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The Role of Unused Storage Phases (Hibernation) in the Overall Lifetime of a Mobile Phone – an Evaluation of Simulation-based Scenarios Including their Environmental Impacts

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Abstract: Life spans of consumer electronics such as mobile phones are often characterized by comparatively long storage phases after their useful lives, in which they do not provide any further service to their owners. This consumer behavior, which is referred to as hibernation, counteracts measures for increasing the lifetimes and use intensity of consumer electronics, which are integral components of a circular economy concept. Modifications in product design such as design for repair or refurbishment are mainly useful if a cascade use system could be realized in which the devices remain in service as long as possible without being stored in between use phases. This contribution builds upon a simulation model of different service lifetimes and storage phases of consumer electronics at the European level. We use this model to evaluate different scenarios for mobile phones, including smartphones. In the first scenario, an increase in service lifetime leads to decreasing demand for new devices, while in the second scenario, transfer probabilities to storage phases and, hence, hibernation are decreased. By linking the simulated scenarios to the impact factors of existing Life Cycle Assessments (LCAs) for mobile phones, we provide an outlook on the environmental benefits and resource conservation of the respective modifications in the use structure of mobile phones.

Introduction

Measures for increasing a product's service lifetime, e.g. through improvements in product design or the provision of repair services, will only succeed if consumers are willing to participate and change current consumption behavior. Particularly consumer electronics are often only used for comparatively short periods of time before they are replaced by new devices. In many cases, particularly when regarding smaller consumer electronics, products are not further used in a cascade system but are kept in households without providing any additional service. Such unused storage phases counteract efforts for increasing service lifetimes and implementing cascade systems in which a product might have a second and a third service lifetime.

The goal of this contribution is to quantify the effect of modifications in the use structure of a mobile phone (classical cell phone and smartphone) taking into account basic consumer behavior and particularly unused storage faces which we refer to as "hibernation" (Oswald and Reller, 2011). Using a cascade simulation model, we assess different scenario-based case studies. To this end, we particularly focus on consumer decisions and their implications for the use structure. As the model only provides potential reduction quantities of new product purchases, we link the simulation results to LCA studies in the discussion section in order to provide an outlook on the environmental effects of the analyzed scenarios.

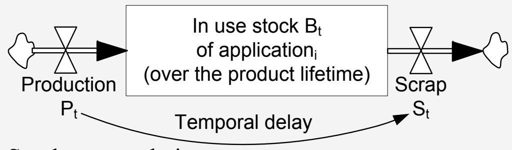
The determination of consumer behavior, their motivations, incentives and obstacles are key aspects of efforts to improving simulation approaches in this context. Therefore, we finally discuss how the simulation tool described here, which is based on a System Dynamics (SD) approach, could be improved by implementing consumer decision-making at the micro level through Agent Based Modelling (ABM). Such improved simulation tools may provide significant additional value for better addressing consumer behavior in the modelling of product life cycles. This is an important aspect for the development of strategies towards increased service lifetimes of electronic devises in particular and consumer goods in general.

Method and Model Structure

For the simulation of different lifetime scenarios, we use a cascade stock and flow model implemented in System Dynamics (SD).

The stock and flow structure within an SD modelling environment enables flexible development of dynamic life cycle simulation models ranging from single stock accumulations over a product's lifetime to detailed aging chains systematically capturing different age cohorts and related exchange flows (cf. e.g. Glöser et al., 2016). The basic concept of stock accumulation over a product's lifetime is shown in a simple illustrative manner in Figure 1. While the valves (flow variables) represent continuous material flows, the boxes (stock variables) accumulate inventories over a certain period of time. The overall system is comparable to a bathtub with in- and outflows. By linking various stocks and flows, detailed life cycle models can be developed.

For the cascade model in this study, which builds upon the work conducted by Thiébaud et al. (2017, 2018) for Switzerland, we distinguish between three different stages in product lifetime and three different storage phases as it is unlikely that mobile phones are used beyond a third lifetime (Thiébaud et al., 2017). After each service lifetime, mobile phones can take three routes: they can directly enter the next service life (e.g. by being sold on to a new user); they can enter hibernation (e.g. by being kept as backup devices); or they can exit the European market by being scrapped or exported to foreign markets. The likelihood of each path is determined by transfer coefficients (see Table 1), which were mainly taken from Thiébaud et al. (2017) and Thiébaud-Müller et al. (2018) and adjusted to the European context with the help of auxiliary data from Chancerel (2010), Huisman et al. (2012), Sander and Schilling (2010) and Sommer et al. (2015).

