content can however be limited by aspects related to regulations and standards, market availability, technical design specifications. In terms of secondary materials, the use of recycled plastic, aluminium, copper, tin and tungsten seems feasible for some manufacturers. However, some of these recycled materials are demanded also by other applications so that their use in smartphones could potentially divert material flows from one product to another one, with limited benefits at macro-level. Moreover, setting recycled content targets at product specific level is challenged by uncertainties relating to the supply and demand of materials and to the traceability of the materials used in the product;
- Avoiding/substituting hazardous materials with inherently safer solutions, as some manufacturers are doing beyond legal requirements.

Any strategy addressing the use of materials should ensure the fulfilment of technical specifications relating to the safety, performance and durability of the products. Moreover, possible trade-offs for other material efficiency aspects should be also assessed (Cordella et al. 2019b). An overview of possible measures to improve the material efficiency of smartphones is provided in Section 6 based on the information gathered along this study.

4.3 Product longevity

Depletion of materials and production of waste are normally reduced when the lifetime of a product is increased[110]. Designing long-lasting products is a key strategy to save materials, and therefore reduce the impacts associated with their production, and to reduce the amount of waste to handle at the End of Life.

A product can function as required, under defined conditions of use, maintenance and repair, until a limiting state is reached. A limiting state is reached when one or more required functions/sub-functions are no longer delivered (Alfieri et al 2018a). The limiting state could either be due to technical failure and/or other socio-economic conditions, so that the lifetime of a product can be differentiated between:

- Technical lifetime (European Environmental Agency 2017), which is the time span or number of usage cycles for which a product is considered to function as required, under defined conditions of use, until a first failure occurs[111];
- Functional lifetime (European Environmental Agency 2017), which is the time a product is used until the requirements of the user are no longer met, due to the economics of operation, maintenance and repair or obsolescence[112].

From a purely technical point of view, an extension of lifetime of products can be pursued through complementary strategies:

1. By increasing the durability of products and postponing the occurrence of a limiting state (Alfieri et al. 2018a, 2018b);
2. By increasing the upgradability of products and enhancing the functionality of a product (Cordella et al. 2018a);
3. By increasing the reparability of products and restoring the functionality of a product after a fault (Cordella et al. 2018a).

[108] Although this could come with possible trade-offs for other material efficiency aspects (see section 4.7)

[109] This should be coupled with the use of standard USB-C interfaces (IEC 63002:2016) to ensure interoperability between EPS owned by users. Information on technical specifications and interoperability of the accessories (voltage, power output and connector type) should be also provided.

[110] This is generally the case when an increase of lifetime is not associated to design choices or repair/refurbishment operations requiring a significant addition of materials. Trade-offs among different material efficiency aspects could otherwise occur

[111] This can be modelled based on statistical data and accelerated tests

[112] This can be differentiated between first and successive users

The concept is represented in Figure 25.

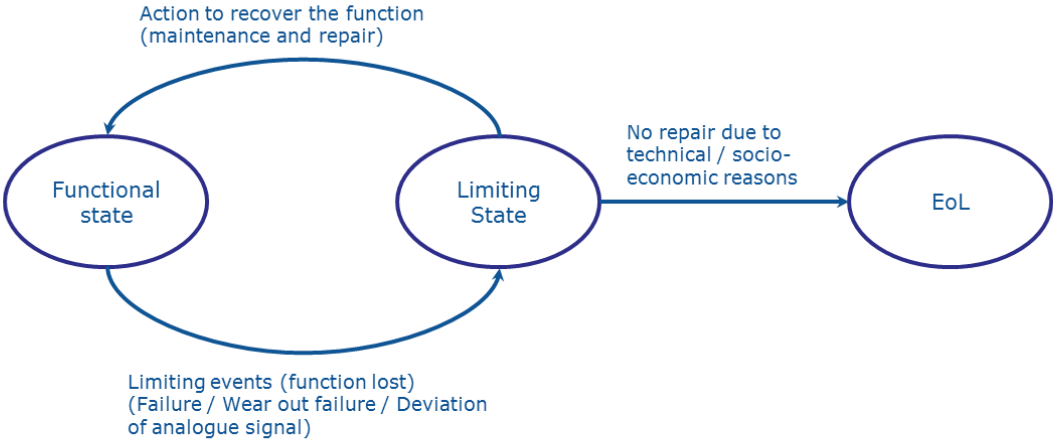


Figure 25: Extending the lifetime of products by maintenance, update, repair

Technical problems that could cause the replacement of a product and measures that could prevent it need thus to be analysed:

a. A durability analysis will focus on how to delay limiting states over time by identifying stress conditions, design aspects and misuses that could produce failures of key parts and loss of function(s)/sub-function(s) during the normal and/or special conditions of operation. Key aspects and/or correction measures to increase the longevity of the product and its parts are identified (Alfieri et al 2018b).

b. A reparability/upgradability analysis will focus on fixing a technical problem and/or extending the function lifetime by identifying barriers and factors influencing the chance of repair/upgrade, and more in general reuse. Key aspects and/or correction measures to increase the reparability and reusability of the product and its parts are identified. Considerations about re-manufacturability can also be included in this analysis (Cordella et al. 2018a).

The two analyses can be based on a common ground of information (see Figure 26):

1. The functional analysis of the product[113], in order to define main functions and sub-functions and to understand conditions of use and interactions between product and users (see Section 4.1);
2. Lifetime and durability expectation (see Section 3.3);
3. The analysis of limiting states, such as failures and other causes of replacements, their frequency and impacted parts, typical repair and upgrade operations;
4. The analysis of the barriers hindering the longevity and repair of products and of the environmental and economic costs and benefits, also considering quality aspects.

This information can also allow identifying priority parts where to focus any design action and further assessment, as well as setting preliminary objectives.

[113] EN 12973:2000 - Value management

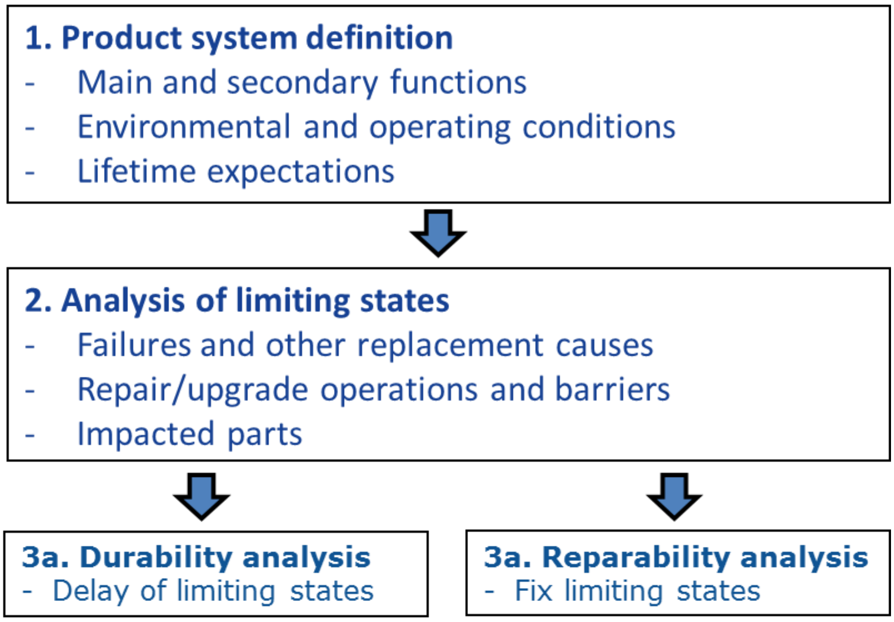


Figure 26: Approach for the analysis of durability and reparability of products

4.3.1 Limiting states

As described in section 3.3, the decision to discard or replace a phone is often based on a perception of functional obsolescence driven by the availability of new models and features, and by social expectations (Watson et al. 2017).

However, loss of performance, failures and breakages of smartphones are other important reasons for replacing the product. Technical factors producing failures and other limiting states include stresses on product's parts and their capability to withstand these constrains and to provide a satisfactory performance level. Stress factors can be linked to environmental conditions (e.g. ambient temperature and humidity, mechanical shocks and vibration due to the transportation) or to operating conditions (e.g. electrical stresses, temperature variation during the turning on/off, shocks and vibration, drops, and mechanical impacts, ingress of dust and water). These stress factors can result in failures of the whole product due to short circuits or disconnection of main parts. Generally, resistance to stress may need to be assessed at product level (even if it affects specific parts) since it can be influenced by several aspects like materials, dimensions and shapes.

Sources of data about limiting states and failures statistics have been analysed including consumer's organization surveys and repairer's statistics and interviews.

A recent survey (OCU 2018b) reports that smartphones are characterized by the highest frequency of failures among a group of 10 products (5 appliances and 5 ICT products). 47% of faults occurred in the first 2 years of use, while an additional 39% of faults occurred between the 2nd and the 3rd year of use. The highest number of problems was related to the battery (42%) and to the operating system (14%).

Additional survey results have been published in 2019 (OCU 2019) showing that mobile users complain especially about failures in batteries and touch screens, although brands can differ in terms of reliability and most common failures. Moreover, about one smartphone out of two was reported to be not repaired in case of failure. This would be mostly due to the relatively high cost of repair compared to the residual value of the device.

The drop on a hard surface (43%) and the contact with water (35%) were also reported as causes of product failures (Watson et al. 2017). However, these statistics refer to 2013 and could be less representative due to the development of new technologies and designs.

Although different from failure data, indirect information about limiting states can be gathered also from repair statistics. The repair platform "Handyreparaturvergleich"[114] reports statistics about failures/repairs for common models of smartphones sold in Germany (see for instance Table 20 and Table 21). In particular, screens appear as the part of smartphones that are most frequently repaired. The dominant importance of screens has been confirmed by the repair organization "Vangerow"[115]. It is also interesting to observe that the repair of back cover became an issue for more recent models.

Table 20: Number of repair services for iPhone models as reported in "Handyreparaturvergleich"at March 2019

Repair requests	**iPhone 6**[116]	**iPhone X**[117]
Display	111 (48.5%)	98 (38.0%)
Back cover	2 (0.9%)	92 (35.7%)
Display glass / Touchscreen	22 (9.6%)	31 (12.0%)
LCD Display	16 (7%)	16 (6.2%)
Battery	39 (17%)	3 (1.2%)
Others	39 (17%)	18 (6.9%)

Table 21: Number of repair services for Samsung models as reported in "Handyreparaturvergleich"at March 2019

Repair requests	**S6**[118]	**S9**[119]
Display	19 (13.7%)	186 (49.9%)
Back cover	2 (1.4%)	81 (21.7%)
Display glass/ Touchscreen	10 (7.2%)	70 (18.8%)
LCD Display	10 (7.2%)	20 (5.4%)
Camera	6 (4.3%)	5 (1.3%)
Buttons	17 (12.2%)	3 (0.8%)
Ports/connectors	6 (4.3%)	2 (0.5%)
Battery	61 (43.9%)	1 (0.3%)
Others	8 (5.8%)	5 (1.3%)

The failure of the screen can have several modalities. For example, after a fall the smartphone no longer responds to inputs, remains completely black, has pixel errors or is scratched, cracked or splintered. In most of the cases, the screen cannot be repaired, but the entire unit must be replaced since the individual components (sensors, LCD display, and touch screen) are firmly glued together and come as one unit[120]. The repair or replacement of the touchscreen is instead necessary if the

[114] https://www.handyreparaturvergleich.de/ (accessed on 13 March 2019)
[115] https://vangerow.de/ (accessed on 13 March 2019)
[116] https://www.handyreparaturvergleich.de/apple-iphones-reparatur/defektes-apple-iphone-6-display-diagnose-reparieren-preisvergleich.html#welche-reparatur (accessed on 27 March 2019)
[117] https://www.handyreparaturvergleich.de/apple-iphones-reparatur/defektes-apple-iphone-x-display-diagnose-reparieren-preisvergleich.html#welche-reparatur (accessed on 27 March 2019)
[118] https://www.handyreparaturvergleich.de/samsung-smartphones-reparatur/defektes-samsung-galaxy-s6-display-diagnose-reparieren-preisvergleich.html#welche-reparatur (accessed on 27 March 2019)
[119] https://www.handyreparaturvergleich.de/samsung-smartphones-reparatur/defektes-samsung-galaxy-s9-display-diagnose-reparieren-preisvergleich.html#welche-reparatur (accessed on 27 March 2019)
[120] https://www.handyreparaturvergleich.de/apple-iphones-reparatur/defektes-apple-iphone-x-display-diagnose-reparieren-preisvergleich.html (accessed on 9 April 2019)

display glass and the touchscreen have broken (scratched, cracked or splintered), no longer reacts, or only reacts with delay or with greater pressure.

With respect to batteries, their performance and endurance over time can affect the lifetime of the smartphones, in particular when they are not replaceable by users. However, some manufacturers claim that ease of disassembly and reassembly by users can lead to some trade-offs in terms of performance of the battery (the physical space being the same), safety issues regarding counterfeit batteries, resistance to dust and water.

It has been reported by stakeholders that batteries can have an endurance of around 300-500 cycles at 80% of the initial capacity, which is equivalent to around 2 years of life. Replacement of batteries by users could be less important in case a longer duration is ensured (e.g. 500-1000 cycles).

According to Table 20 and Table 21, the number of battery replacement has dropped significantly from older models to models that are more recent.

On the other hand, research on smartphone battery ageing (Sustainably SMART 2018) confirms some essential factors for the obsolescence of batteries and devices with embedded batteries (e.g. extreme ambient temperature; state of charge lower than 20% or higher than 80%). Provision of information for consumers could help maximising the battery life and lifespan of devices. Some manufacturers provide tips (e.g. Apple[121]) and tools (Figure 27) to maximise the battery lifespan.

Figure 27: Battery Health tool in iPhone smartphone[122]

Another important factor that can affect the functional lifetime of smartphones can be the end of the software-supporting period offered by manufacturers.

In general, in case of smartphones using Android, the support period vary between 2 and 3 years. This means that many smartphones do not run the most updated version of the OS. Even though the absence of OS updates does not generate any immediate failure, it can result in a loss of security and, at long term, it could affect the functionality of the applications installed on the smartphones (OCU 2017). Manufacturers that do not release updates for the last available Android versions can still provide security patches also for older versions of the OS, supporting the software and prolonging the lifetime of the device.

Table 22 shows the relative number of devices running a given version of the Android OS. Apple claims to provide OS update for a longer period, with more than 80% of the products using the last version of the iOS[123], i.e. iOS 12[124]. Models released up to 5 years ago (e.g. iPhone 5S) are still compatible with these OS updates.

[121] https://www.apple.com/batteries/maximizing-performance/ (accessed on 4 July 2018)
[122] https://support.apple.com/en-us/HT208387 (accessed on 14 March 2019)
[123] https://developer.apple.com/support/app-store/ (accessed on 14 March 2019)
[124] https://www.apple.com/ios/ios-12/ (accessed on 27 March 2019)

Table 22: Percentage of devices running a given version of Android (October 2018)[125]

Version	Code name	Distribution
2.3.3	Gingerbread	0.2%
2.3.7		
4.03	Ice Cream Sandwich	0.3%
4.04		
4.1x	Jelly Bean	1.1.%
4.2x		1.5%
4.3		0. 4%
4.4	KitKat	7.6%
5	Lollipop	3.5%
5.1		14.4%
6	Marshmallow	21.3%
7	Nougat	18.1%
7.1		10.1%
8	Oreo	14.0%
8.1		7.5%

Another relevant aspect is the impact of the Operating System update on the smartphone performance. As result of an investigation launched by the Italian competition authority it was found that certain smartphone software updates had a negative effect on the performance of the devices, without informing adequately consumers or providing them any means of restoring the original functionality of the products. Moreover, a case was found for which no clear information was provided for "essential" characteristics of lithium batteries, including their average life expectancy and how to maintain and replace them[126].

Main limiting states of technical nature for smartphones are summarised in Table 23, with a description of possible failure mechanisms. Such limiting states of smartphones can be handled through alternative measures analysed in the following sections.

[125] https://developer.android.com/about/dashboards/ (accessed on 27 March 2019)
[126] https://www.theguardian.com/technology/2018/oct/24/apple-samsung-fined-for-slowing-down-phones (accessed on 27 March 2019)

Table 23: Main failures for smartphones

Part	Main failures	Failure mechanism
Screen: - Glass cover - Touch screen layer - Display	Screen cracked, scratched, splintered Screen cracked, scratched, splintered Black screen, broken/dead pixels (spots, stripes or similar), no background light	Accidental drops or other mechanical stresses (shocks, vibrations) Accidental drops or other mechanical stresses (shocks, vibrations) Accidental drops or other mechanical stresses (shocks, vibrations)
Back cover	Breakage	Accidental drops or other mechanical stresses (shocks, vibrations)
Battery	Loss of performance in terms of duration of battery cycles Battery not charging Overheating	Aging of the battery due to quality issues or use under stress conditions EPS / battery connection failure
Operating System	Malfunctioning/ loss of security and performance (e.g. device not switching on, error codes, apps crashes)	OS and/or security updates not provided by the manufacturer
Whole Product	Short circuits, disconnection of main parts (including buttons and connectors)	Stress conditions (e.g. exposure dust and water, shocks, vibration).

4.3.2 Durability analysis

The durability analysis aims at the identification of maintenance needs and possible measures to avoid or postpone faults, which address;

- The design of more durable smartphones and the availability of updates over time;
- External accessories to protect the device, as screen protectors and cases[127].

This is based on the analysis of degradation mechanisms and paths that may cause limiting states, i.e. failure modes of main functions and/or sub-functions[128] (Table 23).

Although strengthened glass panels are getting more and more durable, screens are still affected by a relatively high frequency of failures. The failure of the screen can have several modalities. For example, after a fall the smartphone no longer responds to inputs, remains completely black, has pixel errors or is scratched, cracked or splintered. Almost 3/4 of all screen damages are due to drops on corners or edges (Sustainably SMART 2017). Moreover, as pointed out by some testing organizations[129, 130], smartphones with larger glass surfaces are more exposed to impacts and damages.

Screen damages due to falls and contact with water are normally considered to be under the responsibility of consumers and are not covered by legal guarantees. Smartphones can be designed to withstand expected usage profiles and information about how to use them should be provided (Watson et al. 2017). Damages due to water contact seem to have become less relevant due to the development of smartphones featuring a waterproof design[131].

[127] https://www.nytimes.com/2017/05/24/technology/personaltech/reality-check-what-does-and-doesnt-protect-your-smartphone.html (accessed on 9 March 2018)
[128] IEC 60300-3-1 - Dependability management – Part 3-1: Application guide – Analysis techniques for dependability – Guide on methodology
[129] https://www.consumerreports.org/smartphones/iphone-x-review-test-results/ (accessed on 8 April 2019)
[130] https://www.cnet.com/news/apple-iphone-x-drop-test/ (accessed on 8 April 2019)
[131] https://www.cnet.com/news/how-does-waterproofing-work-apple-iphone-7-samsung-galaxy-s7-sony-xperia/ (accessed on 8 April 2019)

Resistance to common causes of failure as fall on a hard surface, immersion in water and ingress of dust can be measured via specific product testing. The following test methods (see section 1.2.4.5) have been already applied by manufacturers:

- Drop tests, to determine how resistant a handset is to physical damages;
- Water- and dust proof tests (IP rating).

Smartphones complying with an IP rating of 67 or 68 (water and dust proof), and drop tested onto a hard surface from a minimum of 1.2 metres (usually as part of support for the MIL-STD-810G) are available on the market and are classified as rugged smartphones[132] (Bullitt 2017). The inclusion of ergonomics and slip resistance considerations in the design of smartphones could also be beneficial for the fitness of use of the device[133]. A manufacturer reported that 1.2/1.5 meters are not representative of common accidents as according to their internal investigations the majority of the drops occur from less than one meter. TCO requires reporting test results from a drop height ≥45 cm (TCO Certified 2018).

Moreover a clear definition of functional requirements to pass the test (e.g. screen undamaged, case remaining integral) should be further defined to ensure a correct interpretation of the test results.

According to the assessment and verification method reported by TCO, after exposure to any of the three specified stress tests the product:

1. Must be able to boot up and operate normally:

    a. Boot or resume time must not be 50% greater than before the test,

    b. No operational fault is observed when using standard software applications,

    c. No major damage to the product is observed that does not allow for standard usage of the product (e.g. usage of critical buttons, functionality of the display).

2. Must not create hazards to end user:

    a. No case or display cracking is observed nor other sharp points are created from failures that could injure a user,

    b. No electrical component failure or access is observed that could result in a user safety issue.

Screen protectors and protective cases (also called bumper) are also effective ways to avoid limiting states due to falls or other mechanical stresses. The frequency of brakeage could be halved in case of protected smartphones (Wertgarantie 2017). Protective accessories are available in many designs from manufacturers or third party companies. Some protective cases even allow upgrading the functionalities of smartphones by adding additional battery capacity or additional lenses. However, rather than relying on the user to purchase protectors for inherently fragile devices, it could be more effective to provide extra-protective functions and/or accessories with the product. Screen protectors are pre-installed for some smartphone models (e.g. Samsung Galaxy S10[134]).

More durable designs could be also incentivised by including failures due to accidental drops (e.g. free falls from up to 1.5 meters) and short-term water contacts in legal guarantees.

Performance of batteries is also very important for the durability of smartphones, especially because new models have bigger screens, faster processors and apps that require more and more energy, and thus long lasting batteries. Longest life batteries currently used in smartphones have a capacity of 4000-5000 mAh[135], which in some cases can allow them to function as a power bank[136]. A long battery lifespan can reduce the chance of replacement of battery and device, with possible economic and environmental benefits (Science for Environment Policy 2018). The lifespan of batteries can be measured in two ways:

[132] A distinction has to be done between rugged smartphones and ultra-rugged smartphones, with the latter specifically designed for industrial uses or to survive extreme rugged testing. Ultra-rugged smartphones are usually considerably more expensive, and will often be engineered to be non-incendiary and intrinsically safe, making them suitable for use in hazardous environments

[133] https://smartphones.gadgethacks.com/how-to/4-most-durable-premium-smartphones-for-clumsy-people-0175454/#jump-comparisonchart (accessed on 23 March 2018)

[134] https://www.samsung.com/au/support/mobile-devices/galaxy-s10-in-box-items/ (accessed on 27 March 2019)

[135] https://www.tomsguide.com/us/smartphones-best-battery-life,review-2857.html (accessed on 22 March 2018)

[136] https://www.xataka.com/tecnologiazen/avances-en-baterias-moviles-cuando-llegara-el-sustituto-del-ion-litio (accessed on 22 March 2018)

1. Calendar life: time during which the battery can be stored with minimal discharges until its capacity decreases below 80% of the initial one, and
2. Cycle endurance: number of times (cycles) a battery can be recharged and discharged before it becomes unsuitable for a given application. This is usually when it can only be charged up to 80% of initial capacity, given that the battery degrades quickly after this point.

The battery endurance in cycles can be tested according to IEC EN 61960[137]. Performance can be assessed as:

a. Remaining full charge capacity of the battery compared to the initial charge capacity, after x and y charge/discharge cycles (e.g. 300 and 500), or
b. Minimum number of full charge/discharge cycles achievable with more than 80% and 60% of the initial capacity.

Software tools can also contribute to optimise the battery endurance in cycles. Pre-installed software can enable limiting the battery state of charge (SoC) when the smartphone is connected to the grid (e.g. overnight charge). Such functionality prevents that the battery is loaded at full charge.

Durability of smartphones is influenced also by the quality of other hardware parts:

- Fingerprint Sensor: a scratched or cracked sensor can for instance hinder the phone's ability to read fingerprints. The use of high-end materials can improve the overall reliability of the device[138].
- Camera lens: a cracked/scratched camera lens can affect the photo quality and compromise the device resistance to water and other contaminants. Sapphire crystal lens are reported to be harder than glass[139].
- Charging port: wear and tear could damage the charging port. Modular designs have been applied to facilitate its replacement[140]. Also symmetric ports reduce the risk of breaking the slot while forcing the cable into the wrong side (e.g. USB-C). However, the current trend towards wireless charging might eliminate or reduce the need for charging ports.

However, as described in section 4.4.1, unavailability of software/firmware updates can make smartphones obsolete even if their hardware parts are still fully functioning (Transform Together 2018). For an effective increase of the durability of smartphones it is thus needed to ensure the possibility of keeping software and firmware updated over time, and that security updates are also provided. From the other side, it has to be ensured that the Operating System updates do not negatively impact the smartphone performance and that the update is reversible.

A commitment on software support provision by manufacturers could increase the lifetime of smartphones. Google, for its own-brand smartphones is communicating the minimum update and support periods ensured for the models on the market. OS and software update (security) are ensured for three years for Pixel 2[141] and Pixel 3[142]. Devices with unsupported operating systems could moreover have limited-to-no resale value.

An overview of possible measures to improve the material efficiency of smartphones is provided in Section 6 based on the information gathered along this study.

[137] IEC 61960-3:2017 – Secondary cells and batteries containing alkaline or other non-acid electrolytes. Secondary lithium cells and batteries for portable applications. Prismatic and cylindrical lithium secondary cells, and batteries made from them

[138] https://smartphones.gadgethacks.com/how-to/4-most-durable-premium-smartphones-for-clumsy-people-0175454/#jump-comparisonchart (accessed on 23 March 2018)

[139] https://smartphones.gadgethacks.com/how-to/4-most-durable-premium-smartphones-for-clumsy-people-0175454/#jump-comparisonchart (accessed on 23 March 2018)

[140] https://smartphones.gadgethacks.com/how-to/4-most-durable-premium-smartphones-for-clumsy-people-0175454/#jump-comparisonchart (accessed on 23 March 2018)

[141] https://store.google.com/product/pixel_2_xl_specs?srp=/product/pixel_2_specs (accessed on 27 March 2019)

[142] https://store.google.com/product/pixel_3_specs (accessed on 27 March 2019)

4.3.3 Reparability and upgradability analysis

The reparability and reusability analysis aims at the identification of measures that could improve the reparability and reusability of products, and thus overcoming a limiting state. The analysis is based on information on repair statistics, typical upgrades and technical, market and legal barriers[143], which is also reported in section 4.4.1.

Lack of spare parts and software/firmware updates (Watson et al. 2017), as well as their relative cost, can be an important barrier to repair. Some manufacturers raised the attention on the presence on the market of counterfeit parts/products, which could undermine the functionality of the device and the brand reputation, especially in case of bad repair.

The availability of repair information is another aspect to consider. Some manufacturers provide information on the web about the availability/cost of the repair services in different EU countries[144], as well as costs of spare parts[145, 146].

According to Watson et al. (2017), repair could be worthwhile even 3-5 years after sale; however, there is huge variation in the cost of repair since many devices do not have easily removable batteries or replaceable screens. Repair costs are in particular a barrier for screens. The repair of a screen can cost up to 40% of the product price and the trend is towards more expensive repairs for more recent models[147].

Ease of disassembly[148] of parts is therefore another important barrier to repair. The disassembly of the product could be facilitated when a modular design is applied and/or when reversible fasteners are used. Moreover, DYI repair can be facilitated when the repair can be carried out with basic or commercially available tools (e.g. suction cup pliers, spudgers).

Effective modular designs should see the non-permanent fixing of parts such as front glass and display module in screens (Schischke et al. 2016). However, there is an apparent trend towards the increased use of adhesives, glues and of glass parts, which can make more difficult to disassemble parts (Greenpeace 2017). According to some manufacturers, main reasons for using adhesive and glues include reduction/control of the mass and volume of devices, as well as reliability and durability considerations (e.g. water and dust protection).

In some recent models of smartphones, the removal of batteries requires the intervention of an experienced repairer. This means that the longevity of the battery can be a decisive factor to determine if users will replace or continue to use a smartphone.

It has been reported that modular designs could require a greater amount of materials then in case of integrated designs. Easy-to-replace batteries could potentially require additional casing and protection layers, which may lead to thicker product designs. However, there are smartphones on the market with removable batteries and modular designs that seem to have weights comparable to those of fully integrated smartphones.

A global support platform for the repair of smartphones is provided by iFixit[149]. Instructions include the replacement of batteries and screens. Reparability scores for smartphones are also calculated by iFixit (2019), as reported in Annex II. The worst 10% performing models[150] in terms of reparability received by iFixit a score between 1 and 3 and were characterised by:

- High difficulty to open the rear case and access to any parts;

- Intensive use of adhesive, making any disassembly step complex;

- Very difficult replacement of the battery (e.g. in case of soldered battery, buried beneath the mother board, or needing very complex disassembly process in terms of steps and time);

- High number of steps to remove the display.

[143] This can cover aspects as obsolescence, cost of repair operations, ease of disassembly of parts, availability of spare parts, updates and instructions
[144] https://support.apple.com/repair (accessed on 29 March 2019)
[145] https://www.parts4repair.com/xiaomi (accessed on 17 October 2018)
[146] https://www.spareslg.com (accessed on 17 October 2018)
[147] Personal communication from stakeholders
[148] Disassembly is defined as the process by which a product can be separated into its parts in a non-destructive way
[149] https://www.ifixit.com/Device/Phone (accessed on 9 March 2018)
[150] At the end of August 2019 iFixit has analysed about 100 models

Technical aspect influencing the repair and upgrade of energy-related products have been analysed by Cordella et al. (2019a). Aspects considered relevant for smartphones are analysed here, with the aim of providing a reference for the identification of best practices and/or minimum performance levels[151] for product and its priority parts[152]. The following priority parts can be considered relevant for smartphones:

1. Screen (display assembly);
2. Back cover;
3. Battery;
4. OS.

Other parts (e.g. ports, buttons, camera) are considered less relevant for repair due to lower frequency of failure and lower repair requests (see Table 20, Table 21 and section 4.4.1). TCO Certified also has established a short list of replaceable parts including the battery, the display panel/display assembly and the charger.

A discussion on possible measures to improve the material efficiency of smartphones is provided below and summarised in Section 6. Such information could be also used as basis for the development of a scoring system (Cordella et al. 2019a). In such case, a higher weight could be considered for:

- Functionally essential parts (screen, battery, operating system);
- Aspects relating to disassemblability and to availability of spare parts, updates and information.

4.3.3.1 Disassembly depth/sequence

The disassembly depth is the number of steps required to remove a part from a product. The analysis of disassembly depths is fundamental to assess the effort required to access and/or replace priority parts. The disassembly sequence is necessary to assess the disassembly depth. This is the order of steps[153] needed to remove a part from a product (which might include getting access to fasteners). In this study fasteners such as screws are not considered as parts.

The repair/upgrade operation can be facilitated by the availability of information about the steps needed to disassemble specific parts, as well as by design options where the number of disassembly steps is reduced. Some of this information may be relevant for some categories of repairers only, also because of safety reasons.

Indications about the steps necessary to disassembly parts of smartphones are provided by iFixit[154]. Based on the analysis of a sample of products[155], and with a focus on priority parts, it was found that disassembly steps range, depending on the model:

- From 2 to 46 for the battery (median value = 28);
- From 15 to 45 for the screen (median value = 30);
- From 1 to 103 for the back cover (median value = 14).

Such values could be used as a starting point to set disassembly depth targets for priority parts of smartphones. It is important to highlight that in terms of real time required the level of skill and experience needed play an important role. As an example, it is reported that the 33 steps required for the replacement of the battery in the iPhone 8 can be performed in 30-120 minutes depending on the experience and skills of the repairer[156]. For this reason the disassembly depth is considered more appropriate than time as a metric to evaluate the disassembly effort.

[151] Depending on the application a more or less ambition level could be considered (Cordella et al. 2018b)

[152] Based on Cordella et al. (2019a), priority parts are those parts that are more important for repair and/or upgrade operations.

