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Abstract

Mobile communications devices are an interesting case study for sustainability. Introduced only a few years ago to the mass market, their sales are increasing at an accelerating rate. At the same time the technology is undergoing rapid development and the consumers are learning to use them through services and applications.
The aim of this study was to study the possible sustainability issues of the emerging technology using the PROSUITE methodology. The study focused on smartphones and their associated products system (including devices, accessories, networks and internet data transfer).

Sustainability was evaluated through the five pillar approach of PROSUITE: human health, prosperity, social wellbeing, natural environment and exhaustible resources. As the methodology was still under development during the case study, all aspects were not quantified thoroughly. The results provided however an overview of the sustainability aspects of smartphones and could be used to identify certain hotspots or key performance indicators in the technology.

In order to facilitate the interpretation across pillars, the impacts on the five pillars were normalized to average world citizens' impacts (i.e. person equivalents) and weighted to an overall single score. Based on the results, the main sustainability issues are related to increased prosperity and on the other hand to increased social inequalities. The impacts on prosperity and social well-being were several orders of magnitude greater than the impacts to human health and natural environment. The impacts on human health and natural environment would seem to be minor based on the PROSUITE methodology. Of the impact categories considered in traditional LCA, the impact on exhaustible resources (metals) would seem to be the main impact.

The case study also highlighted several problems in the PROSUITE methodology:

- **First** of all, the method ignores the dynamics of product sales and focuses on a fixed single year (2030). In the case of smartphones, the sales in 2030 might already be declining; therefore an assessment of a single year underestimates the whole impacts. An integral of the impacts over time would be a more recommended approach.
- **Second**, the impact assessment methods for exhaustible resources do not cover the special metals found in smartphones (indium, neodymium, etc.). More research on including also these rarer elements would be necessary to improve the usability of the method for novel ICT technologies.
- **Third**, the interpretation is sensitive to assumptions about normalization and weighting. For example in the smartphone case study, most of the social impacts were assessed to be caused by the difference of value added in developing and developed countries compared to the average situation. It is difficult to interpret, why an increase of prosperity in both regions would result in a social impact, which would be quantified to be an order of magnitude more damaging than child labour.
- **Fourth**, currently there is no possibility to conduct an uncertainty assessment which would cover the whole analysis from inventory to impact assessment, normalization and weighting. Uncertainty assessment is possible only in relation to the inventory. The lack of uncertainty and sensitivity analysis limits the usefulness of the results in decision making.
- **Fifth**, the instruction to aggregate the qualitative impact indicators of social well-being into a single score is missing. This is required when the aim is to aggregate five sustainable pillars. Without this instruction, there is a great dangerous to misunderstand the role of social well-being pillar in the final interpretation

Based on the assessment and additional information from literature, the following principles (describing key performance indicators) were considered to be important for the smartphone technology:

- to ensure that the rare metals are recycled, and find ways to replace them
- to increase the lifespan of a smartphone in use
- to control the data traffic per phone and improve the energy efficiency of data transfer
- to ensure that child labour or low wage labour is not used in the electronics assembly stage
- to improve the use of smartphones in abating greenhouse gas emissions and other environmental aspects in other product life cycles through green apps

1. Case Study: Multifunctional mobile devices

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1.1. Goal and scope of the case study

1.1.1. Scientific background/description of the case

Sustainability is increasingly important in product design (Nidumolu et al., 2009). At the same time, assessing it has become increasingly complex (Guinée et al., 2011).

Since the concept of sustainable development was invented, it has been considered as a multidimensional issue. Initially it had two pillars: environmental and social sustainability (Brundtland Report, 1987). Later on an economic sustainability pillar was added. Most people agree on the need of having a multidimensional view of sustainability, but very few agree on how to measure it.

Several so called single score indicators for sustainability have been developed. The most commonly used currently is the carbon footprint (Sinden et al., 2008), which equates sustainability with low climate impact per unit of product produced. However, it also is a surprisingly good indicator for other environmental impacts, since many of them are connected to the use of fossil energy (Huijbregts et al., 2006). The main problems, which are ignored by the carbon footprint are the potential toxic effects and biodiversity threats due to land use change (Laurent et al., 2012). To capture the biodiversity losses, species footprints have been developed (Lenzen et al., 2012). The ecological footprint tries to combine fossil energy use and land use requirements into a single metric. Like the carbon footprint, it correlates well with many other aspects of environmental sustainability (Huijbregts et al., 2008), but ignores again the potential toxic effects. The limitations of single score indicators of sustainability become more and more apparent as new impact categories (such as noise and radiation) are added to the field of environmental sustainability (Finnveden et al., 2009). The problem is also amplified when the pillars of social and economic sustainability are included with their arsenal of indicators.

In order to tackle the increasing complexity, some approaches suggest a heuristic for achieving company level sustainability. Some of the most researched approaches are the Natural Step (see Upham, 2000 for a critical appraisal) and Cradle-to-Cradle (Braungart et al., 2007). The One Planet Living network is another example (Desai, 2008). These approaches are based on a set of rules or heuristics to achieve sustainability. For example they might dictate zero carbon, zero waste or the use of only renewable resources as milestones for achieving sustainability. While the rule-based approaches reduce complexity and give straight guidelines, they also lose the transparency in what is meant by sustainability. The heuristics are usually constructed from a given worldview or a framework of sustainability, which might not be the same as for the company managers or stakeholders. If a stakeholder does not agree with the values of the heuristic used by the company, following the rules becomes irrelevant. Heuristics therefore are applicable, if all stakeholders can agree on the set of heuristics to be used, which is not always the case. In addition, in heuristics, all rules are often given the same priority, and all involved parties might not agree with the prioritization.

Sustainability can be thought of as a balancing-act of different goals. Looking from the viewpoint of decision analysis, there are important goals (intrinsic values), sub-goals (means towards ends) and indicators (tools for measuring a progress). Without an overall picture, the indicators may become confusing. Therefore the approach of decision analysis is to organize the indicators into a structured framework. This approach has been used in environmental management in hundreds of applications over the last decade (Huang et al., 2011). (For an accessible overview related to companies see Hammond et al. (1998).) The approach used to quantify sustainability in the PROSUITE project was founded on multiple criteria decision analysis (MCDA). In MCDA, the various facets of sustainable development are brought together in a framework which allows the balancing of different sides of the problem and the identification of common sources for different problems.

In the PROSUITE approach, **a five pillar approach** to sustainability was used instead of the familiar three pillars of environment, economy and society. In the five pillars, sustainability would be measured through the **aspects of** human health, social well-being, natural environment, natural resource availability and economic prosperity**. Throughout the project, preliminary indicators were suggested to measure the five pillars and methods were developed to quantify the impacts. The aim of this case study is to test the new proposed methodology. Also a key goal is to test whether the new framework can give meaningful insights on where to focus product development and on what are the main sustainability issues of an emerging technology. This case study tests the methodology on smartphone technology.

Why smartphones? Mobile phones are not a new technology; they were introduced in Scandinavia in the 1980s. Their global annual sales have been increasing since. By 2008 there were 4 billion mobile phone subscriptions and by 2012 the amount had increased to almost 6 billion (IDC, 2013; Gartner, 2013). The most rapidly growing segment of mobile phones are smartphones (i.e. phones with an operating system, mobile internet and capability for running applications), the annual sales of which have increased from 140 million in 2008 to 700 million in 2012 (IDC, 2013). About 50% of all mobile phones sold in Q1 2013 were smartphones (Ericsson, 2013).

In order to do a prospective assessment of the technology, the future development of it has to be estimated. Future sales are most commonly estimated with a diffusion model, either fitting the model to existing sales statistics or by comparing it to similar products in the market. Like many emerging products, smartphones do not have similar products in the market, but they have a time series of sales from 2008-2012. By using this time series and a widely used market diffusion model (Bass, 1969; Peres et al., 2010), we were able to estimate the sales development of smartphones over the next few decades (Figure 1). The same model was applied to total mobile phones to test the validity of the model and to have an overview of the potential mobile phone technologies, which would eventually replace smartphones. Based on the results, the sales of smartphones are forecasted to grow rapidly in the near future , at which time they have saturated the markets, and repeated purchases will gradually begin to decline. (As a technical note: a repeated purchases rate of 80% was found to give a good fit to data.) It is likely at this stage that another technology would rise to replace the smartphones, but that the overall demand of mobile communication would remain high.

The forecast is naturally filled with uncertainty and could be constructed in different ways. As a sensitivity analysis, two alternative scenarios were constructed: the min and the max scenario. The previously described scenario was considered to be the mid scenario. In the min scenario, no repeated purchases are considered: each consumer will buy only one smartphone. In the max scenario full repeated purchases are assumed: each consumer will keep on buying replacement smartphones forever. The sales scenarios for these three assumptions are presented in the Figure 1.

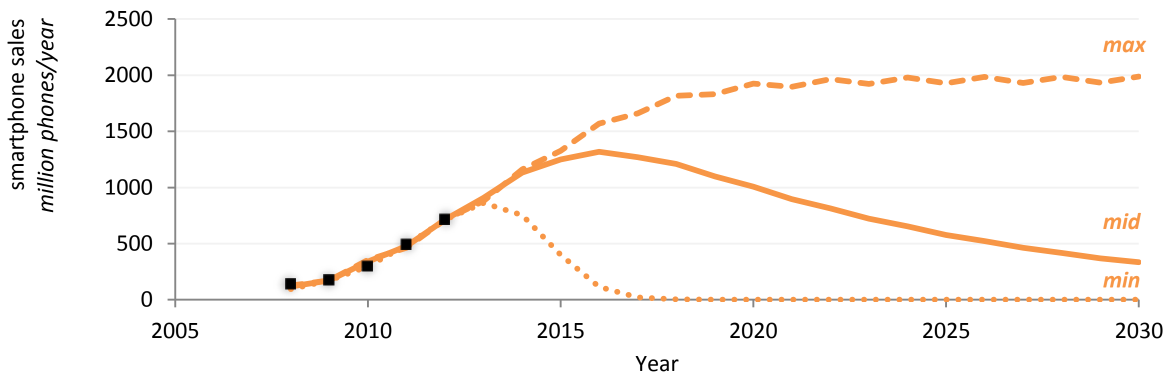


Figure 1. Sales scenarios of smartphones – min (dotted line), mid (full line) and max (broken line). The rectangles observed sales data.

Compared to the earlier mobile phones, the smartphones are much more challenging technically and are manufactured from more energy intensive components. Some of these components, such as the processors and other integrated circuits require large amounts of energy to manufacture (Ecoinvent, 2011; Williams, 2011). Others such as the touchscreen, magnets and batteries require rare metals (neodymium, indium, etc.) with rapidly rising demand and limited supply. Overall it is likely that the supply chain of smartphones is going to have a much larger effect on the surrounding society and environment than what could be predicted from the sales curves.

In addition to sophisticated components, the smartphones also have increased utility. Modern smartphones provide access to the internet and many of the services provided by the smartphones are not possible without internet access. Smartphone applications and usage (such as streaming video) make heavy use of the mobile network, remote data storage and data processing (i.e. "the cloud"). Compared to a previous kind of mobile phone, a smartphone causes approximately 50 times the data traffic in the network (Cisco, 2013). The effects of cloud computing and data storage are not included in this figure. Overall, the rapid increase of smartphones is likely to increase the electricity demand of mobile networks and data centres even further.

Smartphones are entering a point in their development, where the markets are "mature" (Golder and Tellis, 2004). There are several competing manufacturers, who aim to increase their sales by new properties and lower costs. As a part of lowering costs, labour costs have been reduced by moving manufacturing and subcontracting to countries with low labour compensation. This has sparked discussion on the social sustainability of smartphones and on issues of global inequality. From the viewpoint of the European economy in recession, outsourcing has increased import dependency and reduced gross domestic product. On the other hand, providing services and software for smartphones has a great potential for creating employment. Overall, smartphones have a potential for influencing all pillars of sustainability on a macro level.

The aim of this report is to bring together the different aspects of smartphones under the sustainability assessment framework of PROSUITE. The framework builds strongly on the foundation of environmental life cycle assessment (LCA), an assessment methodology which has been developed since the 1980s and is supported by strong standardization and research community (Guinée et al., 2011). Borrowing from that line of thought, the following chapters describe very thoroughly what is analysed ("the functional unit") and with what scope ("system boundaries"). The system boundaries also describe the main data sources used in the study (with detailed description presented in the Annex). The methods for quantifying the five pillars are then reviewed and discussed as they were applied in this case study. That chapter is mainly meant to clarify, and keep transparent, how the results were obtained. Results are first presented per single pillar of sustainability at a time and then integrated. Finally some conclusions about the applicability of PROSUITE methodology to sustainability assessment of emerging technologies are given.

This study is directed to both a scientific audience trying to evaluate the validity of the PROSUITE approach and to businesses interested in assessing the sustainability impacts of their operations. This in itself presents a balancing act between two goals. We hope the scientists reading this are patient with our simplified explanations and the rest of the readers are patient with all the references and loyalty to the scientific prose. Overall we hope that this report will bring some clarity to the main sustainability issues of smartphones.

1.1.2. Functional unit

A functional unit in life cycle assessment is a quantitative measure of the function of a studied system (European Commission, 2010). Since most products could be used in several ways (e.g. a paper weight, a door stopper, concrete filler), it is important to specify in the beginning of the study, on which basis this study has been done. In this study, smartphones are seen as a means of providing mobile communication services to individual people. Alternative formulations could have been to assess smartphones as sources of data traffic in a network, as digital cameras, or as means of remote surveillance. The functional unit in this study focused on consumers and their behaviour.