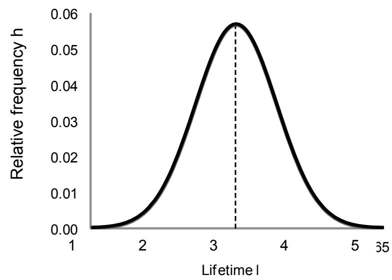


Stock accumulation:

$$B_t = \sum_{t=t_0}^{t} (P_t - S_t) + B_{t_0}$$

Delay with fix average lifetimes:

$S_t = P_{t-l}$ with l as the average lifetime



Delay with lifetime distributions:

$$S_t = \sum_{l=0}^{n} P_{t-l}\, h_l$$ with h as the relative frequency of l

Figure 1. Simulating product life cycles and stock accumulation in use within the System Dynamics (SD) modelling environment (c.f. Glöser et al., 2016; Glöser-Chahoud and Schultmann, 2019).

Transfer coefficients		Smartphones	Cellphones
1st SL	directly to second use	0,30	0,20
	to first storage	0,50	0,60
	to disposal	0,05	0,10
	to export	0,15	0,10
2nd SL	directly to thrid use	0,30	0,30
	to second storage	0,30	0,30
	to disposal	0,20	0,20
	to export	0,20	0,20
3rd SL	to 3rd storage	0,50	0,50
	to disposal	0,25	0,25
	to export	0,25	0,25
1st ST	to second use	0,50	0,50
	to disposal	0,25	0,25
	to export	0,25	0,25
2nd ST	to third use	0,20	0,40
	to disposal	0,40	0,30
	to export	0,40	0,30
3rd ST	to disposal	0,6	0,5
	to export	0,4	0,50

Table 1. Assumed transfer probabilities between different service lifetimes (SL) and storage times (ST).

In the cascade model used here, each phase of a product's life cycle is portrayed by a separate aging chain. An aging chain consists of a series of stock variables, while each stock represents an age cohort (one for each year of a product's lifetime). After each year, the transfer probability to the following stock (survival rate) or, respectively, the probability for leaving the aging chain (failure rate) is calculated from a probability density function. For the underlying probability distributions, Weibull functions were utilized as this distribution shows the highest flexibility for adjusting the shape to empirical data (see Thiébaud et al., 2017). The three paths mobile phones can take are depicted by the three layers in Figure 2. The top layer portrays the aging chains within the three service lives, while the middle layer portrays the three storage phases, which are analogously modeled. The bottom layer represents the respective sinks in the form of exports or scrapping. The assumed lifetime distributions of the respective devices are summarized in Table 2.

	Parameters Weibull	Smartphones	k	Cellphones	k
Service Lifetime	1st service lifetime	3	1,7	2,5	1,7
	2nd service lifetime	2	1,8	2,5	1,7
	3rd service lifetime	1,5	1,9	1,5	1,8
Storage Time	1st storage time	2	1,9	3	1,8
	2nd storage time	2	1,9	2,5	1,8
	3rd storage time	2	1,9	2	1,8

Table 2. Assumed density functions regarding duration of use and storage phases (cf. Glöser-Chahoud et al. 2019). The parameter λ within the Weibull function describes the expected value while k is a shape parameter leading to right skewed distributions with the values chosen here (cf. Figure 2).

While from a modeling point of view, this approach seems reasonable, it has to be kept in mind that the transfer probability in this model structure is a fixed endogenous variable in the form of input data to the model. In reality, this transfer to the next life stage is strongly influenced by individual consumers' decisions and might not only depend on the use phase but also on the age of the respective device and potential further aspects regarding consumers' preferences and resulting behavior. In this context, the structure of the simulation model presented here should be seen as a first attempt to provide a quantitative estimate of product flows in a cascade system that includes hibernation, while further methodological improvements will follow as discussed in the conclusions of this paper.