[153] According to Commission Decision (EU) 2016/1371, a step consists of an operation that finishes with the removal of a part, and/or with a change of tool

[154] https://www.ifixit.com/Device/Phone (accessed on 9 March 2018)

[155] On 8 April 2019, analysed products include: 13 models from Apple (iPhone 6, iPhone 6 Plus, iPhone 6s, iPhone 6s Plus, iPhone SE, iPhone 7, iPhone 7 Plus, iPhone 8, iPhone 8 Plus, iPhone X, iPhone XS, iPhone XS max, iPhone XR), 5 models from Samsung (SIII, S5, S10, S10e, S10 Plus), 1 model from Huawei (P9)

[156] https://www.ifixit.com/Guide/iPhone+8+Battery+Replacement/101279 (accessed on19 August 2019)

4.3.3.2 Fasteners

Fasteners play an important role in the disassembly of a product. Fasteners are closely interlinked to the assessment of necessary tools and skills for repair, re-use or upgrade. The number and type of fasteners, as well as their visibility, may be used as a proxy for the time needed to repair or upgrade a product. However, their visibility (e.g. through labelling and marking) is not as important if repair manuals are available and if fasteners are physically accessible. For the assessment of fasteners, more important criteria are their reversibility and the re-usability.

The best design scenario for the repair of smartphones would be the use of reusable[157], or at least removable[158], fastening systems in the assembly of priority parts. Removable fasteners can include adhesive bonds, if ensured that are easily removable and therefore do not impede the replacement of parts in smartphones. New advancements in liquid adhesive technologies allowing rework and de-bonding are reported by the adhesive's industry.

The worst scenario for reparability sees the use of non-removable fastening systems such as permanent glues. However, also fasteners removable only with proprietary tools constitute a potential barrier to repair.

4.3.3.3 Tools

In the best scenario for repair, the replacement of priority parts such as battery and screen should be feasible with commonly available tools on the market. Examples of toolkits are shown in Figure 28. These could include tools such as:

- Spudgers, i.e. tools that have a wide flat-head screwdriver-like end that extends as a wedge, used to separate pressure-fit plastic components without causing damage during separation;
- Different types of screwdrivers (e.g. Phillips, Flathead, Torx, Torx Security, Pentalobe);
- A plastic triangle opening tool, with each corner offering prying abilities;
- A magnifier;
- A suction cup.

A more generic list of tools is provided in EN 45554:2020 - General methods for the assessment of the ability to repair, reuse and upgrade energy-related products.

Figure 28: Examples of smartphone repair toolkits available on the market

[157] Reusable: an original fastening system that can be completely re-used, or any elements of the fastening system that cannot be re-used are supplied with the new part for a repair, re-use or upgrade process

[158] Removable: an original fastening system that is not reusable, but can be removed without causing damage or leaving residue which precludes reassembly or reuse of the removed part

Repair of smartphones can also require a set of product-specific tools. Since most parts inside smartphones are sensitive to electrostatic discharges (ESD) or static electricity, it would be recommendable to use only ESD-safe tools and equipment. The list of tools and equipment includes[159]:

- Soldering Iron or Soldering Station, used to solder parts and components like capacitor, resistor, diode, transistor, regulator, speaker, microphone, display.
- Cleaning Sponge, used to clean tip of soldering iron while soldering.
- Hot Air Blower, also called SMD (Surface Mount Device) rework system and SMD repair system, regulating or managing temperature and flow or hot air, and used to remove and again solder ICs.
- PCB Holder / PCB Stand, used to hold the PCB of a mobile phone while soldering or repairing.
- Solder Wire and Flux, used to solder electronic components. Flux is applied before soldering to remove any oxide or contamination at the solder joints.
- Solder Paste, which is solder in melted semi-solid form looking like paste and used mainly for Reballing of ICs.
- Desoldering Wire, or Desolder wire, used to remove excess solder from track of PCB. Thinner or PCB Cleaner: Thinner or PCB cleaner is used to clean the PCB of a mobile phone. The most common PCB cleaner used in mobile phone repairing is IPA or Isopropyl Alcohol.
- Jumper Wire, which is a thin laminated or coated copper wire used to jumper from one point to another on the track of a mobile phone while repairing.
- Point Cutter, used for cutting wires.
- Precision Screwdriver, used to remove and tighten screws while assembling and dissembling a mobile phone. Precision screwdrivers of sizes T4, T5, T6 and four head are good for most mobile repairing operations.
- Tweezers, used to hold electronic components while soldering and desoldering.
- ESD-Safe Cleaning Brush, used for cleaning the PCB of a mobile phone while repairing.
- Multimeter, used to find faults, check track and components.
- Battery Booster, used to boost the power of battery of a mobile phone.
- Ultrasonic Cleaner, used to clean PCB of a mobile phone and electronic components.
- BGA (Ball Grid Array) Kit, used to Reball and repair ball-type ICs.
- Magnifying Lamp, used to see the magnified view of the PCB of a mobile phone. Most magnifying lamps also have light. Magnifying lamps are available in different magnification such as 3x, 4x, 5x, 10x, 50x.
- Mobile Opener, used to open the housing or body of a mobile phone.
- DC Power Supply, Regulated DC (Direct Current) power supply, used to supply DC current to a mobile phone to switch on a mobile phone without battery.

Tools needed for repair/upgrade contribute to determine the complexity of the operation itself. Manufacturers can play a significant contribution in defining such complexity. The tools needed for repair are in fact determined by the product design and are therefore an objective characteristic. In particular, the need of non-common or proprietary tools could limit the possibility to carry out a repair/upgrade, whilst repairs are inherently easier when commonly available tools are requested for such operations.

[159] http://www.smartphonetrainingcourses.com/repair-tool-kits/ (accessed on 9 March 2018)

4.3.3.4 Disassembly time

Factors influencing the disassembly process (e.g. disassembly steps, fasteners, tools) could be combined all together through the calculation of disassembly times (Cordella et al. 2019a). Time can be important to determine the operational cost in case a service is paid, but it has also to be considered with other factors (e.g. the cost of spare parts).

Indications about the time necessary to disassembly parts of smartphones are provided by iFixit[160]. Based on the analysis of a sample of products[161], and with a focus on priority parts, it was found that minimum disassembly time ranges, depending on the model:

- From 1 to 120 min for the battery (median value = 30 min);
- From 20 to 120 min for the screen (median value = 40 min);
- From 1 to 180 min for the back cover (median value = 53 min).

Such values could be potentially used to set disassembly time targets for priority parts of smartphones. However, their calculation should be based on standard time units (Zandin 2003) and supported by appropriate methodological guidance, as done in eDiM (Peeters et al. 2018; Vanegas et al. 2016, 2018).

4.3.3.5 Type and availability of information

Provision of information (e.g. through user manuals) is necessary to support the repair/upgrade operation and should recollect relevant information mentioned for the other parameters discussed in this section.

Repair information should be both comprehensive and available to various target groups of repairers. Enabling a broad access to such information (e.g. to independent repair service providers) could contribute to create a level-playing field in the repair sector and to reduce repair costs and the effort to find suitable repair centres.

A distinction can be made between information that should be provided to professional and independent repairers and information for end users, as reported in Table 24. Repair information could be made available for 3-5 years after the placement of the last unit of model on the market[162].

[160] https://www.ifixit.com/Device/Phone (accessed on 9 March 2018)

[161] On 8 April 2019, analysed products include: 13 models from Apple (iPhone 6, iPhone 6 Plus, iPhone 6s, iPhone 6s Plus, iPhone SE, iPhone 7, iPhone 7 Plus, iPhone 8, iPhone 8 Plus, iPhone X, iPhone XS, iPhone XS max, iPhone XR), 5 models from Samsung (SIII, S5, S10, S10e, S10 Plus), 1 model from Huawei (P9)

[162] As reported in the introduction of section 4.4.3, repair could be worthwhile even 3-5 years after sale according to Watson et el. (2017)

Table 24: Information for professional repairers and end users

Information	Professional and independent repairers	Publicly available
Unequivocal identification of the device	X	X
Disassembly map or exploded view, including detailed step-by-step disassembly instructions for batteries and other priority parts and including information supporting the operation (e.g. tools needed, recommended torque for fasteners, diagnostic and error resetting codes)	X	X*
Technical manuals of instructions for repair, including safety issues, testing procedures for after repair and reference values for measurements	X	X*
List of necessary repair and test equipment	X	
Identification of errors, the meaning of the errors, and the action required, including identification of errors requiring professional assistance	X	X
Component and diagnosis information (such as minimum and maximum theoretical values for measurements)	X	
Wiring and connection diagrams and circuit board schematics of electronic parts (including the key (legend) with numbers and symbols explanations)	X	
Diagnostic fault and error codes (including manufacturer-specific codes, where applicable)	X	
Instructions for installation of relevant software and firmware including reset software	X	X
Information on how to access data records of reported failure incidents stored on the product (where applicable).	X	
Correct installation, use, maintenance and upgrade of relevant hardware, software and firmware (including how to optimise the lifetime of the battery and ergonomic aspects)		X
Implications of self-repair or non-professional repair for the safety of the end-user and for the legal guarantee, and when applicable, also to the commercial guarantee		X
Skills needed and environmental conditions for the repair operations		X
How to access to professional repair (internet webpages, addresses, contact details)		X
Functional specification and compatibility of parts (as batteries and External Power Supplies) with other products	X	X
Period during which the spare parts are available	X	X
Price of spare parts	X	X

* It could be limited to some basic repair activities as the battery replacement

4.3.3.6 Spare parts

The availability of spare parts is a paramount parameter to ensure that a repair/upgrade process can take place. Spare parts availability can for example refer to:

i) Availability over a specific period of time;

ii) Availability to various target groups;

iii) Delivery time.

Priority parts should be made available as spare parts for 3-5 years after placing the last unit of the model on the market[163]. These could also include approved-by-manufacturer compatible spare parts produced by third parties. To be practical for users, the delivery time should be within two working days. However, some manufacturers consider that 15 working days can be more reasonable.

Moreover, the list of spare parts, the procedure for ordering them and the related prices should be publicly available on the free access website of the manufacturer, importer or authorised representative. The definition of price thresholds for spare parts (e.g. percentage of total product price) is considered more complicated at policy level, as market conditions can vary over regions and time (Cordella et al. 2019a).

Although not defined as priority parts, the use of standard interfaces could also be beneficial for the replacement of some parts.

The connection between the charger's cable/connector and the product should be either:

- Micro USB specified according to IEC 62684:2018;
- USB type-C specified according to the IEC 62680-1-3 (Figure 29).
- External Power Supply (EPS) specified according to the IEC 63002. (this International Standard is applicable to EPS under 100 watts for portable computing devices, with a focus on power delivery application for notebook computers, tablets, smartphones and other related multimedia devices) and following the Recommendation of ITU-T L.1002 (10/16) (ITU-T 2016). The basic EPS configuration suggested by ITU-T L.1002 consists of an EPS with a detachable input cable and a detachable output cable to the ICT device (Figure 30).

A detachable DC cable would be moreover advantageous for repair since the DC cable is generally the weakest point of the portable power supply, and thus the main point of failure. Adapters which have captive cables, in case of failure of the latter, require all the rest of the equipment and in particular its active part, to be discarded, adding up unnecessary e-waste and cost for the users that could be a barrier for repair. Furthermore, the detachable cable enables more reuse and an increased lifetime of the power supply unit. The connection between the cable/connector and mains plug charger should be either:

- Standard USB Type A/B or
- USB Type C and compliant with the USB 3.1 standard. In this case the charger plug will be clearly marked to show which USB 3.1 voltage profiles it is able to supply (to ensure potential for reuse with other products).

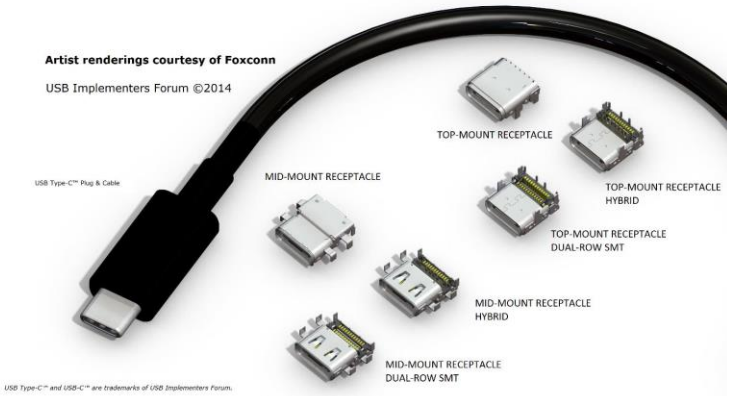


Figure 29: USB type-C cable and connectors (USB Implementers Forum 2016)

[163] As reported in the introduction of section 4.4.3, repair could be worthwhile even 3-5 years after sale according to Watson et el. (2017)

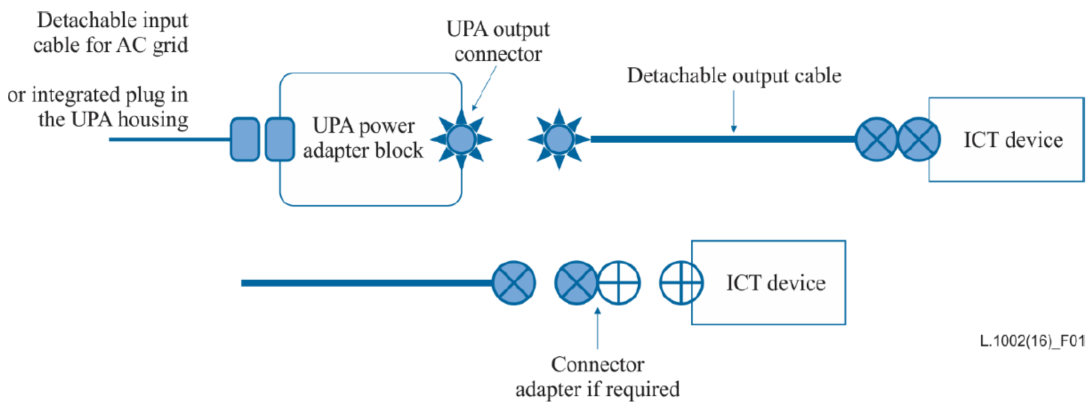


Figure 30: Basic Universal Power Adaptor (UPA) configurations and connection options (ITU-T 2016)

4.3.3.7 Software and firmware

Similarly with spare parts, the availability of software and firmware updates and/or support (including compatibility with open source programs) is a paramount parameter for smartphones (see section 4.4.2). Updates and support should be provided for 3-5 years after placing the last unit of the model on the market[164].

4.3.3.8 Data transfer and deletion

Data transfer and deletion is needed in repair/upgrade operations associated with the continued use or reuse of products (where privacy of personal data must be ensured) or the cleaning of memory space (e.g. for the repair of a smartphone). Secure data deletion/transfer tools should be pre-installed or made available (e.g. via installed or downloadable tools such as an application, a cloud-based service or instructions detailing a manual process). It is thus important that smartphones present such functions that facilitate reparability/reusability of the whole products without the risk of transfer of any sensitive and personal data in reused equipment.

Secure data deletion[165] tools should built-in (or as second option made available on request) and should permanently delete all user data without compromising the functionality of the device for further use. Simplified transfer of data from an old to a new product should also be made available via installed or downloadable tools such as applications, cloud-based services or instructions detailing a manual process.

4.3.3.9 Password reset and restoration of factory settings

Settings for password reset and restoration of factory settings is needed in repair/upgrade operations associated with the continued use or reuse of products (e.g. change of user in the same organisation). Password reset and restoration tools should be pre-installed or made available (e.g. via installed or downloadable tools such as an application, a cloud-based service or instructions detailing a manual process). In addition, the device should also include a software function that resets the device to its factory settings. This should come with detailed instructions.

[164] As reported in the introduction of section 4.4.3, repair could be worthwhile even 3-5 years after sale according to Watson et el. (2017)

[165] According to the Commission Regulation (EU) 2019/424 of 15 March 2019 laying down ecodesign requirements for servers and data storage products "secure data deletion" means the effective erasure of all traces of existing data from a data storage device, overwriting the data completely in such a way that access to the original data, or parts of them, becomes infeasible for a given level of effort.

4.4 End of Life

After their useful life, products are disposed in order to remove and treat properly any source of hazard and to recover value embedded in components and/or materials. This is done in the recycling process. Recovery of materials and energy can also avoid the depletion of new resources. The effectiveness and efficiency of recycling can be facilitated through appropriate designs that can facilitate the recycling process, for instance improving depollution, dismantling, recyclability and recoverability of products, can have positive effects.

4.4.1 End of Life practices

The worldwide collection rates for small electronics are still low (Manhart et al. 2016). Although there are no global statistics available on this issue, data from various authors and regions of the world estimate that global collection rates for end-of-life mobile phones are below 50%, probably below 20% (Manhart et al. 2016). From a review of information reported in the literature:

- 20% of young Norwegian adults throw small electronics in the waste bin (Watson et al. 2017), while 89% of the mobile devices thrown away in the US in 2010 (141 million units) were disposed in landfill (Benton et al. 2015)[166];
- 28-125 million phones languish unused in the UK, meaning that for every phone in use, up to four sit in drawers unused (Benton et al. 2015). A similar situation occurs in Finland, where consumers typically have between two and five functioning mobile phones stored at home that are not in use (Watson et al. 2017), and North Rhine Westphalia, where 106 million of unused mobile phones and smartphones were stored in households in 2016[167].
- Collection rate in Europe for recycling, refurbishing and/or remanufacturing of smartphones was about 15% in Europe in 2012 (Ellen MacArthur Foundation 2012).

Disposal with household waste clearly has negative environmental impacts due to the missed recovery of the residual value of products and to the fact that most household waste management systems are not designed for treating the various chemicals embedded in EEE. However, also prolonged storage in households does have negative impacts since representing a missed reuse/ recycling opportunity.

4.4.2 Collection and end of life services

End-of-life smartphones are managed in Europe according to the WEEE Directive. The end-of-life management of these devices is under the responsibility of producers and importers, who can manage their EEE either individually or through a Producer Responsibility Organisation (PRO) by transferring their obligation to the PRO by paying a fee, in accordance with the principle of the extended producer responsibility (EPR).

In Europe, large distributors of electrical and electronic equipment (EEE) are obliged since 2016 to take back such devices free of charge and to inform consumers about the availability of return facilities. Stationary/online shops with sales/shipment areas relating to EEE of at least 400 m^2 have to take back small WEEE (no external dimension more than 25 cm) like smartphones without the obligation to buy any new EEE (0:1 Take-back).

In terms of targets set by the WEEE Directive, 75% of small IT and telecommunication equipment must be recovered from August 2018, and 55% must be recycled/ prepared for reuse. Despite this commitment, a high share of broken or unused smartphones is not collected for recycling. Statistics from Eurostat show a strong discrepancy between EEE put on the EU market in the period 2010-2015 and the amount of WEEE collected, treated and recycled, with their collection considered being the main barrier.

[166] The US landfill number is very likely not representative for the EU
[167] Personal communication by stakeholders involved in the development of this study

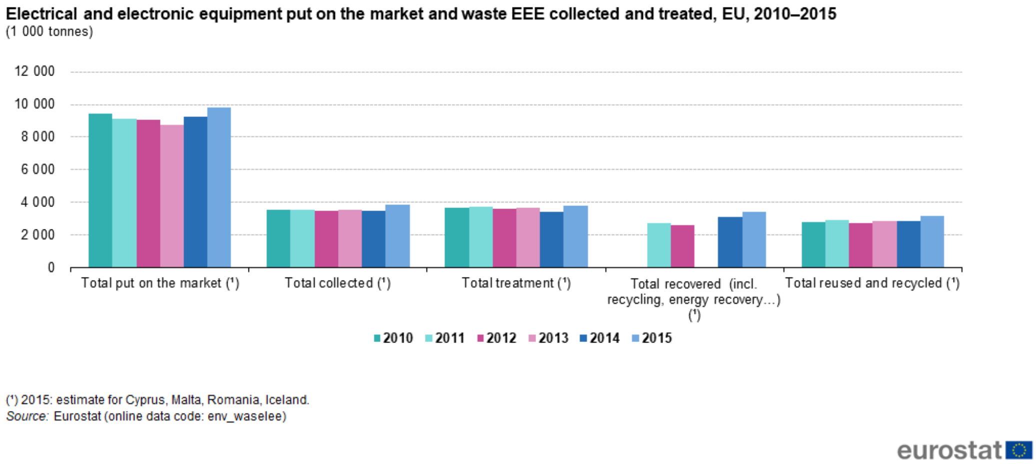


Figure 31: Electrical and Electronic Equipment put on the market and Waste EEE collected and treated in the EU in 2010-2015[168]

This problem of insufficient collection is particularly pronounced for small devices such as smartphones and tablets. Main reasons for low collection rates can be summarised as follows (Manhart et al. 2016; Martinho et al. 2017):

- Lack of information about the disposal of devices;
- Perceived value of unused devices;
- Data security issues.

In particular, collection efficiency could be improved by making consumers aware of the importance of recycling, and changing disposal habits of the society. This could require communication efforts and a broad availability of take back options (Tanskanen 2012).

Beside collection rates, the quality of the collected waste is also an important factor in the end-of-life management of smartphones. Collection and storage should ideally not expose devices to mechanical and physical stresses such as moisture. In addition, the level of sorting is an important factor for the subsequent reuse and recycling logistics. If smartphones are mixed with other product groups such as household appliances at the point of collection, the efforts for effective sorting can increase significantly, which can be economically unfavourable, especially in regions with high labour costs. Innovation in robotics and artificial intelligence can lead to the development of new sorting and data acquisition technologies for recycling.

Apart from manufacturers, offering take-back systems (either for free or with a refund on a new purchase), remanufacture[169], recycle and re-sale of used phones and parts are of interest also for other market players (Watson et al. 2015). However, anti-theft and security software installed on smartphones can be a barrier for independent organisations and professionals since this software can only be removed by the original owner or by the manufacturer (Transform Together 2018).

4.4.3 Recycling process

The recycling process can be split into two main stages:

1. Pre-processing, encompassing all steps necessary to separate and sort parts and materials for safe disposal and recovery operations;
2. End-processing, encompassing all steps necessary to recover secondary materials from the processing of scraps (e.g. in smelters and refineries).

[168] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Figure_1_Electrical_and_electronic_equipment_(EEE)_put_on_the_market_and_waste_EEE_collected_and_treated,_EU,_2010%E2%80%932015.png&oldid=372559e (accessed on 2 April 2019)

[169] See for instance: https://www.remade.com/ (accessed on 3 April 2019)

4.4.3.1 Pre-processing

Pre-processing operations typically start with depollution. The aim of this step is to comply with selective treatment (depollution) requirements, such as those laid out in Annex VII of the European WEEE Directive. Concerning smartphones, selective treatments involve the removal of:

- Battery;
- Printed circuit board;
- External electric cables (chargers).

Moreover, the WEEE Directive states that also BFR containing plastics have to be removed from collected WEEE. Some manufacturers have voluntary committed to avoid the use of BFR (Jardim 2017). Some specific BFRs as polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE) are mandatory restricted in homogeneous materials (< 0.1% by mass) also according to the ROHS Directive.

Design features allowing easy access and removal of the components listed in annex VII of the WEEE Directive are essential to ensure optimal depollution of devices. Specifications for WEEE de-pollution are provided in CLC/TS 50625-3-1[170]. Disassembly instructions for relevant components are provided by Digital Europe on the Recycling Information Platform[171].

Some design principles could help overcome the difficulties associated with recycling lithium-ion technologies and encourage their re-use, as for instance: designs that allow easy separation of parts, use of reversible joining techniques, labelling of parts, use of a minimum number of materials and components, use of standard formats and materials, ease of removal of the battery from the device, minimised use of hazardous materials (Science for Environment Policy 2018).

Batteries can be removed in the de-pollution step in a realistic amount of time, also in case of glued batteries. Separation of other parts can instead be more difficult since they are strongly tied together.

Stakeholders have reported significant advances in the field of battery mounting and removal. The technological trend regarding batteries is apparently a shift towards thinner batteries with higher capacity. Along with this trend, the mounting of batteries into smartphones has changed as well, from mechanical fixation towards bonding with pressure sensitive adhesive (PSA) tapes. Three technologies are currently used which offer the possibility of easy demounting:

1. Batteries are mounted with double-sided PSA tapes with stretch-release-properties that loose adhesion via stretching and thus allow for easy removal of the battery. This is the most widespread technology. Stretching can be applied manually, using finger grip, or with mechanical tools. This can be considered as a very convenient solution for dismantling purposes without compromising safety. This technology could be potentially applied to other components as well.
2. An alternative option is the use of specially formulated PSA systems with adhesion properties that are sensitive to contact with ethanol. For dismantling purposes, droplets of ethanol are brought into contact with the adhesive, which loses adhesion immediately. After the application of a short mechanical impact, batteries can be easily removed from the devices.
3. The third direction is the use of battery wrapping technology. The battery is wrapped into a PET film, which is bonded to the housing with a double-sided PSA tape with two different adhesive sides. The side showing to the battery has relatively low adhesion, allowing for easy removal by applying a peeling movement to the battery. This movement is applied through a pull-tab attached to the battery wrap.

The majority of smartphone producers are reported to have implemented one of these PSA technologies within the last years.

---

[170] CENELEC (2015) CLC/TS 50625-3-1: Collection, logistics & treatment requirements for WEEE - Part 3-1: Specification for de-pollution - General

[171] https://i4r-platform.eu/ (accessed on 3 April 2019)

After depollution, WEEE is broken down into parts and components either by:

- Mechanical processes (e.g. shredding);
- Manual operations (dismantling);
- A combination of the two.

The mixed scrap that is generated is then sorted into material output fractions (e.g. steel scrap, aluminium scrap, copper scrap, printed circuit boards, plastics) that are either passed on to end-processing units or to specialised companies that conduct more specific sorting (e.g. into various grades of aluminium- or steel-scrap).

Mechanical pre-processing steps (e.g. shredding) can lead to losses of metals that cannot be separated perfectly. Furthermore, mechanical stresses can also cause losses of metals in the form of dust (Manhart et al. 2016). Because of this, after the extraction of batteries, mobile phones and comparable devices are often delivered directly to end-processing units specialised in the recovery of copper and other precious metals.

The economic viability of WEEE recycling activities can only be ensured if a large number of appliances are treated in short time and with a satisfactory level of sorting. Processing of well sorted IT-equipment (e.g. smartphones only) can be more attractive from an economic point of view, and can increase the efficiency of recovery of parts and materials. In this way, devices can be screened to select those suitable for repair and reuse, whilst remaining devices can undergo a more thorough depollution where most batteries are removed for separate treatment.

Some European projects (Sustainably SMART[172] and ADIR[173]) are focusing on automated disassembly systems designed to manage and recover materials from smartphones. Apple has also developed automated disassembly systems as the LIAM-robot, custom built for the iPhone 6, and Daisy[174], an improved version of the Liam, that can take apart nine different versions of the iPhone. Daisy seems ensuring a higher granularity, allowing the recovery of Neodymium permanent magnets and tungsten vibration mechanism that are usually not recovered in the current recycling processes. It is however unclear whether robots as Daisy are already applied at industrial scale and at which degree the parts/ materials recovered close the loop in the re-manufacturing process.

4.4.3.2 End-processing

In terms of mass, smartphones are mainly composed of plastics and aluminium. However, the main contribution to the residual value of smartphones is due to the content of precious metals. The recovery of materials from WEEE is the main aim of end processing, although it presents some challenges (Akcil et al. 2015).

Table 25 provides an overview on various recycling options for smartphones and tablets (Manhart et al. 2016). There is no perfect recycling path. Nevertheless, the most typical scenario sees the removal of the battery, separate smelting of the device, and recovery of precious materials (Manhart et al. 2016).

[172] https://www.sustainably-smart.eu/ (accessed on 13 June 2018)
[173] https://www.adir.eu/ (accessed on 13 June 2018)
[174] https://www.apple.com/environment/resources/ (accessed on 1 February 2019)

Table 25: Major recycling options for smartphones and tablets and material recovery capacity (Manhart et al. 2016)

Material		Option 1: Battery is not removed, device fed into secondary Cu-smelter	Option 2: Battery is removed, handset fed into secondary Cu-smelter, battery into battery-smelter	Option 3: Device (incl. battery) is shredded and mechanically sorted into output fractions which are fed into Cu-, Fe- and Al-smelters
Aluminium	Al	No	No	Partly
Copper	Cu	Yes	Yes	Partly
Cobalt	Co	No	Yes	No
Magnesium	Mg	No	No	No
Tin	Sn	Yes	Yes	Partly
Iron (Steel)	Fe	No	No	Partly
Tungsten	W	No	No	No
Silver	Ag	Yes	Yes	Partly
Rare Earth Elements	REE	No	No	No
Gold	Au	Yes	Yes	Partly
Tantalum	Ta	No	No	No
Palladium	Pd	Yes	Yes	Partly
Indium	In	Partly	Partly	Partly
Gallium	Ga	No	No	No

No = no material recovery.
Partly = recovery of up to 80% of the embedded material
Yes = recovery of > 80% of the embedded material

The common recycling route for the recovery of metals in Europe is based on the pyro-metallurgical methods, basically based on smelting (Figure 32, red line) and adopted in different plants (e.g. Umicore in Belgium and Aurubis in Germany). Losses of precious metals can occur if this is associated with mechanical pre-treatments for the separation of steel and aluminium scraps. On the other hand, the practice of feeding smartphones directly into secondary Cu-smelters leads to losses of aluminium and iron as these metals move into the slag phase of the smelters. Plastics are instead reported to be burnt to fuel such smelters (Manhart et al. 2016).

Dedicated smelting processes are also available for recycling of batteries and recovery of cobalt that can be used for new rechargeable batteries (e.g. UHT furnace in Hoboken[175]). Different EU projects have been also investigating innovative routes to recover cobalt and other valuable materials included in the Lithium-ion batteries[176, 177]

Li-ion batteries cannot be landfilled as they leach substances that are toxic and explosive. However, recycling of Li-ion batteries is technologically challenging (Science for Environment Policy 2018) since:

- They contain a large number of blended materials, which makes recycling more complex than for simpler technologies like lead-acid.
- The array of chemical compositions for the electrodes adds a further complication, especially as the composition is not labelled for the recycler's information.
- The two main methods of recycling for lithium-ion batteries are energy intensive.

Recycling of waste lithium-ion batteries is generally aimed at recovering cobalt, nickel and copper due to their economic value. These materials are only partially recovered. Most other substances contained in the battery are not recovered, even if technically possible.

Lithium usually ends up in the slags of recycling processes used as construction materials. The declining use of cobalt in lithium-ion batteries could make recycling unattractive from an economic point of view.

[175] https://csm.umicore.com/en/recycling/battery-recycling/our-recycling-process (accessed on 31 January 2019)
[176] https://h2020-crocodile.eu/project-2/ (accessed on 31 January 2019)
[177] http://www.colabats.eu/ (accessed on 31 January 2019)

Although most industrial applications for WEEE recycling are still restricted to physical and pyro-metallurgical processes, emerging techniques include (Akcil et al. 2015):

- Hydrometallurgical techniques (Figure 32, blue line), which focus on precious metals contained in PCBs. Hydro-based systems are able to process smaller quantities of recyclable material than smelting processes, thus needing a lower initial investment. The hydro-metallurgical process requires a series of pre-treatments on WEEE (collection, sorting and shredding of PCBs) and further separation of ferrous metals and aluminium. PCB granulates then undergo sulphuric acid leaching and solid/liquid separation. The leach liquor, which is rich in copper, is neutralised to recover copper in the solution. The residue obtained from sulphuric acid leaching goes to cyanide or thiourea leaching for the recovery of precious metals such as gold and silver (Rocchetti et al. 2013)
- Biotechnologies, which exploit the ability of microbes to accumulate metal ions for their vital functions. This could be used for the selective recovery of metals. However, at the moment the main barrier seems linked to the low speed of these techniques.