A good functional unit not only describes what is achieved, it also describes how well these things are achieved. In the case of smartphones, that includes a large amount of positive social impacts. According to the TIME magazine review, mobile communication has had profound changes on people's behaviour and the whole social system. For example, it has increased feelings of security and helped people to obtain more information to improve health of their families (Time Magazine, 2012). In addition, there are documented cases of an increased economic activity and profit for small businesses, e.g. in Africa and India due to mobile phones and smartphones (Jensen, 2007; Aker and Mbiti, 2010). Many of the business owners in the TIME review also mentioned that smartphones have allowed them to access more clients and to make their operations more efficient. For this analysis they were considered to be a part of the functional unit.

The functional unit of this study is the annual use of a single smartphone in the EU-27 area. It is defined more precisely as "**the provision of mobile communication services equivalent to the services provided by the annual use of a typical smartphone [unit of smartphone] in the EU-27 area**". The functional unit would have made it possible to compare alternative products to achieve the same functionality. During the PROSUITE project, this approach was attempted by comparing a smartphone with a basket of other products (Figure 2.).

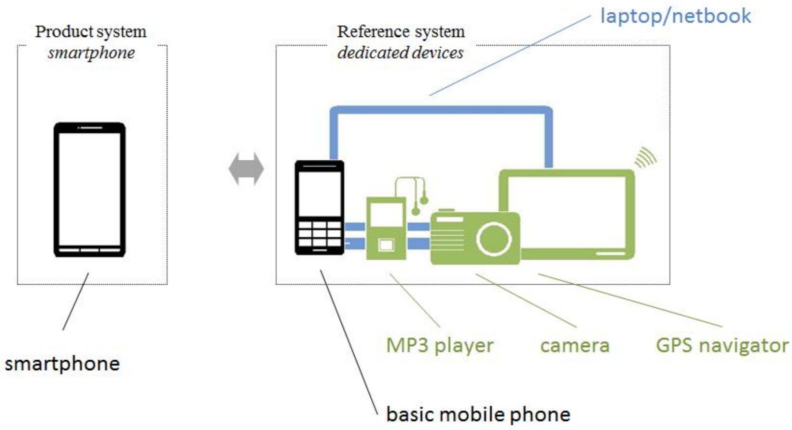


Figure 2. The initial comparative LCA approach - a smartphone device vs. a basket of dedicated devices (Judl et al., 2012).

This approach was abandoned as it became apparent that smartphones provide a very unique set of functionality to users, which is hard to be replaced with other currently available technologies. Smartphones might additionally even induce the use of other devices. Nevertheless, the functional unit helped to specify the analysis and makes it possible to do a comparative analysis, if other products with similar properties become available.

The results are presented per functional unit (one year of smartphone use) and at the technology level (scale of phone sales in in Europe in 2010 and 2030). The European focus was mandated by the funders of the study. In the PROSUITE framework, the impact of an emerging technology is assessed by extrapolating it to year 2030. So the technology level analysis assessed the sustainability of smartphones in Europe in 2030 using two estimates of sales amounts. These were compared to the reference system of year 2010 smartphone sales. The aim was therefore to assess the sustainability impacts of the development of a single technology over time instead of assessing two competing technologies.

Since the analysis was limited to Europe, while the sales forecasts were for the whole World, the European sales had to be estimated. Assuming a similar market penetration in all continents, the division could be done based on population forecasts. Based on Eurostat, the EU 27 population in 2030 would be 520 million. World population according to UN would be 8.3 billion, of which 1.3 billion in more developed regions. Assuming 5 times more phones in developed regions than in less developed would result in EU-27 to have 20% of all smartphone sales. For overview see Table 1.

Table 1.
Historical and calculated future sales figures of smartphones in EU-27. The numbers were used for calculation of technology level impacts.

Year	Units
2010	59 000 000
2030 *min*	0
2030 *mid*	67 000 000
2030 *max*	397 000 000

Most of the results of the sustainability assessment are linear. Therefore they can be scaled based on the expected sales. The impacts per phone are assumed to be constant over the sales range. No economies of scale were therefore assumed. This unrealistic assumption is a common practice in environmental life cycle assessment. In spite of ignoring the potential economies of scale, the use of two alternative sales forecasts gave an indication of the sensitivity caused by the range in sales estimations.

1.1.3. System boundaries (spatial/temporal scope, flowcharts)

Overview

While the functional unit specifies what is analysed, the system boundaries give more details on the how it was analysed and what was included in the overall picture. From the viewpoint of sustainability assessment the system boundaries have to be wide enough that all the main components of sustainability are included. In the technical jargon of LCA, it is stated that nothing essential is "cut-off" from the system. Having a consistent system boundary ensures that separate assessments are consistent and can even be compared.

The system boundary is closely related to the functional unit and the purpose of the study. Therefore the system boundary developed in this case study serves as an indicative example of a thorough system boundary of an ICT product. It cannot be used as a checklist for relevant components for all emerging products, but it will most likely cover all the relevant components of smartphones from the mobile communication perspective.

For this study, the geographical limitations were applied only to the functional unit. The system boundaries of the sustainability assessment were global. Parts of the supply chain which were outside Europe were included in the system boundary, as were the impacts of emissions to those regions, irrespective whether the emissions occurred in Europe or elsewhere. (Note: Regionalisation of PROSUITE impact assessment method was not implemented at the time of writing this report. Thus all impacts occurring outside of Europe were "global".)

The life cycle was followed from cradle-to-grave. This included the extraction and refining of raw materials for the smartphone, manufacturing, use and recycling. Most of the analysis was done by linking the information to background datasets on environmental emissions (life cycle inventory databases), macro economy (economic input-output models) and social impacts (labour condition statistics). Each of these has a different temporal scope, so not all parts of the life cycle could be followed in the same way for all aspects of sustainability. For example the environmental impacts included the long term emissions from metal mining, necessary to supply raw materials for the electronic components. However the economic assessment included only the impacts of producing the products on a given year. So from a temporal viewpoint, the aspiration of the study was to cover the long term impacts, but this could be achieved only for the environmental dimensions (natural environment, human health impacts from environment, resource depletion).

In addition to the physical and temporal boundaries of the system, also the methodological choices should be transparently described. The most recent guidelines on environmental LCA, the ILCD handbook (EC, 2010) gives some guidance based on decision situations. The main decision to be made is whether to include the indirect consequences of implementing the product or not. For example the electricity consumption can either be modelled with the average mix of electricity on a given year, or the effect of the increased demand on the overall electricity mix can be modelled. The choices on these issues can have a considerable effect on the overall results of the study (Soimakallio et al., 2011). Technically the two approaches are known as consequential and attributional LCA (CLCA and ALCA). Unless the methodological choices are documented transparently, the results of the study cannot be compared with other studies.

The choice of methodology should depend on the types of decisions to be supported by the study. The purpose of this study was to assess the sustainability of smartphones on a macro-level scenario. Therefore it was closest to the archetypal decision situation C of the ILCD guidelines. In this case, the results are considered as a descriptive accounting of a situation. We describe how the overall product system looked like in 2010 and how it would look like in 2030 when smartphones are fully in use (scenario 2030 *max*) and when they are on a slow decline (scenario 2030 *mid*). Since the work is descriptive, the potential consequential effects were not taken into account and the system was described as it was embedded in a background economy which is largely left unchanged by the technology. Attributional LCA was used to assess the sustainability implications. This is a common case in sustainability assessment. Consequential effects are usually considered only if the new technology is intended to change the society considerably, for example by substituting all fossil fuels with biofuels. Some guidance on the application of LCA in those situations can be found from (Mattila et al., 2012). Although smartphones may theoretically have a substantial effect on the society, these effects cannot be foreseen and calculated. Thus application of the attributional LCA is more appropriate, but the results should be interpreted carefully as they do not represent the full consequences of implementing the technology.

Once the geographical, temporal and methodological boundaries have been set, a product system can be constructed. The ILCD handbook provides a standard way of compiling a product system by starting from the central process (which provides the functional unit) and expanding from there. The expansion progresses through three questions. It was assembled by going through the three levels of interaction (embodied in the product, touching the product, services needed for operation). The components identified this way are then taken as a central process and the procedure is repeated until either there are no more processes to be added, or the impacts can be covered by an already made LCA. Processes can be excluded ("cut-off") only if it can be justified that the process would have insignificant impacts. This approach ensures the comprehensiveness of the system, irrespective of the availability of data.

The actual system boundary of the smartphone system is presented in Figure 3. It includes the actual device and electricity consumption, but also the mobile network, the internet cloud services, sales and transport and other aspects not typically considered in product carbon footprinting. The indirect impacts were identified at this point, but they were *not included* in the analysis, since they would have required consequential modelling, which was decided not to be used as a method in this study (i.e. methodological boundary). Individual parts of the product system are discussed more in detail further in the text and the data are provided in the Annex. Since the consequential effects were ignored, the main focus of the study was to describe the supply chain of the smartphone and associated services as the supply chain would present itself in a world largely dominated by smartphone mobile communication in 2030.

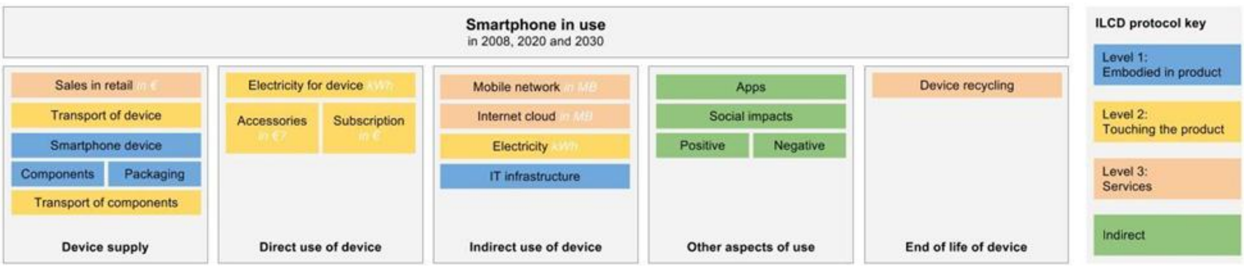
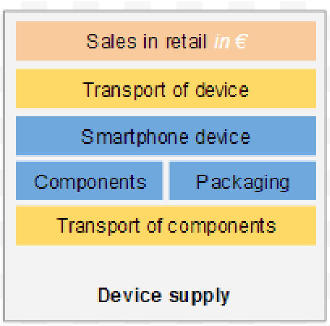


Figure 3. Overall description of the smartphone system.

<u>Data sources</u>

In this section we discuss the reasoning behind each part of the product system and explain what it consists of, what kind of data is ideally needed for sustainability assessment and what kind of data we were able to obtain in practice. We briefly discuss the availability as well as the quality of the data

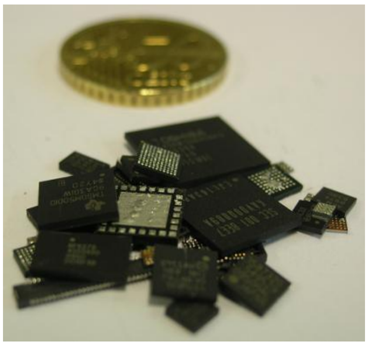


The *Device supply* life cycle stage represents production, distribution and sales of a smartphone. It composes of:

- Electronic components manufacturing;
- Mechanical components manufacturing;
- Battery manufacturing;
- Transport of components;
- Packaging and documentation production and
- Product transport to retail.

Smartphones contain sophisticated components, such as processors, memory chips, touch screens and high power batteries. A typical smartphone is made of hundreds of components, many of which are extremely small. In Figure 4 is shown integrated circuits of the analysed smartphone.

Figure 4.
Example of smartphone integrated circuits (processor, memory chips etc.).



Manual disassembly of a typical smartphone (introduced on the market in Q3 2009) served as the main source of inventory data. The selected smartphone represented a typical device of the time when the PROSUITE project had started (November 2009). Clearly, smartphones have changed significantly since then not only in terms of their computational power but also in size and materials they are made of. Three to four years in the world of consumer electronics is a long time. The Moore's law (doubling of computational power every two years) is valid and breakthroughs in material science together with consumer preferences drive innovations in an enormous speed. Having said that, it is near to impossible to forecast how future smartphones will look like in 2030. Thus, we applied the same inventory obtained in manual disassembly throughout the whole analysis. This is probably a general case of emerging ICT technologies: the representativeness of current level of technology is poor for the future, but there is no better way to assess possible future technologies either.

The manual disassembly consisted of opening the device and separating all separable parts and components. The project partners at Nokia helped with separation of the integrated circuits from the printed wiring boards. All parts and components were photographed, weighed on an analytical scale with precision of three decimals and their visual appearance was described in a bill of materials (BoM). Material composition of the parts was identified according to material codes engraved in components. Magnetism of the parts was tested, too. All information was documented on the confidential BoM.

After the disassembly the parts and components were grouped into two fractions: **electronic components** and **mechanical components**. Such division is somewhat different to the one used by the industry. However, a need for simplification led us to group component into these two fractions. By definition an electronic component is any basic discrete device or physical entity in an electronic system used to affect electrons or their associated fields (*Wikipedia*). Thus as *electronic components* were classified all components which fitted (or seemed to fit) under that definition. These components included e.g. LCD display with connectors, printed wiring boards (PWB) and integrated circuits (IC). All other components which could not be classified as electronic components, or were not the *battery*, were classified as *mechanical components*. These were e.g. the device shell and body and the screen cover.