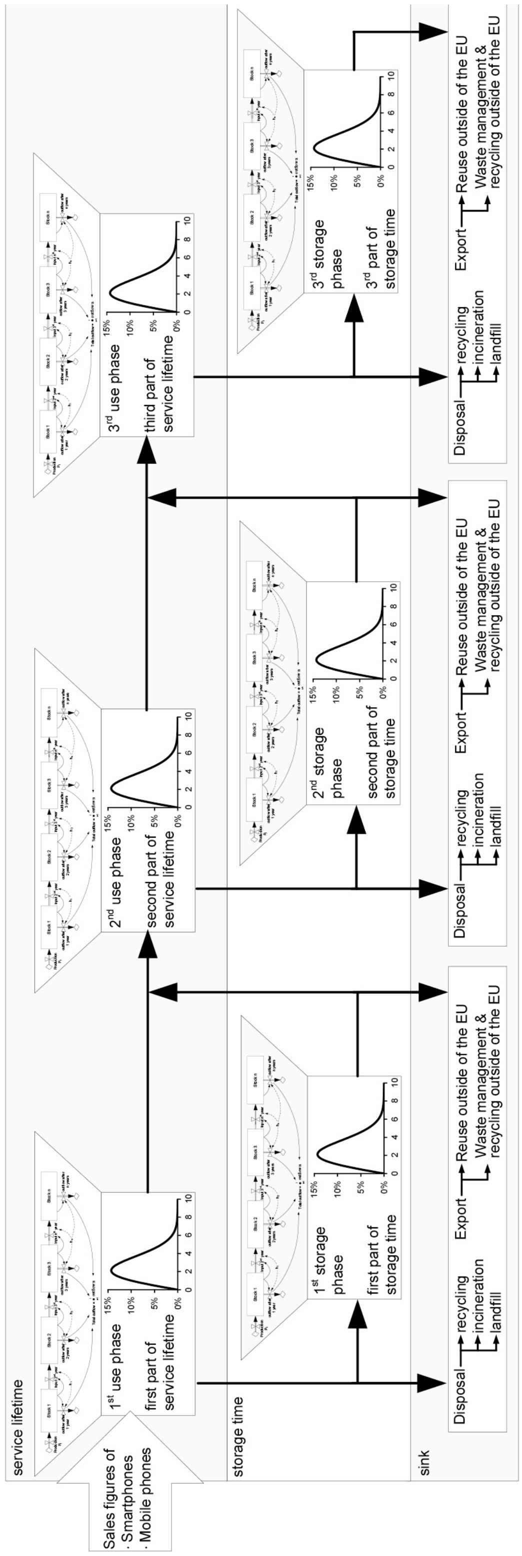


Figure 2. Concept of the cascade use phase model taking into account different stages of service lifetimes and storage (hibernation) of mobile

Beside the transfer probabilities and distributions of the durations of different life stages (summarized in Table 1 and 2), major input data to the model are sales figures of respective electronic devices in Europe. Overall sales figures of portable phones (smartphones and mobile phones combined) were extracted from the STATISTA database (STATISTA, 2018), while their shares were taken from the German Consumer Electronics Market Index (CEMIX, 2000-2016). We distinguish between classical cell phones (for phone calls and messaging) and smartphones with internet connection, touch screens and higher computation capabilities. This distinction seems necessary as historic cell phones were generally less expensive, which increases the probability of ending up in hibernation, while more expensive electronic devices are more likely to form an incentive to resell the used product after replacing it by a new device due to comparatively high residual values. This aspect is indicated by the differing transfer probabilities in Table 1. Figure 3 summarizes the input flows for the past while future development was simply derived from trend extrapolation.

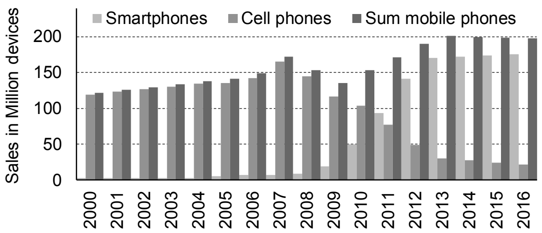


Figure 3. Sales figures of smartphones, cell phones and overall mobile phones in Europe (EU28) based on STATISTA (2018) and CEMIX (2000-2016).