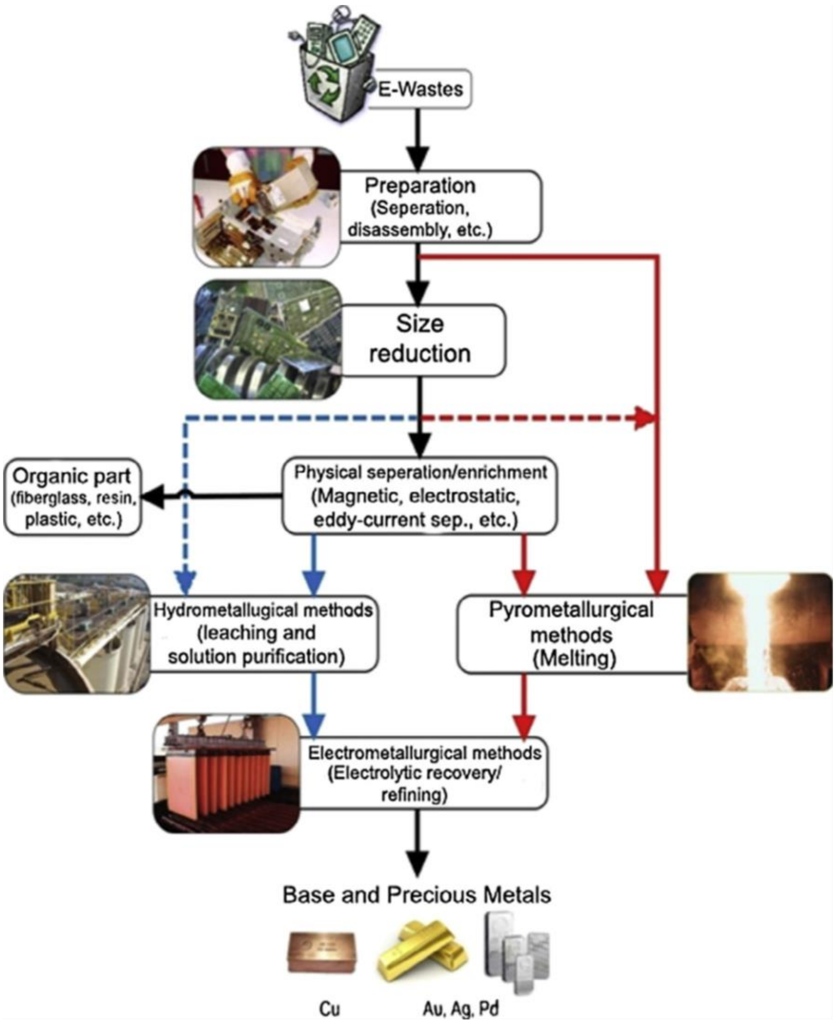


Figure 32: Typical end processing steps for the recovery of precious metals by pyro-metallurgical methods (in red) or hydro-metallurgical methods (in blue) from WEEEs (Akcil et al. 2015)

Several precious materials have a potentially high recyclability rate with the current EoL scenarios, as for instance: cobalt, copper, gold, silver, palladium, and tin (Manhart et al. 2016).

Critical raw materials are other relevant elements for recycling; however, they are not recovered effectively in the current EoL scenarios:

- Tungsten: recycling rates of tungsten are low/moderate in typical recycling plants (Fairphone 2017). However, pilot disassembly programmes are able to recover the vibration module and send it to a dedicated recycler for tungsten recovery[178];
- Rare Earth Elements (REE): less than 1% of REEs are currently recycled from postconsumer waste (Fairphone 2017). The REE4EU project[179] aims to develop and demonstrate the feasibility of an innovative Rare Earth Alloys (REA) recovery route from the recycle of permanent magnets (PM) and batteries;
- Gallium and Indium: less than 1% of gallium is estimated to be recycled from post-consumer waste. Gallium is sometimes substituted by Indium, which is however associated with similar supply and recycling problems (Fairphone 2017).

The Sustainably SMART[180] project is exploring the possibility to separate tantalum-rich, gallium-rich and tungsten-rich components from disassembled smartphones as these metals are currently lost in conventional electronics waste recycling processes.

A significant barrier for the recycling process is the critical volume required by end-processors of speciality metals, as the waste stream of smartphones is relatively small compared to the scale of recycling facilities (and also in comparison with other waste streams from the automotive, machining, building/infrastructure sectors). End-processors often do not accept volumes below 100 t, which is a difficult quantity to accumulate for smartphones.

Moreover, although elements can be available at industrial recycling capacity (e.g. magnesium, tungsten, some rare earth elements, tantalum), pure input of materials is required. Different models of smartphones are instead made of different mixture of heterogeneous materials, which further complicate the recycling process. For example, cases are made of different materials, and metals are alloyed together. Roughly, half of the metals in a cell phone are lost in a smelter during the recycling process[181].

Possible improvements mainly depend on the effective collection and separation of batteries, smartphones and their constituents. However, such effort could be not justified from an economic perspective due to the relatively small quantities of metals contained in smartphones and tablets. Some metals, like critical rare earth elements, are too difficult or too expensive to separate out for recycling.

4.4.4 Transport and risk of illegal export of WEEE

WEEE, including smartphones, can also end up, through informal routes, in countries that do not have appropriate recycling facilities and/or environmental regulation. This can cause environmental pollution and health risks in these countries (Basel Action Network 2019). For instance, the presence of polyvinyl chloride (PVC) plastic and brominated flame-retardants (BFRs) can contribute to the formation of dioxins, among other hazardous chemicals, when scrap is burned, especially if in an uncontrolled way.

Annex VI of the WEEE Directive 2012/19/EU states that in order to distinguish between EEE suitable for reuse and devices not suitable for reuse and legally classified as a waste (WEEE), where the holder of the object claims that they intend to ship or is shipping used EEE and not WEEE, Member States shall require the holder to have available the following to substantiate this claim:

- a copy of the invoice and contract relating to the sale and/or transfer of ownership of the EEE which states that the equipment is destined for direct re-use and that it is fully functional;

[178] https://www.apple.com/lae/environment/resources/ (accessed on 30 January 2019)
[179] http://www.ree4eu.eu/ (accessed on 23 October 2018)
[180] https://www.sustainably-smart.eu/ (accessed on 30 January 19)
[181] https://ifixit.org/recycling (accessed on 8 February 2019)

- evidence of evaluation or testing in the form of a copy of the records (certificate of testing, proof of functionality) on every item within the consignment and a protocol containing all record information;
- a declaration made by the holder who arranges the transport of the EEE that none of the material or equipment within the consignment is waste as defined by Article 3(1) of Directive 2008/98/EC; and
- appropriate protection against damage during transportation, loading and unloading in particular through sufficient packaging and appropriate stacking of the load.

Further Technical Guidelines for the transboundary movements of WEEE and used EEE and for the differentiation between the definition of waste and non-waste are provided by the United Nations (UN 2015).

4.4.5 Improving the efficiency of recycling processes

The recycle and recovery of materials at the end of life can be limited by the presence of specific substances, and by technological and design issues.

The deployment of technologically advanced pre-treatment and recycling processes can increase recycling efficiencies beyond business as usual practices.

From a product design perspective the recycling processes could be also facilitated by:

1. The availability of take-back programmes for the separate collection of smartphones and the proper information of consumers about the importance of giving back unused devices for recycling purposes
2. The marking and ease of removal of:

- - Parts that could be reused (e.g. displays);
- - Parts listed in Annex VII of WEEE because of their hazardousness (battery and PCBs);
- - Parts containing precious/critical materials.

3. The documentation of the sequence of operations needed to access and remove the parts listed above
4. The provision of information on CRM, minerals from conflict-affected and high-risk areas, recyclable materials,

The marking of plastic parts and halogenated flame-retardants used in plastic parts. An overview of possible measures to improve the material efficiency of smartphones is provided in Section 6 based on the information gathered along this study.

4.5 Trade-offs between material efficiency aspects

Possible measures to improve the material efficiency of products should not be seen as a pool of separate alternatives but rather as a set of interconnected options that can affect and/or be influenced by other aspects (Cordella et al. 2019b).

First of all, functionalities of smartphones depend on specific characteristics of parts and materials used. Any strategy addressing directly the materials used in the product should ensure the fulfilment of technical specifications for product safety, performance and durability as well as analyse the related impacts.

Moreover, actions that can potentially have a positive influence with respect to a specific material efficiency aspect could have negative consequences for other aspects (e.g. the use of glues can increase robustness but could make the product more difficult to repair, while recyclability could be affected by materials used in leaner designs).

Durability can be seen as a function of:

i) Reliability and resistance, and

ii) Reparability/upgradability.

Some manufactures claim to prioritise reliability and resistance in the design of their smartphones (e.g. robustness and water/dust proof). This could make more difficult the replacement of parts by users or the repair of the product, as it could be the case for embedded batteries or when sealing techniques are used.

However, it has been reported that several adhesive bonds currently used for electronic applications are removable (also called "reworkable") through the application of heat or other available technologies. This means that the disassembly operation can be still possible, at least for professional repairers and users that are more experienced.

Another aspect to consider for embedded batteries is that they can allow reducing the battery pack's protective cover. It has been reported by stakeholders that their enclosure requires in general less plastic and metal materials to protect the battery cells. The smartphone housing then provides the mechanical containment of the cells, and the battery electronics can be added to the existing system circuity. All in all this can mean a higher energy density. On the other hand, it has to be considered that a reduced protective cover could make more dangerous the handling of the battery for non-professional repairers, as the battery can catch fire in case of punctures.

Other manufacturers instead prioritise ease of repair and upgrade. In particular, the concept of modular smartphone has received lot of attention during the past years. Modular smartphones (e.g. Fairphone, Shiftphone, and Puzzlephone) offer the possibility to replace specific modules of the device. The advantage of this approach is that the replacement (for repair or upgrade) of several parts can be done directly by the user. However, a modular design can come with some challenges due to the larger mass and volume needed to house different parts in a way they ensure full flexibility of the device (Transform Together 2018).

Moreover, smartphones do not need to be fully modular: hybrid solutions could be feasible and provide material efficiency benefits. Research suggests that in order to achieve highest efficiency in terms of material recovery and cost savings, modularity should focus on printed circuit boards (PCBs), screens, shells and batteries (Souchet et al. 2017).

A comparison between iFixit scores and Ingress Protection (IP) levels is presented in Annex II to investigate on the possible existence of trade-offs between more reparable devices and more reliability/resistance-oriented designs. Several models with IP67 or IP68 declaration/certification have been found with a reparability score from 3 to 7. None of these models is modular, meaning that it can be possible to design reliable and resistant devices without compromising reparability excessively. This is in line with the findings of a recent study from the University of Berlin (Clemm 2019) suggesting that some smartphones models are able to achieve good levels of ingress protection (IP67) without penalising the easiness of replacement of the battery (that in one case was possible manually without the use of tools). No indications about the reliability/resistance of more reparable products have been found.

The analysis of material efficiency should be also supported by LCA considerations to understand which aspect can be more important from a life cycle perspective (Cordella et al. 2019b).

4.6 Networks, cloud offloading and data centres

The use of smartphones relies on mobile networks (voice and data) and data servers storing user (e.g. photos, videos) and provider data (e.g. music, maps, apps and their back-end data).

The monthly average consumption of mobile data has grown between 2012 and 2017 from 450 MB to up to 3.9 GB and 6.9 GB in Western Europe and North America, respectively. The monthly mobile data traffic per active smartphone in North America could reach 26 GB in 2022. Despite the increase in energy efficiency, the higher volumes of transferred data might cause a net increase in energy consumption of networks and of data centres (Transform Together 2018).

In Europe, data centres have been report to account for approx. 2% of the total energy consumption (Bertoldi et al. 2012). Furthermore, increased transmission speeds require continuous updates of the physical infrastructures (Transform Together 2018) with a continuous increase of the power needs foreseen for the next years (Figure 33).

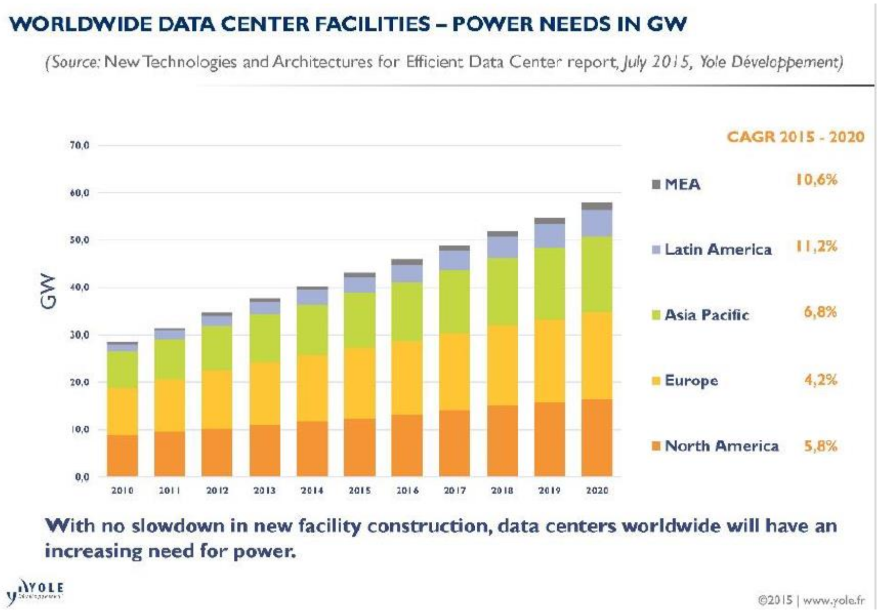


Figure 33: Global power demand of data centres[182]

Impacts from networks and data centres could be reduced by:

- Developing active networks adjusting their-selves based on the activity of users and building zero-emission radio access networks (RAN) to increase energy-efficiency of telco networks, which also requires greater use of renewable energy and innovative energy-efficiency solutions such as liquid cooling of base stations (BTS) connected to local or district heating (Transform Together 2018);
- Designing apps that demand smaller amounts of data in order to function;
- Improving the energy efficiency of data centres and sourcing them with clean forms of energy. For example, it has been reported that 60-70% of the energy consumed in Apples' worldwide corporate offices, retail stores, and data centres come from renewable sources.

A study from Pihkola (et al. 2018) shows that energy efficiency increased for new network technologies (e.g. 4G vs. 3G) and that this trend may not continue with 5G. However, even in case 5G leads to a disruptive reduction of power consumption, this is expected to be counterbalanced by an increased traffic of data. As a result, power consumption in future mobile access networks may increase.

[182] http://www.yole.fr/iso_upload/News/2015/PR_DataCenterTechnologies_SiPhotonics_YOLE_Oct2015.pdf (accessed on 3 April 2019)

5 MATERIAL EFFICIENCY HOT-SPOTS

Based on the information gathered in the previous steps, the fifth step of the guidance is

1. To define one or more product design options which can be considered representative for average performance conditions,
2. To assess impacts associated to possible options and alternative scenarios contributing to improve material efficiency from a life cycle perspective;
3. To understand the relevance of alternative strategies and analyse the occurrence of trade-offs.

5.1 Material efficiency concept

Material efficiency could be defined as the ratio between the performance of a product, a service or an energy system and the input of materials required to provide such output. It is thus apparent that material efficiency can increase either by improving the performance with the same input or by reducing the input of materials to provide a certain performance (Cordella et al. 2019b).

From a system perspective, material efficiency can be considered as a range of strategies relating to the use and management of resources throughout the life cycle of a product or service, and which aim to minimise material consumption, waste production, and their related environmental impacts (Allwood et al. 2011; Huysman et al. 2015), without affecting functionalities negatively.

Figure 34 shows alternative routes for products before their final disposal in landfill, which can contribute to improving their material efficiency. At the macro-scale level, material efficiency can mean moving from a linear model of production and consumption (i.e. from virgin material extraction, to short/single use of products, and final disposal in landfill) to a more circular model, where input of virgin materials can be reduced and landfill disposal is minimised, or at least kept controlled in a growing economy.

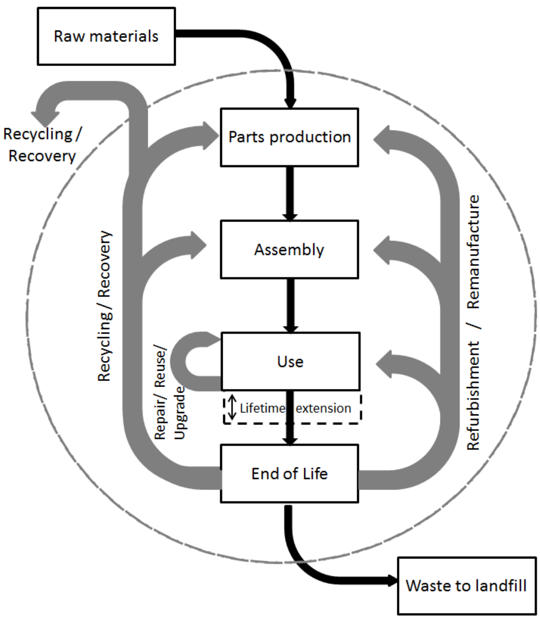


Figure 34: Material efficiency aspects in the life cycle of a product (Cordella et al. 2019b)

Material efficiency strategies can be quite well mirrored by the hierarchical approach set out by the Waste Framework Directive (Allwood et al. 2011; Bakker et al. 2014), as shown in Figure 35. The waste hierarchy aims at reducing the waste output and its disposal in landfill. Material efficiency goes beyond and promotes also the prevention of material consumption. Taking the example of waste management, the following hierarchy of strategies can be drawn for handling material efficiency aspects at the product level (Cordella et al. 2019b):

1. Reduction of material consumption;
2. Value retention in product systems;
3. Recycling and recovery of materials.

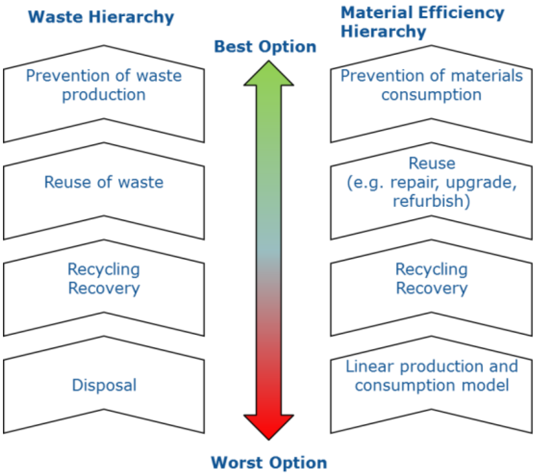


Figure 35: Analogy between waste and material efficiency hierarchies (Cordella et al. 2019b)

In general, material efficiency aspects could be more or less relevant for a product/ service depending on its specific characteristics. For example, depending on the relative magnitudes of impacts due to production, use phase and end of life, it could be either more convenient to prolong the use of energy-related products or to replace them with more efficient products (Alfieri et al. 2018a; Cordella et al 2018; Iraldo et al. 2017, Tecchio et al. 2016).

An assessment of the relative importance of material efficiency aspects is thus needed, on a product-by-product basis, to understand which hotspots can potentially produce most tangible benefits and the magnitude of possible trade-offs.

5.2 Guidance for the LCA-supported analysis of hotspots

The analysis of material efficiency hotspots calls for the consideration of technical, environmental and economic information over the life cycle of products (see sections 1 to 4) and the further quantification of impacts. Life cycle assessment (LCA) (ISO 2006a; ISO 2006b) and Life cycle costing (LCC) are the general methodological references for the quantification of environmental and economic impacts of products and services along their life cycle. This can allow: i) determining main contributions in terms of stages, processes, parts and/or specific emissions and inputs, and ii) understanding which improvement options and scenarios can be more beneficial and under which conditions, as well as if relevant trade-offs exist (Cordella et al. 2015; Cordella and Hidalgo 2016; Cordella et al. 2019b).

The scope of the analysis has to be defined with respect to:

1. Functional unit (FU) and reference flow;
2. Impact categories and related indicators;
3. Reference product(s)/ types of products;
4. System Boundary and modelling approach[183].

[183] The modelling of the life cycle can include the application of assumptions and the further processing of foreground and LCI data for the calculation of the inputs and outputs associated to the key elements of the product's life cycle: Bill of Materials (BOM) and manufacturing

For a comprehensive assessment of environmental impacts, the most ambitious level would be to use the indicators proposed in PEF, which would require carrying out a full LCA with the aid of commercially available databases (and software tools).

The assessment could however be streamlined by referring to shorter lists of key indicators[184], and/or simplified tools. For example, Ecoreport is a simplified LCA tool used in MEErP preparatory studies in study supporting Ecodesign/Energy Label. Although coming with a more moderate assessment effort, the current version of the Ecoreport lacks in terms of modelling flexibility, indicators addressing scarcity of resources (e.g. ADP), and harmonisation with PEF. Reference impact categories could be identified also based on the observation of Product Category Rules and relevant studies, as for instance described by Cordella and Hidalgo (2016).

Depending on the quality of the available information, the assessment can be based on existing studies (Cordella and Hidalgo 2016) and/or ad-hoc models which match, as close as possible, the stock/market conditions of the analysed product (Cordella et al. 2015).

5.3 LCA of smartphones

5.3.1 Goal and scope

The aim of this LCA application is to analyse material efficiency hot-spots relating to the average use of smartphones in the EU. Alternative scenarios potentially leading to an improvement of the material efficiency of smartphones are defined and assessed. The assessment is assisted by an ad-hoc LCA model, which follows an attributional approach.

Carrying out the LCA of a smartphone is a challenging exercise due to the limited availability of foreground data and the presence of data gaps in LCI databases for electronics. The LCA model has been developed based on the information available in the literature and in the Ecoinvent 3 database[185].

LCA results for recent models of smartphones are available from OEMs (e.g. Apple[186], Huawei[187]). However, although describing the environmental impacts of their products, the available information from OEMs lacks in sufficient details at modelling level to enable a consistent comparison of models and scenarios.

LCA studies available in the scientific literature and published after 2010[188] were screened, based on elements provided by Cordella and Hidalgo (2016), to identify those which could constitute a potentially valuable resource for the analysis in terms of scope of the analysis, data quality and representativeness, impact assessment metric, relevance and robustness of findings.

Selected studies (Andrae 2016; Ercan 2013; Ercan et al. 2016; Manhart et al. 2016; Moberg et al. 2014; Proske et al. 2016; Suckling and Lee 2015) have been used as source of inputs for this LCA study. These are at least 3-year old, which is longer than the average cycle of replacement of smartphones. Although these studies could be less representative for more recent devices on the market, they still provide a reference for the identification of hot-spots.

processes, transports and distribution, expected time of use, maintenance and repair activities, EoL scenarios. A sensitivity analysis should be carried out when the uncertainty of assumptions and/or data is significant.

[184] For example: 1) an environmental indicator where contribution to the impacts due to materials is dominant (e.g. 75-100% of the overall impact); 2) an environmental indicator where contribution to the impacts due to the use phase is dominant; 3) an environmental indicator where contribution to the impacts from both materials and use phase is significant (e.g. 30-50% each); 4) total cost of ownership (EUR)

[185] As general rule, an attributional approach with cut-off system model has been considered, see: https://www.ecoinvent.org/database/system-models-in-ecoinvent-3/cut-off-system-model/allocation-cut-off-by-classification.html (accessed on 27 August 2019)

[186] https://www.apple.com/environment/ (accessed on 31 January 2019)

[187] https://consumer.huawei.com/en/support/product-environmental-information/ (accessed on 31 January 2019)

[188] Considering that smartphones have been introduced on the market in 2007 (Arthur 2012) and that some years are needed before relevant LCA information is made available.

To handle the existing data input limitations, the LCA model has been streamlined through expert assumptions based on best available information, which are transparently presented and critically analysed in the following sections.

5.3.2 Impact categories and related indicators

The assessment of smartphones involves the analysis of a complex product system. LCA studies for smartphones (Ercan 2013; Ercan et al. 2016; Manhart et al. 2016; Moberg et al. 2014; Proske et al. 2016; Suckling and Lee 2015) typically focus on the analysis of the Carbon Footprint (CF) of the product, i.e. the greenhouse gases (GHGs) emitted along the product life cycle and measured as $CO_{2,eq.}$ in terms of Global Warming Potential over 100 years (GWP_{100}).

GWP100 is a widely used indicator which represents a global environmental priority and which correlates to a number of indicators (Askham et al. 2012; Huijbregts et al. 2005). The contribution to greenhouse gas emissions from production and use of smartphones (and other ICT products) could moreover increase in the future (Belkhir and Elmeligi 2018).

A more comprehensive sustainability assessment should be based on a broader metric of indicators (including categories such as resource scarcity, biodiversity and toxicity). When a broader metric of environmental indicators was analysed (Ercan et al. 2016; Moberg et al. 2014; Proske et al. 2016) the outcomes confirmed the importance played by manufacturing processes and the extraction of materials used in smartphones (e.g. cobalt, copper, gold, silver) for all impact categories (although with different relative contributions).

Given the illustrative nature of this application, the quantitative assessment has been simplified by focusing on the calculation of the GWP100 along the life cycle of smartphones. This has been complemented with environmental information from the literature relating to materials, and with economic considerations about the life cycle costs for consumers (expressed in EUR 2019).

5.3.3 Functional Unit and Reference Flow

This LCA application refers to the average use of smartphones in the EU. The definition of a representative Functional Unit (FU) is complicated by the fact that smartphones integrate many functions at different levels of performance (potentially replacing the use of other products such as cameras and music players).

For comparative purposes, equivalency between smartphone systems must be ensured by selecting and defining relevant function(s) and functional unit(s). This would include the consideration of quantitative and qualitative aspects:

- What, when and how well: e.g. a smartphone produced in 2018, enabling 3G/4G speed and Wi-Fi access, equipped with a 5.9 inch display of 1440 × 2560 pixels, with 64 GB of storage memory and 4 GB of RAM, with a 20 Mega Pixel (MP) video-camera, and with a 4000 mAh battery capacity;
- How much and how long: e.g. 1 hour calling, 1 hour web browsing, 1 hour video watching per day, during "N" years of use.

In practice, it is likely that conducting a coherent comparison between models is hindered by the different characteristics of such models.

The FU can be converted in terms of Reference Flow, which is the amount of product(s) needed to deliver defined functions. The use of a phone for a certain number of years is the most commonly used reference flow (ETSI 2018). This simplification is considered useful for the analysis of the relevance of material efficiency hot-spots in the life cycle of a generic product.

The analysis has been thus referred to the individual use of smartphones for 4.5 years in Europe. This corresponds to the median lifespan of a mobile phone as reported in section 3.3. Further assumptions are defined in the next section with the aim to adhere, as far as possible, to plausible conditions for the EU market.

5.3.4 Environmental modelling

Smartphones on the market are multi-functionality products offering different levels of performance depending on the technologies used. The comparison of specific models of smartphones should be carried with an adequate level of granularity, so that products with similar characteristics are assessed within the same product category.

Since this application does not aim to compare specific models of smartphones, but rather produce general considerations for this product group, a virtual (non-existing) product made up of different technologies/materials is considered as reference for this assessment.

The System Boundaries include the evolution of the product from cradle-to-grave:

a. Production of parts (i.e. extraction, processing and transportation of materials and assembly of parts, including the packaging);
b. Assembly of the device (i.e. transportation of parts and further assembly and packaging of the device);
c. Distribution (i.e. transportation of the product from manufacturing plants to retailers and customers);
d. Use (including system aspects associated to data consumption and related communication infrastructures, where analysed);
e. End of Life (i.e. typical disposal scenarios, including transportation and recycling of the product, where analysed).

Foreground data has been gathered from the literature; elementary input/output flows have been then calculated based on LCI datasets of the Ecoinvent database, as described in the following sections. Services and material goods necessary to support the business (e.g. research and development activities, marketing) are not considered.

5.3.4.1 Materials, manufacturing and assembly

Based on Section 4.2.1, an average smartphone is considered to have a display size of 75.53 cm^2 and a weight of about 160 grams, including 39 g for the battery and excluding accessories and packaging. The weight of the smartphone has been estimated approximately as 29 g per display size inch (+/- 15%).

Additional materials are necessary for packaging, documentation and accessories as headset, USB-cable, charger. Packaging is typically made of fibre (e.g. cardboard) and, to a lower extent, plastic materials.

A Bill of Materials has been estimated based on the available information and reported in Table 26. The objective was to find a balance between comprehensiveness of materials, and simplicity for the modelling. LCI datasets of the Ecoinvent database were considered, as reported in Table 26, to obtain an indication of the potential impact associated to each part (including extraction and processing of materials). Alternative processes were used as proxy in presence of data gaps.

The manufacturing of one unit of smartphones has been considered to require 4.698 kWh (Proske et al. 2016) and to happen in China. Regarding the transport of parts to the assembling factory, it has been considered that:

- Housing and packaging materials have to be transported for 1000 km and 100 km by lorry, respectively;
- Other materials (mostly electronics) have to be transported for 1000 km by flight and for 100 km by lorry.

The following processes from Ecoinvent were considered:

- “Transport, freight, lorry 16-32 metric ton, EURO4 {GLO} market”;
- “Transport, freight, aircraft {GLO} market”.

Table 26: Bill of Materials for a generic smartphone in the EU

Module	**Part**	**Avg. weight (g)**	**LCI dataset**[1]
Housing	Plastic elements	9.5	Polycarbonate {GLO} market + Injection moulding {GLO} market
	Metal frame and case:		
	- Aluminium	22	Aluminium, primary, cast alloy slab from continuous casting {GLO} market + Impact extrusion of aluminium, 2 strokes {GLO}| market
	- Steel	6.5	Steel, low-alloyed {GLO} market + Impact extrusion of steel, cold, 2 strokes {GLO} market
Screen/Display	LCD display (75.5 cm2)	30	Liquid crystal display, unmounted {GLO} market + Liquid crystal display production, minor components, auxiliaries and assembly effort {GLO} market
Electronics	PWB (14 cm2)	28	Printed wiring board, for surface mounting, unspecified, Pb free surface {GLO} market
	IC (7 cm2)	2	Integrated circuit, logic type {GLO} market
	Resistors	2	Resistor, surface-mounted {GLO}| market
	Diodes	0.9	Electronic component, passive, unspecified {GLO} market (proxy)
	Capacitors	0.7	Capacitor, for surface-mounting {GLO} market
	Transistors	0.1	Transistor, surface-mounted {GLO} market
	Connections	0.25	Electric connector, peripheral component interconnect buss {GLO} market
	Inductors	0.2	Inductor, ring core choke type {GLO} market
Battery	Battery	39	Battery cell, Li-ion {GLO} market
Others	Cameras	1.9	Electronic component,

Module	Part	Avg. weight (g)	LCI dataset[1]
			passive, unspecified {GLO} market (proxy)
		1.9	Electronic component, active, unspecified {GLO} market (proxy)
	Speakers and microphone	2	Electronic component, passive, unspecified {GLO} market (proxy)[2]
	Buttons	0.1	Electronic component, passive, unspecified {GLO} market (proxy)
	Filters	0.1	Electronic component, passive, unspecified {GLO} market (proxy)
	Connection ports	0.25	Electric connector, peripheral type bus {GLO} market
	Vibration motor	1	Permanent magnet, for electric motor {GLO} market for permanent magnet, electric passenger car motor
	Other electro-mechanical components	11.9	Electronic component, passive, unspecified {GLO} market (proxy)
Accessories	Charger	50	Transformer, low voltage use {GLO}, market
	USB cable	20	Cable, unspecified {GLO} market + Plug, inlet and outlet, for computer cable {GLO} market
	Headset	15	Polyethylene, high density, granulate {GLO} market (14g) + Electronic component, passive, unspecified {GLO} market (1g) (proxy)
Packaging and documentation	Paper	50	Printed paper {GLO} market
	Cardboard	110	Folding boxboard/chipboard {GLO} market
	LDPE film	20	Polyethylene, low density, granulate {GLO} market + Extrusion, plastic film {GLO} market for

Notes:

1) Unless stated differently, process contained in the Ecoinvent 3 database based on attributional approach and cut-off system model are considered

2) As a sensitivity analysis, the process was modified to add neodymium (0.05 grams) and praseodymium (0.01 grams), which did not result in a significant variation for the GWP (although it could affect other impact categories related to resource depletion)

5.3.4.2 Distribution

The following means of transport are considered for the distribution of the product from China to the EU:

- 100 km by truck, in China;
- 8000 km by flight (distance from Beijing to Brussels[189])
- 500 km by truck > 32t, in Europe.

5.3.4.3 Use

The use of smartphones mainly implies consumption of electricity in the battery recharge cycles. Actual consumption depends on user behaviour and on efficiency of battery/charger.