In order to model the environmental impacts of electronic components, we had to link them to a background dataset of emission inventories. Types of electronic components were identified with a help of the *ecoinvent report No.18*, industry experts and internet databases (Alibaba.com, etc.). Electronic components selection in the *ecoinvent database (v2.2)* is fairly good. However, datasets are already somewhat outdated. The report No.18 was written in 2007, so the data is of that year at the best. Also, modern devices contain many new specific parts such as different antennas like GPS, WiFi, NFC or 3G/4G modems. These, and other components, identification of which was for example impossible, had to be classified as *unspecified electronic components* for which a unit process in the ecoinvent database exists. This may lead to slightly distorted results. Other available commercial databases would maybe have provided a better and more up-to-date selection of LCI datasets for single components but these are very costly (c.a. 8000 €/dataset) and it was not economically feasible to obtain them for the sake of the case study. Furthermore, the ecoinvent database is widely accepted, validated and used source of LCI data among the scientific community.

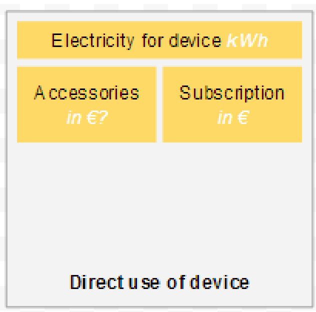
Transport of components from their suppliers to the main factory was approximated based on discussions with industry experts. The dominant mean of freight transport in the mobile phone industry is an airplane. Even packaging is reported to be often transported over the air because it is not convenient for the OEM (original equipment manufacturer) to keep a stock of cardboard boxes or other material. Flexibility is one of the top priorities in the industry. Thus we selected air transport as the mean of transport for electronic component and batteries. For mechanical components and packaging we modelled two transportation options - an airplane and a lorry. We present results for truck transport only.

All components must be packed for transport from the supplier to the OEM factory. We cut such packaging off the system boundary, mainly due to limited knowledge and lack of data. In some cases this packaging might be reusable while in other cases it is not. If such knowledge exists, we recommend inclusion of component packaging within the system boundary.

Results of every LCA study heavily depend on data quality. That may vary and depends on many factors. In this case study the quality of the inventory is limited due to several factors. One is that it was not possible to identify all components as well as material composition of the mechanical parts. Some materials used in the analysed smartphone do not even exist in the ecoinvent database (like Polycarbonate-ABS Blend reinforced with glass fibre). Disassembly and component identification was a good learning experience as were discussions with industry experts. But it was not possible to implement all of the comments due to high demands on technical laboratory equipment. For example, identification of the size of a wafer in an integrated circuit, which pretty much defines the amount of its embodied energy, would require an X-ray scanner. Similarly, for counting of the number of layers in a printed wiring board a microscope is needed.

Iterative adjustment of the inventory data. Since the identification and linking of components was difficult and prone to errors, an iterative adjustment was done on the inventory in the end. The carbon footprint of the product was adjusted to be of similar magnitude to those presented in environmental product declarations of smartphone manufacturers (Apple, 2012; Nokia, 2012). This was achieved by multiplying the amount of integrated circuits and printed wiring boards was by two. In a sense this represents the technological development from 2009 (year of disassembly data) and 2012. Modern smartphones contain more processors and several more layers of printed wiring boards. After the adjustment, the inventory did not represent a specific type of model or manufacture, but a more general typology of smartphone, which corresponds to the models generally sold. This was in line with the aim of highlighting sustainability issues. If the purpose would have been to compare two competing products, this approach would have to been revised and the inventory should be based on specific data. In that case primary data would be required.

<u>Direct use of a device</u>



The *Direct use of device* life cycle stage comprises of:

- Electricity consumption of the device;
- Mobile subscription and
- Accessories.

Mobile subscription and accessories were included to a certain extent through IO modelling (economic and social assessment).

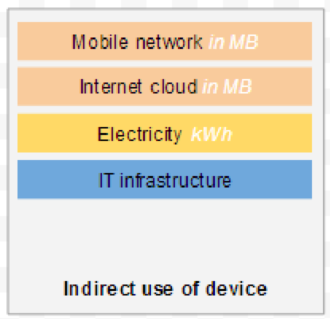
In principle the only *direct input* a smartphone needs to operate is electricity. Typically this is the only aspect of a smartphone use to date presented by manufacturers in their LCAs (see Nokia and Apple for reference). But that is not all what a smartphone needs for it to be usable in reality. The other important *semi-direct input* of the smartphone use phase is a *mobile subscription*. Subscription represents a phone bill which is in a sense a link to the life cycle stage *Indirect use of device* as through it a smartphone user buys an access to the mobile network and to the Internet. Impacts associated with subscription can be attributed to the mobile network operation (presented separately in the following section) and to own operations of a mobile subscription provider (offices, travel etc.).

An average annual energy consumption of a smartphone (iPhone) was used as a reference value. Energy consumption of a smartphone depends on several factors. It may be screen size and brightness, the type of connection with the network (2G, 3G, 4G, WiFi), processor speed and other functions in use, such as navigation or music playback (Hu and Ruutu, 2011). For example watching streamed video over a 3G network will draw the battery a lot faster than sending emails over a 2G network. Therefore it is users who can influence the overall electricity consumption of their smartphones. Also the chosen components have an impact on the device’s power consumption. As a result, direct electricity consumption can vary significantly.

The subscriptions were considered only for social and economic impacts through input-output analysis. The impact for environmental categories was not evaluated.

The sustainability aspects of accessories (e.g. chargers, headsets, covers and cases) were excluded from the analysis due to poor reliability of data as well as large variety of items belonging to this group of products. However, it could be argued that smartphone accessories in some cases might play an important role in the overall results. This can be the case of docking and charging stations, external speaker or wireless headphones.

Indirect use of a device



The *Indirect use of device* life cycle stage comprises of:

- Mobile network and
- Internet cloud.

These are very complex systems but in principle can be simplified to flows of electricity and IT infrastructure (computers in data centres).

Smartphones are multifunctional devices and they need mobile telecommunication networks and the Internet in order to deliver all their functions. They are fully dependent on this infrastructure. With growing popularity of smartphones naturally increases the overall data traffic in networks. According to the Ericsson Mobility Report (Ericsson, 2013) 450 MB of data was produced by an average smartphone each month at the end of 2012. Ericsson expects the per user data traffic grow in 2018 to up to 2 GB per month. This still might be a conservative forecast considering currently exploding popularity of remote storage and other cloud services. Inevitably, inclusion of mobile telecommunication networks, as well as the Internet infrastructure, in an LCA-based sustainability assessment of smartphones is essential. Excluding them would not show the entire impacts of smartphone use.

Compiling inventory of this infrastructure is, however, not easy as the Internet is rather abstract to most people, and its users, and so are the networks. Literature is available on the topic of mobile networks (Malmodin at al. 2001; Malmodin et al., 2010; Faist Emmenegger et al., 2004; Scharnhorst at al., 2006; Scharnhorst, 2006; Yu at al., 2010; AT&T, 2012) but most papers do not provide data easily applicable on current mobile networks or focus on overall description of the systems. We refer to Malmodin et al. (2010a) for electricity consumption of mobile network connected to voice transmission. Since the data was a few years old, and the data transfer had improved in energy efficiency, we assumed similar improvements in voice transfer. Subsequently the figure was divided by three. (Note: after the analysis had been done, personal discussions with the industry (J.Malmodin, 2013.) revealed that the issue of energy consumption of voice transfer is highly complicated and requires further studies. The original approach of division by three might overestimate the reduction, but it was kept in the analysis for now.)

Literature about Internet's energy and material requirements is even scarcer than mobile networks (Koomey, 2008; Koomey, 2011; Raghavan and Ma, 2011; GeSI and Boston Consulting Group, 2012). The Internet is a worldwide decentralised network of interconnected computers. Therefore only an experts' judgement can give an indication of the energy and material intensities of it.

It was felt that it is of high importance, at least to some extent, to include mobile networks and the Internet in the analysed system. For mobile networks we did that on the basis of an average data transfer (MB) of a smartphone used and an energy intensity of data transfer (kWh/MB). For energy consumption of the Internet we reviewed available literature (Koomey, 2011; Raghavan and Ma, 2011; GeSI and Boston Consulting Group, 2012) and found out that reported energy consumption of data centres in 2010 (here assumed to represent the Internet) does not differ from paper to paper extremely much (Figure 5).

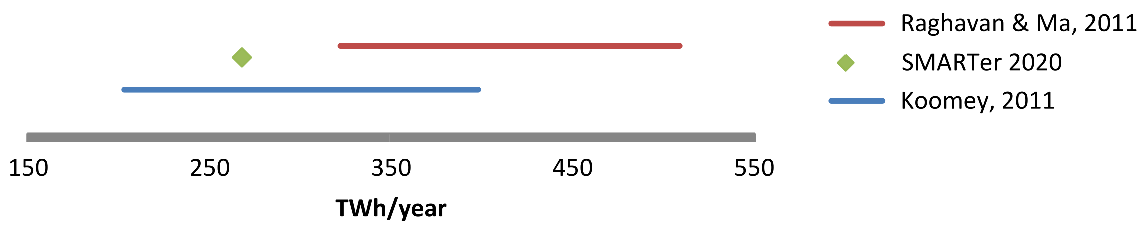


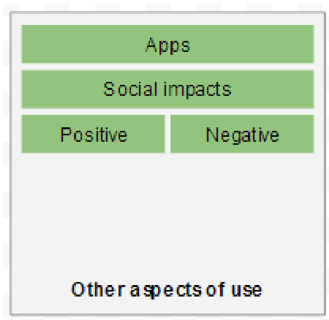
Figure 5. Ranges in published energy consumption of the Internet.

In the Ericsson's Mobility Report 2013 (Ericsson, 2013) we found information on estimated global data traffic (approx. 204 EB) and used that value to calculate average energy intensity of Internet (data centres) per MB, 0.001-0.0025 kWh/MB.

Data centres are not the only elements of the Internet. Including at least those, however, helps us to capture a larger part of the whole system involved in smartphone use life cycle.

Koomey (2008) differentiates between several elements of data centres - servers, storage, communications and infrastructure. The author also estimates the share of datacentres in different parts of the world. This information was utilised and combined with current and future electricity mixes calculated in the PROSUITE project. In order to use the future electricity mixes we had to modify the original data of Koomey. We simplified the distribution of data centres and their elements. In our analysis we assume that data centres in the world are distributed between North America, European Union, Pacific Asia and rest of the world, which we modelled as India.

Other aspects of use



The life cycle stage *Other aspects of use* describes other aspects of smartphone use. However, these aspects were indirect and dependent on consumer behaviour. Therefore they were not quantified, but were qualitatively discussed to give an understanding of the parts left out of the product system.

The *direct* and *indirect use* describes what inputs are needed to use the device. The *other aspects of use* describe what is caused by the use of the device. These consequential effects were not modelled quantitatively as the analysis was done as attributional, but were described to give an estimate on the order of magnitude that these items could have on the overall life cycle and the society. In the future it is expectable, or would at least be desirable, that sustainability research of ICT would concentrate on this area even more than it currently does.

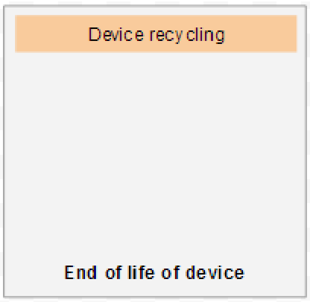
ICT technologies, especially their mobile derivatives like smartphones, have a huge potential to drive the sustainable development forward through smart and green apps (GeSI and Boston Consulting Group, 2012). On the other hand, increased use of smartphones can also lead to a spread of unsustainable lifestyles. Should that be coupled with inefficient and "dirty" infrastructure the impacts may be far-reaching.

Apps play important role in the use of smartphones. An app is a commonly used abbreviation for an application, a software program which can be installed and ran on a device with an operating system, e.g. a smartphone. There are hundreds of thousands of apps existing in the world and they are designed to be used in almost any area of the human life. Most apps are used for entertainment or some form of communication. Gaming and entertainment apps are currently the most popular (downloaded) according to Portio Research (2013) and MobiThinking, (2013). The second most popular type is messaging apps, such as WhatsApp.

Smartphone apps also have a potential to support sustainable development in both social and environmental aspects. For this reason, smartphones can cause both negative and positive impacts on social and environmental issues. Already such apps exist which make sharing of goods easier (e.g. cars, rides, tools). Other apps allow for remote control of house heating and cooling or for smart farming. All such apps provide their user an immediate financial benefit while help to decrease material and energy consumption, and furthermore greenhouse gases (GeSi 2012). A review of the climate impact reducing potential of smartphones and green apps is presented in (Mattila et al., 2014).

Smartphones have been documented to increase the quality of life by increasing people's feeling of belonging, security and connectedness to friends and family. They are also used for entertainment and information seeking. These positive effects will affect human behaviour in a more general way, which will likely have sustainability impacts. On the other hand, smartphones can induce addictive behaviour, information overload and isolation from real life social networks. Both types of changes will affect the use of time, money and other resources. An analysis of these issues would require a separate study focusing only on the consequential behaviour issues induced by the technology and were left for further studies.

Device recycling



This life cycle stage describes the end-of-life stage of a smartphone. It is common practice in LCA to assume that the device would be properly handled in the end-of-life, which was the assumption followed here. Therefore it was assumed that 100% of smartphones would be recycled. Alternative assumptions are discussed, but would require separate studies in themselves.

As described in the device section, the smartphone contains several components with rare and valuable metals. The purpose of the end of life treatment is to recover the valuable resources without causing excessive harm to the environment. Unfortunately ICT devices have been highlighted for sustainability problems related with illegal recycling, where devices are burnt and the metals are recovered by primitive methods in developing countries. The health and environmental risks of these operations can be considerable (Williams, 2011). For smartphones currently sold in Europe, the end of life is still largely unknown. People have the habit of storing used mobile phones at homes or selling used phones for reuse Tanskanen (2012). Therefore there is a considerable delay between sales and eventual end of life. In addition, the end of life may occur outside EU.