Exemplary Scenarios

As outlined above, two scenarios were modeled with this setup. The basic intention of the two scenarios is to analyze the potential reduction of demand for new devices by modifications in the system structure. With these scenarios, we do not attempt to represent real future development but to provide a basic understanding of the system behavior and of the main drivers to achieve resource conservation.

The first scenario assumes technical improvements, e.g. regarding product design, durability of specific components or software update services reducing technical obsolescence. In this scenario, the underlying transfer probabilities to unused storage faces resulting in hibernation of mobile phones are kept at a constant level compared to the baseline scenario without any modifications. Of course, the individual effect of technical improvements varies and needs case specific evaluation. However, general aspects of such modifications can be captured by the simulation tool presented here. As we do not assume modifications in consumer behavior in this scenario, the increasing product durability is likely to not directly affect the duration of the first service lifetime as the product's functionality in this use phase remains relatively equal compared to the baseline scenario. Only the second and third service lifetimes – as the products are likely to reach technical or functional obsolescence in these phases – are increased by these technical improvements. However, as clearly shown in the simulation results, such technical measures are counteracted by the unused storage phases and the only partly existing cascade use structure in the form of second hand products. The majority of European mobile phones does not even enter the second and third service lifetime but ends up in hibernation and subsequent disposal or export without providing any additional service. Hence, the effectiveness of these technical improvements is expected to be relatively low. This effect is quantified based on the following assumption: From the baseline scenario, the overall stock of mobile phones in service until 2030 is extracted. This is the reference number of mobile devices used in Europe. Figure 4 illustrates relevant results from the baseline scenario.

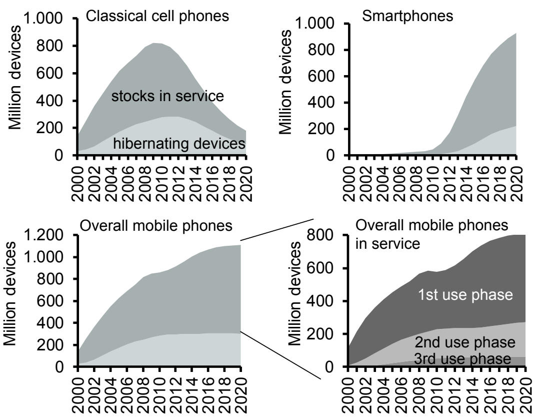


Figure 4. Baseline scenario as a reference case to the following two scenarios. As this scenario is not intended to be forward looking, we only ran the simulation until 2020.

By increasing the second and third service lifetime, the theoretical stock of devices in use would increase. This theoretical increase is balanced by reducing the demand for new devices. Hence, the longer service time leads to a certain reduction of demand and a shift from first to second and third service lifetimes. However, as mentioned before, this effect is moderate as only a mere fraction of overall mobile phones really reaches the second and third service lifetime. In the scenario shown in Figure 5, we assumed an increase of second service lifetime by half a year and an increase of third service lifetime by one year.

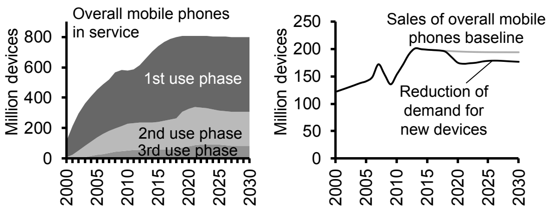


Figure 5. Effect of increasing service lifetime in the second and third use phase.

The second scenario assumes a reduction of hibernation time to 0 by the year 2030, which is achieved by successively reducing the transfer probabilities to hibernation. Such an effect – even though highly theoretical – could e.g. be achieved through product oriented product service systems (PSS) in which the consumer no longer owns the device and simply returns it after the use phase. The potential reduction of demand for new devices in this scenario is shown in Figure 6.