An electricity consumption of 4.9 kWh per year is calculated by Proske et al. (2016) considering a battery capacity of 2420 mAh, 3.8 V of voltage, 69% of recharge efficiency, and 365-charge cycle per year. According to Andrae (2016), energy consumption is 1.538 times the battery capacity and can vary between 2 and 6 kWh per year. Ercan et al. (2016) estimated that the annual electricity demand of a smartphones could range from 2.58 kWh, considering 1 recharge every 3 days, to 7.74 kWh, considering 1 recharge per day. Manhart et al. (2016) instead report that the electricity consumption vary between 3 and 6 kWh/year.

Based on the available information it is considered that the electricity consumption associated to the use of smartphones in the EU is 4 kWh/year on average.

In terms of lifetime, it is considered that the average technical lifetime of a smartphone can be 4.5 year, while the time of use of the first user is 2 years, on average. This corresponds to the default scenario; additional scenarios are assessed, as described in Section 5.3.4.1.

5.3.4.4 End of Life

Based on the information reported in Section 4.4.1 and in Ercan (2013), it is considered that:

- 49% of smartphones are kept unused at home, once they reach their end of life;
- 36% of smartphones find a 2nd user, either as donation or through the 2nd hand market;
- 15% of smartphones are collected and recycled/remanufactured.

As default scenario, it is assumed that smartphones are kept unused at home. However, alternative scenarios are modelled as described in Section 5.3.6.

Based on Proske et al. (2016), for recycling it is considered that:

- Smartphones are disposed of by the user at a point of collection and then transported from the collection point to a pre-processing facility, where the phone is depolluted (i.e. removal of the battery from the unit);
- For the depollution process, the separation rate is 100 %, i.e. no losses are generated in the separation process;
- After depollution, the phone unit (without battery) is transported to a recycling facility for metals recovery without further dismantling steps;
- In total, waste smartphones have to be transported 1125 km by truck and 375 km by train.

[189] https://www.distance.to/Brussels,BEL/Beijing (Accessed on 5 August 2019)

Burdens and credits associated to the recovery of materials from a smartphone of 168 g are reported in Table 27 as calculated by Proske et al. (2016). The authors of the study considered the fractions that can be currently disassembled from the product. These values have been adapted to the modelling conditions set in this study, as described in the table.

In addition, credits associated to the recovery of materials and energy from housing materials have been estimated based on the following assumptions:

- Aluminium

  - Only primary aluminium is used in the original product,
  - Aluminium can be totally recycled at the End of Life and this avoids the production of new primary material,
  - 1.01 g of $CO_{2,eq}$ are emitted per g of metal processed (recycled), based on the analysis of Ecoinvent datasets.

- Steel

  - Both primary and secondary steel (57% vs 43% by mass) is used in the original product,
  - Steel can be totally recycled at the End of Life but credits are assigned only to the primary material,
  - 0.85 g of $CO_{2,eq}$ are emitted per g of metal processed (recycled), based on the analysis of Ecoinvent datasets.

- Plastic

  - Plastic materials are incinerated at the End of Life, producing 1.04 g of $CO_{2,eq}$ per g of plastic incinerated (based on the analysis of Ecoinvent datasets) and avoiding the production of 0.094 Wh of electricity (per g of plastic incinerated).

As a result, it is estimated that the recycling of the virtual model of smartphone considered in this study could lead to a net credit of 1631 g of $CO_{2,eq}$ (see Table 27).

However, such figure presents some considerable variance:

- The full recovery of precious metals could avoid the emission of more than 1600 g of $CO_{2,eq}$[190] (under the assumption that this is technologically feasible), compared to the ~1000 g of $CO_{2,eq}$ estimated in Table 27, which would lead to a net credit of 2143 g of $CO_{2,eq}$ (+31%);
- A study from Andrae (2016) reports instead a net burden of 400 g of $CO_{2,eq}$ (credits: 600 g of $CO_{2,eq}$; burdens: 1000 g of $CO_{2,eq}$) for the recycle of a smartphone of about 220 grams, which would correspond to about 290 grams if adapted to the virtual model considered in the present study.

Such variance can depend on the characteristics of the analysed product, on the assumptions considered for recycling process and applied technologies, as well as on the data used for the assessment.

Table 27: GWP impact associated to the End of Life of a smartphone

Process	**GWP (g $CO_{2,eq}$/ unit of product)**		**Comment**
	Proske et al. (2016)	**Adapted to this case study**	
Battery recycling	- 60	- 30	In Proske et al. (2016) this value refers to two batteries per

[190] Estimated by integrating information in Table 18 with data from Andrae (2016)

			product life cycle. Half of the impact is to be considered for an individual smartphone
Copper smelter	50	47	Considering a weight of 160 grams instead of 168 grams (and excluding the battery)
Precious metals recovery	- 1160	-1088	Considering a weight of 160 grams instead of 168 grams (and excluding the battery)
Transports	30	29	Considering a weight of 160 grams instead of 168 grams
Recovery from other materials	-	- 589	Considering the recovery of material and/or energy from the housing materials
Total	- 1140	- 1631	To be considered as a credit from the recycling process

5.3.4.5 System aspects

In addition to the consumption of electricity associated to the recharge of batteries, energy is consumed for running the communication infrastructures associated to the transfer and storage of data.

Ercan et al. (2016) estimates the electricity consumption associated to network usage for representative, light and heavy users, as reported in Table 28.

According to Andrae (2016), the electricity consumption would be 1.16 kWh per GB of data used (1 kWh due to extra wireless networks; 0.1 kWh due to Wi-Fi/fixed backhaul; 0.06 kWh due to data centres). Considering an average consumption of 4 GB per month (see Section 3), or 48 GB per year, the annual consumption would be 55.7 kWh/year, which is close to the heavy use scenario of Ercan et al. (2016). This estimation is considered representative for the current use of smartphones, also because of the apparent trend towards an increased consumption of data.

As described in section 4.7, energy efficiency increased for new network technologies (e.g. 4G vs. 3G) and this trend may not continue with 5G. However, even in case 5G leads to a disruptive reduction of power consumption, this could be counterbalanced by an increased traffic of data.

Table 28: Consumption of electricity associated to network usage (adapted from Ercan et al. 2016)

	Light user	Representative user	Heavy user
Mobile network + Wi-Fi data traffic per year	5.5 GB + 5.5 GB	11 GB + 11 GB	30 GB + 30 GB
Mobile network (kWh/year)	27	30	40
Wi-Fi Operation (kWh/year)	1.7	3.3	9
Total (kWh/year)	28.7	33.3	49

5.3.5 Life Cycle Cost modelling

5.3.5.1 Calculation of the life cycle costs for end-users

Life Cycle Costs for end-users, expressed in Euros, can be calculated according to equation below:

$$LCC = PP + \sum_{1}^{N} PWF * OE + MRC + EOL$$

Where:

- LCC: Life Cycle Costs for end-users;

- N: reference lifetime in years;
- PP: purchase price (including installation costs);
- OE: annual operating expenses for each year of use;
- MRC: maintenance and repair costs (when applicable);
- EOL: end-of-life costs/revenues for end-users, if any;
- PWF: present worth factor.

PWF can be calculated as:

$$\boldsymbol{PWF = 1 - \left(\frac{1+e}{1+d}\right) \times \left[1 - \left(\frac{1+e}{1+d}\right)^{Y}\right], with\ d \neq e}$$

Where

- e is the escalation rate (= aggregated annual growth rate of the operating expenses);
- d is the discount rate (= interest – inflation);
- Y is the considered lifetime in years.

Assuming that d and e are the same (e.g. 4%), that PWF is 1, and that end-users in Europe do not have separate costs for the disposal of smartphones (Boyano et al. 2017), the formula can be simplified as follows:

$$\boldsymbol{LCC = PP + \sum_{1}^{N} OE + MRC}$$

5.3.5.2 Purchase price and operative costs

From section 2.3.4, it is considered that the purchase price of an average smartphone in the EU is 320 EUR. The price could change to less than 130 EUR and more than 480 EUR for low and high-end products, respectively.

The operative costs considered for the product are:

- The consumption of electricity to recharge the battery of the smartphone: 0.2113 EUR per kWh[191];
- The mobile service contract: 31.8 EUR per month[192] (DG CONNECT 2018).

The value of the device can drop to 54% of the original price after 1 year, 32% of the original price after 2 years, 20% of the original price after 3 years (Culligan and Menzies 2013). Lifespan and residual value of smartphones can vary depending on manufacturers and models. In particular, high-end smartphones have a higher residual value (Makov 2018).

In case of purchase of a reused product it is considered that the product value drops to one third of the original value, and that a 40% margin is applied (149 EUR). The purchase price for remanufactured products is roughly estimated as the total costs for the professional replacement of battery and display (270 EUR).

[191] https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics (accessed on 6 august 2019)

[192] As average in the EU28 in 2017 for a service contract including 5 GB of data and 100 calls. The average cost would decrease to 14.11 EUR for 100 MB and 30 calls.

5.3.5.3 Cost considerations for more durable devices

Extended use scenarios could be pursued through designs aimed to increase the durability of devices. From a technical point of view, this could be achieved by implementing measures such as:

- IP67 or IP68 protection level (dust and waterproof): it is mainly associated to current high-end devices[193] or to the specific market segment of rugged smartphones. However also some devices not belonging to the high-end class are reported to be IP68[194]. IP67 protection levels (dust and waterproof) are claimed for more models on the market[195]. IP67 and 68 cannot be ensured in case of modular design[196]). Based on this information, no significant additional costs seem associated to the fulfilment of IP68 protection levels.

- Resistance to drops: drop tests results and compliance with related standards are usually reported for rugged smartphones[197]. However also some devices classified to have a medium price are claimed to have a high mechanical resistance[198]. Mechanical resistance can come with some trade-offs. For example, use of glass in the back cover and bezel-free smartphones are more fragile. Higher resistance could be ensured with different materials, smaller screen sizes and the use of bezels. Moreover, mechanical resistance can be improved through protective covers/bumpers. Some manufacturers provide certified model-specific bumpers[199]. Pre-installed protective layers are also provided for some models[200]. Based on this information, no significant additional costs seem associated to the fulfilment of a high mechanical resistance.

- Longer battery life: a manufacturer reports that their batteries are designed to retain up to 80% of its original capacity at 500 complete charge cycles[201] (equivalent to about 2 years). Since the cost of battery is relatively small compared to the total price of the products, no significant additional costs seem associated to the provision of long battery lives.

- Minimum guaranteed OS support period: this appears feasible, as claimed by a manufacturer[202], and without entailing significant additional costs.

Apart from an extension of the product lifetime, other positive effects could include:

- Direct saving in maintenance/ repair;
- Increased recovery of value (value retention) at the end of the first use.

On the other hand, a more durable design is normally associated to high-end products which present higher purchase prices, although this is also implemented in some products that are in the medium price range. To take this aspect into account, Life Cycle Costs of scenarios where products are used for longer time (without being repaired) are calculated considering the purchase price of both average and high-end devices.

5.3.5.4 Cost considerations for change and repair of parts

The following assumptions are made for the assessment of alternative scenarios:

- The average cost for replacing a battery is 20 EUR when done by the user[203] and 69 EUR when involving professional repairers[204];

[193] E.g. Galaxy S8 Plus, LG V30, LG G6, Sony Xperia XZ1, Sony Xperia XZ Premium and the Samsung Galaxy S7, iPhone XS and XS Max

[194] E.g. LG X venture, Samsung Galaxy A8, Xiaomi Pocophone F1claim - IP68 dust/water proof (up to 1.5m for 30 mins). LG X venture also claims to be compliant with MIL-STD 810G

[195] E.g. Huawei P20 Pro, Apple iPhone X , The Pixel 2 XL, Nokia 8 Sirocco, Sony Xperia XZ2 Compact, Motorola X4 4th Gen

[196] E.g. Fairphone, see: https://support.fairphone.com/hc/en-us/articles/115001535486-Is-the-Fairphone-2-dust-or-water-resistant- (accessed on 5 April 2019)

[197] https://www.toughgadget.com/best-rugged-smartphones-unlocked/ (accessed on 5 April 2019)

[198] e.g. LG X venture claims - IP68 dust/water proof (up to 1.5m for 30 mins) and MIL-STD 810G certified

[199] Samsung is providing protective covers certified to be compliant to drop tests according to the MIL-STD-810G-516.7(United States Military Standard Test - Shock), see: https://www.amazon.com/Samsung-Official-Protective-Standing-EF-RG965CBEGKR/dp/B07BNCLSVY (accessed on 5 April 2019)

[200] https://www.samsung.com/au/support/mobile-devices/galaxy-s10-in-box-items/ (accessed on 5 April 2019)

[201] https://www.apple.com/batteries/service-and-recycling/ (accessed on 5 April 2019)

[202] https://store.google.com/product/pixel_3_specs (accessed on 5 April 2019)

- The average cost for replacing the display is 87 EUR when done by the user[205] and 201 EUR when done by professional repairers[206].

Based on the assumptions made:

- Repair cost for the battery would correspond to 6-21% of the purchase price of an average smartphone and 4-14% of the purchase price of a high-end device.
- Repair cost for the display would correspond to 27-63% of the purchase price of an average smartphone and 18-42% of the purchase price of a high-end device.

Repair costs are comparable as order of magnitude with the illustrative indications reported in Section 2.3.4 (15-40% of the purchase price for the display and 5-10% of the purchase price for the battery). According to the information reported in Section 2.3.4 and Section 4.4.1 it can be considered also that the frequency of replacement of displays and batteries is 24% and 50%.

5.3.5.5 Additional cost considerations addressed qualitatively

Design for reparability

An extension in the product lifetime and a reduction in maintenance/ repair costs could be achieved also through designs focused to increase the reparability of smartphones (especially with respect to the replacement of batteries and screens). Such designs should cover at least: ease of disassembly of critical parts, availability of tools and spare parts, provision of repair information, as well as data erasure/transfer features and provision of software/firmware updates.

Reduction in repair costs could offset additional costs potentially associated to this design strategy. In case of modular designs (which are by definition easier to repair and upgrade) possible trade-offs with durability features could moreover occur (e.g. waterproofing).

Design for recycling

WEEE fees are considered integrated in the product purchase price. Design strategies targeting the recycling process could generate economic benefits from a life cycle perspective. Ease of dismantling of batteries, PCBs and screens could potentially increase their separate collection and recovery. Smartphones should be designed in a way that the access and removal of these components is possible with commercially available tools. Moreover, the sequence of dismantling operations should be provided to recyclers. In general, no additional costs seem associated to such measures.

Materials can also have an influence on price and feasibility/ profitability of the recycling process. However, an analysis of their impact is quite difficult due to the broad heterogeneity of material design options and market value fluctuations. This also apply to the use of recycled materials, which can present uncertainty with respect to their availability and value over time, as well as unwanted side effects (e.g. diverting materials from one sector to another).

Lean design

Lean design practices can reduce or control use of materials in smartphones and the associated life cycle impacts. Practical benefits could be obtained if lean design does not lead to an increased production of manufacturing waste and is not used to compensate increased display sizes.

---

[203] Based on: https://shop.fairphone.com/en/spare-parts (accessed on 11 June 2019)

[204] Based on: https://support.apple.com/es-es/iphone/repair/service/pricing (accessed on 11 June 2019)

[205] Based on: https://shop.fairphone.com/en/spare-parts (accessed on 11 June 2019)

[206] Based on: https://support.apple.com/es-es/iphone/repair/service/pricing (accessed on 11 June 2019) and https://phone-service-center.de/en/ (accessed on 6 August 2018)

As a special form of lean design, the inclusion of less accessories in the packaging could contribute to save materials and costs. For example, smartphones could be put on the market without an external power supply and when a standard power supply is provided, this comes with detachable cables.

5.3.6 Scenarios of assessment

Alternative scenarios have been defined for the assessment of material efficiency aspects. Scenarios are reported in Table 29. Each scenario addresses different material efficiency aspects and can be associated to specific design, technological and behavioural practices.

Table 29: Scenarios considered for the assessment of material efficiency aspects in the life cycle of smartphones

Scenario	Key LCA assumptions	Additional consideration for LCC
I. Baseline (BL)	Smartphone are replaced with a new device (the same model) every 2 years; new units are bought and allocated to cover the reference lifetime (4.5 years) (see 5.3.4) The old product is kept unused at home (see 5.3.4.4) Impact associated to data consumption during the use phase, and related communication infrastructures, is not considered (see 5.3.4.5) For the sensitivity analysis, the following scenarios are considered: a) BL1, where impact associated to data consumption during the use phase, and related communication infrastructures, is included (see 5.3.4.5) b) BL2, where recycling with pre-treatment for battery recovery is included (see 5.3.4.4)	Costs associated to the mobile contract service are included For the sensitivity analysis, the following scenarios are considered: a) BL-HE, where a high-end product is considered b) BL-LE, where a low-end product is considered (see 5.3.5.2)
II. Extended use (EXT)	As BL with replacement cycle increased to 3 (EXT1) and 4 years (EXT2)	EXT1: as BL with replacement cycle increased to 3 years EXT1-HE: as BL-HE with replacement cycle increased to 3 years EXT2: as BL with replacement cycle increased to 4 years EXT2-HE: as BL-HE with replacement cycle increased to 4 years (see 5.3.5.4)
III. Battery change (BC)	As EXT1/EXT2 with battery change (see 5.3.4): BC1: replacement cycle increased to 3 years with the change of the battery BC2: replacement cycle increased to 4 years with the change of the battery	BC1a: as EXT1 with change of the battery made by the user BC1b: as EXT1 with change of the battery made by a professional repairer BC2: as EXT2 with change of the battery made by the user (see 5.3.5.3)

Scenario	Key LCA assumptions	Additional consideration for LCC
IV. Display repair (DR)	As EXT1/EXT2 with display repair: DR1: replacement cycle increased to 3 years with the repair of the display DR2: replacement cycle increased to 4 years with the repair of the display	DR1a: as EXT1 with repair of the display by the user DR1b: as EXT1 with repair of the display by a professional repairer DR2: as EXT2 with repair of the display by the user (see 5.3.5.3)
V. Battery change + display repair (BC-DR1 / BC-DR2)	As EXT1/EXT2 with battery change and display repair: BC-DR1: replacement cycle increased to 3 years with the change of the battery and the repair of the display BC-DR2: replacement cycle increased to 4 years with the change of the battery and the repair of the display	Not assessed directly
VI. Remanufacture (RM)	Remanufactured smartphones bought by users every 2 years Impacts of the products are due to battery change + display change + energy for manufacturing and transport New units bought and allocated to cover the reference lifetime (4.5 years) The old product is kept unused at home	Purchase price of the product calculated as the cost of battery change + display repair (see 5.3.5.3)
VII. Re-use (RU)	Reused smartphones bought by users every 2 years Impacts of the products are due to battery change + display change + transport New units bought and allocated to cover the reference lifetime (4.5 years) The old product is kept unused at home	Purchase price of the product calculated as one third of the original price + a margin of 40% (see 5.3.5.2)
VIII. Light-weighting (LW)	As BL with the consideration of less materials for housing and display in the product design: LW1: -10% by weight of housing and display materials LW2: -20% by weight of housing and display materials LW3: -30% by weight of housing and display materials	Not assessed directly

5.4 Results and discussion

5.4.1 Carbon footprint

5.4.1.1 Baseline scenarios

Baseline

In the baseline scenario smartphones are replaced every 2 years in a reference period of 4.5 years. The old device is kept unused at home; impact related to data consumption and related communication infrastructures is not considered. The life cycle impact has been quantified to be 77.2 kg $CO_{2,eq}$. Table 30 shows the GWP calculated for each life cycle stages and their contributions to the overall life cycle impact.

Table 30: GWP results for the BL scenario

Indicator	BOM	Device assembly	Distribution	Use	EOL	Tot.
GWP (kg $CO_{2,eq}$)	48 (62%)	12 (16%)	8.7 (11%)	8.5 (11%)	- -	77.2 (100%)

76% of the life cycle impact comes from materials and manufacturing processes. 88% of the impacts from materials are due to five parts:

- 47% Printed Wiring Board;
- 15% display;
- 13% Integrated Circuit;
- 10% camera;
- 3% housing.

Other relevant parts include:

- 2% packaging;
- 2% accessories (charger, headset);
- 1% battery.

In terms of GWP impact of priority parts, the significant contribution of IC, PCB and display is confirmed by other studies (Andrae 2016, Ercan et al. 2016, Manhart et al. 2016, Proske et al. 2016), although absolute values vary because of different data and operational assumptions. Proske et al. 2016 also support the relevance of the camera unit. Results obtained for battery are comparable with Andrae (2016) although lower than indicated in Ercan et al. (2016) and Proske et al. (2016). As calculated by Proske et al. (2016), the relative contribution of different parts to life cycle impacts could be qualitatively similar for other impact categories (abiotic depletion potential, human toxicity and ecotoxicity).

The environmental impacts of the device and its parts are mainly due to both their manufacturing process and to the extraction and sourcing of materials (Moberg et al. 2014). With a narrow focus on GWP100, the impact associated to the extraction and sourcing of gold and other metals (e.g. palladium) and plastic materials might be relevant (less than 10%, mainly due to gold) for smartphones (Andrae 2016). Cobalt, copper, gold and silver are also important materials for impact categories relating to resource scarcity, eutrophication and human toxicity (Ercan et al. 2016).

5.4.1.2 System aspects

Comparing BL1 with BL2 (see Table 31) it can be appreciated that the impact due to data consumption and related communication infrastructures is considerably higher than the benefits achievable through recycling.

Table 31: GWP results for BL, BL1 and BL2 scenarios

Scenario	Total (kg $CO_{2,eq}$)
Baseline (BL)	77.2 (100%)
BL + data (BL1)	196.0 (254%)
BL + recycling (BL2)	73.6 (95%)

Where data consumption is considered in the modelling (BL1), the GWP100 is 2.5 times compared to the baseline scenario, due to the energy needed to run data network infrastructures. This calls for the significant and hidden contribution of data consumption and communication in determining the life cycle impacts of smartphones.

Impact from the use of data would be considerably increased (1.8 times BL) also for a user scenario in which data consumption was halved. However, the technological and behavioural trends described in this report (improved efficiency of data network v. larger data consumption) suggest that impact from data consumption in smartphones could increase in future or, at best, remain constant.

When considering the recycling of the smartphone at the EOL (BL2), the GWP100 is reduced by 5% compared to the baseline scenario, thanks to recovery of materials and generation of electricity from incineration of plastics. Such benefit could be qualitatively considered as a proxy for the saving potential achievable using recycled materials in the product (it has been estimated that the use of recycled materials for the housing would allow an overall reduction of the GWP by 2%).

It should be remarked that recycling has been modelled by considering information from the literature referring to state-of-art practices. More advanced technologies could allow a more efficient recovery of CRM and other precious materials: net $CO_{2,eq}$ credit could be ~30% higher (based on the estimation provided in section 5.3.4.4). This would mean that life cycle saving of $CO_{2,eq}$ at the EOL would increase from ~5% to ~6%. On the other hand, recycling could even result in net burdens if materials are not recovered efficiently.

Benefits of recycling would be better depicted through indicators relating to the scarcity of materials (e.g. Abiotic Depletion Potential). For example, according to Proske et al. (2016), recycling at the EOL could reduce impacts due to materials and manufacturing stage by 3% for GWP, by 6% for ecotoxicity, by 9% for abiotic depletion of fossil fuels, by 10% for human toxicity and by 59% for abiotic depletion of elements.

5.4.1.3 Quantitative results for different devices

Results from the life cycle assessment of smartphones can vary broadly (Manhart et al. 2016) depending on factors such as:

- design, size and weight of the product model,
- input data available and assumptions made in the life cycle modelling,
- reference time of use,
- intensity of use,
- inclusion of network infrastructures,
- end of life practices.

In terms of life cycle impacts, Proske et al. (2016) quantified the climate change impact for a specific smartphone model as about 44 kg $CO_{2,eq}$. (over a period of 3 years) Adapted to the time of use considered in the present study (4.5 years), this would equivalent to about 66 kg $CO_{2,eq}$. Andrae (2016) and Ercan et al. (2016) instead quantified impacts of about 39 kg $CO_{2,eq}$ and 57 kg $CO_{2,eq}$ for the respective case studies (when network infrastructures are not considered). These considered a time of use of 2 and 3 years, which would correspond to about 88 and 86 kg $CO_{2,eq}$ if 4.5 years are considered.

The order of magnitude of the results obtained in the baseline appears thus comparable with those presented in the literature. Results are also in line with the literature in highlighting the important contribution of materials and manufacturing processes to the carbon footprint of smartphones (Andrae 2016; Ercan 2013; Manhart 2016; Suckling and Lee 2015) and the significant indirect impacts relating to the data exchange was also highlighted (Andrae 2016; Ercan 2016).

Some OEMs provides information about key design characteristics of different models of smartphones and the carbon footprint associated to the extraction of materials and the manufacture of the device. Information from Apple[207] and Huawei[208] has been analysed and elaborated to interpret further the results of this study and understand if any possible trend can be observed on the market. Results are shown in Figure 36 and in
Figure 37.

The weight of smartphone models produced by Apple varies from 133 to 199 grams, with 170 grams as average. Models from Huawei weight from 142 to 232 grams with 163 grams as average. This provides support for the value considered in section 5.3.4.1.

A carbon footprint of about 27 kg $CO_{2,eq.}$ was calculated in this study for the manufacture of a unit of product (i.e. 60 kg $CO_{2,eq.}$ divided by 2.25 units used in 4.5 years). Carbon footprints reported by OEMs for the manufacturing of their products vary from 25 to 63 kg $CO_{2,eq.}$ for Apple and from 41 to 70 kg $CO_{2,eq.}$ for Huawei. However, it should be observed that:

- Results refer to smartphone models presenting different functional characteristics and produced in different years;
- Results cannot be directly compared due to different methodological assumptions, to variation of the data input, and to its refinement over time.

Although the direct comparison of results is not possible, it can be observed from Figure 36 and in

Figure 37 that:

1. Weight, display size and carbon footprint of devices seem to have increased over time for the analysed models (as well as their performance characteristics);
2. The carbon footprint referred to an unit of weight is scattered and does not seem to follow a clear growth trend;
3. No evident difference was found depending on the type of model;
4. The increase in display size and memory configuration could be important factors in determining variations of the carbon footprint.

[207] https://www.apple.com/environment/ (accessed on 31 January 2019)
[208] https://consumer.huawei.com/en/support/product-environmental-information/ (accessed on 31 January 2019)

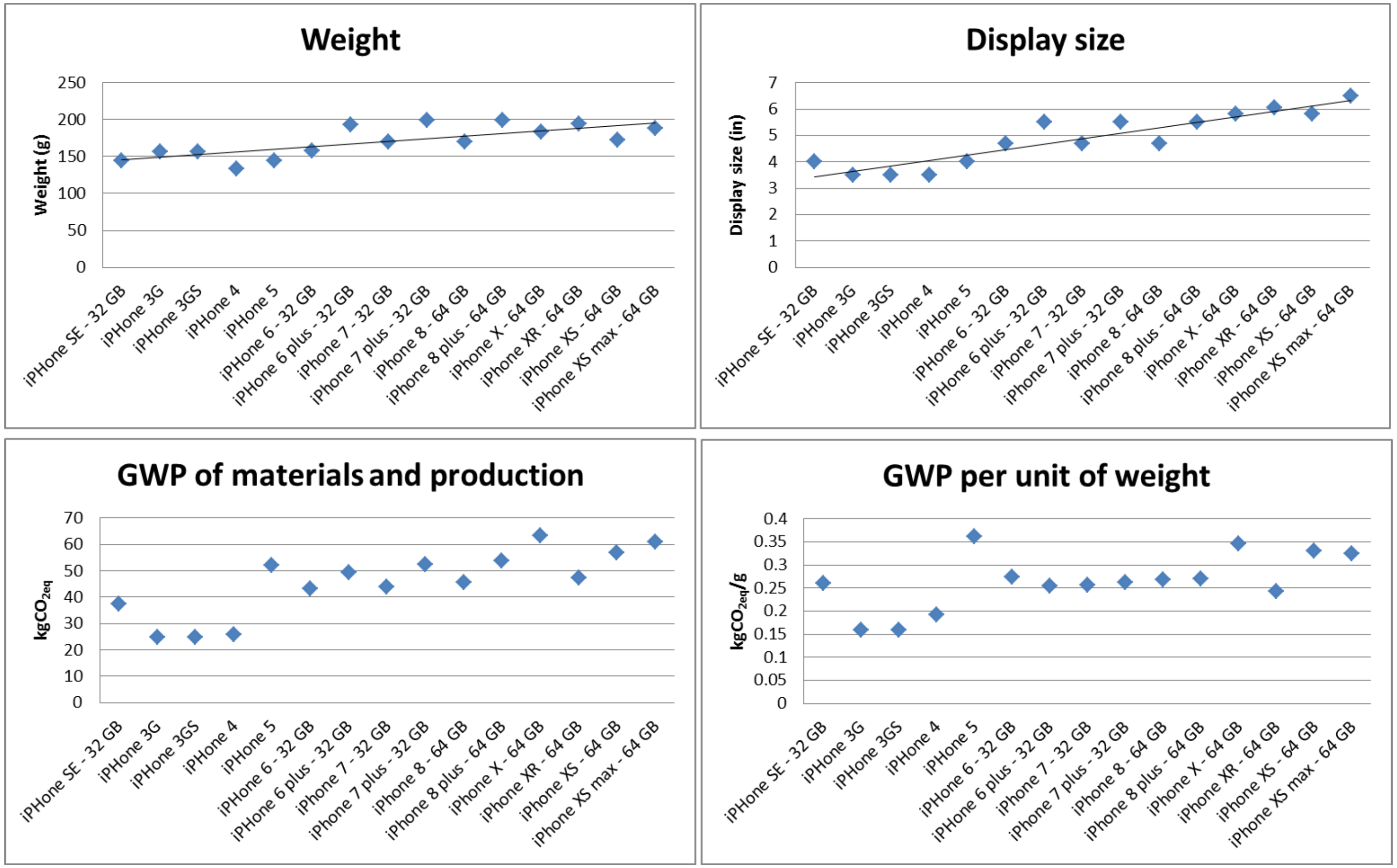


Figure 36: Variance of key parameters for different models of Apple's smartphones[209]

[209] Produced from https://www.apple.com/environment/ (accessed on 31 January 2019)

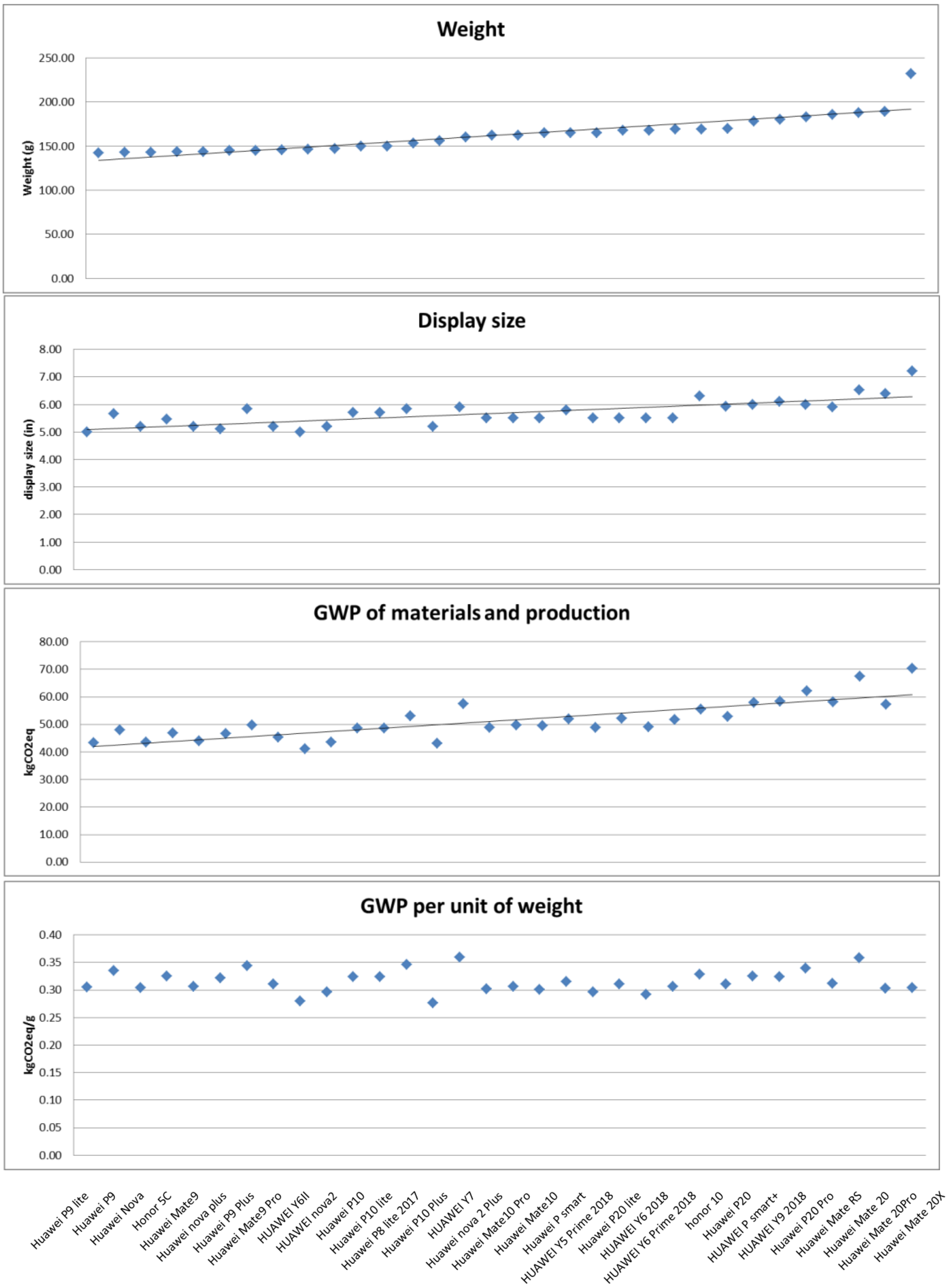


Figure 37: Variance of key parameters for different models of Huawei's smartphones[210]

[210] Produced from https://consumer.huawei.com/en/support/product-environmental-information/ (accessed on 31 January 2019)

5.4.1.4 Extended years of use (with/without repair)

In scenarios EXT1 and EXT2, replacement cycle of devices is extended to 3 and 4 years, respectively. The rest of the parameters are maintained as in BL. Such scenarios simulate the situation in which the device is still functioning and the user decides not to replace it.