In spite of high potential hazards of illegal recycling, in this study we focused on the legal and official recycling. Smartphones are designed to be recycled properly, and it can be argued that illegal activities in recycling are outside the responsibility of the product designer. This part of the life cycle then describes the recycling in an idealized state, but care should be taken to avoid the illegal recycling in real life.

The end of life included the transport to a collection point by passenger car, the freight transport to a pre-processing centre, disassembly, transport to a copper smelter and eventual metal recovery. Plastics in the phone were assumed to be recycled (for the cover) and undergoing energy recovery (plastics in the electronic components which come to the smelter). The plastic recycling was assumed to occur in China so the transport was included. The energy from the plastics was credited to the system by assuming that it replaces some of the other fuels used at the smelter.

The data for the inputs and outputs of recycling came from the sustainability report of Rönnskär Boliden Smelter (Boliden, 2012). The material composition of the phone was obtained from a previous report of the PROSUITE study focusing on metal recovery (Navazo et al., 2013). The recovered metals (gold, platinum, silver, etc.) were credited as by-products to the smartphone product system. Therefore since the metals were considered as a burden in the electronic components side, the overall assessment focused on the net demand of metals of the technology (i.e. the amount needed for materials less the amount recovered in recycling).

Publicly available data sources could be used to provide a good overview of the recycling and recovery of the most common materials. However for rare metals such as neodymium and indium, there was no recycling data, and it was uncertain whether they would be recovered in the future. Therefore their recycling was excluded from the study. Also even if they would have been included, the current methodology for sustainability assessment of exhaustible resources would have not included them. In that sense, they fall under the category of *sustainability aspects which could not be captured by the current analysis*. It is important to communicate these transparently to stakeholders.

Prospective modelling

One of the aims of the PROSUITE project is to carry out carry out a prospective assessment. In the ICT case study we simulate that by two means - estimation of **future sales of smartphones** (see Figure 1), an updated inventory for data transfer and applying the LCI of **electricity mixes for 2010 and 2030** developed within the PROSUITE project.

As described in the Section *Mobile networks and the Internet*, we used the PROSUITE specific electricity mixes in those unit processes which model the use phase of the mobile networks and the Internet. This step was straightforward as no modifications of already existing commercial or other data sets were required. But also the device (components) manufacturing requires substantial amounts of electricity (e.g. wafer manufacturing). As the smartphone device model in openLCA is based on the ecoinvent database v2.2, the only way of implementing the PROSUITE specific electricity mixes was to modify the directly ecoinvent unit processes used in the model. The modification was based on replacing inputs of ecoinvent electricity supply unit processes with the PROSUITE electricity mixes. The model was parameterised in order to enable simple switch between the 2010 and 2030 electricity mixes for prospective assessment.

In order to identify those ecoinvent unit processes which to modify we first analysed the contribution of components and transport to the climate impacts of smartphone manufacturing. The reason why to use category climate impacts is that it correlates well with energy use (mostly generated by burning fossil fuels). Unit processes with a significant contribution (over 2%) to smartphone manufacturing we flagged as eligible for modification. In them we replaced ecoinvent electricity inputs with the PROSUITE future electricity mixes.

Identification of unit processes which should be modified:

- 59% of climate change impacts are caused by *electronic components* where the two main contributors are unit processes *printed wiring board, surface mounted, unspec., Pb free, at plant* and *integrated circuit, IC, logic type, at plant*.
- Other important components are *electronic component, unspecified, at plant*; *LCD module, at plant* and *printed wiring board, through-hole mounted, unspec., Pb free, at plant*.
- 20% of climate change impacts are caused by the process of *transport of the device to the market* - almost entirely due to the *freight air transport*. This process was not modified.
- Around 17% of climate change impacts are caused by *mechanical components* where the dominant contributor is *magnesium-alloy, AZ91 diecasting, at plant*. That represents the phones main body structure. Nowadays this part is often made of aluminium or polycarbonate.

Closer analysis of the process *printed wiring board, surface mounted, unspec., Pb free, at plant*, which is an electronic module, reveals that the main component contributing to its climate impacts is already mentioned *integrated circuit, IC, logic type, at plant*. Analysis of this process reveals that the electricity mix used in production of it is *electricity, medium voltage, production UCTE, at grid*. This is surprising because typically electronic components are manufactured in Asia and not in Europe (as the code UCTE would suggest). Thus we replaced the UCTE electricity mix by the PROSUITE process *electricity generation process, CN, 2010* and *2030* and like that simulated production of the IC in China in 2010 and in 2030.

The same unit process, *integrated circuit, IC, logic type, at plant*, plays the main role also in the other electronic component manufacture. Another unit process which was modified was *integrated circuit, IC, memory type, at plant*.

In the unit process *LCD module, at plant* were replaced inputs of Chinese and Japanese electricity (electricity, medium voltage, at grid) by PROSUITE process *electricity generation process, CN, 2010 (2030)* and PROSUITE process *electricity generation process, PAC, 2010 (2030)*, respectively.

The main assumptions related to e.g. data traffic in 2030 can be found in Appendix 1.

1.1.4. Alternative system boundary for input for economic assessment

The previous sections described the processes and products which were included in the environmental LCA based sustainability assessment. At the stage when the PROSUITE methodology was tested for this case study, the economic modelling needed to assess prosperity and some social impacts was not directly linked to the environmental inventory. Therefore a separate description of the smartphone as an economic product had to be made. This served as the input data for economic and social assessment.

The economic product system begins with the costs of production for a smartphone. Similar to the environmental LCA, the basis for that cost breakdown was a smartphone manufactured in Finland in 2008. This data was then modified to better describe the situation in 2015 onwards. The cost breakdown data for the whole sector of communications devices was obtained from Statistics Finland, but were protected under the statistics law, since there were too few mobile phone companies in Finland to permit public data. We aggregated and rounded the figures to avoid violating the statistics law. The obtained cost breakdown data is presented in Table 2. Most companies applying the tool would not have to look for official statistics, as they would know their costs quite well.

In order to take into account changes which had already happened between the years 2008-2013, and in anticipation of the price decreases of smartphones, the inventory was modified. Production costs were assumed to be decreased due to economies of scale as well as the decreased labour costs. The obtained inventory is presented in Table 2. The changes dropped the manufacturing costs from 200 € to 120 €. If a fixed ratio is assumed between retail trade margins and product costs, this would amount to a 240 € smartphone for the consumer.

In addition to the operational costs, there are investment costs of approximately 5 € per phone to take into account the additional capital needed for production. Or at least that was the case in 2008 in Finland. In the stage of expanding mass production, increasing production volumes and finally gradually stabilizing and decreasing sales, the investment costs are likely to be different in different points of time.

Recycling of metal waste and scrap is represented by the recycling fee of approximately 1 € per phone. This was assumed to be split 50%/50% between metal recycling and non-metal recycling. For phones consumed in the EU, this would occur in specialized copper smelters.

The main costs associated with a smartphone are the operator and network costs. These belong to the post and telecommunications sector and were estimated to be 540 €. In addition, some software and applications are bought. These were assumed to be 36 €. For the sake of simplicity, it was assumed that both purchases were initially from EU (the supply chain for those would be calculated in the THEMIS IO model used in the PROSUITE framework). The direct electricity costs for recharging were estimated to be 0.24 € for electricity production and 0.24 € for distribution.

The description of the smartphone as an economic system allowed the linking to the background economy. This allowed the analysis of potential multiplier effects and the tracking of value creation across the world economy. In later versions of the PROSUITE methodology, the environmental inventory and the economic inventory are more interlinked, so the user is not required to do the economic modelling separately. It can however be a good exercise to understand better the cost components of a new product and how they might develop in the near future. In the case of the smartphone, the modified economic system presented a low cost device, much different from the original inventory obtained from year 2008 data. This estimated year 2015 dataset was used for the economic analysis.

Table 2. An illustrative cost breakdown data for the smartphone manufactured in China in 2015. The inventory was obtained by modifying the available inventory of 2008 by removing research and development costs and decreasing worker compensation and gross operating margins. (Regions: EU = EU-27, NA = North America, CN = China, IN = India). All prices are in €.

Cost item	Finland 2008		China 2015	
Total price of manufacture	200		120	
Gross operating margin	43		**32**	
Communication equipment	36	CN, EU	36	CN
Research and development	32	NA, EU	**0**	
Compensation of workers	20	EU	**6**	CN
Other business activities	34	EU, IN	**17**	CN, IN
Computer and related activities	12	EU, IN	**10**	CN, IN
Manufacture of electrical apparatus, nec	10	EU, CN	10	CN
Real estate	2	EU	2	CN
Construction	0.3	EU	0.3	CN
Post and telecommunications	2	EU	2	CN
Publishing	2	EU	2	CN
Wholesale trade	2	EU, CN	2	CN
Retail trade	2	EU	2	CN
Insurance	0.3	EU	0.3	CN
Activities of financial intermediation	0.3	EU	0.3	CN

1.2. Case specific methodology

1.2.1. Impact on human health

The impact on human health was conceptually divided into three components in the PROSUITE framework: environmental effects, occupational health and consumer effects. The consumer effects could not be assessed, because no methodology was available during the assessment, but the two other components were assessed. The occupational health was obtained from the economic input-output model, using economic costing and market volumes for the input-data. The environmental health was calculated using the environmental LCIA factors included in the PROSUITE DSS. ***However the LCIA impacts of stratospheric ozone depletion were missing at this point of implementation and they were excluded.***

1.2.2. Impact on natural environment

The impact on natural environment was quantified through the methods described in D.5.2. and implemented in the PROSUITE DSS. The impacts were calculated at the endpoint level, and expressed in species years. For comparison the results were also characterized with an older LCIA methodology (RECIPE). **The impacts of climate change to terrestrial species and the impacts of land use to all species were excluded, as the methodology was not operational at the time of testing.** In the normalization figures the corresponding impact categories were also removed in order to maintain consistency between analysis and normalization.

1.2.3. Impact on exhaustible resources

The impact on exhaustible resources was quantified through the methods described in D5.2. For comparison, the results were also calculated with an older LCIA methodology (RECIPE). **The impacts to fossil fuel depletion were excluded as the impact assessment methodology was not operational at the time of testing.**

1.2.4. Impact on prosperity

The impact on prosperity was quantified through the impact on gross domestic product. This was quantified using the economic model THEMIS, which was also used for human occupational health and social well-being indicators.

1.2.5. Impact on social well-being

The impact on social well-being was quantified through economic modelling from THEMIS and with some additional qualitative indicators applied according to the social assessment cookbook.

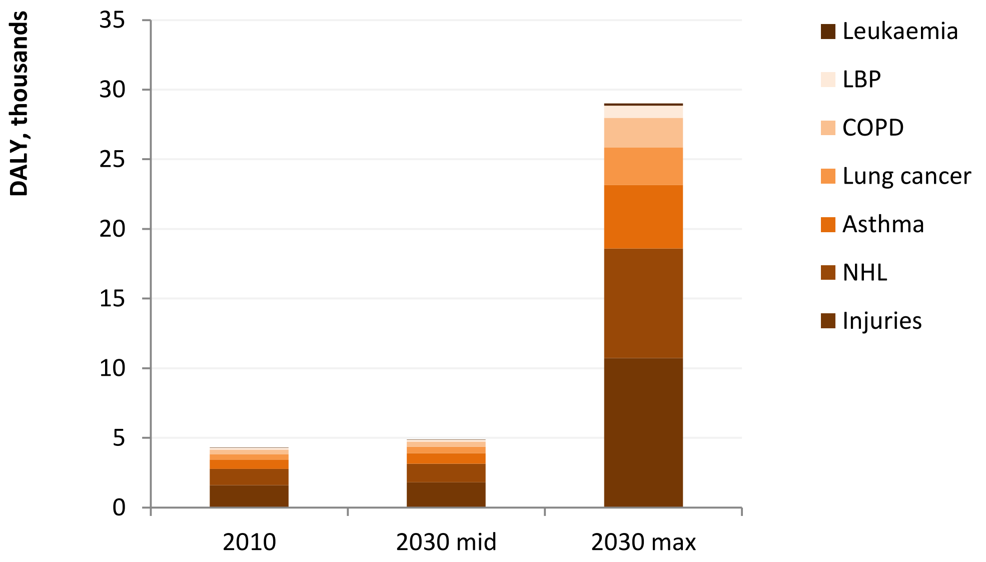
1.2.6. Integration

The impact indicators of social well-being were aggregated into a single social well-being score using simple additive model with equal weights for all indicators. **In the actual methodology, default weights for social categories are provided, but they were not available during the writing of this report.**

1.3. Results and discussion

1.3.1. Impact on human health

The occupational health was obtained from the THEMIS model results, where occupational injuries were linked to sector level data on employment. According to the results, one smartphone increases occupational health issues by 0.000073 DALYs (disability adjusted life years), mainly through occupational injuries and respiratory illnesses. The processes in the supply chain with the highest contribution to DALYs were the communications equipment in China, post and telecommunications in the EU and crude petroleum production in Pacific Asia (Figure 6). The occupational health impacts were assumed to be the same per phone in year 2010 and year 2030. However at the technology level the impacts are larger, because sales may be much higher in 2030.