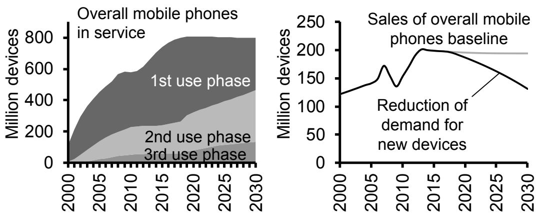


Figure 6. Effect of decreasing transfer probabilities to hibernation.

It is likely that such a theoretical modification in the use structure will be difficult to achieve in practice. Nevertheless, this scenario underlines the counterproductive effect of hibernation of functioning products in the transition towards a more sustainable consumption. This becomes even clearer when combining the results derived in these two scenarios with LCAs of mobile phones and, hence, the environmental impact associated with the production of new devices.

Discussion of results

By increasing the useful lifetime of a product, the need for new devices decreases. Taking the stock level from the baseline scenario as a reference, we analyze to which extent new product flows can be reduced while still reaching the same stock level in service as in the reference case. We thus follow a stock-driven approach such as proposed by Müller (2006). The methodological details of how new product flows are adapted in relation to the desired stock level are described in detail in Pfaff et al. (2018). In order to provide an outlook on the potential environmental impact of the modifications shown in the two scenarios, we additionally utilize LCA data for mobile phones. The body of literature on LCAs of different mobile phones is wide and contains varying results due to different system boundaries, data basis, variations among producers and underlying assumptions. However, some major results can be generally summarized. As shown in Figure 7, mobile phones are among those products which have their main environmental impacts during production and fabrication (particularly for the required material basis and the energy intensive fabrication of these high-tech components).

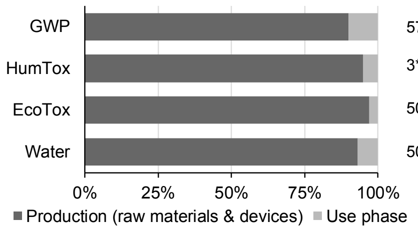


Figure 7. Major environmental impact of a smartphone illustrated in the form of different impact categories from a LCA study (Ercan et al., 2016). Abbreviations: Global Warming Potential (GWP), Comparative Toxic Units (CTU) regarding human toxicity non cancer effects (h) and eco toxicity (e).

Hence, an increase in service lifetimes in order to decrease the need for new devices strongly affects environmental impacts. While the replacement of other consumer products with high emissions during the use phase may be ecologically beneficial, this is not the case for mobile phones. Figure 8 provides the spread and range of CO_2 equivalents (GWP) from a review of existing LCAs for mobile phones (extracted from Suckling and Lee, 2015), which illustrates this point.

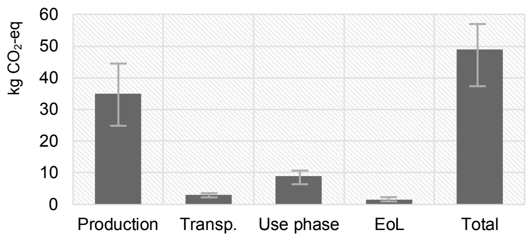


Figure 8. Spread and share of global warming potential (GWP) of different LCAs for smartphones (see Suckling and Lee (2015) for a comprehensive overview of different LCAs of mobile phones).

From an ecological perspective, lifetime extensions appear to be a sound strategy for the product categories considered in this study, as the majority of environmental impacts, including material use, occur during their production and not their use phase (Bakker and Schuit (2017), see also LCA data in Figure 7 and 8). For other product types, this is not the case. For instance, Bakker and Schuit (2017) report in a meta study that lifetime extensions of white goods beyond 10 years do not appear to be environmentally beneficial due to relatively high shares of use phase energy consumption and large efficiency gains between product vintages. Thus, a quicker replacement of less energy efficient white goods may lead to higher energy savings than lifetime extensions. Wieser et al. (2015), however, suppose that this may not be the case for much longer as efficiency gains for some product categories have been slowing down in the recent past.

As illustrated by Box (1983), lifetime extensions can in principle address either the production side (through technical improvements of products) or the consumption side (through behavioral change leading to a longer use of products). However, in practice, a combination of both is necessary to keep products longer in use, since products that would theoretically last longer are not necessarily used for longer periods by consumers. This is because lifetime extensions cannot be considered universally desirable, as different demands towards products may be influenced differently by lifetime extensions (Wieser et al., 2015). For instance, certain products are mainly valued with respect to functional and/or aesthetic characteristics. As functional and/or aesthetic preferences change, old products may not fulfill them anymore. Smartphones, and mobile phones fall into this broad category of products.