A significant GWP reduction can be achieved by extending the average replacement cycle of devices from 2 years to 3 or 4 years (-29% and -44%, respectively). In this case, the reduction of impacts is associated to the lower amount of devices, and thus parts and materials, needed to cover the reference period of 4.5 years.

When the extension of the product comes with the change of the battery and/or the repair of the display, benefits are lower but still significant:

- When the replacement cycle of the product is 2 years, the total GWP impact is increased by 1% and 9%, compared to the BL, when the battery or the display are replaced, respectively. This is due to the need to manufacture additional parts that replace the faulty ones.
- When the change of battery is associated to a replacement cycle of 3 or 4 years, the total GWP impact is reduced by 29% and 44% compared to the BL, respectively. Basically, the change of battery would not cause significant increase in the climate change impact compared to the equivalent scenarios implying no change of battery.
- When the repair of the display is associated to a replacement cycle of 3 or 4 years, the total GWP impact is reduced by 23% and 40% compared to the BL, respectively.

GWP is reduced because the impacts associated to the manufacture of additional parts are compensated by the benefits of using product units longer.

Table 32: Life cycle GWP and percentage change for scenarios involving a longer replacement cycle

Replacement cycle (years)	BL (kg $CO_{2,eq}$)	EXT (kg $CO_{2,eq}$)	BC (kg $CO_{2,eq}$)	DR (kg $CO_{2,eq}$)	BC-DR (kg $CO_{2,eq}$)
2	77.2 (100%)	-	77.9 (101%)	84.5 (109%)	85.1 (110%)
3	-	54.4 (70%)	54.8 (71%)	59.2 (77%)	59.6 (77%)
4	-	42.9 (56%)	43.2 (56%)	46.5 (60%)	46.8 (61%)

Table 33: GWP of BOM and manufacturing process for scenarios involving a longer replacement cycle

Scenario	BOM (kg $CO_{2,eq}$)		Device assembly (kg $CO_{2,eq}$)	
Baseline (BL)	48	(100%)	12	(100%)
EXT1 (3 yr)	32	(67%)	8	(67%)
EXT2 (4 yr)	24	(50%)	6	(50%)
Battery (2 yr) (BC1)	48.6	(101%)	12	(100%)
Battery (3yr) (BC2)	32.4	(68%)	8	(67%)
Battery (4 yr) (BC3)	24.3	(51%)	6	(50%)
Display (2 yr) (DR1)	55.2	(115%)	12	(100%)
Display (3 yr) (DR2)	36.8	(77%)	8	(67%)
Display (4 yr) (DR3)	27.6	(58%)	6	(50%)
Battery + Display (2 yr) (BC-DR1)	55.8	(116%)	12	(100%)
Battery + Display (3 yr) (BC-DR2)	37.2	(78%)	8	(67%)
Battery + Display (4 yr) (BC-DR3)	27.9	(58%)	6	(50%)

5.4.1.5 Remanufacturing and reuse

In the remanufacturing scenario the user buys remanufactured smartphones, while in the case of reuse the user gets 2nd hand devices.

The remanufacturing scenario can reduce the GWP of smartphones to about half of the baseline; reduction is even higher for the reuse scenario, where it is about 80%. Environmental savings are essentially due to the avoidance of manufacturing new parts/devices; however, it is important to ensure that expectations of new users are met.

Table 34: Life cycle GWP for the remanufacturing and reuse scenarios

Scenario	Total ($kgCO_{2,eq}$)
Baseline (BL)	77.2 (100%)
Remanufacturing (RM)	37 (48%)
Reuse (RU)	16.3 (21%)

Table 35: GWP of BOM and manufacturing stage for the remanufacturing and reuse scenarios

Scenario	BOM ($kg\ CO_{2,eq}$)	Device assembly ($kg\ CO_{2,eq}$)
Baseline (BL)	48 (100%)	12 (100%)
Remanufacturing (RM)	7.8 (16%)	12 (100%)
Reuse (RU)	7.8 (16%)	0 (0%)

5.4.1.6 Material design change

Material design change was assessed in terms of light-weighting, where quantities of housing and display materials are decreased by 10%, 20% and 30%. It is estimated that the GWP could be reduced up to 7%.

However, it should be pointed out that:

1. Actual variation of impacts depends also on specific design choices in terms of material selection and supply, which can ultimately have an impact on the recycling process and the market;
2. Design choices can also affect the material efficiency of the manufacturing process (e.g. if a certain shaping of materials can produce more or less scraps);
3. In this simplified case, it was considered that the display size was kept constant. Light-weighting can otherwise counterbalance the increase of impacts due to larger displays.

Table 36: GWP results for light-weighting scenarios

Scenario	Total ($kg\ CO_{2,eq}$)
Baseline (BL)	77.2 (100%)
10% Lighter (LW1)	75.5 (98%)
20% Lighter (LW2)	73.7 (95%)
30% Lighter (LW3)	71.9 (93%)

5.4.2 Life Cycle Cost

The overall cost for consumers associated to the use of smartphones for 4.5 years can be 3.4 times the purchase price of product units in the baseline scenario (BL), with the larger contribution due to the use phase (70.5%), mainly because of the service contract.

Overall costs are 18% higher for the high-end product (purchase price: +50%) and 14% lower for the low-end product (purchase price: -40%). The variation is less than proportional to the purchase price change since the main contribution to the LCC is due to the use phase.

In case of longer replacement cycles of 3 or 4 years, LCC costs decrease by 10% and 15%, respectively. If the increased lifetime of the product is associated to high-end products, economic benefits for consumers could be more moderate or even offset by the higher purchase price.

In case the longer replacement cycles depend on the change of the battery, there could be still economic benefits for consumers from a life cycle point of view, although these would be lower when the change has to be made by a professional repairer. This indicates that costs relating to the service contract can be more significant than the repair costs associated to battery changes. In case the longer replacement cycles depend on the repair of the display, there could be less or no economic benefits for consumers from a life cycle point of view, due to higher repair costs.

A reduction of the LCC by 5% and 16% is finally calculated for scenarios involving the purchase of remanufactured or reused devices, respectively.

If lower costs for the contract service are considered (e.g. 14.11 EUR/month instead of 31.8 EUR/month), fluctuations over the baseline would be more significant due to the increased importance of the product-related costs.

All in all, results indicate that the analysed material efficiency strategies can be economically appealing for consumers. Additional benefits could be achieved if the product is sold at the end of life to the 2nd-hand market to recover its residual value[211].

Table 37: LCC results in case of higher costs for the service contract

Scenario	TOTAL (EUR 2019)	
Baseline (BL)	2441	(100%)
Baseline, high-end product (BL-HE)	2801	(114%)
Baseline, low-end product (BL-LE)	2014	(82%)
EXT1: as BL with replacement cycle increased to 3 years	2201	(90%)
EXT1-HE: as BL-HE with replacement cycle increased to 3 years	2441	(100%)
EXT2: as BL with replacement cycle increased to 4 years	2081	(85%)
EXT2-HE: as BL-HE with replacement cycle increased to 4 years	2261	(93%)
BC1a: as EXT1 with change of the battery made by the user	2231	(91%)
BC1b: as EXT1 with change of the battery made by a professional repairer	2305	(94%)
BC2: as EXT2 with change of the battery made by the user	2104	(86%)
DR1a: as EXT1 with repair of the display by the user	2332	(96%)
DR1b: as Ext1 with repair of the display by a professional repairer	2503	(103%)
DR2: as EXT2 with repair of the display by the user	2179	(89%)
RM: Purchase of remanufactured device	2329	(95%)
RU: Reuse (purchase of second-hand device)	2057	(84%)

[211] As reported in section 5.3.5.2, the value of the device can drop to 54% of the original price after 1 year, 32% of the original price after 2 years, 20% of the original price after 3 years. Lifespan and residual value of smartphones can vary depending on manufacturers and models.

Table 38: LCC results in case of lower costs for the service contract

Scenario	TOTAL (EUR 2019)	
Baseline (BL)	1486	(100%)
Baseline, high-end product (BL-HE)	1846	(124%)
Baseline, low-end product (BL-LE)	1058	(71%)
EXT1: as BL with replacement cycle increased to 3 years	1246	(84%)
EXT1-HE: as BL-HE with replacement cycle increased to 3 years	1486	(100%)
EXT2: as BL with replacement cycle increased to 4 years	1126	(76%)
EXT2-HE: as BL-HE with replacement cycle increased to 4 years	1306	(88%)
BC1a: as EXT1 with change of the battery made by the user	1276	(86%)
BC1b: as EXT1 with change of the battery made by a professional repairer	1349	(91%)
BC2: as EXT2 with change of the battery made by the user	1148	(77%)
DR1a: as EXT1 with repair of the display by the user	1376	(93%)
DR1b: as Ext1 with repair of the display by a professional repairer	1547	(104%)
DR2: as EXT2 with repair of the display by the user	1224	(82%)
RM: Purchase of remanufactured device	1373	(92%)
RU: Reuse (purchase of second-hand device)	1102	(74%)

5.4.3 Average EU scenario

Results reported above provide an answer to "what if" questions referring to specific scenarios of use and disposal. Frequencies of repair and end-of-life disposal routes can be used to build an average EU scenario.

The following end-of-life routes are considered (based on Section 5.3.4.4):

- 49% of smartphones are kept unused at home, once they reach their end of life;
- 36% of smartphones find a 2nd user, either as donation or through the 2nd hand market;
- 15% of smartphones are collected and recycled/remanufactured (same share of recycling and remanufacturing process).

Based on the modelling assumptions made, this would correspond to a change of batteries and displays in 43.5% of devices. As a result,

- the average GWP would be 52 kg of $CO_{2,eq}$ over a period of 4.5 years, 33% less than in the BL;
- the average LCC would be EUR 2294 over a period of 4.5 years, 6% less than in the BL.

These results support the importance of promoting remanufacturing, reuse, repair and recycle of smartphones.

Significant improvements could be achieved also by extending the years of use of the product. If the extension of the product lifetime comes with a likelihood of replacing battery and displays of 50% and 24% (see Section 5.3.5.3), the average GWP over a period of 4.5 years would be

- 56 kg of $CO_{2,eq}$ (-28%), in case products are used for 3 years instead than 2 years;
- 44 kg of $CO_{2,eq}$ (-43%), in case products are used for 4 years instead than 2 years.

The LCC over 4.5 years would instead be:

- EUR 2247 (-8%), in case products are used for 3 years instead than 2 years and repaired by users;

- EUR 2325 (-5%), in case products are used for 3 years instead than 2 years and repaired by professional repairers.

Results indicate that increasing the durability of the product is a priority intervention for mitigating the impacts due to smartphones, and that repair could be convenient from a life cycle perspective also when requiring the intervention of by professional services.

5.4.4 Conclusions

Based on the results of this LCA application, the strategies considered for improving the material efficiency of smartphones can have a positive impact on climate change and life cycle costs for consumers.

In particular, the most promising options appeared those allowing a lifetime extension of the entire device or some of its parts. As described in section 4.3, a lifetime extension can be pursued through different technical measures:

- First of all, this requires the use of reliable and durable parts (e.g. electronics, battery), sufficient capacity (memory) for running the Operating System and the availability of software and firmware updates (i.e. Operating System and/or security updates);
- Secondly, considering the main causes of failure for smartphones, it can be important to ensure their resistance to accidental drops as well as the protection of devices from water and dust;
- Thirdly, 2nd hand market and repair of products can be eased by facilitating the disassembly of parts and the access to quality-compliant spare parts, and by integrating data transfer and deletion and password reset and factory-setting restoration functions.

The improvement in lifetime achieved by these technical measures could be partially offset by rebound mechanisms consisting of a reduced care from consumers, more confident of the stress resistance of their devices. The effective extension of the lifetime of smartphones and its parts relies also on actions addressing user behaviour, such as:

- Informing and educating consumers about the correct use and maintenance of smartphones, including instructions and tips to preserve the battery life and the possibility to increase the resistance of smartphones with protective accessories;
- Promoting the collection of unused devices for the recovery of their residual value through refurbishment / remanufacturing processes and 2nd hand markets;
- Communicating the advantages of repairing broken devices and of purchasing remanufactured or 2nd-hand devices.

However, Makov et al. (2018) estimate that at least one third of the emission savings resulting from smartphone reuse could be lost because of an increase of the overall consumption of devices at global level.

Product design strategies oriented to facilitate the recycle of materials can be considered as complementary to the previous ones, and considered in relation to the technologies applied in a certain context as well as the volume of WEEE collected. With the current common practice in Europe, it seems possible to recycle only a small fraction of devices and materials. A change of consumer's habits, in particular regarding the reluctance to dispose of old EEE as WEEE, is necessary as well as further innovations to facilitate the recovery of materials that are not recovered with the current recycling practices.

Moreover, although the focus was on material efficiency aspects, it is interesting to observe that

- In terms of climate change impact, energy efficiency of smartphones appears to play a secondary role (the contribution of the use phase to the life cycle impact was about 10%, without considering data consumption and related communication infrastructures). On the other hand, from a system perspective network infrastructures and data centres can cause a massive impact (the life cycle impact increased by

150% when impact from data consumption was included). This calls for the importance of addressing energy and material efficiency of communication infrastructures, as well as informing users about the hidden impacts of data consumption.

- In terms of costs, the greatest contribution is due to the service contract, which can make the cost of recharging the battery of the device marginal and the repair of the device more attractive. Service contracts can also have an influence on the environmental impacts of smartphones since they can affect the amount of data that users exchange and the how frequently devices are replaced.

Finally, it should be noted that results refer and apply to smartphones in the general context of this analysis. Further analyses would be required before extending results to other products.

6 DEFINITION OF POSSIBLE DESIGN MEASURES FOR IMPROVING MATERIAL EFFICIENCY

As final step of the guidance, all the qualitative and quantitative evidence gathered is used to define possible measures that could improve the material efficiency of the analysed product.

An illustrative list of possible measures to improve the material efficiency of smartphones is reported in Table 39. The following aspects are considered for each measure:

- Relevance of the issue addressed;
- Techno-economic feasibility;
- Assessment and verification methods.

It should be remarked that the list does not constitute a regulatory proposal but rather provides examples of improvement options that could be considered in practical applications targeting smartphones (e.g. design optimisation by manufacturers, product testing by consumer organisations, regulatory interventions to push or pull the market).

Depending on the goal and scope of the considered application, options may need further discussion and refined in terms of requirements and desired level of ambition (to discriminate between worse and better products). In particular, in the potential case of policy implementation, the discussion should take place in a formal process involving a broader pool of stakeholders and aimed at better understanding market implications and side effects of each option.

In general, manufacturers usually prioritise alternative strategies in the design of their devices, e.g. increased reparability vs. reliability and resistance. Because of the trade-offs described in Section 4.5, it could be difficult to find a one-size-fits-for-all option. A possible solution could be to integrate considerations for reliability/resistance, reparability and recyclability in all smartphones on the market. The level of ambition of such considerations can vary depending on the strategy that a manufacturer decides to prioritise. This concept could be translated in requirements as shown in the following examples:

- Minimum longevity for batteries is 500 (or 1000) cycles or 300 (or 500) cycle at 80% of their initial performance depending if the battery is integrated or replaceable by users without specific tools;
- Priority parts are removable by the user without specific tools, unless an IP level 68 is ensured and professional repair services are available.

Table 39: Possible strategies and measures to improve the material efficiency of smartphones

Strategy	Measure	Relevance	Feasibility	Indications for assessment and verification
Use of materials	<u>1) Reducing the amount of materials used</u> a. Provision of smartphones without External Power Supplies (EPS) and other accessories Measure (a) to be complemented by the following measured: b. Fulfilment of IEC 63002:2016 - Identification and Communication Interoperability Method for External Power Supplies Used with Portable Computing Devices c. Provision of information on the compatible technical specifications (voltage, power output and connector type) for the EPS d. Compliance with the USB Type-C™ receptacle is defined according to the standard IEC 62680-1-3:2018 - Universal serial bus interfaces for data and power - Part 1-3: Common components - USB Type-C™ Cable and Connector Specification and USB 3.1 (transfer speed functionality).	Many users have chargers/cables at home which could be compatible and reused[212] Impacts can be quantified via LCA/LCC. As described in section 5.4, climate change impact of charger and accessories is about 2% of the full life cycle impact of the product (~1.5 kg $CO_{2,eq}$), which is in line with estimations provided by stakeholders	Technically feasible and already applied on the market. It is possible to ensure compatibility and interoperability of EPS for devices up to 100 W.	Visual check of the product as packaged Documental review of the claimed specifications in the instruction manual provided with the product (voltage, power output and connector type) Compliance with standards
	<u>2) Due diligence for the supply of CRM and conflict minerals</u> Note: a. at least for cobalt and 3TG (tantalum, tin, tungsten and gold) b. possible consideration of other materials reported in Table 18 such as indium, gallium, neodymium and praseodymium	Social impacts can be associated to the extraction of materials (apart from additional environmental considerations). A due diligence measure would avoid/mitigate social impacts associated to the sourcing of materials	Some manufacturers are currently committed in supply chain transparency and/or due-diligence on conflict minerals (See section 4.2.2). From January 2021 a due diligence of conflict minerals will be mandatory for importers of minerals or metals	The OECD "Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas" is the main reference for the implementation of a due diligence system

[212] https://support.fairphone.com/hc/en-us/articles/201065667-Why-don-t-you-offer-a-charger-with-Fairphone-2- (accessed on 10 April 2019)

Strategy	Measure	Relevance	Feasibility	Indications for assessment and verification
	3) Restrictions on substances of concern The use of following substances should be restricted: BFRs, beryllium, PVC, antimony, phthalates, arsenic, and cadmium by the implementation of a substance control system.	Stimulation of safer designs and processes.	Several manufacturers in the ICT sector have implemented Substance Control systems restricting the use of the mentioned chemicals	IEC TR 62476:2010 - Guidance for evaluation of product with respect to substance-use restrictions in electrical and electronic products. Other examples of substance control systems for smartphones are provided by TCO Certified Generation 8 and by the UL 110 Standard.
Increase of durability	1) Resistance to accidental drops a. Compliance with specifications of standard drop tests b. if (a) is not passed, provision (at the point of sale) of screen protectors and protective cases that enable the same/higher level of protection Note: alternatively to (b), provision of information (at the point of sale) about the availability of screen protectors and protective cases that enable the same/higher level of protection	Increasing the durability of products can be beneficial from both an environmental and economic point of view[213]. Accidental drops are one of the main reasons of product failure	There are models of smartphones that are compliant with standard drop tests Moreover, it has been demonstrated that protective accessories are effective in preventing the breakage of products due to accidental drops.	a. For example - MIL-STD-810G (freefall from 750 mm), or - IEC 60068 Part 2-31: Tests – Test Ec: Rough handling shocks, primarily for equipment-type specimens (Freefall, procedure 1 - Free fall) b. Visual check of the product as packaged and of the instruction manual provided with the product
	2) Protection from water and dust Compliance with the IP67 and/or IP68 levels of protection	Increasing the durability of products can be beneficial from both an environmental and economic point of view (see Section 5.4) Accidental ingress of water and dust is a relevant reason of product failure	There are models of smartphones on the market that are compliant with IP67 and/or IP68 levels. Possible trade-offs with reparability have to be considered, as discussed in section 4.5.	IEC 60529 – Degrees of protection provided by enclosures (IP Code)

[213] As described in Section 5.4 a significant GWP reduction could be reached extending the average replacement cycle of devices from 2 years to 3 or 4 years (up to -29% and -44%, respectively).

Strategy	Measure	Relevance	Feasibility	Indications for assessment and verification
	<u>3) Battery endurance in cycles</u> a. Minimum number of cycles with the battery properly functioning (e.g. 500-1000 cycles at 80% of initial performance for integrated batteries, or 300-500 cycles if the battery is easy to replace by users) b. Software for the battery management is pre-installed to - enable a limit on the battery state of charge (SoC) when the smartphone is connected to the grid (e.g. overnight charge). - enable keeping the state of charge in the 20%-80% boundary - measure the charging cycles of the battery c. Information for the correct use of the battery is provided, including conditions to extend the lifespan of the battery by avoiding extreme ambient temperatures and keeping the state of charge higher than 20% / lower than 80%	Increasing the durability of products can be beneficial from both an environmental and economic point of view (see Section 5.4) Battery aging is a common problem in smartphones	Already feasible for products on the market	a. Battery life testing according to IEC EN 61960 (including the part on thermal stresses). Note: Alternatively, IEEE 1680.1-2018 could be considered b/c. Provision of information from manufacturers and visual check of the instruction manual provided with the product
	<u>4) Operating System, software and firmware</u> a. Availability of update support (e.g. 3-5 years after the placement of the last unit of the model on the market), including information on impact of updates and reversibility of updates b. The possible use of open source OS or open source Virtual Machine software is allowed c. The capacity of the device allows the installation of next OS versions and future functionalities (e.g. 4 GB for the RAM and 64 GB for the HDD could be considered reasonable for current models on the market)	Increasing the durability of products can be beneficial from both an environmental and economic point of view (see Section 5.4) Software issues in terms of performance and safety can be a limiting state even for products with a still functioning hardware	Availability of updates is technically feasible for products on the market	Provision of information from manufacturers

Strategy	Measure	Relevance	Feasibility	Indications for assessment and verification
	5) Guarantee a. Inclusion of failures due to accidental drops and contact with water in the legal guarantee b. Extended guarantee Note: the guarantee could also include "commitment to free repair as first remedy" in case of failures and a "commitment to upgrade the product periodically	Increasing the durability of products can be beneficial from both an environmental and economic point of view (see Section 5.4) The inclusion of common failures in legal guarantees and/or the provision of extended guarantees could stimulate the design of more durable devices. However, higher costs for consumers and rebound effects could be expected and should be further investigated.	Already feasible for some products/countries	Declaration from manufacturers and legal check of the guarantee conditions
Increase of reparability and reusability	1) Disassemblability a. Batteries, screens and back covers to be removable in less than a defined number of steps. Different levels of ambition are possible (e.g. 2-28 steps for batteries, 15-30 steps for screens, 1-14 steps for back cover, based on the information reported in Section 4.3.3.1). b. Non-removable and non-reusable fasteners are avoided for the assembling of batteries, screens and back cover. Note: an exemption from the avoidance of non-reusable fasteners could be given for more durable designs. c. Batteries, screens and back cover to be easily accessible and replaceable using commonly available tools (see Section 4.3.3.3). Note: commonly available product-specific tools could be also used for devices that are more durable.	Increasing the durability of products can be beneficial from both an environmental and economic point of view (see Section 5.4) Priority parts should be easy-to-disassemble in order to facilitate the repair process (and reduce the related costs) Preliminary list of priority parts (see Section 4.3.3): - Screen (display assembly); - Back cover; - Battery; - OS.	There is a broad heterogeneity in product designs with some devices being more reparable than others	Availability and check of the following information (to be reported in an instruction manual): - Exploded diagram of the device - Illustration of how parts can be accessed, replaced and reassembled - Indication of tools required and associated difficulty (e.g. disassembly steps/time needed – depending on the approach followed)

Strategy	Measure	Relevance	Feasibility	Indications for assessment and verification
	As an alternative to a, b and c: d. Batteries, screens and back covers to removable in less than an estimated amount of time. Different levels of ambition are possible (e.g. 1-30 minutes for batteries, 20-40 minutes for screens, 1-53 minutes for the cover, based on the information reported in Section 4.3.3.4)			
	2) Provision of information Repair and maintenance information to be provided to final users and professional/independent repairers for at least 3-5 years after the placement of the last unit of the model on the market. Information for different target groups can differ as described in Section 4.4.3.5.	Increasing the durability of products can be beneficial from both an environmental and economic point of view (see Section 5.4) The provision of information is necessary to enable the repair of the product in case of failure, especially with respect to priority parts	Not all information could be shared with all target groups, because of safety, confidentiality and liability issues For example, thinner products present highly integrated electronics which may require prior technical training for their repair	Provision and check of repair and maintenance information
	3) Availability of spare parts a. Priority parts are available as spare parts for at least 3-5 years after placing the last unit of the model on the market. These can also include compatible and approved-by-manufacturer spare parts produced by third parties. b. List of parts and prices are available on-line and delivered within 2 (to 15) working days after having received the order. c. Standardised interfaces are used for connectors and EPS (see Section 4.3.3.6)	Increasing the durability of products can be beneficial from both an environmental and economic point of view (see Section 5.4) a/b. The availability of spare parts is essential for the repair/upgrade of devices c. Replacement of standardised interfaces could facilitate the replacement of parts (and reduce costs)	The time of delivery could be a barrier for repair: users need the product repaired in short time	Declaration by manufacturers and check of actual availability over time

Strategy	Measure	Relevance	Feasibility	Indications for assessment and verification
	4) Data transfer and deletion Data deletion and data transfer from an old to a new product are possible via installed or downloadable tools (such as applications, cloud-based services) or instructions detailed in a user manual	These functions are important for data protection and privacy of users, and can facilitate the transfer/deletion of data in case of reuse, repair, refurbishment or remanufacturing of devices. The reuse of products can be beneficial from both an environmental and economic point of view (see Section 5.4)	No specific barrier identified	Declaration by manufacturers and check of actual availability
	5) Password reset and restoration of factory tools Password reset and restoration are possible via installed or downloadable tools (such as applications, cloud-based services) or instructions detailed in a user manual	These functions are important for data protection and privacy of users, and can facilitate the transfer/deletion of data in case of repair/reuse The reuse of products can be beneficial from both an environmental and economic point of view (see Section 5.4)	No specific barrier identified	Declaration by manufacturers and check of actual availability
Improving the recycling of smartphones/parts/materials	1) Collection of products a. Take-back programmes are implemented for the collection smartphones b. Information is provided to consumers about the importance of giving back unused devices for recycling purposes	Collection of old/broken devices is essential for exploiting the environmental and economic benefits of reuse, remanufacturing and recycling of smartphones and their parts	No barrier identified apart from being able to effectively stimulate a user behaviour change	Check of provided information and effectiveness of the take back programme
	2) Ease of disassembly and identification of parts: a. Smartphones are designed in a way that identification, access and removal of the following parts is possible: - Parts that could be reused (e.g. display) - Parts of concern according to Annex VII of WEEE (batteries and PCBs)	The removal of certain parts at the EOL is necessary for the safe disposal of the device and an efficient recycling and recovery of materials	Potentially feasible but its practical effectiveness depends on the recycling technologies applied in a certain context as well as the volume of WEEE collected	Provision of information needed to identify and disassemble/dismantle parts, including the type and the number of fasteners to be unlocked and the tools/techniques to be applied

Strategy	Measure	Relevance	Feasibility	Indications for assessment and verification
	- Parts containing precious/critical raw materials			
	<u>3) Provision of additional information for recyclers</u> a. Content in the product of CRM and minerals from conflict-affected and high-risk areas b. Content of recyclable materials c. Marking of parts containing halogenated substances or hazardous substances/SVHC d. Marking of plastic parts > 5g in accordance to ISO 11469	The recovery of CRM, minerals from conflict-affected and high-risk areas as well as recyclable materials should be facilitated because of their socio-economic and environmental impacts Halogenated flame retardants can hinder the recycling of plastics Marking of plastics could improve their separation and recycling efficiency	No specific barriers are in general identified for the provision of information. For the marking of plastic parts, some exemptions can be considered based on: shape or size of the part; impact on the performance or functionality; moulding method applied. The following plastic parts could be exempted: (i) Packaging, tape, labels and stretch wraps; (ii) Wiring, cables and connectors, rubber parts and anywhere not enough appropriate surface area is available for the marking to be of a legible size; (iii) PCB assemblies, PMMA boards, optical components, electrostatic discharge components, electromagnetic interference components, speakers; (iv) Transparent parts where the marking would obstruct the function of the part in question.	a. EN 45558:2019 – General method to declare the use of critical raw materials in energy-related products b. EN 45555:2019 - General methods for assessing the recyclability and recoverability of energy-related products c. ISO 1043-4:1998 - Plastics - Symbols and abbreviated terms - Part 4: Flame retardants d. ISO 11469:2016 - Plastics - Generic identification and marking of plastics products

Note: As described in the table above, some of the measures are related to the provision of information along the life cycle of the product. In particular, the provision of information about the correct use and maintenance of the device is expected to influence positively users by possibly correcting behavioural patterns that can cause early failures and/or replacement of devices.

7 CONCLUSIONS

A guidance for the analysis of material efficiency aspects of products is presented in this report. This is oriented to the definition of tangible design measures that could potentially improve the material efficiency of products and promote a transition towards a more circular economy.

The guidance comprises the analysis of technical, economic and environmental aspects of material efficiency for a product. The aspects covered include consumption of materials, durability, reparability, upgradability, and recyclability. LCA/LCC considerations are then integrated to understand the relevance of possible measures on material efficiency.

Main findings related to the application of the guidance to smartphones are provided below.

Different organisations have been working worldwide for the development of standards and labels on smartphones (Section 1) that can be used as a starting point for improving the material efficiency and the sustainability of the product

The market sales of new smartphones globally appear to have slowed down in recent years, while the 2nd-hand market has slightly increased in size (Section 2). Two main business strategies of manufacturers and service providers can be outlined: i) focusing on the upgrade of models and the integration of new technological features; and ii) contributing to the development of circular business models that can allow retaining the product's value (e.g. via more durable/reparable designs).

Smartphones are on average replaced by users every two years (Section 3). In more than half of the cases, the replacement was found to be due to the user wanting a new model/software (in absence of failures). Results may differ from one country to another. The technical lifetime of smartphones could be reasonably extended.

From a technological point of view, functionality of smartphones has been increasing over time, with consequent increase of power demand, storage capacity and materials needed (Sections 4.1 and 2).

Smartphones are made of a variety of materials, some of them used in very small quantities but of global concern because of their social, economic and geopolitical impacts (CRM and minerals from conflict-affected and high-risk areas). At the end of life, smartphones are typically left unused at home (one out of two). This diverts resources from processes aimed at the reuse, recycling and recovery of materials (Sections 4.2 and 4.4.).