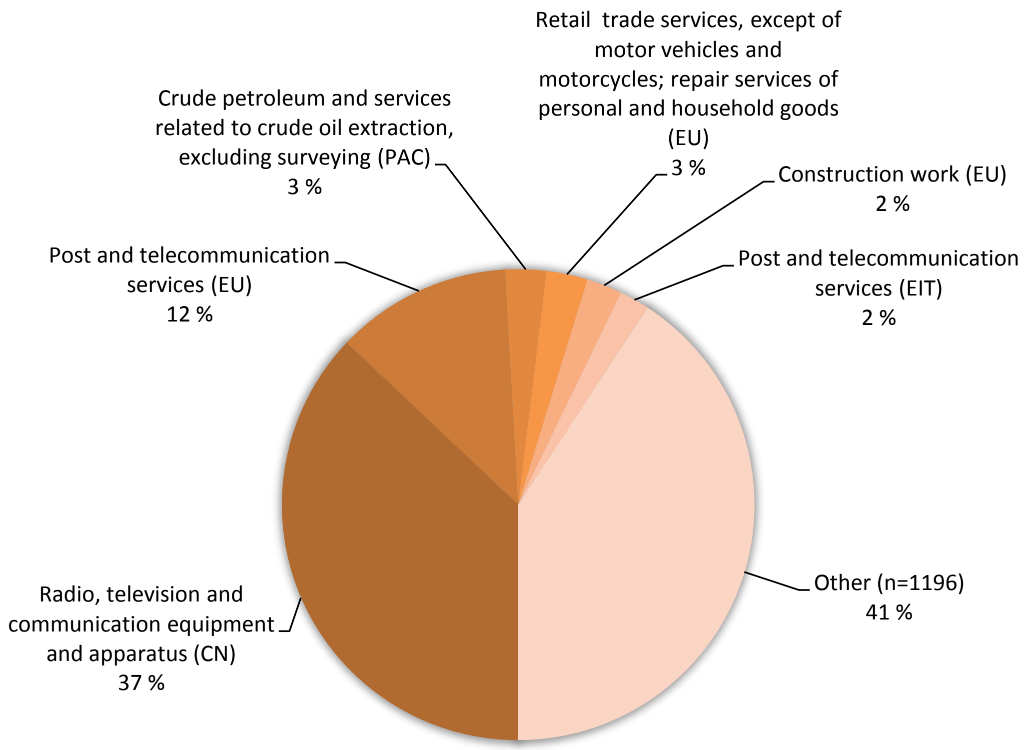


Figure 6. The occupational health impacts of smartphones in the three assessed scenarios in DALYs *(technology level)* (above). Contribution of economy sectors to the impact category (below).

The environmental health impacts were estimated to be 0.000055 DALYs per smartphone in 2010, increasing to 0.000067 DALY's in 2030. The health impacts were caused mainly by to climate change impacts and non-cancer human toxicity (Figure 7). The overall increase in sales was the main contributor to the technology level increase.

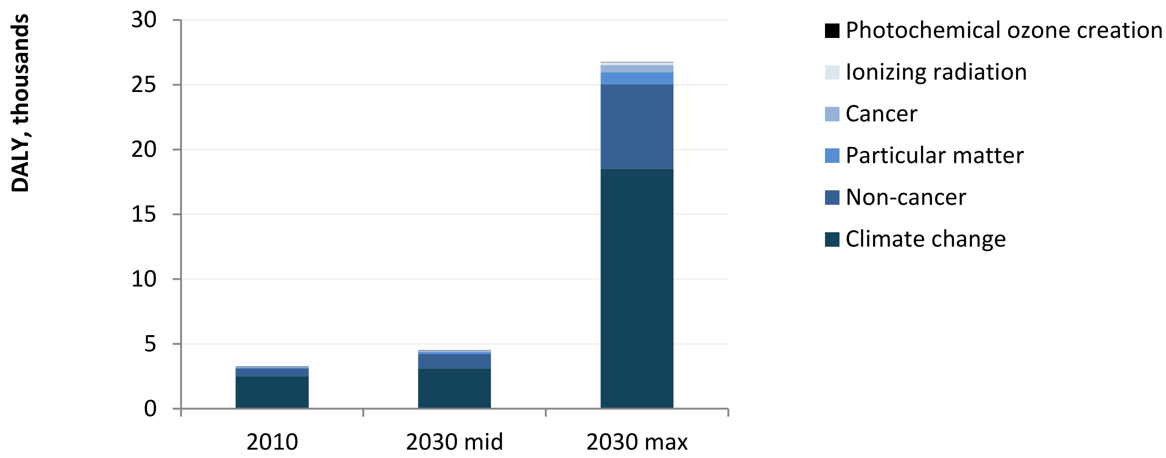


Figure 7. The environmental health impacts of smartphones in the three assessed scenarios.

1.3.2. Impact on natural environment

The natural environment was quantified through species years. Impacts on natural environment per smartphone were calculated to be $2.4 \cdot 10^{-7}$ species years, not including the effects through land use, ecotoxicity or marine eutrophication. The technology level impacts for climate change are presented in Figure 8. As climate change contributed to 99% of the overall impact, the following figures present the impacts only through that midpoint category.

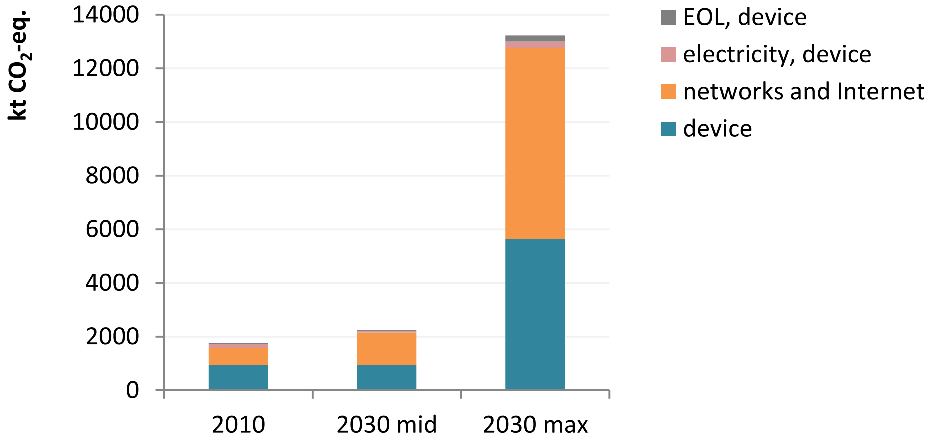


Figure 8. Climate change impacts, kg CO_2-eq. *(technology level)*

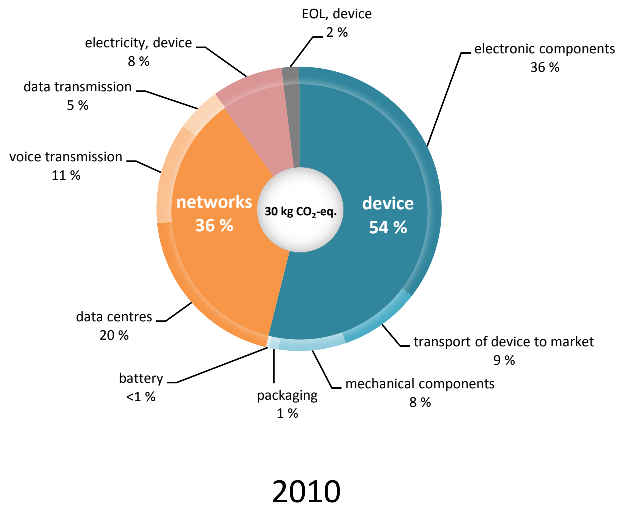
In tables 3 and 4 are presented climate change impacts per functional unit. The same results are presented as sunburst diagrams below the tables (Figure 9). The sunburst diagram represents the embodied impacts of the two first tiers of production.

Table 3. Contribution tree to climate change impacts, PROSUITE Midpoint LCIA. Per one year of single smartphone use in **2010**

Climate change, kg CO_2-eq.			
device	16.05	*electronic components*	*10.54*
		transport of device to market	*2.73*
		mechanical components	*2.26*
		packaging	*0.30*
		battery	*0.12*
network and Internet	10.75	*data centres*	*5.83*
		voice transmission	*3.41*
		data transmission	*1.53*
electricity, device	2.38		
EOL, device	0.59		
use of smartphone, 1 year	**29.79**		

Table 4. Contribution tree to climate change impacts, PROSUITE Midpoint LCIA. Per one year of single smartphone use in **2030**

Climate change, kg CO_2-eq.			
network and Internet	17.94	*data centres*	*14.23*
		data transmission	*2.81*
		voice transmission	*0.89*
device	14.19	*electronic components*	*8.78*
		transport of device to market	*2.73*
		mechanical components	*2.26*
		packaging	*0.30*
		battery	*0.12*
electricity, device	0.62		
EOL, device	0.56		
use of smartphone, 1 year	**33.31**		



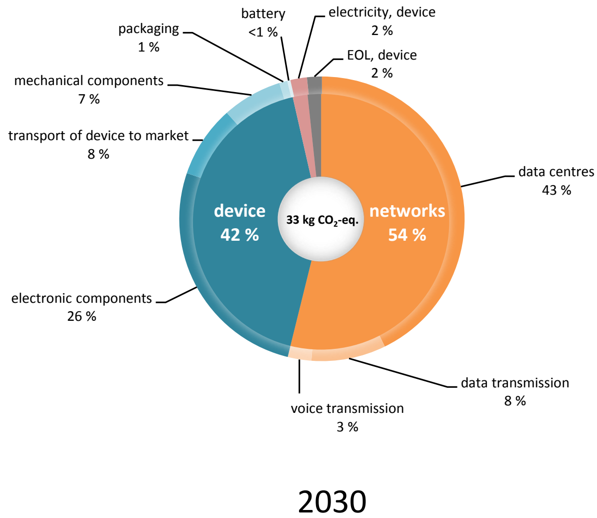


Figure 9. Sunburst diagrams of life cycle stages' contributions to climate change impacts. PROSUITE Midpoint LCIA. Results per functional unit for 2010 and 2030.

1.3.3. Impact on exhaustible resources

The impact on exhaustible resources was 0.8 USD2010 per smartphone, and did not change from 2010 to 2030. This however included only metals, as the impact assessment methodology for fossil fuels was not properly linked to the LCI databases at this point. The main contributors to metal depletion were palladium, gold and silver. It should be noted, that the impact to exhaustible resources, such as indium, neodymium and germanium were excluded in the impact assessment methodology. The inclusion of these metals may increase the impact to resource depletion considerably.

1.3.4. Impact on prosperity

While the first three pillars focused on humans and their life support system, the pillar on prosperity focuses on the economic system. The sustainability (continued existence) of the economic system is seen to rely on constant economic growth, measured as GDP. Therefore the economic analysis focused on value creation, through increased labour productivity, capital productivity or novelty. As additional analysis it could also be seen in which sectors the value creation increased and whether it was produced as labour compensation, capital compensation or net operating surplus. Focusing on labour compensation allowed the analysis of potential job creation.

The assessment on prosperity was constructed in a manner where the smartphones were considered to be an absolutely novel product. That means that the consumption of smartphones did not substitute other consumption items. In reality, smartphones may substitute regular cell phones as well as the costs of maintaining a smartphone could reduce consumption of luxury items such as traveling or larger apartments. Due to the large element of "what if" in the substitution, these aspects were left completely out of the analysis. The following results therefore show the impact the introduction of smartphones has on the economy, without considering possible rebound effects.

Since it was assumed that the product would not decrease overall consumption of other goods, the effect on world GDP is the same as the overall demand of smartphones assessed: 49-327 billion €. As 18% of the direct inputs (and much more of the indirect inputs) of the smartphone are from outside EU, the smartphone production will increase European GDP by only 38-256 billion €. The remaining 20% will occur outside European Union, therefore shifting the import dependency of the EU by 11-76 billion €.

Looking more closely at the labour compensation, 83% of it would occur in the EU-27. The main sectors affected would be post and telecommunications, retail trade, other business services, computer and related activities and financial intermediation services. Together the labour compensation in these five sectors amounted to 80% of the increase in labour compensation caused by the smartphones. Outside EU the main labour compensation occurred in China (communications equipment), North America (software and other business services). Overall it would seem that the most of the labour compensation would be focused on very few sectors and could have a considerable impact on those. For example compared to the background scenario, the smartphones might increase the labour compensation of post and telecommunications sector by a factor of five (i.e. from 7.5 billion € to 43 billion €).

The increase in GDP is not coupled to any improvements in capital, labour or resource productivities, but instead to increased consumption through novelty. It is unknown how this increased consumption would be maintained. Of the GDP, 47% is compensation of employees. This could keep the economy circulating, allowing more wages, which could be used on smartphone services. However, with the trade imbalance in the product, additional overall production would be needed to support the use of smartphones in the EU. What this additional production would be and how that would affect the consumer behaviour was however outside the scope of this study, as at the outset consequential assessment was ruled out as a methodological boundary. Nevertheless, these results warrant further study on overall scenarios if the impacts of smartphones on economic sustainability are to be assessed in detail.

The calculated impacts on prosperity are presented in table 5.

Table 5. Main economic impacts of the smartphone product system. Indicators normalized to the world economy in 2010 are presented in parenthesis.

Smartphone impacts on world economy	2010	2030 *mid*	2030 *max*
Production volume (M€)	48 835 (0.04%)	55 086 (0.04%)	327 067 (0.25%)
Total compensation of employees (M€)	23 183 (0.08%)	26 151 (0.09%)	155 266 (0.51%)
Total compensation of capital (M€)	10 059 (0.11%)	11 347 (0.13%)	67 371 (0.75%)
Total net operating profit (M€)	15 586 (0.06%)	17 582 (0.07%)	104 387 (0.43%)
Total GDP world (M€)	48 829 (0.08%)	55 080 (0.09%)	327 023 (0.51%)
Total GDP EU-27 (M€)	38 242 (0.25%)	43 138 (0.29%)	256 123 (1.69%)
Import dependency (M€)	11 325 (1.03%)	12 775 (1.16%)	75 847 (6.89%)

1.3.5. Impact on social well-being

The impact on social well-being was quantified through three midpoints and six indicators. The midpoints were (1) safety, security and tranquillity, (2) autonomy and (3) equality. These midpoints try to capture the various dimensions of social well-being, ranging from individual human rights to society level functioning. In addition to these three quantified midpoints, various qualitative indicators were used to capture possible issues of concern in the studied technology.