In conclusion, an extension of service lifetime of a mobile phone leads to a reduction of demand for new devices. However, as only a comparatively small proportion of devices really reaches the second and third service lifetimes, which we expect to be increased by technical improvements, the overall effects shown in the first scenario are comparatively moderate. Nonetheless, this scenario still includes the problem of unused storage phases, which indirectly leads to resource losses as existing and functioning devices are still hibernating in large numbers.

The second scenario, which simulates a reduction of hibernation times, presupposes the willingness of additional consumers to purchase used products. This implies a shift from the first service stocks towards the second and third service stocks. Even though this is a purely theoretical analysis, it quantifies the potential effect of resource conservation through reduction of unused storage times in the life cycles of electronic equipment.

Both scenarios are not directly comparable because the lifetime extension scenario exemplarily assumes increases in second and third service lifetime, while the hibernation times are successively reduced to 0. However, it can be shown that such a gradual change in consumer behavior can by itself lead to considerable changes in product flows without requiring technological measures. Since the willingness of consumers to forego the storing of products after the use phase is a precondition of any reduction of hibernation times, it is therefore important to understand the causes of product hibernation. Wilson et al. (2017) have identified a number of reasons for product hibernation. Two prominent reasons are data/privacy concerns and emotional attachment. In the former case, consumers are hesitant to directly sell or dispose of products after the use phase because they are unable or unwilling to delete their private data. This appears to be a larger problem if it is impossible for the current owner to access and eventually delete sensitive data but may not be for future (specialist) owners. In the latter case, consumers associate products with personal memories etc. and therefore opt to keep products despite not using them anymore. Consumers have also been found to keep "secondary phones" as backups to their current devices, without actively using them. This behavior partly goes so far that (multiple) predecessors to these secondary phones are kept to the point of "[forgetting] about their existence", which together with a lack of knowledge about environmental implications and disposal options has been described as "recycling lethargy" (Wilson et al., 2017, p.529).

Depending on the underlying reason for keeping products beyond their service lifetimes, different measures may be necessary to reduce hibernation. Data concerns may be remedied through, e.g., information on "shredder" software that irrevocably deletes data or instructions on the removal of storage units. The desire to keep a spare phone due to emotional attachment in contrast requires other instruments, for example ones that provide economic incentives, such as deposit return schemes. Recycling lethargy may be addressed by information campaigns illustrating the environmental implications of product hibernation and channels through which products can enter secondary markets or the recycling stream. Another possibility are new business models in which the traditional roles of producers and purchasers are dissolved and with that the ownership of and responsibility for products.

Conclusions

The presented cascade stock and flow model can be seen as a first approach to better addressing hibernation and consumers' decisions in the simulation of product life cycles. As indicated with the theoretical scenarios presented above, a reduction of hibernation of functioning electronic devices could reduce the demand for new products. However, this would also require changes in consumer behavior as the shift towards the second and third use phase of mobile phones requires the willingness to purchase or, more generally, to use second hand or refurbished devices. The same is true when regarding the scenario of lifetime extensions. In the current model structure, this particularly affects the second and third service lifetime.

A model is always a simplification of reality and simulation models are generally intended to assess and better understand system behavior under different settings. The model structure presented here allows for the simulation of a cascade use system. However, the durations of different use phases as well as transfer probabilities between different stages in the lifetime of a product are static input data and dynamics derive from modifications of these data. In fact, the duration of a use phase as well as the underlying transfer probabilities are results of individual consumer decisions. The system dynamics approach presented here is not capable of addressing these individual decisions at the micro level. To this end, a hybrid model simulating both the behavior of individual agents and the aging process of products used by these agents would be necessary. Therefore, the combination of a cascade life cycle simulation presented here with an Agent Based Model (ABM) in a hybrid simulation approach would provide a significant methodological improvement for addressing the effect of consumer behavior on the lifetime of a product. This will require further research regarding both implementation approaches and the gathering of the required data.

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