Limiting states of smartphones are often associated to a failure of screens and batteries and, for more recent device models, back cover. The upgradability of Operating System, firmware and software are also important aspects to ensure the longevity of smartphones (Section 4.3). Design strategies followed by manufacturers to extend the lifetime of smartphones focus on reliability and resistance of the device and/or on their reparability/upgradability.

A broad variety of products is available on the market that presents different functionalities, characteristics and impacts. Life Cycle Thinking can be used to better understand trade-offs and investigate if any material efficiency strategy can be prioritised over the others (Section 5). In the case of smartphones, it was found that remanufacturing and reuse should come first, followed by extending the years of use of the device, especially in absence of repair interventions. The impact of replacing a battery appears in particular low if compared to the benefits achievable with an extension of the product lifetime. It should also be observed that benefits from the use of second-hand devices could be partially offset by an increase of the global purchase of smartphones. Recycling can be then considered as an important complementary strategy, especially whenever the lifetime of the smartphone cannot be further extended, in order to recover precious metals and critical materials.

Significant impacts from the life cycle of smartphones are associated to data consumption and related communication infrastructures, which constitute an "invisible" source of impact of which to make consumers, operators and policy makers more aware. On the other hand, energy consumption due to the recharge of the battery seems to play only a secondary role. Moreover, service contracts appear the most important cost for consumers along the life cycle of the product (Section 5).

A series of possible measures to improve the material efficiency of smartphones has been presented based on the information gathered (Section 6). These cover both technical and behavioural aspects of smartphones since also consumers can play a dramatic role in determining the life cycle impact of their devices.

Results of the study could be used for the integration of material efficiency aspects in decision-making processes targeting the design, manufacture and purchase of smartphones.

It should be remarked that results are general in nature, so that do not take into account the characteristics of specific models on the market, and should not be extended directly to other product categories. However, these can serve as an information basis for broader discussion about the possible regulation and standardisation of ICT products.

The guidance could be moreover adapted to the specificities of any product on the market, and integrated in ecodesign and eco-labelling studies aimed at identifying measures to improve the sustainability of product groups. In this respect, the guidance is considered compatible with the MEErP. The integration in MEErP of the following aspects described in this study is recommended to handle material efficiency aspects in Ecodesign:

- Circular business models and costs associated to repair/reuse (Section 2);
- User behaviour, with special regard to determine distributions of technical and functional lifetimes (Section 3);
- Design and innovation cycles (Section 4.1);
- Durability/reparability analysis (Section 4.2), based on frequency and time of occurrence of limiting states and identifying measures to overcome such limiting states based on standards and available assessment and verification methods;
- Use of materials and chemicals in alternative product design and influence on recycling practices (Sections 4.2 and 4.4);
- Trade-offs and impact assessment of alternative scenarios via Life Cycle Assessment and Life Cycle Costing (Section 5), preferably following standardised methodology and datasets such as Product Environmental Footprint methods.

The study also highlights that the discussion on material efficiency is complex and can be limited by lack of quantitative information and data. As remedy to such limitation, the study has been conducted through a structured consultation process involving stakeholders with different backgrounds and interests (e.g. representatives of manufacturers, repairers, recyclers, NGOs and testing organisations, Member States and scientific institutions). From the one hand, this has allowed access to best available information from alternative sources; from the other hand, this has allowed a quality check of the information reported. As a general rule it is thus remarked the importance of engaging with a comprehensive and heterogeneous pool of stakeholders, as well as to interpret, analyse critically and report transparently the information processed and any result proceeding from modelling activities.

8 ACKNOWLEDGEMENTS

The authors are grateful to the European Commission for financing this work through the Administrative Agreement N. 070201/2015/SI2.719458/ENV.A.1 signed by DG ENV and DG JRC.

The authors would like to thank the experts involved in the development of this study for the valuable input provided. Experts represented Member States, industry, repair and recycling sectors, NGOs, consumer testing organisations and the scientific community.

The authors are also grateful to Mr. Alejandro Villanueva (DG JRC) and colleagues from DG ENV, DG ENER and DG GROW for reviewing this document, as well as to Mr. Rick Nowfer and Ms. Carmen Ramirez (DG JRC) for the editorial support provided.

9 REFERENCES

Akcil A, Ceren Erust C, Sekhar Gahan C, Ozgun M, Sahin M, Tuncuk A (2015) Precious metal recovery from waste printed circuit boards using cyanide and non-cyanide lixiviants – A review. Waste Management 45, 258–271

Agrawal J, Patel R, Mor P, Dubey P, Keller JM (2015) Evolution of Mobile Communication Network: from 1G to 4G. Int. J. of Multidisciplinary and Current Research, Vol.3 (Nov/Dec 2015). ISSN: 2321-3124, http://ijmcr.com (accessed on 19 October 2018)

Alfieri F, Cordella M, Sanfelix J, Dodd N (2018a) An Approach to the Assessment of Durability of Energy-related Products. Proc CIRP, 69: 878-891, https://doi.org/10.1016/j.procir.2017.11.082

Alfieri F, Cordella M, Stamminger R, Bues A (2018b) Durability assessment of products: analysis and testing of washing machines, EUR 29487 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-98136-4, doi:10.2760/115684, JRC114329

Allwood JM, Ashbya MF, Gutowski TG, Worrell E (2011) Material efficiency: A white paper. Resour Conserv Recy 55: 362–381, doi:10.1016/j.resconrec.2010.11.002

Andrae A. (2016) Life-Cycle Assessment of Consumer Electronics - A review of methodological approaches. IEEE Consumer Electronic Magazine, Volume: 5, Issue 1, 51-60. DOI: 10.1109/MCE.2015.2484639

Apple (2018a) Environmental Responsibility Report 2018 Progress Report, Covering Fiscal Year 2017, https://www.apple.com/lae/environment/pdf/Apple_Environmental_Responsibility_Report_2018.pdf (accessed 5 March 2019)

Apple (2018b) Apple Regulated Substances Specification 069-0135-K, https://www.apple.com/supplier-responsibility/pdf/Apple_Regulated_Substances_Specification_Sept2018.pdf (accessed on 5 March 2019)

Ardente F, Mathieux F (2014) Identification and assessment of product's measures to improve resource efficiency: the case study of an energy using Product. Journal of Cleaner Production, 83: 126-141, https://doi.org/10.1016/j.jclepro.2014.07.058

Arthur C (2012) The history of smartphones: timeline, https://www.theguardian.com/technology/2012/jan/24/smartphones-timeline) (accessed on 4 April 2019)

Askham C, Hanssen OJ, Gade AL, Nereng G, Aaser CP, Christensen P (2012) Strategy tool trial for office furniture. Int. J. Life Cycle Assess. 17, 666–677, http://dx.doi.org/10.1007/s11367-012-0406-y

Bakker C, Wang F, Huisman J, den Hollander M (2014) Products that go round: exploring product life extension through design. Journal of Cleaner Production 69, 10-16, doi:https://doi.org/10.1016/j.jclepro.2014.01.028

Basel Action Network (2019) Holes in the Circular Economy: WEEE Leakage from Europe, http://wiki.ban.org/images/f/f4/Holes_in_the_Circular_Economy-_WEEE_Leakage_from_Europe.pdf (accessed on 3 April 2019)

Belkhir L, Elmeligi A (2018) Assessing ICT global emissions footprint: Trends to 2040 & recommendations. Journal of Cleaner Production Volume 177, 448-463 doi.org/10.1016/j.jclepro.2017.12.239

Benton D, Coats E, Hazell J (2015) A circular economy for smart devices: Opportunities in the US, UK and India, Green Alliance, https://www.green-alliance.org.uk/a_circular_economy_for_smart_devices.php (accessed on 27 February 2019)

Bertoldi P, Hirl B, Labanca N (2012) Energy Efficiency Status report 2012. Electricity Consumption and Efficiency Trends in the EU -27. Joint Research Centre - Institute for Energy and Transport, https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/energy-efficiency-status-report-2012-electricity-consumption-and-efficiency-trends-eu-27 (accessed on 19 April 2018)

Boyano Larriba, A., Cordella, M., Espinosa Martinez, M., Villanueva Krzyzaniak, A., Graulich, K., Rüdinauer, I., Alborzi, F., Hook, I. and Stamminger, R. (2017) Ecodesign and Energy Label for household washing machines and washer dryers, EUR 28809 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-74183-8, doi:10.2760/029939, JRC109033

Bullitt (2017) Rapid Growth in Rugged Phones, https://bullitt-group.com/wp-content/uploads/2017/08/Rugged-market-position-paper-v8.pdf (accessed on 5 April 2019)

CEN/CENELEC JTC 10, Energy-related products - Material Efficiency Aspects for Ecodesign, https://www.cenelec.eu/dyn/www/f?p=104:7:1299206399119101::::FSP_ORG_ID:2240017 (accessed on 27 February 2019)

Clemm C (2019) Stronger anchoring of resource efficiency and waste prevention in product policy instruments: Final Report (On behalf of the Federal Environment Agency). Available at https://www.umweltbundesamt.de/publikationen/staerkere-verankerung-der-ressourceneffizienz (accessed on 19 August 2019)

COM(2015) 614 "Closing the loop - An EU action plan for the Circular Economy"

COM(2016) 773 "Ecodesign Working Plan 2016-2019"

COM(2017) 490 "on the 2017 list of Critical Raw Materials for the EU"

Compoundchem (2014) The Chemical Elements of a Smartphone, https://www.compoundchem.com/2014/02/19/the-chemical-elements-of-a-smartphone/ (accessed on 8 March 2019)

Compoundchem (2015) The Recycling Rates of Smartphone Metals, https://www.compoundchem.com/2015/09/15/recycling-phone-elements/ (accessed on 8 March 2019)

Cordella M, Alfieri F, Sanfelix J (2019a) Analysis and development of a scoring system for repair and upgrade of products – Final report, EUR 29711 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-01602-1, doi:10.2760/725068, JRC114337

Cordella M, Alfieri F, Sanfelix J, Donatello S, Kaps R, Wolf O (2019b) Improving material efficiency in the life cycle of products: a review of EU Ecolabel criteria, Int J Life Cycle Assess (2019), https://doi.org/10.1007/s11367-019-01608-8

Cordella M, Bauer I, Lehmann A, Schulz M, Wolf O (2015) Evolution of disposable baby diapers in Europe: life cycle assessment of environmental impacts and identification of key areas of improvement. J Clean Prod, 95: 322-331, http://dx.doi.org/10.1016/j.jclepro.2015.02.040

Cordella M, Hidalgo C (2016) Analysis of key environmental areas in the design and labelling of furniture products: Application of a screening approach based on a literature review of LCA studies. Sustainable Production and Consumption, 8: 64-77; https://doi.org/10.1016/j.spc.2016.07.002

Cordella M, Sanfelix J, Alfieri F (2018a) Development of an Approach for Assessing the Reparability and Upgradability of Energy-related Products. Proc CIRP, 69: 888-892, https://doi.org/10.1016/j.procir.2017.11.080

Cordella M, Sanfelix A, Alfieri F, Bennett M (2018b) Investigating alignment and potential synergies on circular economy requirements between sustainable product policy instruments, JRC114333, http://susproc.jrc.ec.europa.eu/E4C/docs/task_6_requirements&policies_analysis_final_v2.2.pdf (accessed on 14 March 2019)

Counterpoint Research (2016) https://www.counterpointresearch.com/almost-half-of-smartphone-users-spend-more-than-5-hours-a-day-on-their-mobile-device/ (accessed on 20 February 2018)

CRM Alliance (2017) Antimony, http://criticalrawmaterials.org/antimony/ (accessed on 13 March 2019)

Culligan K, Menzies B (2013) The value of consumer electronics for trade-in and re-sale, WRAP's report for the project HWP200-401, http://www.wrap.org.uk/sustainable-electricals/esap/resource-efficient-business-models/reports/value-consumer-electronics-trade-and-re-sale (accessed on 15 February 2018)

Deloitte (2016) There's no place like phone - Consumer usage patterns in the era of peak smartphone - Global Mobile Consumer Survey 2016: UK cut, www.deloitte.co.uk/mobileuk2016/assets/pdf/Deloitte-Mobile-Consumer-2016-There-is-no-place-like-phone.pdf (accessed on 20 February 2018)

Deloitte (2018) Mobile Consumer Survey 2018: The UK cut, https://www2.deloitte.com/uk/en/pages/technology-media-and-telecommunications/articles/mobile-consumer-survey.html (accessed on 5 March 2019)

DG CONNECT (2018) Mobile Broadband Prices in Europe, 2017 – FINAL REPORT and EXECUTIVE SUMMARY, doi:10.2759/547994, https://ec.europa.eu/digital-single-market/en/news/mobile-broadband-prices-europe-2017 (accessed on 6 August 2019)

ECHA (2013) Evaluation of new scientific evidence concerning DINP and DIDP in relation to entry 52 of Annex XVII to REACH Regulation (EC) No 1907/2006, https://echa.europa.eu/documents/10162/31b4067e-de40-4044-93e8-9c9ff1960715 (accessed on 4 April 2019)

Ellen MacArthur Foundation (2012) In-depth - Mobile Phones, https://www.ellenmacarthurfoundation.org/news/in-depth-mobile-phones (accessed on 4 April 2019)

Ercan EM (2013) Global Warming Potential of a Smartphone - Using Life Cycle Assessment Methodology, Master of Science Thesis, Stockholm, http://kth.diva-portal.org/smash/get/diva2:677729/FULLTEXT01.pdf (accessed on 4 April 2019)

Ercan M, Malmodin J, Bergmark P, Kimfalk E, Nilsson E (2016) Life Cycle Assessment of a Smartphone. Proceedings of the 4th International Conference on ICT for Sustainability (ICT4S 2016). DOI: 10.2991/ict4s-16.2016.15

ETSI (2018) Draft ETSI TR-MICT2 2 V0.0.10 (2018-12): Environmental Engineering (EE); Explore the challenges of developing product group-specific Product Environmental Footprint Category Rules for Smart Phones. http://www.etsi.org/standards-search (accessed on 4 April 2019)

European Commission (2018) Summary document of the Waste electrical and electronic equipment rates and targets, https://ec.europa.eu/eurostat/documents/342366/351758/Target-Rates-WEEE (accessed on 7 March 2019)

European Environment Agency (2017) Circular by design. Products in the circular economy. doi:10.2800/860754

Fairphone (2015) Cost breakdown of the Fairphone 2, https://www.fairphone.com/it/2015/09/09/cost-breakdown-of-the-fairphone-2/ (accessed on 9 October 2018)

Fairphone (2016) How we got Fairtrade certified gold in the Fairphone 2 supply chain, https://www.fairphone.com/en/2016/01/27/how-we-got-fairtrade-certified-gold-in-the-fairphone-2-supply-chain/ (accessed on 8 March 2019)

Fairphone (2017) Smartphone Material Profiles Opportunities for improvement in ten supply chains, https://www.fairphone.com/wp-content/uploads/2017/05/SmartphoneMaterialProfiles_May2017.pdf (accessed on 19 April 2018)

Farmer A (2015) SIM-only on the march as consumers hold on to handsets for longer, 19th August 2015, https://yougov.co.uk/news/2015/08/19/sim-only-march-consumers-hold-handsets-longer/ (Accessed on 9 February 2018)

Fossbytes (2017) https://fossbytes.com/whats-inside-smartphone-depth-look-parts-powering-everyday-gadget/ (accessed on 2 March 2018)

Greenpeace (2017) How repairable is your device? A product guide to best-selling smartphones, tablets and laptops. A product guide to best-selling smartphones, tablets and laptops. Available at http://www.greenpeace.org/eastasia/Global/eastasia/publications/reports/toxics/2017/howrepairableisyourmobiledevice.pdf

GSMARENA (2019) Mobile phone news, reviews and specification. Available at https://www.gsmarena.com/

Hobson K, Lynch N, Lilley D, Smalley G (2018) Systems of practice and the Circular Economy: Transforming mobile phone product service systems. Environmental Innovation and Societal Transitions 26, 147–157

Huijbregts MAJ, Rombouts LJA, Hellweg S, Frischknecht R, Hendriks AJ, van de Meent D, Ragas AMJ, Reijnders L, Struijs J (2006) Is cumulative fossil energy demand a useful indicator for the environmental performance of products? Environ. Sci. Technol. 40, 641–648. http://dx.doi.org/10.1021/es051689g

Huysman S, Sala S, Mancini L, Ardente F, Alvarenga RAF, De Meester S, Mathieux F, Dewulf J (2015) Toward a systematized framework for resource efficiency indicators. Resour Conserv Recy, 95: 68–76, http://dx.doi.org/10.1016/j.resconrec.2014.10.014

IDC, Smartphone Market Share, https://www.idc.com/promo/smartphone-market-share/vendor (accessed on 13 February 2018)

IFixit (2019) Smartphone Reparability Scores, https://www.ifixit.com/smartphone-repairability?sort=score (accessed on 29 March 2019)

Iraldo F, Facheris C, Nucci B (2017) Is product durability better for environment and for economic efficiency? A comparative assessment applying LCA and LCC to two energy-intensive products. J Clean Prod, 140: 1353-1364, http://dx.doi.org/10.1016/j.jclepro.2016.10.017

ISO (2006a) International Organization for Standardization. ISO 14040: 2006 Environmental management— life cycle assessment— principles and framework

ISO (2006b) International Organization for Standardization. ISO 14044: 2006 Environmental management — life cycle assessment — requirements and guidelines

ITU-T (2016) ITU-T L.1002 (10/16) External universal power adapter solutions for portable information and communication technology devices

Jardim E (2017) FROM SMART TO SENSELESS: The Global Impact of 10 Years of Smartphones. Greenpeace, http://www.greenpeace.org/usa/wp-content/uploads/2017/03/FINAL-10YearsSmartphones-Report-Design-230217-Digital.pdf (accessed on 1 March 2018)

Kantar World Panel (2017) AN INCREDIBLE DECADE FOR THE SMARTPHONE: WHAT'S NEXT? The Future of Mobile is in Combining Devices, Content, and Services - Rev 2017-24-Feb-0925, https://www.kantarworldpanel.com/dwl.php?sn=news_downloads&id=1361 (accessed on 27 February 2019)

Li Du (2016) An Overview of Mobile Capacitive Touch Technologies Trends, https://arxiv.org/pdf/1612.08227 (accessed on 4 March 2019)

Makov T, Fishman T, Chertow MR, Blass V (2018) What affects the second value of Smartphones. Journal of Industrial Ecology 0(0) DOI: 10.1111/jiec.12806

Manhart A, Blepp M, Fischer C, Graulich K, Prakash S, Priess R, Schleicher T, Tür M (2016) Resource Efficiency in the ICT Sector – Final Report, November 2016, Oko-Institut e.V., https://www.greenpeace.de/sites/www.greenpeace.de/files/publications/20161109_oeko_resource_efficency_final_full-report.pdf (accessed on 6 March 2019)

Martinho G., Magalhãnes D, Pires A (2017) Consumer behaviour with respect to the consumption and recycling of smartphones and tablets: An exploratory study in Portugal. Journal of Cleaner Production 156, 147-158

Moberg A, Borggren C, Ambell C, Finnveden G, Guldbrandsson F, Bondesson A, Malmodin J, Bergmark P (2014) Simplifying a life cycle assessment of a mobile phone. Int J Life Cycle Assess, 19:979–993. DOI 10.1007/s11367-014-0721-6

Mugge R, Jockin B, Bocken N (2017) How to sell refurbished smartphones? An investigation of different customer groups and appropriate incentives, Journal of Cleaner Production 147, 284-296, https://doi.org/10.1016/j.jclepro.2017.01.111

Nield D (2015) Our smartphone addiction is costing the Earth, https://www.techradar.com/news/phone-and-communications/mobile-phones/our-smartphone-addiction-is-costing-the-earth-1299378 (accessed on 13 March 2019)

Nielsen (2013) The Mobile Consumer: A Global Snapshot – February 2013, http://www.nielsen.com/content/dam/corporate/us/en/reports-downloads/2013%20Reports/Mobile-Consumer-Report-2013.pdf (accessed on 13 February 2013)

OCU (2017) Obsolescencia del software, una vida demasiado corta. Compra Maestra 423 - Marzo 2017

OCU (2018a) Análisis de teléfonos móviles: Guía de compra, https://www.ocu.org/tecnologia/telefono/guia-compra/analisis-moviles (accessed on 27 February 2019)

OCU (2018b) https://www.ocu.org/consumo-familia/derechos-consumidor/noticias/obsolescencia-prematura (accessed on 13 March 2019)

OCU (2019) Tecnología: ¿qué marcas son las más fiables y satisfactorias? https://www.ocu.org/tecnologia/telefono/noticias/fiabilidad-satisfaccion-tecnologia (accessed on 21 August 2019)

OECD (2014) The State of Play on Extended Producer Responsibility (EPR): Opportunities and Challenges, Global Forum on Environment: Promoting Sustainable Materials Management through Extended Producer Responsibility (EPR), 17-19 June 2014, Tokyo, Japan, https://www.oecd.org/environment/waste/Global%20Forum%20Tokyo%20Issues%20Paper%2030-5-2014.pdf (accessed on 6 April 2018)

Peeters JR, Tecchio P, Ardente F, Vanegas P, Coughlan D, Duflou J (2018) eDIM: further development of the method to assess the ease of disassembly and reassembly of products — Application to notebook computers, EUR 28758 EN, Publications Office of the European Union, Luxembourg, ISBN 978-814 92-79-73189-1, doi:10.2760/864982, JRC107773

Pihkola H, Hongisto M, Apilo O, Lasanen M (2018) Evaluating the Energy Consumption of Mobile Data Transfer—From Technology Development to Consumer Behaviour and Life Cycle Thinking. Sustainability, 10, 2494; doi:10.3390/su10072494

Prakash S, Dehoust G, Gsell M, Schleicher T, Stamminger R (2015) Einfluss der Nutzungsdauer von Produkten auf ihre Umweltwirkung: Schaffung einer Informationsgrundlage und Entwicklung von Strategien gegen „Obsoleszenz", ZWISCHENBERICHT: Analyse der Entwicklung der Lebens-, Nutzungs- und Verweildauer von ausgewählten Produktgruppen. TEXTE 10/2015, Umweltforschungsplan des Bundesministeriums für Umwelt, Naturschutz, Bau und Reaktorsicherheit Forschungskennzahl 371332315, http://www.umweltbundesamt.de/publikationen/einfluss-der-nutzungs-dauer-von-produkten-auf-ihre (accessed on 22 February 2018)

Priya L, Visalaxi S, Mohana E (2016) A Study on Smart Phone Batteries and its Power Utilization. International Journal of Innovative Research in Computer and Communication Engineering, Vol.4, Special Issue 3, April 2016. ISSN(Online): 2320-9801; ISSN (Print): 2320-9798

Product Bureau, http://susproc.jrc.ec.europa.eu/product_bureau/ (accessed on 27 February 2019)

Proske M, Clemm C, Richter N (2016) Life cycle assessment of the Fairphone 2. Fraunhofer IZM. Berlin, November 2016, https://www.fairphone.com/wp-content/uploads/2016/11/Fairphone_2_LCA_Final_20161122.pdf

Prunel D, Roy A, Arnould R (2015). Environmental labelling of electronic products: mobile phones, laptop and tablet. DOI: 10.13140/RG.2.1.2730.8007

Rocchetti L, Vegliò F, Kopacek B, Beolchini F (2013) Environmental impact assessment of hydrometallurgical processes for metal recovery from WEEE residues using a portable prototype plant. Environ. Sci. Technol. 47 (3), 1581–1588

RPA (2014) Study on the Impact of the MoU on Harmonisation of Chargers for Mobile Telephones and to Assess Possible Future Options Final Report (Main Report) prepared for DG Enterprise and Industry, https://ec.europa.eu/docsroom/documents/7432/attachments/1/translations/en/renditions/pdf (accessed on 5 March 2019)

Schischke K, Proske M, Nissen NF, Lang K (2016) Modular Products: Smartphone Design from a Circular Economy Perspective. Electronics Goes Green 2016+, DOI: 10.1109/EGG.2016.7829810

Science for Environment Policy (2018) Towards the battery of the future. Future Brief 20. Brief produced for the European Commission DG Environment by the Science Communication Unit, UWE, Bristol, doi:10.2779/674936, http://ec.europa.eu/science-environment-policy (accessed on 6 March 2019)

Sony (2018) Reduction and Replacement of Chemical Substances of Very High Concern, https://www.sony.net/SonyInfo/csr_report/environment/products/replace.html (accessed on 13 March 2019)

Sony (2019) Management Regulations for the environment related substances to be controlled which are included in parts and materialsSS-00259 for General Use, Seventeenth Edition, https://www.sony.net/SonyInfo/procurementinfo/ss00259/ss_00259e_General_use_17E.pdf (accessed on 5 March 2019)

Souchet F, Meloni M, Sturges D (2017) Your circular electronic product must have these three features, https://circulatenews.org/2017/12/circular-electronic-product-must-three-features/?lipi=urn%3Ali%3Apage%3Ad_flagship3_feed%3BHD7nUnWAR0ik%2FdKTHcRqWg%3D%3D) (accessed on 4 April 2019)

Statista (2018a) Smartphones industry: Statistics & Facts, https://www.statista.com/topics/840/smartphones/ (accessed on 12 February 2018)

Statista (2018b) Smartphone user penetration as percentage of total global population from 2014 to 2021, https://www.statista.com/statistics/203734/global-smartphone-penetration-per-capita-since-2005/ (accessed on 12 February 2018)

Statista (2018c) Smartphone unit shipments in Western Europe from 2013 to 2017 (in million units), https://www.statista.com/statistics/412224/global-smartphone-shipments-western-europe/ (accessed on 12 February 2018)

Statista (2018d) Smartphone unit shipments in Central & Eastern Europe from 2013 to 2017 (in million units), https://www.statista.com/statistics/412204/global-smartphone-shipments-central-and-eastern-europe/ (accessed on 12 February 2018)

Statista (2018e) Global smartphone shipments forecast from 2010 to 2022 (in million units), https://www.statista.com/statistics/263441/global-smartphone-shipments-forecast/ (accessed on 12 February 2018)

Statista (2018f) Smartphone unit shipments worldwide from 2013 to 2017 (in million units), by region, https://www.statista.com/statistics/412108/global-smartphone-shipments-global-region/ (accessed on 12 February 2018)

Statista (2018g) Smartphone sales value in Western Europe from 2013 to 2017 (in billion U.S. dollars), https://www.statista.com/statistics/412280/global-smartphone-sales-value-western-europe/ (accessed on 12 February 2018)

Statista (2018h) Smartphone sales value in Central and Eastern Europe from 2013 to 2017 (in billion U.S. dollars), https://www.statista.com/statistics/412256/global-smartphone-sales-value-central-and-eastern-europe/ (accessed on 12 February 2018)

Statista (2018i) Number of smartphone users worldwide from 2014 to 2020 (in billions), https://www.statista.com/statistics/330695/number-of-smartphone-users-worldwide/ (accessed on 12 February 2018)

Statista (2018j) Smartphone user penetration as percentage of total population in Western Europe from 2011 to 2018, https://www.statista.com/statistics/203722/smartphone-penetration-per-capita-in-western-europe-since-2000/ (accessed on 12 February 2018)

Statista (2018k) Number of smartphone users in France from 2015 to 2022 (in millions), https://www.statista.com/statistics/467177/forecast-of-smartphone-users-in-france/ (accessed on 12 February 2018)

Statista (2018l) Number of smartphone users in Germany from 2015 to 2022 (in millions), https://www.statista.com/statistics/467170/forecast-of-smartphone-users-in-germany/ (accessed on 12 February 2018)

Statista (2018m) Forecast of the smartphone user penetration rate in Germany from 2015 to 2022, https://www.statista.com/statistics/568095/predicted-smartphone-user-penetration-rate-in-germany/ (accessed on 12 February 2018)

Statista (2018n) Number of smartphone users in Italy from 2015 to 2021 (in millions), https://www.statista.com/statistics/467179/forecast-of-smartphone-users-in-italy/ (accessed on 12 February)

Statista (2018o) Forecast of the smartphone user penetration rate in Italy from 2014 to 2021, https://www.statista.com/statistics/568187/predicted-smartphone-user-penetration-rate-in-italy/ (accessed on 12 February 2018)

Statista (2018p) Number of smartphone users in Spain from 2015 to 2022 (in millions), https://www.statista.com/statistics/467185/forecast-of-smartphone-users-in-spain/ (accessed on 12 February 2018)

Statista (2018q) Forecast of the smartphone user penetration rate in Spain from 2015 to 2022, https://www.statista.com/statistics/568268/predicted-smartphone-user-penetration-rate-in-spain/ (accessed on 12 February 2018)

Statista (2018r) Forecast of smartphone user numbers in the United Kingdom (UK) from 2015 to 2022 (in million users), https://www.statista.com/statistics/553464/predicted-number-of-smartphone-users-in-the-united-kingdom-uk/ (accessed on 12 February 2018)

Statista (2018s) Forecast of the smartphone user penetration rate in the United Kingdom (UK) from 2015 to 2022, https://www.statista.com/statistics/553707/predicted-smartphone-user-penetration-rate-in-the-united-kingdom-uk/ (accessed on 12 February 2018)

Statista (2018t) Smartphone shipments by vendor worldwide from 4th quarter 2009 to 4th quarter 2018 (in million units), https://www.statista.com/statistics/271490/quarterly-global-smartphone-shipments-by-vendor/ (accessed on 12 February 2018)

Statista (2018u) Global smartphone shipments market share of Lenovo by quarter from 2012 to 2015, https://www.statista.com/statistics/299121/global-market-share-held-by-lenovo-smartphones/ (accessed on 12 February 2018)

Statista (2018v) Global market share held by smartphone operating systems from 2009 to 2017, https://www.statista.com/statistics/263453/global-market-share-held-by-smartphone-operating-systems/ (accessed on 12 February 2018)

Statista (2018w) Global smartphone sales to end users from 1st quarter 2009 to 2nd quarter 2018, by operating system (in million units), https://www.statista.com/statistics/266219/global-smartphone-sales-since-1st-quarter-2009-by-operating-system/ (accessed on 12 February 2018)

Statista (2018z) Global mobile OS market share in sales to end users from 1st quarter 2009 to 2nd quarter 2018, https://www.statista.com/statistics/266136/global-market-share-held-by-smartphone-operating-systems/ (accessed on 12 February 2018)

Statista (2018aa) Installed base of smartphones by operating system from 2015 to 2017 (in million units), https://www.statista.com/statistics/385001/smartphone-worldwide-installed-base-operating-systems/ (accessed on 12 February 2018)

Statista (2018ab) Average selling price of smartphones worldwide from 2012 to 2017 (in U.S. dollars), https://www.statista.com/statistics/510668/smartphone-average-selling-price-worldwide/ (accessed on 14 February 2018)

Statista (2018ac) Manufacturing costs for Google Pixel XL by component in 2016 (in U.S. dollars), https://www.statista.com/statistics/625527/manufacturing-costs-of-google-pixel-xl/ (accessed on 12 February 2018)

Suckling J, Lee J (2015) Redefining scope: the true environmental impact of smartphones? Int J Life Cycle Assess, 20:1181–1196. DOI 10.1007/s11367-015-0909-4

Sustainably SMART (2017) Sustainable Smart Mobile Devices Lifecycles through Advanced Redesign, Reliability, and Re-use and Remanufacturing Technologies. Deliverable 7.1, https://www.sustainably-smart.eu/app/download/9094936482/DisassemblyStudies.pdf?t=1548940654 (accessed on 7 March 2019)

Sustainably SMART (2018) Eco-design of Policy Conclusion - Policy Brief No. 1, https://www.sustainably-smart.eu/app/download/8928556482/sustainablySMART_Policy_Brief_No.1_25012018.pdf?t=1527258511 (accessed on 4 July 2018)

Sustainably SMART (2019) Policy initiative on standard chargers for mobile phones, Policy Brief No. 2, https://www.sustainably-smart.eu/app/download/9262387882/sustainablySMART_Policy_Brief_No.2_28012019.pdf?t=1548941170 (accessed on 27 March 2019)

Tanskanen P (2012) Electronics Waste: Recycling of Mobile Phones, Post-Consumer Waste Recycling and Optimal Production, Prof. Enri Damanhuri (Ed.), ISBN: 978-953-51-0632-6, InTech, http://cdn.intechopen.com/pdfs/37110/InTechElectronics_waste_recycling_of_mobile_phones.pdf (accessed 2 April 2019)

TCO Certified (2018) TCO Certified Generation 8, for laptops. Available at: https://tcocertified.com/files/certification/tco-certified-generation-8-for-smartphones.pdf (accessed 28 June) 2019)

Tecchio P, Ardente F, Mathieux F (2016) Analysis of durability, reusability and reparability — Application to washing machines and dishwashers, Publications Office of the European Union, EUR 28042 EN, doi:10.2788/630157

Transform Together (2018) Creating sustainable smartphones: Scaling up best practice to achieve SDG 12, https://transform-together.weebly.com/uploads/7/9/7/3/79737982/report_-_creating-sustainable-smartphone_scaling-up-best-practice-to-achieve-sdg-12.pdf (accessed on 4 March 2019)

Triggs R (2019) Build materials: metal vs glass vs plastic, https://www.androidauthority.com/build-materials-metal-vs-glass-vs-plastic-617553/ (Accessed on 13 March 2019)

UN (2015) Technical guidelines on transboundary movements of electrical and electronic waste and used electrical and electronic equipment, in particular regarding the distinction between waste and non-waste under the Basel Convention. UNEP/CHW.12/5/Add.1/Rev.1

U.S. Department of Energy (2013) International Efficiency Marking Protocol for External Power Supplies Version 3.0, September 2013, https://www.regulations.gov/document?D=EERE-2008-BT-STD-0005-0218 (accessed on 18 April 2018)

Vanegas P, Peeters JR, Cattrysse D, Tecchio P, Ardente F, Mathieux F, Dewulf W, Duflou JR (2018) Ease of disassembly of products to support circular economy strategies. Resources, Conservation and Recycling 135, 323-334

Vanegas P, Peeters JR, Cattrysse D, Duflou JR, Tecchio P, Mathieux F, Ardente F (2016) Study for a method to assess the ease of disassembly of electrical and electronic equipment - Method development and application in a flat panel display case study. EUR 27921 EN. doi:10.2788/130925

Vencovsky D, Fleet D, Le Crom Y, Marshall S, Floyd P, Risk&Policy Analysts (2014) Study on the Impact of the MoU on Harmonisation of Chargers for Mobile Telephones and to Assess Possible Future Options, Final Report (Main Report) prepared by Risk&Policy analysis for DG Enterprise and Industry, https://publications.europa.eu/en/publication-detail/-/publication/4b3e4ea8-4f44-4687-96e4-cd3264407c5b (accessed on 27 February 2019)

Watson D, Gylling AC, Tojo N, Throne-Holst H, Bauer B, Milios L (2017) Circular Business Models in the Mobile Phone Industry, Nordic Council of Ministers 2017, http://dx.doi.org/10.6027/TN2017-560

Wergarantie (2017) Mit Schadendaten von rund einer Million Smartphones, https://www.clickrepair.de/images/presse/downloads/pdf/clickrepair-smartphone-studie-2017.pdf (accessed on 05 April 2019)

Wiens K (2014) Smartphone Repairs You Can Do on Earth Day, https://ifixit.org/blog/6448/smartphone-repairs/ (accessed on 6 March 2019)

Zandin KB (2003) MOST Work Measurement Systems. New York: Marcel Dekker. ISBN 0-8247-816 0953-5

ANNEX I – ECOLABELLING REQUIREMENTS FOR SMARTPHONES

The following tables summarises the requirements that smartphones have to fulfil to be labelled according to Blue Angel (Table 40), TCO (Table 41) and EPEAT (Table 42).