Safety, security and tranquillity

Safety, security and tranquillity refer to the continued functioning of the society. In the Prosuite framework, the main indicators for measuring this are related to employment: total employment and knowledge intensive jobs. The outcome of the macroeconomic modelling related to these indicators is presented in table 6.

Table 6. The effect of smartphones to the amount of knowledge intensive and total employment. Comparison of the induced change to the reference scenario total amounts in 2030 is presented in parenthesis.

		Reference	Change		
		2030 total	2010	2030 mid	2030 max
Knowledge intensive jobs	million hours	1 630 000	428 (0.03%)	483 (0.04%)	2 867 (0.21%)
Total employment	million hours	7 530 000	1 336 (0.02%)	1 507 (0.02%)	8 945 (0.14%)

Looking at the contribution of sectors, 85% of the knowledge intensive work is created in five sectors: communications equipment in China, post and telecommunications in EU, other business services in China, computer services in China and other business services in the EU.

In all cases the effect is considered to be neutral, as the changes induced are minor compared to the background economy. Applying a Likert scale to rank the effects, this would be a score of 0 on a range of -2 (highly negative) to 2 (highly positive).

Autonomy

Autonomy refers to the basic human rights of being able to control your own life. Its violations are measured in Prosuite by focusing on two indicators: forced labour and child labour. As a sub-specification, the forced labour does not include child labour or work done by prisoners in democratic countries. Additionally child labour includes only hazardous child labour.

The results are presented in Table 7. Overall the levels of change are so minor compared to the background economy, that they can be considered to be neutral (score 0 in a Likert scale of -2 to 2). The difference between the three technology points in time is driven by the change in production scale. Per phone the impacts were assumed to be the same.

Of the hazardous child labour, most was occurring in the electronics manufacturing industry of China, with some activities also occurring in retail trade in EU. It should be noted that since the data is based on industry averages, it does not represent the actual situation in the smartphone supply chains, where manufacturers have already focused on the use of child labour. It does however highlight the need to monitor the labour conditions in those areas in order to ensure that the potential risks do not actualize.

Table 7. The indicators related to personal autonomy in the reference scenario and the induced change of different levels of smartphone technology implementation.

		Reference	Change		
		2030 total	2010	2030 mid	2030 max
Hazardous child labour	million hours	154 000	19 (0.01%)	21 (0.02%)	126 (0.09%)
Forced labour	million hours	19500	2 (0.01%)	2 (0.01%)	13 (0.08%)

Equality

Equality describes the equality in income across regions and across individuals globally. The regional inequality is measured through value creation in developing and developed countries and the global income inequality is measured through the GINI index.

The GINI index measures the evenness of wages paid to workers. If one person has all the wages, the GINI is one, with all people having and equal wage, the GINI is 0. Increase in GINI can be thought to be connected to potential social unrest.

The effect of smartphone technologies to the GINI index is presented in table 8 for the two future scenarios and for the reference level in 2030. It was not possible to assess the effect of smartphones to GINI in 2010, since data was available only for year 2030.

At the world level the smartphones would seem to increase inequalities, by creating more unevenly paid jobs (i.e. highly paid jobs). Looking at regions, most of the GINI change is seen to occur in China, where the effect is to increase GINI. On the other hand, India has the highest GINI, and the smartphone technology would seem to reduce the GINI slightly there.

The effect on World GINI is minor, only about 0.01% of the total value. Therefore the effect is considered to be neutral (0 score in the Likert scale of -2 to 2).

Table 8. The GINI index for various regions and the overall World in the different scenarios. The reference in 2030 describes the GINI index in 2030 without smartphones. The two scenarios show the absolute change in GINI in those situations.

	Reference 2030	2030 mid	2030 max
Africa and Middle East	0.513	0.000002	0.000010
Other developing Asia	0.588	-0.000000	-0.000002
China	0.451	0.000049	0.000289
Economies in transition	0.389	-0.000023	-0.000139
OECD Europe	0.132	-0.000042	-0.000246
India	0.593	-0.0000004	-0.000002
Latin America	0.483	0.000002	0.000012
North America	0.220	0.000001	0.000004
OECD Pacific	0.404	0.0000003	0.000001
World	0.654	0.000012	0.000073

Looking at the distribution of value generation between developed and developing countries (Table 9), the smartphone sales in Europe would seem to increase global inequalities. This is caused by more value added generated in developed countries than in developing. However, both regions have value added and therefore this can be thought of as a weak influence.

Compared to the reference scenario, the maximum level of change introduces quite a considerable level of change (i.e. 16% change in the difference). This would be a -2 in a Likert scale of -2 to 2.

Table 9. The effect of three levels of smartphone sales on the distribution of value added between OECD and non-OECD countries. In millions of €.

	Reference 2030	Change		
		2010	2030 mid	2030 max
Non-OECD countries	58 568 223	7 819	8 821	52 370
OECD countries	57 152 908	41 009	46 259	274 653
Difference	-1 415 315	33 190	37 438	222 283

Qualitative indicators

The other issues were considered by having an expert panel with the report authors and one external expert from the project team (Petrus Kautto). These results are therefore an application and testing of the methodology and do not represent absolute truths. Prior discussing the conclusions, it is important to state that although the assessment was done in as objective way as possible the conclusions are a prone to be subjective.

Change in risk perception was assessed by mapping smartphones to a psychometric plot of various hazards. For the analysis it was specified, which aspects of the smartphone were considered. Here the main issues considered were: *information overload, radiation* and *online security*.

By *information overload* we mean the virtually unlimited availability of information on the Internet accessible at any time on a smartphone. If people were machines information overload would probably not be characterised as a risk because in principle the availability and accessibility of information is a benefit for society. But based on current research, it might be indeed difficult to filter relevant information found on the Internet and control the time spent online. This has been typically studied on the organisational level (Edmunds and Morris, 2000; Jackson and Farzaneh, 2012). Nowadays, with the wide spreading mobile devices' technology, this issue is more perceptible to consumers.

By *radiation* we mean all kinds of radio wave radiation ranging from smartphone radiation to the wireless networks (mobile networks, WiFi networks). When accessible feature phones entered the marked in the 1990's public feared the potential health impacts linked to their radiation. These concerns may seem to have almost disappeared. Although, more concern may these days pose wireless mobile networks. Impacts of pervasive mobile signal (so much needed and appreciated) are generally unknown to the public.

By risk of *online security* we mean the risk of loss of personal data (e.g. photos. documents. music) or even in some cases an identity theft (e.g. social networks. mobile banking. email. passwords). It is interesting to evaluate the risk of online security as an increasing number of consumers are using smartphones and are unaware of the risks of "going online". Even experienced users often underestimate risk connected to online security.

The results are presented in Figure 10. Information overload and radiation was considered to be highly unknown hazards. Information overload was considered to have a potentially high hazard effect, since it affects human thought and brains in unknown ways. Online security was considered to be a much more known threat, but also quite dreadful, as the consequences of identity theft can be devastating socially and economically.

In the assessment, the current level situation was considered to be the reference case and the effect of smartphone increase by 2030 was considered against that. Therefore the risk perception is likely to change due to smartphones, as more is known about them. At the same time the volume of smartphone usage and data traffic is increasing, which will likely increase the dread factors of information overload and online security. On the other hand, radiation is quite unknown issue now, with additional information, its dread factor could either increase or decrease.

Overall, the increase of smartphones was considered to increase risk perception as well. Therefore a qualitative scale of -2 was given.

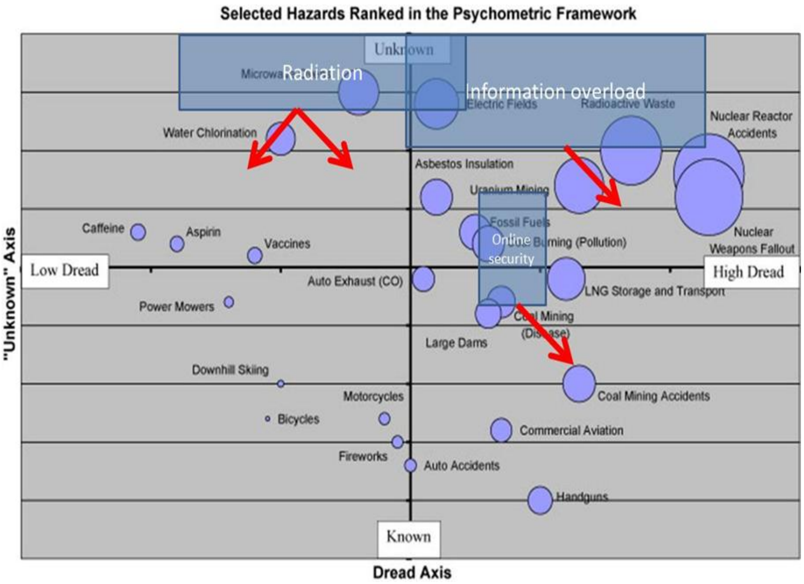


Figure 10. A psychometric plot of the hazard issues associated with smartphone use. The arrows describe the direction, where the development would go by 2030.

Possibility of misuse was assessed by applying a framework with four factors. Misuse is likely if accessibility is high, the outcome of misuse is certain and there are no security measures. For the analysis, two different forms of misuse were considered: using smartphones to conduct a terrorist attack and stealing private data.

The summary of the analysis is presented in Table 10. Smartphones are easily accessible, which increases the potential for misuse. For a terrorist attack, smartphones could be applied with minimal skill, by using the texting and calling options to launch bombs or by using the GPS and data transfer to track targets. A terrorist attack is however quite uncertain and dependent on outside influence, therefore it is not certain that each attempt would result in damage. The smartphones have minimal security measures to prevent their use for terrorism. The main alternatives are blocking networks in certain regions or for certain persons. Overall the risk score is high (15-17), making it almost certain that smartphones would be used for terrorist attacks.

For data theft, the technology is just as accessible, but the sophistication level needed is higher and the consequences of data theft are not as straightforward, and there are some security measures against data theft. This makes is only moderately to highly probable that an individual user would suffer data theft. At the technology level it is certain that data theft incidences will happen.

Table 10. Evaluation of the potential of the technology to be misused in terrorist attacks or data theft.

	Terrorist attack		Data theft	
Accessibility of technology	5	(accessible)	5	(accessible)
Sophistication of attack	3-5	(some to little knowledge)	2	(extensive knowledge needed)
Control over outcome	3	(some outside influence)	2-4	(some outside influence)
Security measures	4	(minimal security measures)	3	(limited security measures)
Total	15-17	(highly probable/certain)	12-14	(moderately to highly probable)

Trust in risk information was assessed by discussing how likely it would be that if smartphones would cause a hazard that the general public would know about it. Based on the discussion we concluded that since they are a widely used information device, it is very likely that the message would get to the media if hazards were involved. At the same time the devices amount to information overload and this may reduce the significance of those messages. Overall trust in risk information was considered to be ok.

Stakeholder involvement was assessed by considering five groups of stakeholders: users, developers, retailers, network operators and government. Also three parts of the supply chain were considered: product use through apps, network data services and the supply chain. The results were collected into a matrix (Table 11).

Based on the results, users of the product have limited chances to affect the system. But this is likely to improve in in the future, when the technology becomes more familiar.

Table 11. The possibility of various stakeholders to participate in the various elements of the product.

	Apps	Network	Supply chain
Users	x		
Developers	x		
Retailers		x	x
Network operators		x	x
Government		x	

Long term control functions were discussed in relation to the current situation and future development. Currently the material content, recycling and energy use of smartphones is fairly well controlled by EU regulations. Network radiation is also monitored, but not controlled. Data traffic is not directly controlled, but operators aim to seek ways to control it, since the rise in data traffic proves to be energy intensive and costly.

Compared to most other consumer items, smartphones are highly controlled, so it is likely that the level of control will increase to a sufficient level as the product matures and the control functions of the society get used to it.

Aggregation of social assessment to a single score and overview

As a first step the indicators were collected to a single table (Table 12), with a semi-qualitative ranking of their importance. A five stage Likert scale was used together with the performance reference points specified in the Prosuite methodology.

Table 12. An evaluation of the indicators and their relevance. It would seem that regional inequalities, risk perception and possibility of misuse are the main indicators to consider in the social assessment of smartphones.

Indicator	Likert score
Knowledge intensive work	0
Total employment	0
Regional inequalities	-2
Global inequalities	0
Child labour	0
Forced labour	0
Change in risk perception	-2
Possibility of misuse	-2
Trust in risk information	0
Long term control functions	0

In this version of social assessment the aggregation to a single score proceeded through normalization and taking a weighted average. Equal weights were used at this stage, but they can be refined at later stages.

The normalized results are presented in table 13. It can be seen that for the most part the impacts are caused by regional inequalities. For the aggregation to a single score a negative signum was used for the positive indicators (more jobs) as well as to the regional inequality to fix the problems of a negative normalization factor (higher GDP in non-OECD than in OECD countries). This resulted in a weighted single score. It can be observed that the social impacts in the maximum scenario increase almost sevenfold, while in the mid scenario they remain fairly constant and may even decrease slightly due to increased amount of jobs. However it should be also noted that the GINI of 2010 could not be estimated so it was ignored in the calculation (increasing the weights of other indicators to 1/5ths).

Table 13. Normalized results for social assessment and aggregation to a single score. Expressed in millions of person equivalents.