Table 40: Requirements for the award of the Blue Angel to mobile-phones

Aspect	Requirement
3.1 Battery State-of-Charge Indicator	The mobile phone must have an integrated charge indicator indicating the current state of battery charge during use and charging. Also, the device must show in a clear manner that the charging has been completed.
3.2External Power Supply	The applicant shall provide a distribution channel for the mobile phone through which the mobile phone is marketed without an external power supply
3.3Secondary Batteries 3.3.1Replaceability of the battery 3.3.2 Battery Capacity 3.3.3 Battery Marking 3.3.4 Durability of the Battery	The mobile phone shall be designed so as to allow the user to replace the rechargeable battery without special expert knowledge and without damaging the telephone. The battery capacity shall be measured in accordance with paragraph 7.3.1 „Discharge performance at 20 °C (rated capacity)" of EN 61960 standard „Secondary cells and batteries containing alkaline or other non-acid electrolytes - Secondary lithium cells and batteries for portable applications", as amended (current version: DIN EN 61960:2012-04). The rated 9/24 DE-UZ 106 Edition July 2017 capacity (C) thus determined must be at least as high as the nominal capacity (N) indicated on the battery and in the product documents. The battery (or battery pack) must be marked in accordance with EN 61960 providing at least the following information: - nominal capacity (N), - nominal voltage, - type designation, - date of manufacture (may be coded). These specifications (except for the date of manufacture) shall also be given in the product documents. In case the date of manufacture is coded the product documents shall include instructions for decoding. In addition, the battery (or battery pack) shall be marked with an international recycling symbol as given in ISO 7000 (Graphical symbols for use on equipment) and specify the cell chemistry of the battery (e.g. Li-Ion, Ni-MH). This symbol shall be colour-coded in accordance with the recommendations of the Battery Association of Japan15 or the draft IEC 62902 standard. The battery must achieve a minimum of 500 full charge cycles: full charge cycles ≥ 500.

Aspect	Requirement
	A full charge cycle is to be understood as the drain of a quantity of electricity (in ampere hours) from the battery to the amount of its nominal capacity (N) that has been stored in the battery by one or more charging processes. The minimum number of full charge cycles achievable shall be specified in the product documents. After 500 full charge cycles the battery must, in addition, have in a fully charged state, a remaining capacity (QRem) of at least 90 percent of the nominal capacity (N). $QRem \geq 90\% * N$ Full charge cycles shall be calculated and remaining capacity shall be measured in accordance with the requirements set out in Appendix A.
3.3.5 Battery Safety	The batteries must meet the test requirements of EN 62133-2 "Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications – Part 2: Lithium systems", as amended.
3.4 Longevity	
3.4.1 Warranty	The applicant undertakes to offer a free minimum 2-year warranty on the mobile phone, except for the batteries. In addition, the applicant shall offer a free minimum 1-warranty on the battery which covers a remaining capacity of at least 90%, provided that the phone is properly used and charged with the manufacturer's own or another suitable charging device. The product documents shall provide details of such warranties.
3.4.2 Availability of Spare Parts and Repair	The applicant undertakes to make sure that the availability of spare parts for device repair is guaranteed for at least 3 years from the time that production ceases. Spare parts shall be offered at reasonable prices by the manufacturer itself or a by third party. Spare parts are those parts which, typically, may fail or break down within the scope of the ordinary use of a product, especially batteries, displays and front glasses. The mobile phones shall be so designed as to enable qualified specialist workshops to replace such spare parts with reasonable effort. The product documents shall provide information on spare parts supply and repair services.
3.4.3 Software Updates	The device shall come with a free function to allow the user to update the operating system. The aim of these updates is, above all, the closing of security holes, as well as other software updates, if applicable. The applicant undertakes to offer security updates for the operating system of the mobile phone to be eco-labelled for at least 4 years from the time that production ceases.
3.4.4. Data Deletion	To allow reuse of the device it shall be designed so as to enable the user to completely and securely delete all personal data without the help of pay software. This can be accomplished by either physically removing the memory card or the use of free manufacturer-provided software. As an alternative to removing the data, it shall also be possible to encode the personal data on the data medium by means of software provided, thus allowing a secure deletion of the key. In addition, the device shall include a software function that resets the device to its factory settings. The product documents shall include detailed instructions on how to securely delete data and how to reset the device to its factory settings.

Aspect	Requirement
3.5 Take Back and Recycling 3.5.1 Take Back 3.5.2 Recyclable Design	The applicant shall operate its own take-back scheme for mobile phones to direct all collected devices to reuse or professional recycling. The applicant shall actively communicate this system to its customers. This take-back scheme can be based on collections at the branches, return campaigns, deposit systems or the like. A mere reference to the collection governed by the Elektro- and Elektronikgesetz (ElektroG) (Electrical and Electronic Equipment Act) would not be sufficient. The collection system can be organised by the applicant itself, by contracting partners and/or together with other manufacturers of mobile phones. An efficient removal of the secondary batteries for recycling purpose shall be possible with no special knowledge being required (guidance value: in no more than 5 seconds). The battery chemicals must be prevented from leaking during the removal.
3.6 Material Requirements 3.6.1 Plastics used in Housings and Housing Parts 3.6.2 Use of Biocidal Silver	The plastics used in housings and housing parts must not contain, as constituent components, any substances with the following characteristics16: 1. Substances that have been identified as substances of very high concern according to Regulation (EC) No 1907/2006) (REACH6) and have been included in the list (so-called Candidate List) set up in accordance with REACH, Article 59(1).17. 2. Substances that have been classified according to the CLP Regulation18 in the following hazard categories or meet the criteria for such classification19: - carcinogenic of category Carc. 1A or Carc. 1B - mutagenic of category Muta. 1A or Muta. 1B - reprotoxic of category Repr. 1A or Repr. 1B Halogenated polymers shall not be permitted in housings and housing parts. Nor may halogenated organic compounds be added as flame retardants. Nor shall any flame retardants be permitted which are classified under the CLP Regulation as carcinogenic of Category Carc. 2 or as hazardous to waters of Category Aquatic Chronic 1. The hazard statements (H-phrases) assigned to the hazard categories can be seen from Appendix 2: „Assignment of Hazard Categories and Hazard Statements“. The following shall be exempt from this requirement: - fluoroorganic additives (as, for example, anti-dripping agents) used to improve the physical properties of plastics, provided that they do not exceed 0.5 weight percent; - plastic parts weighing 10 grams or less, where - with regard to multiple part housings - the total weight of all parts made of the same plastic shall be the decisive factor in determining the mass. The use of biocidal silver on touchable surfaces shall not be permitted.
3.7 Electromagnetic Radiation	Devices to be Blue Angel eco-labelled shall be designed so as to make sure that - when used at the ear - the specific absorption rate (SAR) induced by the radio-frequency electromagnetic radiation emitted does not exceed 0.5 watts per kg and - when used near the body - 1.0 watt per kg - locally averaged over 10 grams of tissue.

Aspect	Requirement
3.8 Additional Functions	The mobile phone must provide the technical tools needed to make phone calls without holding the mobile phone close to ear or mouth. To achieve this aim the mobile phone 1. must be equipped with an interface for connecting a headset (combination of headphones and microphone) and 2. offer a speakerphone function.
3.9 Social Corporate Responsibility 3.9.1 Due Diligence for Conflict Minerals 3.9.2 Working Conditions	As regards the conflict minerals used in mobile phones, such as tin, tantalum, tungsten and their ores as well as gold the applicant shall perform its corporate due diligence by complying with the „OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas"22,23. The applicant shall present a list of the components that contain the predominant mass fraction in relation to the respective conflict mineral. The applicant shall name the supplier and the respective supply chain scheme or project for each component to ensure responsible sourcing of conflict minerals used in the mobile phone. In addition, the applicant shall support at least one of the initiatives listed in Appendix C which promotes responsible sourcing and trading of the above-mentioned minerals in line with OECD Guidance. Fundamental principles and universal human rights as stipulated by the applicable core labour standards of the International Labour Organisation24 (ILO) must be observed during the final assembly of Blue Angel eco-labelled products. Employee rights and benefits shall apply to all forms of employment, including atypical forms of employment, such as part-time work, piecework, seasonal workers or home workers as well as to employees of subcontractors and those employed by subcontract. All workers shall receive a written employment contract that is in line with the legal provisions. The applicant shall ensure compliance with the following core labour standards: i) Conventions against child labour: - Minimum Age Convention, 1973 (No. 138) - Worst Forms of Child Labour Convention, 1999 (No. 182) ii) Conventions against forced and compulsory labour: - Forced Labour Convention, 1930 (No. 29) and the protocol of 2014 to the Forced Labour Convention - Abolition of Forced Labour Convention, 1957 (No. 105) iii) Freedom of association and the right to collective bargaining: - Freedom of Association and Protection of the Right to Organise Convention, 1948 (No. 87) - Right to Organise and Collective Bargaining Convention, 1949 (No. 98) - If the ILO core labour standards on freedom of association and collective bargaining are not or only insufficiently implemented due to national framework

Aspect	Requirement
	conditions the companies shall provide evidence of their efforts and achievements in supporting freely elected and true workers' representations by presenting relevant documentations in order to verify that concrete measures have been taken to allow independent observers to monitor elections and that measures have been taken to promote a constructive dialogue between workers/workers' representations and the management. iv) Conventions against discrimination: - Equal Remuneration Convention, 1951 (No. 100) - Discrimination (Employment and Occupation) Convention, 1958 (No. 111) In addition to the ILO core labour standards compliance with the following additional ILO conventions shall be ensured during the final assembly: v) Adequate hours of work and remuneration: - Hours of Work (Industry) Convention, 1919 (No. 1) - Minimum Wage Fixing Convention, 1970 (No. 131) - Living wages: The applicant shall make every effort that wages paid for a standard working week at least meet legal or industry standards and are always sufficient to meet the basic needs of personnel and provide some discretionary income. vi) Protection of health and safety: - Occupational Safety and Health Convention, 1981 (No. 155) - Chemicals Convention, 1990 (No. 170) (Convention concerning Safety in the use of Chemicals at Work).
3.10 Operating Instructions	The product documents included with the devices shall include both the technical specifications and the user information relating to environment and health. They shall be either installed on the mobile phone, easily accessible on the Internet or supplied as a data medium or in printed form together with the device. The product documents shall include and manufacturer's website shall allow easy access to the following basic user information: 1. Information on the significance and correct interpretation of the state-of-charge indicator (cf. para. 3.1). 2. Instructions to disconnect the charger from the mains upon completion of the charging process in order to reduce no-load losses. 3. Instructions that charging on non-used PCs should be avoided in order to reduce power consumption during charging. 4. Instructions for using a proper charging unit. 5. Information on how to extend the battery life. 6. Instructions for replacing the battery (cf. para. 3.3.1). 7. Specification of nominal capacity, nominal voltage and type designation of the battery as well as information on the recycling process (cf. para. 3.3.3) 8. Indication of the number of full-charge cycles achievable (cf. para. 3.3.4). 9. Information on the warranty periods for mobile phone and battery as well as on the warranty terms (cf. para. 3.4.1).

Aspect	Requirement
	10. Information on the availability of spare parts and repair services (cf. para. 3.4.2). 11. Information on software updates (cf. para. 3.4.3). 12. Information on secure data deletion and the reset function to restore factory settings (cf. para. 3.4.4). 13. Information on environmental and resource significance of proper product disposal as well as information on the take-back scheme (cf. para. 3.5.1). 14. Information on an environmentally sound disposal at the end of use in accordance with the German Elektrogesetz (Electrical and Electronic Equipment Act) as well as instructions that the battery should not be disposed of as normal household waste but instead should be taken to a battery collection facility. 15. Specification and explanatory information on the SAR data (cf. para. 3.7). 16. Information on how to reduce health effects from radio waves when using the mobile phone, at least by recommending the use of headset or speakerphone function (cf. para. 3.8).
3.11 Outlook on Possible Future Requirements	A future revision of these Basic Criteria is expected to further toughen the requirements for social corporate responsibility. For this purpose, additional conflict-affected ores will probably be added to the list of conflict minerals (currently: tin, tantalum, tungsten and gold) and the criteria for social working conditions (currently: final assembly plants) will have to be met by additional plants along the supply chain (e.g. component suppliers). Also, the availability of spare parts is expected to be extended from 3 to 4 years.

Table 41: Requirements and related background information for TCO Certified Generation 8 for Smartphones.

Aspect	Background	Requirement
1. Product and sustainability information		
1.1. Information to End-Users	End users must clearly be able to identify which products are certified and what sustainability features the product fulfills	The information document for end users must be written in English or in the local language of the country where the product is to be sold. It must accompany the product in at least one of the following ways: - As a separate printed or digital document. - Included in a printed or digital user manual. - As a separate digital document that is hosted on the brand owner's website. A direct link to the document must be included in the printed or digital user manual mentioned above. The product and its packaging must be labeled with the TCO Certified logo.
1.2 Product Specification	It is important to ensure that each product to be certified corresponds exactly to the product specification. Therefore, a physical sample of each product to be certified must be sent to an approved verifier, that examines it carefully to ensure that product marking and physical aspects conform with the reported information from the applicant or brand owner.	A product specification and marking label must be provided for the product.
1.3 Sustainability performance	The sustainable performance indicators will help us follow the development of products and brand owners, enabling us to set criteria that are challenging but yet reasonable, and that cover the most relevant parts of the product life cycle.	By the end of April each year, information on the previous calendar year's global production volume of the product must be reported in TCO Certified Portal (This applies until the year after a certificate has expired). Complete all fields for the sustainability performance indicators in chapter 11.3.
2. Socially responsible manufacturing		
2.1 Supply chain responsibility	Supply chains of IT products are complex and spread all over the world. The most basic aspect of socially responsible manufacturing in the supply chains is to define the responsibility. After this is done, the level of conformity and the implementation in the supply chains need to be defined. Finally, to get required results, verification is crucial. Without verification there are no considerable results. The contribution of TCO Certified is to:	By signing this mandate, the brand owner agrees to the commitment and agrees to conduct the structured work. Additionally TCO Development requires that the brand owner shows proof of the commitment and the structured work by allowing random inspections, by sharing audit reports and CAPs and by providing other documented proof.

Aspect	Background	Requirement
	- Place the responsibility on the brand owners' which are on the top of the value chains. - Define a minimum level of conformity to the code of conducts of the brand owners. - Provide a control system to ensure that the brand owners take responsibility and work in a structured way in accordance with their code of conducts. - Create an incentive for brand owners to work proactively.	
2.2 Supply chain transparency	Supply chain transparency includes two vital parts: a) the extent to which information about a company and its sourcing locations is made public to end-users and stakeholders and b) the company's process of taking action through supply chain visibility, to manage it effectively. Companies struggle to achieve supply chain transparency since they lack a solid process and structure to manage risks and monitor behaviour in their extended supplier network. Without visibility into their supply chains, brand owners create a blind spot where damage to reputation can emerge. Transparency toward a third party provides a company not only with the possibility to measure its own performance in key areas against their peers, but also a way to share and gain knowledge about solutions. Supply chain transparency requires a solid management system, where improvements are achieved by acting on responses to shared information.	The brand owner must appoint a Senior Management Representative (SMR) for supply chain responsibility, who reports directly to senior management. Irrespective of other duties, this person must have the authority to ensure that certified products meet the supply chain criteria in TCO Certified. The SMR must annually complete the TCO Certified self-assessment questionnaire (SAQ) and complete a follow-up interview with an approved verifier.
2.3 Anti-corruption management system	The risk of corruption can never be completely eliminated, but it can be minimized through strict monitoring and enforcement procedures that are in place to prevent it. Organizations have a responsibility to prevent corruption within their businesses and their supply chains. Many organizations rely on their ability to create programs that align with their own risk profiles, but conformity standardization is the best way to verify that business policy, monitoring and enforcement mechanisms are compatible with internationally recognized best practices against corruption.	The brand owner must have internal processes and routines in place to prevent and respond to all forms of corruption that, at a minimum, aligns with the following: - ICC Rules on Combating Corruption article 10 points a-p. - ICC Guidelines on Whistleblowing.

Aspect	**Background**	**Requirement**
2.4Responsibly sourced minerals	To certify products according to TCO Certified, brand owners must develop a global approach in their understanding, traceability and policies for a responsible mineral supply chain. They must also support in-region initiatives working in conflict-affected and high-risk areas. Commonly mentioned risk minerals are considered as tantalum, tin, tungsten, gold (3TG conflict minerals) and cobalt, mica, lithium, copper, nickel and rare earth elements	The brand owner must: - Have a strict supply chain policy for responsible minerals sourcing that can be considered to cover at least 3TG and cobalt. The policy must be both public and communicated to the supply chain. - Have a process to identify smelters and refiners of at least 3TG and cobalt. - Be a part of an established multi-stakeholder program that works at supporting responsible sourcing programs for at least 3TG and cobalt
2.5 Process chemicals	Scientific research shows that exposure to chemical substances used in the manufacture of electronic products is linked to increased rates of cancer, reproductive damage, birth defects and other serious illnesses among workers. Chemicals such as benzene (used as a cleaning agent) and n-hexane (an industrial solvent) have well-documented toxic human health effects. These chemicals need to be phased out of production, and not be replaced with equally hazardous chemicals. To replace chemicals with safer alternatives, process chemicals and their suitable safer alternatives must be identified and assessed. The Personal Protective Equipment (PPE), training and exposure monitoring provided to the workers who risk toxic chemical exposure also need to be reviewed and improved. This mandate is focused on cleaners and industrial solvents used in final assembly factories	Every final assembly factory manufacturing certified products: - must have a structured health and safety management system in place, that is independently audited. - must complete the process chemical data template provided by TCO Development - must provide exposure controls and personal protective equipment as recommended in section 8 of the 16 section format safety data sheet.
3 Environmentally responsible manufacturing		
3.1 Environmental management system	A certified environmental management system helps an organization work in a systematic way with environmental performance, and make continuous improvement at both company and product levels. To be efficient, an environmental management system must include independent, external reviews.	Each final assembly factory manufacturing the certified product must be certified in accordance with ISO 14001, or EMAS registered.
3.2 Energy efficiency indicators	While IT products become increasingly energy efficient in the use phase, there are still improvements to be made in the manufacturing phase. Life cycle assessments show that many IT products consume more energy during manufacturing than during the use phase.	Each final assembly factory must report the previous calendar year energy efficiency indicators by the end of August each year. (This applies until the year after a certificate has expired.)

Aspect	Background	Requirement
4 User health and safety		
4.1 Electrical safety	IT products must be safe to use. Electrical safety refers to the electrical design of the product. Electrical insulation and other arrangements must be in place to prevent the user from touching live components. Faulty or inadequate electrical insulation can also result in an electrical flashover that may cause a fire or an explosion.	The product and external power supply/supplies must be certified according to EN/IEC 60950 or EN/IEC 60065 or EN/IEC 62368-1.
4.2 Material characteristics	Background Skin allergies, in the form of rash or inflammation, may happen when the skin comes in contact with substances that irritate the skin. It is medically termed as "contact dermatitis". Nickel is a well-known contact allergen and irritant, which may cause skin reactions upon exposure, including itching, irritation, inflammation and rashes.	The smartphone must not release nickel from the surfaces that come in contact with user´s skin during normal use. For the maximum value, see the clarification below
5. Product performance		
5.1 Energy efficiency – external power supply	Energy production is a large source of greenhouse gas emissions globally. Therefore, one of the most important factors in decreasing the carbon footprint of IT products, is to make sure that they are energy efficient. With an ever-increasing volume of IT equipment in use, the energy efficiency in the production and use phase of each product is vital. To reduce the energy consumption of the product the external power supply must conform with the International Efficiency Marking Protocol for External Power Supplies.	The external power supply must meet at least the International Efficiency Protocol requirement for level VI.
5.2 Display resolution	Image quality is negatively affected by a low fill factor, visible "jaggies", and poor rendering of details. All of these parameters are related to the resolution of the display. For display resolution characteristics, it is important to take the viewing distance into account.	The display panel should have a pixel density of at least 165 PPI.
5.3 Correlated color temperature	Physical measurements of color stimuli can only give an indication of the color appearance in a practical situation. The color of the frame, the spectral composition of the lighting, the color of various areas in the visual field, and the complexity of brightness variations in the visual field all influence the color appearance of an tablet display image. It is important to be able to set a color temperature that represents average	The product default preset correlated color temperature may have any name but must have a color difference $\Delta u'v' \leq 0.02$ when compared to CIE u' and v' chromaticity coordinates for D65.

Aspect	Background	Requirement
	daylight. It will be intuitive to most users to have their document background and photo editing in this color temperature as this is a light source that users will be exposed to daily. Average atmospheric filtered daylight has a correlated color temperature of approximately 6500K and is reproduced by a number of standards ex. D65, sRGB, ITU rec 709 which are widely used in photo and video editing.	
5.4 Color gamut	Accurate color rendering is important when realistic color images or color presentations are presented on the smartphone display. Poor color rendering can lead to poor readability and misinterpretation.	Minimum color triangle according to 5.4.1
5.5 Color uniformity	The human visual system is very sensitive to changes in color hue in white and gray areas. White and gray color hues also serve as reference colors on the screen, that affect how all other colors are perceived. Patches of color variation on an active white or gray screen may reduce the contrast locally, be disturbing and affect readability, color rendering and color differentiation.	The maximum color deviation between measured active areas on the screen that are intended to maintain the same color must be $\Delta u'v' \leq 0.012$.
5.6 Luminance level	Poor screen luminance can lead to low contrast, poor readability and color discrimination, which may cause misinterpretations and eye strain. Therefore, it is important that the luminance levels can be set both high and low enough, with respect to the ambient lighting	The maximum luminance must be ≥ 200 cd/m2 The minimum luminance must be ≤ 100 cd/m2
5.7 Luminance uniformity	When poor luminance uniformity is visible, it can locally affect the contrast and consequently the readability of information on the display. The areas of deviating luminance can have different sizes and cause varying contour sharpness	Luminance variation across the active screen, the Lmax to Lmin ratio, shall be ≤ 1.50
Product lifetime extension		
6.1 Product lifetime extension	By extending product lifetime, natural resources are used more efficiently and the pollution to air and water is reduced. A precondition for an extended product lifetime is that the product is of high quality. A product warranty provides the brand owner with an economic incentive to design a durable product that lasts longer.	The brand owner must provide a product warranty for at least one year, covering all markets where the product is sold.

Aspect	Background	Requirement
6.2 Replaceable components	Extending the lifetime of IT products is the most effective way to reduce their environmental impact. Components that often break or become outdated may limit the total lifespan of the product and must be replaceable. By making these critical replaceable components available and providing the user with clear instructions on how to exchange them, IT-products can live longer.	The brand owner must provide a service manual describing how to replace at least all critical replaceable components. The service manual must be available online for anyone to read, free of charge. The brand owner must guarantee that, during the validity of the certificate, all critical replaceable components for the product type, that are listed in the clarifications of this criterion; - are available for anyone to purchase, or - may be replaced by a service network for repair and maintenance of the certified product on all markets where it is sold. For Smartphones critical replaceable components are: - Battery - Display Panel/Display assembly - Charger
6.3 Standardized connectors	By using one standardized interface (USB Type-C) for charging and data transfer, fewer cables need to be manufactured and the re-use of chargers and data cables can increase. USB Type-C is also designed to be more robust and future-proof than the existing USB Type-A and Type-B. Therefore, using USB Type-C help prevent problems with failing ports.	The device must carry at least one USB Type-C connector that is backward compatible with USB 2.0.
6.4 Product durability	The military standard MIL-STD-810G and the International Electrotechnical Commission IEC 60068-2 include a series of endurance tests such as low and extreme temperature and drop tests. Products that meet these requirements can last longer and be reused to a larger extent.	The product must be tested according to the MIL-STD-810G w/CHANGE 1 or IEC 60068-2 test procedure with the modified storage / operational temperature interval and duration as well as the drop test height according to the table in 6.4.1. The results will be reported on the certificate.
6.5 Secure data removal from products	By reusing IT products, their usable life can be extended which is an effective way of reducing their environmental impact. However, fear of confidential data leakage often prevents companies and individuals from making their products available on the second-hand market. By providing software that wipes the storage of the device, the owner can more safely recirculate their product.	The brand owner must provide media sanitization software, either by: A. pre-installing it on the product before it is shipped. B. providing the software for download on their webpage, free of charge. C. providing a direct link on their own webpage to an external webpage where the software is available for download, free of charge.

Aspect	Background	Requirement
6.6 Battery longevity	Short life cycles for IT products is a global problem connected to product design, user habits and end of life solutions. One important reason to why the products are discarded or replaced is the short life of main batteries installed in portable IT products. To extend the products' usable life, the main battery must withstand a minimum of 300 charging cycles.	The main battery must be able to withstand a minimum of 300 charging cycles with at least 60% of the initial capacity. The minimum amount of charging cycles with at least 60% of the initial capacity for the main battery must be written on the certificate.
6.7 Battery replaceability	atteries are consumables, often with a shorter life than the product they are installed in. To extend the total lifespan of the product, main batteries must be replaceable, so that products can be repaired and reused. Another concern that makes replaceability important is that the explosive cells of Lithium-ion batteries may pose a fire risk when shredded in the recycling process, causing a hazardous situation for recyclers.	The brand owner must guarantee that the main battery is replaceable by the end-user and/or technician. Instructions on how to replace the battery must be available for anyone to read, free of charge online throughout the whole lifetime of the certificate. The brand owner must provide instructions on how to replace the batteries, either by: A. a digital file or printed in the user manual. B. a direct link to the document on the manufacturer's website.
7 Reduction of hazardous substances		
7.1 Heavy metals	Electronic devices contain hazardous substances like heavy metals and brominated flame retardants. The effects of cadmium, mercury, lead and hexavalent chromium are well documented as substances hazardous both to human health and the environment. They may cause problems, both in the manufacturing phase where workers or the environment can be exposed, in the use phase where additives can leak from the plastic and accumulate in dust, harming both our health and the environment, and at the material recovery, where uncontrolled recycling can cause the release of toxins such as dioxins and furans. This criterion is harmonized with EU RoHS2 Directive (2011/65/EU), except that TCO Certified does not allow mercury in the display panel backlight. As TCO Certified is a global certification, this also affects products sold outside the EU.	7.1.1 Mandate The product must not contain cadmium, mercury, lead and hexavalent chromium.
7.2 Halogens	Halogenated flame retardants and plasticizers are often persistent and can bio-accumulate in living organisms. They are problematic from both a human health and environmental perspective throughout the product life cycle and should be phased out. Workers may be exposed during manufacturing. The substances may migrate from the products to	1. Parts that weigh more than 25 grams (10 g for headsets and 5 g for smartphones) and are made mainly of plastics must not contain flame retardants or plasticizers with halogenated substances or intentionally added halogens as part of the polymer. Exempted are printed wiring board laminates, electronic components and all kinds of cable insulation.

Aspect	Background	Requirement
	humans during the use phase, with unknown health effects. At end of life, the substances risk leaking out into the natural environment. PVC is by far the most common halogen-containing plastic.	2. The product must not contain PBB, PBDE and HBCDD. a. Note: This applies to components, parts and raw materials in all assemblies and sub-assemblies of the product, such as batteries, paint, surface treatment, plastics and electronic components
7.3 Non-halogenated substances	The purpose of this criterion is to increase the knowledge of what non-halogenated substances are used in certified products, how hazardous they are to human health and the environment, and to drive a shift towards less hazardous alternatives. Non-halogenated substances may be problematic in the manufacturing and material recovery phases where workers and the environment can be exposed. This mandate uses the hazard assessment and decision logic framework GreenScreen® for Safer Chemicals, developed by the non-profit organization Clean Production Action (CPA). The GreenScreen criteria are in line with international standards and regulations including the Globally Harmonized System of Classification and Labelling of Chemicals (GHS), OECD testing protocols and the European REACH Regulation. The U.S. EPA's Design for Environment (DfE) Alternatives Assessment is also an important influence for GreenScreen.	Non-halogenated flame retardants used in parts that weigh more than 25 grams (10 g for headsets and 5 g for smartphones) and are made mainly of plastics must have been assigned a GreenScreen benchmark score of 2, 3 or 4 by a licensed GreenScreen Profiler and appear on the public TCO Certified Accepted Substance List. (A benchmark U may only be accepted when the "worst case scenario" for data gaps is considered to be a benchmark 2 or above.) All substances of a mixture must be accounted for. Non-accepted substances must not exceed concentration levels of 0.1% by weight of the flame retardant. Exempted are printed wiring board laminates, electronic components and all kinds of cable insulation.
7.4 Plasticizers	Plasticizers are increasingly associated with negative environmental and human health impacts. RoHs is a restricted substances list that, beginning in 2019, restrict the use of four phthalates. TCO Development is committed to take a much broader approach by identifying and restricting not only these four, but all substances of high concern used in IT products. Our criteria are therefore designed to make sure that replacement substances are independently assessed as safer alternatives, and that transparency increases. The full list of safer alternatives is available on tcocertified.com.	Plasticizers used in product housing and cable insulations must have been assigned a GreenScreen benchmark score of 2, 3 or 4 by a licensed GreenScreen profiler and appear on the public TCO Certified Accepted Substance List. A benchmark U is only accepted when the "worst case scenario" for data gaps is considered to be a benchmark 2 or above. The product must not contain Bis (2-ethylhexyl) phthalate (DEHP), Butyl benzyl phthalate (BBP), Dibutyl phthalate (DBP), and Diisobutyl phthalate (DIBP). No parts of the product are exempted. All substances of a plasticizer mixture must be accounted for. Non-accepted ingredients must not exceed concentration levels of 0.1% by weight of the plasticizer.
7.5 Hazardous substances in product packaging	The use of hazardous substances in packaging materials is problematic and should be minimized. It poses a risk to human health and the environment, not least because packaging materials have a short lifespan and generate large volumes of waste. Several hazardous substances are regulated in many countries, and the use of them should be phased out.	The packaging material must not contain lead (Pb), cadmium (Cd), mercury (Hg) or hexavalent chromium (Cr6). Plastic packaging material must not contain organically bound halogens.

Aspect	Background	Requirement
8 Material recovery		
8.1 Material coding of plastics	The best way of reducing IT products' environmental impact is to extend product life through reuse. Once this no longer is possible, the materials must be recycled. By coding the plastic parts, recycling is made easier and the materials can be used in new products	Parts made mainly of plastics weighing more than 25 grams (5 grams for smartphones) must be material coded in accordance with ISO 11469 and ISO 1043-1, -2, -3, -4. Exempted are printed wiring board laminates as well as plastic parts containing other materials in any significant amounts.
8.2 Product packaging	Packaging is a well-known environmental problem that is regulated in many countries worldwide. Packaging material has a short lifetime and generates large volumes of waste.	Non-reusable packaging components weighing more than 25 grams must be possible to separate into single material types without the use of tools. Exempted is reusable packaging.
8.3 Take back system	The vast amount of electronic waste in the world today is a rapidly growing environmental problem. It is therefore important that manufacturers provide mechanisms to take back their equipment. This is consistent with the principle of individual producer responsibility, wherein each manufacturer must be financially responsible for managing its own branded products at end-of-use. Currently, large amounts of electronic waste is being exported to developing countries where it is managed unsustainably, burdening local communities with this global environmental problem. The Basel Convention governs the export of many types of electronic waste, however it is not properly implemented in all countries. With this mandate,TCO Development aims to influence the expansion of better electronic waste management practices to more countries.	The brand owner (or its representative, associated company or affiliate) must offer their customers the option to return used products for environmentally acceptable recycling methods in at least one market where the product is sold and where electronics take back regulation is not in practice at the date of application. At least one option must be fulfilled: 1. Product sold on WEEE legislation markets or similar 2. World-wide product take back 3. One additional market lacking WEEE legislation where product take back is offered

Table 42: EPEAT requirements for Mobile Phones [based on UL 110 Edition 2 – 2017 Standard for Sustainability for Mobile Phones

Area	Requirement
7. Supply Chain Management of Materials	R 7.1.1 Compliance with the European Union REACH Regulation O 7.2.1 Reduction of European Union REACH Candidate SVHC Substances O 7.3.1 Substitutions assessment O 7.4.1 Requesting substance inventory O 7.4.2 Receiving substance inventory
8. Sustainable Materials Use	R 8.1.1 Declaration of post-consumer recycled and biobased plastics content O 8.1.2 Post-consumer recycled plastic and biobased plastic content in the mobile phone O 8.1.3 Post-consumer recycled plastic and biobased plastic content in accessories
9. Substances of Concern	R 9.1.1 Compliance with the European Union RoHS Directive R 9.2.1 Restrictions of extractable nickel O 9.2.2 Restrictions of DEHP, DBP, and BBP product O 9.2.3 Restriction of bromine and chlorine R 9.2.4 Restriction of cadmium and mercury in the mobile phone battery cell R 9.2.5 Restriction of substances in textile and leather
10. Energy Use Requirements	R 10.1.1 Battery charger systems O 10.1.2 Reduction of energy consumption of battery charging systems R 10.1.3 External power supply energy efficiency O 10.1.4 Reduced maintenance mode power
11. End of Life Management	R 11.1.1 Take-back program R 11.2.1 Primary recyclers third party certified R 11.3.1 Battery removability/replacement by qualified repair service providers or authorized repair providers O 11.3.2 Battery removability/replacement instructions O 11.3.3 Battery removability/replacement without use of tools R 11.4.1 Ease of disassembling mobile phone O 11.4.2 Further ease of disassembling mobile phone R 11.5.1 Feature to erase user data from mobile phone R 11.6.1 Repair and refurbishment O 11.6.2 Further repair and refurbishment R 11.7.1 Availability of replacement parts R 11.8.1 Notification regarding and the identification of materials and components requiring selective treatment

Area	Requirement
12. Packaging	O 12.1.1 Use of recyclable fiber based packaging materials R 12.2.1 Separability and labelling of plastics in packaging O 12.3.1 Use of post-consumer recycled plastic packaging R 12.4.1 Expanded polystyrene packaging (EPS) restriction R 12.5.1 Recycled content in fiber packaging O 12.6.1 Environmentally preferable paper/paperboard in POS packaging O 12.6.2 Environmentally preferable paper/paperboard for printed content R 12.7.1 Restriction of chlorine in packaging materials R 12.8.1 Heavy metal restriction in packaging O 12.9.1 Improve packaging efficiency
13. Corporate Sustainability	R 13.1.1 Corporate sustainability (CS) reporting O 13.2.1 Corporate sustainability (CS) reporting in the supply chain O 13.3.1 Third party assurance of corporate sustainability (CS) reporting
14. Life Cycle Assessment	O 14.1.1 Conducting a life cycle assessment O 14.2.1 Product LCA third-party verification of making LCA publicly available
15. Supply Chain Impacts	O 15.1.1 Supplier responsibility R 15.2.1 Final assembly facilities environmental management system O 15.2.2 Supplier production facilities environmental management system R 15.3.1 Conflict minerals public disclosure O 15.4.1 Reduce fluorinated gas emissions resulting from flat panel display manufacturing

ANNEX II – REPARABILITY SCORES FOR SMARTPHONES BY IFIXIT AND IP LEVELS

Reparability Scores for smartphones available on the market as published by iFixit (2019). IP Levels for model on the market are provided by the GSMARENA[214].

Table 43: Reparability Scores vs IP Levels for smartphones available on the market (iFixit 2019 and GSMARENA 2019)

Model (Year)	Characteristics	Score	IP Level
Fairphone 2 (2015)	+ The most commonly failing components, battery and display, can be replaced without tools. + Internal modules are secured with Phillips #0 screws and simple spring connectors. + Individual modules can be opened, and many components can be individually replaced.	10	NA
Shift 6m	+ Battery and screen repairs are prioritized. + Throughout the phone only one type of screw head and length. + Manufacturer provides a few repair guides and a screwdriver is shipped with the phone.	9	NA
Motorola Droid Bionic 2011	+ No tools are necessary for changing the SIM and microSD + The battery can be removed in seconds. +The phone is held together with a limited number of screws and plastic clips. Adhesive is minimally used in its construction	9	NA
Motorola Atrix 4G 2011	+The LCD is separable from the glass front panel, making them independently replaceable. + The phone is held together with a limited number of screws and plastic clips. Adhesive is minimally used in its construction. + The battery can be removed in seconds..	9	NA
Xiaomi Redmi Note 3 2015	+ Despite no external screws, the rear case is fairly easy to remove. + Battery is easy to access and remove. − Display assembly is a single fused component, that requires disassembling the entire phone to replace.	9	NA
LG G5 2016	+ The user-removable, slide-out battery is a huge boon to phone lifespan. + No glue and few screws make for a relatively simple opening procedure. − The fused display assembly will need to be replaced if the LCD or glass breaks, increasing costs.	8	NA

[214] https://www.gsmarena.com/ (Accessed on 6 September 2019)

Model (Year)	Characteristics	Score	IP Level
LG G4 2015	+ Rear panel and battery can be removed with no tools. +Many components are modular and can be replaced independently. − Fused display assembly—glass and LCD will need to be replaced together if one or the other breaks.	8	NA
Google Nexus 5 2013	+ Very modular design allows independent replacement of several wear-prone components—like the headphone jack and speakers. + Only very mild adhesive holds the battery in place, making it fairly easy to safely remove and replace. − The glass and LCD are fused to the display frame. Fixing broken glass will be either expensive or very difficult.	8	NA
Samsung Galaxy S4 2013	+ The battery can be replaced in seconds, without any tools. + Very easy to open for access to internal components. − The glass is fused to both the display and the display frame, increasing repair costs.	8	NA
Blackberry Z10 2013	+The battery can be replaced without any tools. +Motherboard and display come out with little difficulty and are held in place with little adhesive Smaller components (headphone jack, camera) are modular and can be replaced individually, but have somewhat strong adhesive holding them in place.	8	NA
Samsung Galaxy Note II 2012	+Battery is easy to replace. +Very easy to open for access to internal components. −Components adhered to the back of a fused display assembly.	8	NA
Samsung Galaxy S III 2012	+The battery can be replaced without any tools. +Very easy to open and access internal components. The glass is fused to both the display and the display frame, increasing repair costs.	8	NA
Samsung Galaxy Note 2011	+Battery is easy to replace +Very easy to open for access to internal components. −Components adhered to the back of a fused display assembly.	8	NA
Samsung Galaxy S II 2011	+Battery is easy to replace. +Very easy to open for access to internal components. −Components adhered to the back of a fused display assembly.	8	NA

Model (Year)	**Characteristics**	**Score**	**IP Level**
Nokia N8 2010	+The battery, although considered by Nokia not to be user-serviceable, can be easily removed. +The AMOLED display easily comes apart from the glass, which means that you can replace the glass and the display independently. −Removing the cameras is near-impossible, and requires tedious, potentially detrimental steps..	8	NA
Moto Z 2017	+Pull-tab on battery, easy to access once you have the device open. +Modular assembly allows independent replacement of many components −Charging port soldered to the motherboard means a common repair will be very expensive.	7	NA
Vivo X7 Plus 201	+Battery is fairly easily accessible and removable. +Parts could be more modular, especially mechanical/high wear components. −The single unit display assembly is annoying to reach, and will be a costly part.	7	NA
Oppo R9m 2017	+Battery is fairly easily accessible and removable. +Most components are extremely modular making for cheaper repairs. −The opening procedure is extremely tough, clips are very stiff and likely to be broken.	7	NA
OnePlus 5 2017	+There are no proprietary screws. +The OnePlus 5's display is held on by easy to dispatch reusable plastic clips. −The display and glass are fused and the home button is integrated into the display assembly making repair of all three of these parts more complicated and expensive.	7	NA
Wiko Pulp 4G Phone 201	+Replacing the battery is easy as pie with the swappable back cover. +This phone doesn't use excessive glue nor proprietary screws—we found only Phillips throughout the entirety. −Unfortunately, the components on the daughterboard are soldered on, making a repair on an individual component difficult.	7	NA
Meizu MX6 2016	+The display assembly is the first component out, simplifying screen repairs. +Modular components with spring contacts, large screws, and thoughtful cabling all make repair cheaper and easier. −The MX6 uses Pentalobe security screws on the exterior, requiring a specialty screwdriver to open the phone before any repair.	7	NA
Google Pixel 2016	+The battery is secured with removable adhesive tabs, making replacement simple. +Many components are modular and can be replaced independently. −The fused display is thin and unsupported, and must be removed to access any other component.	7	NA

Model (Year)	Characteristics	Score	IP Level
Google Pixel XL 2016	+Many components are modular and can easily be replaced once the display assembly is removed. +The battery has a removal tab and is adhered by a modest amount of adhesive, making its removal painless. −The opening procedure requires prying up a thin, poorly-supported display assembly making it difficult to open the phone without damage.	7	NA
Apple iPhone 7 Plus 2016	+The battery is straightforward to access. Removing it requires specialty screwdrivers and knowledge of the adhesive removal technique, but is not difficult. +The solid state home button eliminates a common point of failure. −With the addition of tri-point screws, many iPhone 7 Plus repairs will require up to four different types of drivers.	7	IP67
Apple iPhone 7 2016	+The battery is straightforward to access. Removing it requires specialty screwdrivers and knowledge of the adhesive removal technique, but is not difficult. +The solid state home button eliminates a common point of failure. −With the addition of tri-point screws, many iPhone 7 repairs will require up to four different types of drivers.	7	IP67
Huawei P9 2016	+Modular components with spring contacts, thoughtful cabling, and minimal adhesive all make repair cheaper and easier. +The battery is straightforward to access. Removing it requires knowledge of the adhesive removal technique, but is not difficult. −The display assembly is a fused unit, and replacement requires near complete disassembly of the phone.	7	NA
Nexus 5x 2015	+Many components are modular and can be replaced independently. +Standard Phillips screws means a driver is easy to find. −Fused display assembly—glass and LCD will need to be replaced together if one or the other breaks.	7	NA
Apple iPhone 6 Plus 2015	+The display assembly continues to be the first component out, simplifying screen repairs. +The battery is straightforward to access. Removing it requires a proprietary +Pentalobe screwdriver and knowledge of the adhesive removal technique, but is not difficult. −The iPhone 6s Plus still uses proprietary Pentalobe screws on the exterior, requiring a specialty screwdriver to remove.	7	NA
iPhone 6s 2015	+The display assembly continues to be the first component out, simplifying screen repairs. +The battery is straightforward to access. Removing it requires a proprietary pentalobe screwdriver and knowledge of the adhesive removal technique, but is not difficult. −The iPhone 6s still uses proprietary Pentalobe screws on the exterior, requiring a specialty screwdriver to remove.	7	NA

Model (Year)	Characteristics	Score	IP Level
OnePlus 2 2015	+A single (non-proprietary) screw head decreases cost of tools for repairs. +Many components are modular and can be replaced independently. −The LCD and digitizer glass are fused together and must be replaced as a single part; heat is required to remove it from the midframe.	7	NA
Google Nexus 6 2014	+Pressure contacts and cable connectors make the modular components (cameras, buttons, headphone jack) easy to replace. +The Nexus 6 uses a single kind of screw, although it's a fairly uncommon size (T3). −Several components (vibrator, SIM slot, speaker, USB port) are soldered directly to the motherboard and will be more difficult to replace than if they were connected by cable.	7	NA
iPhone 6 Plus 2014	+Continuing the trend from the iPhone 5 series, the display assembly comes out of the phone first, simplifying screen repairs. +The battery is straightforward to access. Removing it requires a proprietary pentalobe screwdriver and knowledge of the adhesive removal technique, but is not difficult. −The iPhone 6 Plus still uses proprietary Pentalobe screws on the exterior, requiring a specialty screwdriver to remove.	7	NA
iPhone 6 2014	+Continuing the trend from the iPhone 5 series, the display assembly comes out of the phone first, simplifying screen repairs. +The battery is straightforward to access. Removing it requires a proprietary pentalobe screwdriver and knowledge of the adhesive removal technique, but is not difficult. The iPhone 6 still uses proprietary Pentalobe screws on the exterior, requiring a specialty screwdriver to remove.	7	NA
Fairphone 1.0 2014	+The battery can be replaced without any tools. +It's very easy to open and access the internal components. −Several smaller components are soldered to the motherboard, increasing repair difficulty (front-facing camera, vibrator motor, LED flash, and headphone jack).	7	NA
Motorola Moto X 1st Generation 2013	+Pressure contacts and cable connectors make the modular components (cameras, buttons, headphone jack and speakers) easy to replace. +The Moto X uses a single kind of screw, although it's a fairly uncommon size (T3). Sticky adhesive on the back cover is annoying and will slow opening the phone.	7	NA
Samsung Galaxy Nexus 2011	+Battery replacement is incredibly simple thanks to the removable rear panel. +Minimal adhesive makes removal of the motherboard and other components a snap. −Removing the rear case to access the motherboard and other internals requires a lot of careful prying and guitar-picking.	7	NA

Model (Year)	**Characteristics**	**Score**	**IP Level**
Nexus S 2010	+Battery is very easily replaceable -- just remove the back cover to swap it out. +The motherboard comes out easily once you're inside, as it's held in place by regular screws and connectors. −Front panel is attached with adhesive instead of screws, so it's harder to take off than on the iPhone.	7	NA
iPhone 3G 2009	+LCD and front glass are not fused and can be replaced individually. +Standard Phillips screws used throughout. Battery is buried under the logic board, making it difficult to replace.	7	NA
iPhone 3GS 2009	+LCD and front glass are not fused and can be replaced individually. +Standard Phillips screws used throughout. −Battery is buried under the logic board, making it difficult to replace.	7	NA
iPhone XR 2018	+The display-first opening procedure and easy access to the battery remain design priorities. +A broken display can be replaced with minimal hardware removal, and with a little care you can preserve Face ID. − Glass on front and back doubles the crackability—and broken back glass requires an entire chassis replacement.	6	IP67
iPhone XS 2018	+Critical display and battery repairs remain a priority in the iPhone's design. +A broken display can be replaced without removing the biometric Face ID hardware. − Glass on front and back doubles the likelihood of drop damage—and if the back glass breaks, you'll be removing every component and replacing the entire chassis.	6	IP68
Google Pixel 2 XL 2017	+Many components are modular and can be replaced once the display assembly is removed. +All of the screws are common Phillips #00 screws, and there are only 9 of them. The battery's loss of pull-tab adhesive, plus tightly walled-in placement, makes it much harder to remove.	6	IP67
Google Pixel 2 2017	+Front panel is fairly easy to remove and replace +Standard screws used throughout. Cable placement makes battery removal more difficult than necessary.	6	IP67
iPhone 8 Plus 2017	+The display and battery are straightforward to access—with the proper knowledge and tools. +Wireless charging means less wear on the all-purpose Lightning port, a common point of failure. − Despite alleged durability, the back glass is breakable and next to impossible to replace when cracked.	6	IP67

Model (Year)	Characteristics	Score	IP Level
iPhone 8 2017	+The two most commonly replaced components, display and battery, remain straightforward to access with the proper knowledge and tools. +The addition of wireless charging means less strain on your Lightning port, a common point of failure. − The durability of the glass back remains to be seen—but replacements are likely to be very difficult.	6	IP67
Sony Xperia X Compact 2017	+Modular design allows for replacement of many individual components. Battery is fairly easy to access and remove, but requires removal of the delicate NFC antenna to replace. − Adhesive used throughout will need to be replaced during reassembly, and may never be as waterproof again.	6	IP68
Xiaomi Mi 5 2017	+The motherboard and battery can be replaced independently and easily. +Most components are modular and can be replaced independently. − The display is difficult to replace, requiring complete disassembly and purchasing consumables.	6	NA
AsusZenfone 3 Max 2017	+Battery is easily accessible and removable. Parts could be more modular, especially mechanical/high wear components. − The opening procedure is extremely tough, clips are stiff and likely to be broken, and the SIM slot bends easily.	6	NA
Vivo X7 2017	+Battery is fairly easily accessible and removable. Parts could be more modular, especially mechanical/high wear components. −The opening procedure is extremely tough, clips are very stiff and likely to be broken.	6	NA
Huawei Mate 8 2017	+Many components are modular and can be individually replaced. Opening the phone requires only a Torx screwdriver and a prying tool (No adhesive holding it together). − A tamper evident sticker must be removed when disconnecting the battery.	6	NA
Lenovo K5 Note 2017	+Battery is replaceable with just a couple of tools. +A single Phillips 00 driver takes care of all the screws. − Replacing the display assembly requires removing every other component from the device first.	6	NA
Shift 5.1	+Cover and battery are easy to remove and can be swapped without using tools. +No excessive glue and no proprietary screws are used, only Phillips #000. − Lots of components and connectors are soldered to the motherboard. They could be soldered by hand if needed but this makes repairs more difficult.	6	NA

Model (Year)	**Characteristics**	**Score**	**IP Level**
iPhone SE 2016	+The display assembly is the first component out of the phone, simplifying screen replacements. +The battery is fairly easy to access, even though it's not technically "user replaceable." − The Touch ID cable could be easily ripped out of its socket if a user is not careful when opening the phone.	6	NA
iPhone 5c 2013	+Just like in the iPhone 5, the display assembly is the first component out of the phone, simplifying screen replacements. +The battery is still fairly easy to access, even though it's not technically "user replaceable." − Adhesive on the antenna connectors hinder disassembly.	6	NA
iPhone 5s 2013	+Just like in the iPhone 5, the display assembly is the first component out of the phone, simplifying screen replacements. +The battery is still fairly easy to access, even though it's not technically "user replaceable." −The fingerprint sensor cable could be easily ripped out of its socket if a user is not careful while opening the phone.	6	NA
iPhone 4S 2011	+The iPhone 4S is still held together primarily with screws and limited adhesive. +The rear panel and battery are both easy to remove and replace (provided you have the correct screwdriver). Apple is again using Pentalobe screws to secure the rear panel and keep people out	6	NA
SamsungGalaxy S 4G2011	+Removing the rear panel to replace the microSD/SIM cards and the battery requires no tools. +Attaching components like the headphone jack to separate cables makes their replacement less costly than replacing the entire motherboard. −The front panel is adhered to the AMOLED display, so they must be replaced as one expensive unit.	6	NA
Motorola Droid 3 2011	+There were no security screws in the entire device. +The battery was not soldered to anything and was easy to replace. There is a lot of adhesive holding things together, making disassembly and reassembly difficult.	6	NA
iPhone 4 Verizon 2011	+The iPhone 4 is held together primarily with [lots of] screws, sans tabs, and limited adhesive. +The rear panel and battery are both easy to remove and replace (provided you have the right screwdriver). −Apple is using Pentalobe screws to secure the rear panel and keep people out.	6	NA
OnePlus 6 2018	− Display replacement, the most common repair, is not prioritized in the design and will take a lot of work. − Front and back glass means twice the risk of cracks—without even the benefit of wireless charging. +The battery can be accessed almost the moment you open the phone, and is only lightly adhered in place. Plus, there's a convenient pull tab.	5	NA

Model (Year)	**Characteristics**	**Score**	**IP Level**
Huawei Mate 9 2017	− Replacing a broken display, one of the most common repairs, will be one of the most difficult ones on this phablet. The battery is trapped behind some flex cables and is glued tightly into place, but still can be swapped out when its power starts to fade away. Most of the components—like both camera units, the loudspeaker, and the USB +board—can be replaced. Even the proximity sensor and the NFC antenna are modular.	5	NA
LG G6 2017	−Front and back glass doubles the crackability, and strong adhesive on both makes it tough to begin any repair. −Components adhered to the back of a fused display assembly. +Many components are modular and can be replaced independently.	5	IP68
Samsung Galaxy Alpha 2014	−The display assembly is held in with a significant amount of adhesive and requires very careful prying and a considerable amount of heat to remove without cracking the thin glass or cutting cables. −Replacing anything other than the battery requires first removing the display, risking extra damage on the way to a repair. +The battery is incredibly easy to remove and replace.	5	NA
Samsung Galaxy S5 Mini 2014	− Replacing anything other than the battery requires first removing the display, risking extra damage on the way to a repair. − The display is now one of the first components out, making its replacement a little faster. However, it is held in with a significant amount of adhesive and requires very careful and persistent prying, as well as a considerable amount of heat to remove without cracking the glass or cutting cables. + The battery is incredibly easy to remove and replace.	5	NA
OnePlus One 2014	− Replacing anything other than the battery requires first removing the display, risking extra damage on the way to a repair. The display is now one of the first components out, making replacements a little faster. However, it is held in with a significant amount of adhesive and requires very careful and persistent prying and a considerable amount of heat to remove without cracking the glass or cutting cables. +The battery is incredibly easy to remove and replace.		NA
HTC Surround 2011	− Unable to access the internal MicroSDHC card without voiding the warranty. − It is very difficult to access the front panel and LCD for replacement. Relatively easy to remove the rear case to replace the battery.	5	NA

Model (Year)	Characteristics	Score	IP Level
Huawei Mate 20 Pro 2018	− Glued-down front and back glass means greater risk of breakage while making repairs difficult to start. − Screen repairs require a lot of disassembly while battling tough adhesive. Many components are modular and can be replaced independently.	4	IP53
Google Pixel 3 2018	− Display repairs are much more difficult than previous models, requiring complete disassembly of the phone. − To service any component, you'll have to painstakingly un-glue (and later re-glue) the glass rear panel. +The only screws are standard T3 Torx fasteners.	4	IP68
Google Pixel 3 XL 2018	− Display repairs are much more difficult than previous models, requiring complete disassembly of the phone. −To service any component, you'll have to painstakingly un-glue (and later re-glue) the glass rear panel. +The only screws are standard T3 Torx fasteners.	4	IP68
LG G7 Thin Q 2018	− Front and back glass make for double the crackability, and strong adhesive on both makes it tough to access the internals for any repair. − Screen repair, the most common type repair, is not prioritized, requiring an almost complete disassembly while battling tough adhesive. +Lots of components are modular and can be replaced independently	4	IP68
Huawei P20 Pro 2018	− Double the risk for breakage with glass front and back. − Replacing the screen requires going through at least two layers of adhesive and some disassembly. +Many components are modular and can be replaced independently.	4	IP67
SamsungGalaxy S9 2018	− Glued-down glass both front and back means greater risk of breakage, and makes repairs difficult to start. − Screen repairs require a lot of disassembly while battling tough adhesive. +Many components are modular and can be replaced independently.	4	IP68
SamsungGalaxy S9 Plus 2018	− Glued-down glass both front and back means greater risk of breakage, and makes repairs difficult to start. − Screen repairs require a lot of disassembly while battling tough adhesive. +Many components are modular and can be replaced independently	4	IP68

Model (Year)	**Characteristics**	**Score**	**IP Level**
Huawei Mate 10 Pro 2017	– A damaged front camera means switching the whole display including the frame, or damaging the display while trying to remove it. – And replacing the display—the most common repair—means taking out almost every component. +Despite the IP67-rated seals, the back cover is fairly easy to open.	4	IP67
Samsung Galaxy Note 2017	– All repairs require removing the glass rear panel, which is challenging due to the large amount of adhesive. – Replacing the display requires removing the glass rear panel and the display, both of which are fragile and secured with strong adhesive. +Many components, including all of those that experience wear, are modular and can be replaced independently.	4	IP68
Samsung Galaxy Note Fan Edition 2017	– Front and back glass make for double the crackability, and strong adhesive on the rear glass makes it very difficult to gain entry into the device. – Because of the curved screen, replacing the front glass without destroying the display is probably impossible. +Many components are modular and can be replaced independently.	4	IP68
Samsung Galaxy S8 2017	– Front and back glass make for double the crackability, and strong adhesive on both makes it tough to access the internals for any repair. – Because of the curved screen, replacing the front glass without destroying the display is extremely difficult. +Lots of components are modular and can be replaced independently.	4	IP68
Samsung Galaxy S8 Plus 2017	– Front and back glass make for double the crackability, and strong adhesive on both makes it tough to access the internals for any repair. – Because of the curved screen, replacing the front glass without destroying the display is extremely difficult. +Many components are modular and can be replaced independently.	4	IP68
Samsung Galaxy Note7 2016	– Front and back glass make for double the crackability, and strong adhesive on the rear glass makes it very difficult to gain entry into the device. – Because of the curved screen, replacing the front glass without destroying the display is probably impossible. +Many components are modular and can be replaced independently.	4	IP68
Samsung Galaxy S6 2015	– Front and back glass make for double the crackability, and strong adhesive on the rear glass makes it very difficult to gain entry into the device. – Replacing the glass without destroying the display is probably impossible. Many components are modular and can be replaced independently.	4	NA

Model (Year)	Characteristics	Score	IP Level
Motorola Droid 4 2012	− Keyboard contacts are located on the motherboard, making keyboard replacement costly and difficult. − Tons of glue adheres the glue that is securing the glue to the glue that holds the phone together. +The lack of security or proprietary screws is a welcome sight.	4	NA
Motorola Droid RAZR 2011	− The front panel is adhered to the AMOLED display, so they must be replaced as one expensive unit. − All plastic frames and casing proved to be incredibly tedious to remove, and felt like they would break at any moment. Once the battery and motherboard are within reach, replacement is easy—no soldering required.	4	NA
Samsung Galaxy S10 2019	− Battery replacement is possible, but still unnecessarily difficult. − Glued-down glass both front and back means greater risk of breakage, and makes repairs difficult to start. +A single Phillips driver takes care of all the screws.	4	IP68
Samsung Galaxy S7 Edge 2016	−The display needs to be removed (and likely destroyed) if you want to replace the USB port. −Front and back glass make for double the crackability, and strong adhesive on the rear glass makes it very difficult to gain entry into the device. +Many components are modular and can be replaced independently.	3	NA
Samsung Galaxy S7 2016	−The display needs to be removed (and likely destroyed) if you want to replace the USB port. −Front and back glass make for double the crackability, and strong adhesive on the rear glass makes it very difficult to gain entry into the device. +Many components are modular and can be replaced independently.	3	NA
Samsung Galaxy S6 Edge 2015	−Front and back glass make for double the crackability, and strong adhesive on the rear glass makes it very difficult to gain entry into the device. −The battery is very tightly adhered to the back of the display, and buried beneath the midframe and motherboard. + components are modular and can be replaced independently.	3	NA
Amazon Fire 2014	−Tons of cables and connectors make disassembly tedious and reassembly difficult. −The four Dynamic Perspective cameras are encased in glue. Replacement will mean heat and cutting. +External, non-proprietary screws means no adhesive holding the device together, and an easier time getting in.	3	NA

Model (Year)	Characteristics	Score	IP Level
Nexus 6P 2015	−It's very difficult—although not impossible—to open the device without damaging the glass camera cover. Because of the unibody design, this makes every component extremely difficult to replace. −The display assembly cannot be replaced without tunneling through the entire phone. This makes one of the most common repairs, a damaged screen, difficult to accomplish. −Tough adhesive holds the rear cover panels and battery in place.	2	NA
HTC One M9 2015	−The battery is buried beneath the motherboard and adhered to the midframe, hindering its replacement. −The display assembly cannot be replaced without tunneling through the entire phone. This makes one of most common repairs—a damaged screen—very difficult to accomplish. −Intense adhesives make many components difficult, and even dangerous, to remove and replace.	2	NA
HTC One M8 2014	−It's very difficult—although no longer impossible—to open the device without damaging the rear case. This makes every component extremely difficult to replace. −The battery is buried beneath the motherboard and adhered to the midframe, hindering its replacement. −The display assembly cannot be replaced without tunneling through the entire phone. This makes one of most common repairs, a damaged screen, very difficult to accomplish.	2	NA
iPhone 1st Generation 2009	−Hidden clips make it nearly impossible to open rear case without damaging it. −Soldered battery is very difficult to replace. +Standard Phillips screws used throughout.	2	NA
Essential Phone 2017	−The USB-C port is soldered to the motherboard, and with no headphone jack it'll be subject to extra wear. −Nearly invisible seams and copious adhesive means any attempt at repair is likely to inflict as much damage as it fixes. −Did we mention we had to freeze it?	1	NA
HTC One 2013	−Very, very difficult (possibly impossible?) to open the device without damaging the rear case. This makes every component extremely difficult to replace. −The battery is buried beneath the motherboard and adhered to the midframe, hindering its replacement. −The display assembly cannot be replaced without removing the rear case—this will make the most common repair, a damaged screen, nearly impossible.	1	NA

NA: not available

KJ-NA-30068-EN-N

The European Commission's science and knowledge service

Joint Research Centre

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

EU Science, Research and Innovation

EU Science Hub

Publications Office of the European Union

doi:10.2760/037522

ISBN 978-92-76-15411-2