Signum		Normalization figure	2010	2030 mid	2030 max
-1	Knowledge intensive jobs	195	2.19	2.48	14.70
-1	Total employment	898	1.49	1.68	9.96
1	Child labour	19.6	0.97	1.07	6.43
1	Forced labour	2.22	0.90	0.90	5.86
1	Global inequality	$9.13 \cdot 10^{-11}$	n.a.	0.13	0.80
-1	Regional inequality	-2190	-15.16	-17.09	-101.50
	Weighted sum		**13.34**	**15.04**	**89.92**
	Averaged single score		**2.67**	**2.51**	**14.99**

The problem with resulting in an overview at this stage is the lack of subjective weights. Hours of child labour and hours of total employment are not as valuable. The overall scaling can be updated when default weights become available or if the interpreter of the results wishes to undergo a weighting exercise.

As an overview, the smartphone consumption in EU might result in considerable increases in regional inequalities as value added is produced mainly in the developed countries. This effect is slightly offset by the creation of total employment and knowledge intensive jobs. In addition the issues with child labour and forced labour should be considered.

1.4. Integration

The results from the separate assessments are collated to Table 14. Furthermore, the impacts are normalised (Table 15) and finally aggregated to the total scores (Table 16, Figure 11). Based on the results, the main impacts of the smartphone would be the positive impacts on GDP and total employment and the negative impacts on occupational health injuries and work related issues.

According to the integration the overall development of smartphone technology in terms of sustainability can be negative or positive depending on the weights of sustainable pillars in the assessment. The default weights of PROSUITE produce more negative impacts in both scenarios of 2030 than in the situation of 2010. The aspects of prosperity (GDP) and social wellbeing determine the final results together with exhaustible resources. Under social well-being regional inequality plays a biggest role in the scores.

The analysis shows that traditional LCA issues such impacts of natural environment and human health have only marginal contribution to the total scores of smartphone technology in 2010 and 2030 (Figure 11).

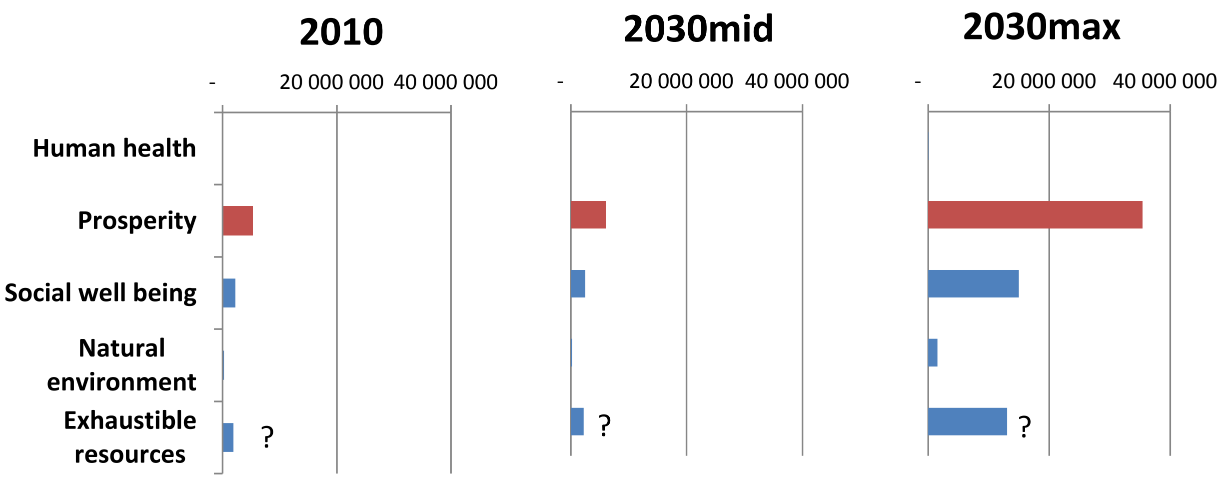


Figure 11. The five pillars of sustainability for the three assessed technology scenario situations. Figures are normalized results presented in person equivalents. The results for exhaustible resources are highly uncertain because of missing rare earths in impact assessment and problems in modelling recycling.

The aggregated results are based on so-called compensatory approach used commonly in decision support systems. The alternative is non-compensatory approach such as outranking. An outranking method recommended in PROSUITE gave a similar result than compensatory weighting with the default weights. At the technology level, the situation of 2010 is best in terms of sustainability due to the lowest level of sales. It could be said that this is an obvious result with the structure of the analysis assuming increasing sales. However the tradeoffs between increased prosperity and employment and also increased social and environmental impacts make the analysis less straightforward. With the default weights of the Prosuite DSS, the increased prosperity cannot compensate for the other impacts. It is important to note that the impact to exhaustible resources, such as indium, neodymium and germanium and other rare earth metals were excluded in the impact assessment methodology. The inclusion of these metals may increase the impact to resource depletion considerably. Both effective recycling of rare metals and longer lifespan of a smartphone improve the situation of resource depletion.

In social pillar there are also many factors that could be only assessed as qualitative indicators but they can play important role in sustainable development. In our subjective assessment smartphone technology can have remarkable potentials to cause negative impacts on change in risk precipitation (radiation. information overload. online security) and possible of misuse (causing harmful effects). However, it is impossible to predict the role of these aspects in 2030.

Table 14. Summary of quantitative impact assessment data from the separate assessments in Sections 1.3.1-1.3.5. The midpoints of social assessment are reproduced in order to present the integration to a single pillar in table 15.

Pillar	**Indicator**	**Units**	**Impact assessment**		
			2010	**2030mid**	**2030max**
Human health	**Environmental**	DALYs	3 235	4 501	26 724
	Occupational	DALYs	4 335	4 890	29 032
	Consumer	DALYs	-	-	-
Prosperity	**GDP**	€2010	48 828 534 726	55 079 513 322	327 023 226 307
Social well being	**Knowledge intensive jobs**	hours	428 000 000	483 000 000	2 867 000 000
	Total employment	hours	1 336 000 000	1 507 000 000	8 945 000 000
	Child labour	hours	19 000 000	21 000 000	126 000 000
	Forced labour	hours	2 000 000	2 000 000	13 000 000
	Global inequality	GINI	n.a.	0.000012	0.000073
	Regional inequality	€	33 190 000 000	37 438 000 000	222 283 000 000
Natural environment	**Ecosystem damage**	species years	14	18	108
Exhaustible resources	**Metal depletion**	USD2010	14 832 330	17 215 836	102 215 467

Table 15. The quantitative impact assessment results normalized to person equivalents.

Pillar	**Indicator**	**Normalization impact/person**	**Normalized result**		
			2010	**2030mid**	**2030max**
Human health	***Environmental***	*7.4*	*437*	*608*	*3 611*
	Occupational	*7.4*	*586*	*661*	*3 923*
	Consumer	*7.4*	*n.a.*	*n.a.*	*n.a.*
	Human health total		**1 023**	**1 269**	**7 535**
Prosperity	**GDP**	9237	5 286 084	5 962 803	35 402 910
Social well being	***Knowledge intensive jobs***	*195*	*2 194 872*	*2 476 923*	*14 702 564*
	Total employment	*898*	*1 487 751*	*1 678 174*	*9 961 024*
	Child labour	*19.6*	*969 388*	*1 071 429*	*6 428 571*
	Forced labour	*2.22*	*900 901*	*900 901*	*5 855 856*
	Global inequality	$9.13 \cdot 10^{-11}$	*n.a.*	*131 435*	*799 562*
	Regional inequality	*-2190*	*- 15 155 251*	*-17 094 977*	*- 101 499 087*
	Aggregated social impacts		**2 223 820**	**2 507 274**	**14 986 581**
Natural environment	**Ecosystem damage**	$6.91 \cdot 10^{-7}$	205 642	262 244	1 557 019
Exhaustible resources	**Metal depletion**	7.83	1 894 295	2 198 702	13 054 338

Note: In the aggregation of social well-being impacts the value of global inequality in 2010 is assumed to be the same as in the case of 2030 mid. Equal weights (=1/6) were used in the aggregation.

Table 16. Total scores of pillars according to the default weights of PROSUITE and equal weights. Positive values describe negative impacts and positive values describe negative impacts. The best scenario under each pillar is bolded.

	Integration			Weights	
	2010	2030 *mid*	2030 *max*	Default	Equal
Human health	**1 023**	1 269	7 535	0.3	0.25
Prosperity	5 286 084	5 962 803	**35 402 910**	- 0.1	- 0.25
Social well being	**2 223 820**	2 507 274	14 986 581	0.25	0.25
Natural environment	**205 642**	262 244	1 557 019	0.25	0.25
Exhaustible resources	**1 894 295**	2 198 702	13 054 338	0.1	0.25
Overall: default weight	268 493	316 350	1 903 303	0.8	-
Overall: equal weight	- 240 326	- 248 328	- 1 449 359	-	1.0
Concorcet wins	4	0	1		

1.5. Conclusions

From the viewpoint of final interpretation, there is a need to discuss about the effects of the chosen system boundaries. It is important to understand that the current analysis does not include some important benefits that smartphones offer their users. For example, they have increased feelings of security and helped people to obtain more information to improve the health of the family (Time Magazine, 2012). The effects of apps are complicated. It is impossible to forecast the indirect economic effects caused by smartphones. For example, there are well documented cases of increased economic activity and profit for small businesses in developing countries due to smartphones (Jensen, 2007). In addition, there is a huge potential to improve energy and material efficiency and promote renewable energy production with new ICT applications in which smartphone technology plays important role (GeSI and Boston Consulting Group, 2012).

In summary, the sustainability assessment of smartphone technology in the PROSUITE project is based on uncertain data, many assumptions and choices. Therefore it cannot be objectively stated whether smartphone technology is moving towards more or less sustainability from 2010 to 2030. However the analysis has highlighted several potential hotspots in the sustainability aspects of smartphones. For this reason, it is more important to focus on the key performance indicators. Using the identified key performance indicators is possible to direct the overall development of smartphone technology towards increased sustainability.

Based on the assessment and additional information from literature, the sustainability of smartphone technology could be best improved by the following way (not taking into account the potential for reducing sales):

- to ensure that the rare metals are recycled and find ways to replace them
- to increase the lifespan of a smartphone in use
- to control the data traffic per phone and improve the energy efficiency of data transfer
- to ensure that child labour or low wage labour is not used in the electronics assembly stage
- to improve the use of smartphones in abating greenhouse gas emissions and other environmental aspects in other product life cycles through green apps

1.6. References

Aker, J.C., Mbiti, I.M., 2010. Mobile Phones and Economic Development in Africa. Journal of Economic Perspectives 24, 207–32.

AT&T, 2012. AT&T Sustainability Report 2012.

Bass, F.M., 1969. A New Product Growth for Model Consumer Durables. Management Science 15, 215–227.

Boliden, 2012. Sustainability report Rönnskär 2012.

Braungart, M., McDonough, W., Bollinger, A., 2007. Cradle-to-cradle design: creating healthy emissions – a strategy for eco-effective product and system design. Journal of Cleaner Production 15, 1337–1348.

Cisco, 2013. Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2012–2017 (white paper).

Desai, P., 2008. Creating Low Carbon Communities: One Planet Living Solutions. Globalizations 5, 67–71.

Ecoinvent, 2011. Ecoinvent database v.2.2, Swiss Centre for Life Cycle Inventories [WWW Document]. URL www.ecoinvent.ch

Edmunds, A., Morris, A., 2000. The problem of information overload in business organisations: a review of the literature. International Journal of Information Management 20, 17–28.
Ericsson, 2013. Ericsson Mobility Report 2013.
European Commission, 2010. International Reference Life Cycle Data System (ILCD) Handbook - general guide for life cycle assessment - detailed guidance. Joint Research Centre, Institute for Environment and Sustainability.
Faist Emmenegger, M., Frischknecht, R., Stutz, M., Guggisberg, M., Witschi, R., Otto, T., 2004. Life Cycle Assessment of the Mobile Communication System UMTS: Towards Eco-efficient Systems (12 pp). Int J Life Cycle Assessment 11, 265–276.
Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in Life Cycle Assessment. J. Environ. Manage 91, 1–21.
Fischer, B., 2012. How much does it cost to charge an iPhone 5? A thought-provokingly modest $0.41/year [WWW Document]. OPOWER. URL http://blog.opower.com/2012/09/
Gartner, 2013. Press Release: Gartner Says Worldwide Mobile Phone Sales Declined 1.7 Percent in 2012.
GeSI, Boston Consulting Group, 2012. SMARTer 2020.
Golder, P.N., Tellis, G.J., 2004. Growing, Growing, Gone: Cascades, Diffusion, and Turning Points in the Product Life Cycle. Marketing Science 23, 207–218.
Guinée, J.B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., Rydberg, T., 2011. Life Cycle Assessment: Past, Present, and Future†. Environ. Sci. Technol 45, 90–96.
Hammond, J.S., Keeney, R.L., Raiffa, H., others, 1998. The hidden traps in decision making. Harvard Business Review 76, 47–58.
Hu, Z., Ruutu, J., 2011. Comparison of energy consumption between a mobile device and a collection of dedicated devices, in: 2011 IEEE International Symposium on Sustainable Systems and Technology (ISSST). Presented at the 2011 IEEE International Symposium on Sustainable Systems and Technology (ISSST), pp. 1–6.
Huang, I.B., Keisler, J., Linkov, I., 2011. Multi-criteria decision analysis in environmental sciences: ten years of applications and trends. Sci. Total Environ. 409, 3578–3594.
Huijbregts, M.A.J., Hellweg, S., Frischknecht, R., Hungerbühler, K., Hendriks, A.J., 2008. Ecological footprint accounting in the life cycle assessment of products. Ecological Economics 64, 798–807.
Huijbregts, M.A.J., Rombouts, L.J.A., Hellweg, S., Frischknecht, R., Hendriks, A.J., Van de Meent, D., Ragas, A.M.J., 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.
IDC, Llamas, R.T., Stofega, W., 2013. Worldwide Smartphone 2013–2017 Forecast and Analysis.
Jackson, T.W., Farzaneh, P., 2012. Theory-based model of factors affecting information overload. International Journal of Information Management 32, 523–532.
Jensen, R., 2007. The Digital Provide: Information (Technology), Market Performance, and Welfare in the South Indian Fisheries Sector. The Quarterly Journal of Economics 122, 879–924.
Judl, J., Mattila, T., Seppala, J., Koskela, S., Kautto, P., 2012. Challenges in LCA comparisons of multifunctional electronic devices, in: Electronics Goes Green 2012+ (EGG), 2012. Presented at the Electronics Goes Green 2012+ (EGG), 2012, pp. 1–5.
Koomey, J.G., 2008. Worldwide electricity used in data centers. Environ. Res. Lett. 3, 034008.
Koomey, J.G., 2011. Growth in data center electricity use 2005 to 2010. Analytics Press.
Laurent, A., Olsen, S.I., Hauschild, M.Z., 2012. Limitations of carbon footprint as indicator of environmental sustainability. Environmental science & technology 46, 4100–4108.
Lenzen, M., Moran, D., Kanemoto, K., Foran, B., Lobefaro, L., Geschke, A., 2012. International trade drives biodiversity threats in developing nations. Nature 486, 109–112.
Malmodin, J., Moberg, Å., Lundén, D., Finnveden, G., Lövehagen, N., 2010. Greenhouse Gas Emissions and Operational Electricity Use in the ICT and Entertainment & Media Sectors. Journal of Industrial Ecology 14, 770–790.
Malmodin, J., Oliv, L., Bergmark, P., 2001. Life cycle assessment of third generation (3G) wireless telecommunication systems at Ericsson, in: Proceedings EcoDesign 2001: Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing, 2001. Presented at the Proceedings EcoDesign 2001: Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing, 2001, pp. 328–334.
Mattila, T., Judl, J., Seppälä, J., 2014. Carbon footprint of mobile devices: Open questions in carbon footprinting of emerging mobile ICT technologies, in: Muthu, S.S. (Ed. . (Ed.), Assessment of Carbon Footprint in Different Industrial Sectors, Volume 1. Springer.
Mattila, T., Lehtoranta, S., Sokka, L., Melanen, M., Nissinen, A., 2012. Methodological Aspects of Applying Life Cycle Assessment to Industrial Symbioses. Journal of Industrial Ecology 16, 51–60.

MobiThinking, 2013. Global mobile statistics 2013 Section E: Mobile apps, app stores, pricing and failure rates [WWW Document].
Navazo, J.M.V., Méndez, G.V., Peiró, L.T., 2013. Material flow analysis and energy requirements of mobile phone material recovery processes. Int J Life Cycle Assess 1–13.
Nidumolu, R., C.Prahalad, C.K., Rangaswami, M.R., 2009. Why Sustainability Is Now the Key Driver of Innovation. Harvard Business Review.
Peres, R., Muller, E., Mahajan, V., 2010. Innovation diffusion and new product growth models: A critical review and research directions. International Journal of Research in Marketing 27, 91–106.
Portio Research, 2013. Fast growth of apps user base in booming Asia Pacific market [WWW Document]. URL http://www.portioresearch.com/en/blog/2013/fast-growth-of-apps-user-base-in-booming-asia-pacific-market.aspx
Raghavan, B., Ma, J., 2011. The energy and emergy of the internet, in: Proceedings of the 10th ACM Workshop on Hot Topics in Networks, HotNets-X. ACM, New York, NY, USA, pp. 9:1–9:6.
Scharnhorst, W., 2006. Life cycle assessment in the telecommunication industry: A review. Int J Life Cycle Assess 13, 75–86.
Scharnhorst, W., Hilty, L.M., Jolliet, O., 2006. Life cycle assessment of second generation (2G) and third generation (3G) mobile phone networks. Environment International 32, 656–675.
Sinden, G., Skea, J., Jefferiss, P., Clift, R., Jackson, T., Ilott, T., Kenber, M., Roberts, M., Kelly, R., Reeson, S., Monger-Godfrey, N., Dickie, N., Double, K., Staniaszek, D., 2008. PAS 2050:2008 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services.
Soimakallio, S., Kiviluoma, J., Saikku, L., 2011. The complexity and challenges of determining GHG (greenhouse gas) emissions from grid electricity consumption and conservation in LCA (life cycle assessment) – A methodological review. Energy 36, 6705–6713.
Tanskanen, P., 2012. Electronics Waste: Recycling of Mobile Phones, in: Damanhuri, E. (Ed.), Post-Consumer Waste Recycling and Optimal Production. InTech.
Time Magazine, 2012. 10 Ways mobile technology is changing our world. Time Magazine.
United Nations World Commission on Environment and Development (WCED), 1987. Our Common Future.
Upham, P., 2000. An assessment of The Natural Step theory of sustainability. Journal of Cleaner Production 8, 445–454.
Williams, E., 2011. Environmental effects of information and communications technologies. Nature 479, 354–358.
Yu, J., Williams, E., Ju, M., 2010. Analysis of material and energy consumption of mobile phones in China. Energy Policy 38, 4135–4141.

2. Conclusions and input to method developers

The PROSUITE sustainability assessment framework was tested as it was at the time of doing the assessment (final update June 2013). The results on sustainability metrics are therefore only indicative and should not be used for overall conclusions of the sustainability of smartphones. The results may be updated, when improved methods become available and are accepted by the wider scientific community.

The overall framework was found to be useful in highlighting various sustainability aspects. The high reliance on sector level input-output data limits the results of this study to screening only. Further studies using detailed process level data could improve the situation.

It seems that there is a need to define many social well-being indicators case by case. Now some of the selected indicators are not relevant for our case study. On the other hand, many relevant social aspects related to the use of mobile devices are missing.

It is not clear how to assess consumer impacts under the pillar of human health. In addition, it is not clear how the Pedigree matrix will be applied in the social assessment. Or in general, how uncertainty aspects could be taken into account in the assessment?

The case study also highlighted several problems in the PROSUITE methodology:

- **First** of all, the method ignores the dynamics of product sales and focuses on a fixed single year (2030). In the case of smartphones, the sales in 2030 might already be declining; therefore an assessment of a single year underestimates the whole impacts. An integral of the impacts over time would be a more recommended approach.
- **Second**, the impact assessment methods for exhaustible resources do not cover the special metals found in smartphones (indium. neodymium. etc.). More research on including also these rarer elements would be necessary to improve the usability of the method for novel ICT technologies.
- **Third**, the interpretation is sensitive to assumptions about normalization and weighting. For example in the smartphone case study, most of the social impacts were assessed to be caused by the difference of value added in developing and developed countries compared to the average situation. It is difficult to interpret, why an increase of prosperity in both regions would result in a social impact, which would be quantified to be an order of magnitude more damaging than child labour.
- **Fourth**, currently there is no possibility to conduct an uncertainty assessment which would cover the whole analysis from inventory to impact assessment, normalization and weighting. Uncertainty assessment is possible only in relation to the inventory. The lack of uncertainty and sensitivity analysis limits the usefulness of the results in decision making.
- **Fifth**, the instruction to aggregate the qualitative impact indicators of social well-being into a single well-being score is missing. This is required when the aim is to aggregate five sustainable pillars. Without this instruction there is a risk of misunderstand the role of social well-being pillar in the final interpretation

3. Annex

The annex should e.g. include all input data to the DSS as well as all other information, which is necessary to reproduce the results, but not essential for understanding the message (the latter should go to the main chapters). If the annex is confidential, please mark it as such so that we can detach it from the deliverable when published.

Annex 1: Inventory analysis of a smartphone

Table 17. Material and component inventory of a generic smartphone manufactured after 2010.

Part of device	Ecoinvent unit process	weight (g)
Packaging and documentation		
Materials	Kraft paper, bleached, at plant/RER U	7.314
	Packaging film, LDPE, at plant/RER U	1.554
	Packaging, corrugated board, mixed fibre, single wall, at plant/RER U	88.29
	Polystyrene, general purpose, GPPS, at plant/RER U	60.388
	Steel, low-alloyed, at plant/RER U	0.469
	Unidentified (excluded)	112.493
Processing	Injection moulding/RER U	60.388
	Wire drawing, steel/RER U	0.469
Gross total mass		270.508
Total mass	*unidentified parts cut-off from analysis*	**158.015** [a]
Battery		
	Battery, LiIo, rechargeable, prismatic, at plant/GLO U	25.754
Total mass		**25.754**
Electronic components		
Materials/components	Chromium steel 18/8, at plant/RER U	4.727
	Copper-nickel-zinc alloy, at plant, PROSUITE/RER U	0.276
	Diode, glass-, SMD type, surface mounting, at plant/GLO U	0.059
	Electronic component, unspecified, at plant/GLO U	3.154
	Integrated circuit, IC, logic type, at plant/GLO U	1.793 [b]
	LCD module, at plant/GLO U	10.092
	Polypropylene, granulate, at plant/RER U	0.638
	Polystyrene, high impact, HIPS, at plant/RER U	0.504
	Printed wiring board, surface mount, lead-free surface, at plant/GLO U	12.708 [b]
	Printed wiring board, through-hole, lead-free surface, at plant/GLO U	4.403 [b]
Processing	Calendering, rigid sheets/RER U	0.638
	Injection moulding/RER U	0.504
	Sheet rolling, chromium steel/RER U	4.727
	Sheet rolling, steel/RER U	1.148
	Steel, low-alloyed, at plant/RER U	0.872
Total mass		**39.226**

	Ecoinvent unit process	weight (g)
Mechanical components		
Materials/components	Chromium steel 18/8, at plant/RER U	17.556
	Copper, at regional storage/RER U	0.015
	Magnesium-alloy, AZ91, diecasting, at plant/RER U	23.044
	Polycarbonate, at plant/RER U	4.902
	Polycarbonate-ABS Blend, glass fibre reinforced 20%, PC-ABS-GF20/PROSUITE	17.036
	Polypropylene, granulate, at plant/RER U	0.565
	Polyurethane, flexible foam, at plant/RER U	0.106
	Steel, low-alloyed, at plant/RER U	5.704
Processing	Calendering, rigid sheets/RER U	0.565
	Foaming, expanding/RER U	0.106
	Injection moulding/RER U	21.938
	Sheet rolling, chromium steel/RER U	17.556
	Sheet rolling, copper/RER U	0.015
	Sheet rolling, steel/RER U	5.704
	Unidentified (excluded)	5.694
Gross total mass		74.622
Total mass		**68.928** [a]

[a] Unidentified parts/components were cut-off from the analysis.

[b] In the model we multiplied these values by the factor of 2. This adjustment was based on a comparison of preliminary results of the case study with reported carbon footprint of manufacturing and use of an Apple's iPhone and Nokia's Lumia range smartphones. If left without modifications the impacts of the device would be heavily underestimated due to imperfect inventory and outdated datasets of the ecoinvent database.

Table 18. Transport inventory for a generic smartphone.

Transported item (from/to)	Distance	Mode of transport (ecoinvent)
Battery, from supplier to OEM	1000 km	transport, aircraft, freight
Electronic components, from supplier to OEM	1000 km	transport, aircraft, freight
Mechanical components, from supplier to OEM	200 km	transport, lorry 16-32t, EURO 5
Packaging and documentation, from supplier OEM	100 km	transport, lorry 16-32t, EURO 5
Final product, from OEM to airport	100 km	transport, lorry 16-32t, EURO 5
Final product, intercontinental transport	9000 km	transport, aircraft, freight
Final product, from airport to retail	400 km	transport, lorry 16-32t, EURO 5

Table 19. Smartphone use inventory.

Activity	Measure	Source/Note
Lifespan	1.5 year	Tanskanen. 2012
Smartphone energy consumption, lifetime	5.25 kWh	Fischer (2012)
Data consumption, per user, per month, in 2010	450 MB	Ericsson (2013)
Data consumption, per user, per month, in 2030	3166 MB	*based on predictions of Ericsson*
Mobile network energy consumption, in 2010	$415 \cdot 10^{-6}$ kWh/MB	AT&T. 2013
Mobile network energy consumption, in 2030	$415 \cdot 10^{-7}$ kWh/MB	*assumed improvements in energy consumption*
Energy intensity of voice transmitting, mobile network	5 kWh/user/year	*estimation based on* Malmodin et al. (2010)
Energy intensity of data centres	0.0015 kWh/MB	*own estimation based on* GeSI and Boston Consulting Group (2012), Koomey (2011) and

Annex 2. Comparison of ReCiPe and PROSUITE LCIA

A comparison between ReCiPe and Prosuite LCIA methods for human health, natural environment and exhaustible resources.

Table 20. Human health

	Prosuite	ReCiPe
Overall score per phone	$5.5 \cdot 10^{-5}$	$1.1 \cdot 10^{-4}$
Normalized result	$2.1 \cdot 10^{-3}$	$7.8 \cdot 10^{-3}$
Climate change	76%	39%
Non-cancer	20%	
Particulate matter	2%	13%
Cancer	2%	
Human toxicity total		47%

Table 21. Species years

	Prosuite	ReCiPe
Overall score per phone	$2.4 \cdot 10^{-7}$	$2.7 \cdot 10^{-7}$
Normalized result	$3.5 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$
Climate change	99%	90%
Tropospheric ozone	1%	
Land use		9%
Freshwater eutrophication		1%

Metal depletion

ReCiPe $ 2 → normalized result $8.4 \cdot 10^{-3}$

Prosuite $ 0.25 → normalized result $3.2 \cdot 10^{-2}$