Analysing impacts of product life extension through material flow analysis: the case of EEE and paper

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Abstract: Material consumption is an important driver for environmental pollution. Total material throughput can be reduced through the extension of product life. The paper suggests Material Flow Analysis (MFA) as a method to assess the potential material throughput reductions due to increased product longevity. The method is applied to the case of Electrical and Electronic Equipment (EEE) and paper products. The paper first collates data from different sources to give an overview of material inputs and outputs for both material/product categories in the United Kingdom. Subsequently, it reviews the literature for a selection of interventions and calculates the potential savings in the total material throughput. For EEE, the analysis emphasises the issue of optimal life times that need to balance the impact generated in the production phase and during the use of the product. For paper, a key issue is the practical limitations on reusing a material that is easily damaged and worn. It is concluded that there is considerable potential for MFA in estimating the impacts of product life extension on material throughput although limitations in data availability and quality are acknowledged.

Introduction

Material consumption is associated with important environmental impacts (Fischer-Kowalski and Swilling, 2011). In the United Kingdom only, annual consumption is estimated at around 600 megatons, about 40% of which is discarded as waste (Eurostat, 2015a, 2015b). Much of the policy emphasis has been put on recycling but extending the use life of products, and also of the materials contained in them, could play an equally important role in reducing the environmental impacts of consumption and the preservation of natural resources.

Longevity can be understood as the interval between the point in time where the products come into the market to the point in time where they are discarded and turned into waste. Longevity can play an important role in reducing consumption and waste, but it is little understood, since it relates to dimensions of design, business models, manufacturing, behaviour, waste management, and many different factors and drivers. Material Flow Analysis (MFA)[1] can help understand some of these aspects.

[1] Abbreviations used in this article: Electrical and Electronic Equipment (EEE), Global Warming Potential (GWP), Life Cycle Assessment (LCA), Material Flow Analysis (MFA), Waste Electrical and Electronic Equipment (WEEE).

Material flow analysis is the systematic assessment of flows and stocks within a predefined system (Brunner and Rechberger, 2004). It does not describe environmental pressures directly unless emissions are included as material flows, but it is argued that material flows can serve as good proxies for environmental sustainability (Hinterberger et al., 1997). When presented as a Sankey diagram, MFAs can provide visual insights in material flows and help identifying inefficiencies and areas of potential material savings (Schmidt, 2008).

This paper analyses two main areas of concern: electronic and electrical equipment (EEE) and paper and paper products. The consumption of EEE is on the rise globally, especially in developing countries. The amount of discarded computers in China and South Africa is expected to increase with 500% in 2020 compared to 2007 levels (Schuelp et al., 2009) and substantial increases are also expected in other emerging economies (Wang et al., 2012). In the United Kingdom, the EEE market has grown rapidly in the last years and waste arisings have increased correspondingly (Eurostat, 2015c). EEE contain important valuable metals, such as copper, and critical metals, such as palladium (He et al., 2006; Reck and Graedel, 2012). They also contain many hazardous substances that can lead to important health and environmental risks if improperly managed (Huang et al., 2009).

Paper is a relevant material given its high impact in terms of life cycle carbon emissions and its high annual conversion rate into waste compared to other important material categories such as steel and plastics (Allwood et al., 2010). At the same time, paper is generally perceived as a success story in terms of recycling, with the European recycling rates being at around 70% (CEPI, 2012), and is a role model for the sharing economy in the form of libraries. Environmental impacts of paper include carbon emissions and dioxins released during production as well as methane emissions from landfills.

This paper aims to show the utility of MFA for assessing the impact of longevity on total material throughput by applying tailored MFAs to two case studies representing very different material/product categories. The paper has been structured as follows. Section 2 reviews some of the literature on longevity and section 3 explains MFA. Section 4 analyses material flows and suggests interventions for EEE and paper. The article wraps up with discussion (section 6) and conclusions (section 7).

Longevity

Product longevity can be expressed as the interval between the point in time where the products comes into the market to the point in time where they are discarded and turned into waste. However, this definition does not capture reuse after waste collection. In addition, a product can be used very intensively by different users in a single lifetime, or be used by several users sequentially. Table 1 presents the different options. The *life time* can consist of a single use life or multiple use lives depending on the number of successive owners. In each use life, the product may be used by one user only or by multiple users at the same time. Combining these options gives four use profiles ranging from single use by one user to successive use by groups of users.

Cooper et al. (2014) identify four reasons for ending the life of a product or material. First, a product might be degraded or spent to such an extent that it can't be used or (viably) repaired anymore. Second, it might have become inferior compared to alternatives that have come on the market. Third, it might have become unsuitable through changes in the context such as user preferences. Lastly, the product may be rendered worthless though new legislation or other radical changes in the product's environment.

Table 1 – Users and use lives.

	Single user	*Multiple users*
Single use life	Product is used by a single user, then discarded, and not reused	Product is used by multiple users and then discarded
Multiple use lives	Product is used by a single person but for instance resold second-hand	Product is used by many users and moves second-hand to a new user group

Extending product life in part equates challenging current practices that aim to achieve the opposite since firms actively pursue strategies to make products last shorter to boost sales. Products are sometimes designed such that they: 1) break early, lose aesthetic quality, and are hard to repair, 2) quickly become out of fashion, and 3) are rapidly succeeded by new products with more desirable features (Guiltinan, 2009). These practices respond respectively to the product failure reasons of degradation, unsuitability, and inferiority as identified by Cooper et al. (2014).

An important trade-off exists between environmental impacts of replacement and the gains of having more efficient new products, i.e. between overall material efficiency and energy efficiency in the use phase. Van Nes and Cramer (2006) analyse trade-offs between energy investments in the production of new products and increased efficiency in the use phase. The lowest overall environmental impact is achieved only when both are taken into account and products are replaced at the right time.

Product life extension is not directly demanded or promoted through regulation. First, consumers are protected against non-conformities through the minimum two-year warranty for most EEE (EC, 1999). This pressures producers to avoid production errors that lead to early failure and prevents extreme forms of planned obsolescence. It does however not stimulate companies to design product with significantly longer life-times. Second, the eco-design directive addresses environmental consequences of design but does not explicitly mention the need for longer lifetimes. Third, several directives promote Extended Producer Responsibility (EPR) but focus on end-of-life considerations rather than postponing the end-of-life phase (BIO Intelligence Service, 2014).

The role of longevity in EEE flows has been the focus on a number of country-specific studies. Oguchi et al. (2008) conducted a product flow analysis for a number of consumer durables in Japan. Lifespan of products has been used in delay models to estimate the lag between the moment an EEE product is put in the market and the moment it becomes waste. A number of European studies looked at specific EEE waste streams. For example, Elshkaki et al. (2004)studied lead-containing products such as CRT and lead batteries in the Netherlands and estimated flow and stock of lead containing products. Kleijn et al. (2000) used a material flow and stock model for PVC and Hischier et al. (2005) used a combination of MFA and LCA to assess the impact of take back systems in Switzerland. Wang et al. (2013) analysed the role of data quality in the accurate description of e-waste using a multivariate input-output method that combines different data points.

Consumer associations have voiced increasing concerns about "built-in obsolescence" of EEE. A recent study by the OEKO-Insititut (2015) showed that the reasons behind ending appliances' first-use life vary by product category. Most of the replacements of flat screen TVs were down to product upgrades, but for white goods such as washing machines and fridges, around 55-67% of purchases were made to replace a faulty product.

Very little research has been done on the reuse possibilities for paper. The relatively fragility of paper products possibly explains this lack of interest in extended use. Most studies focus on end-of-life treatment scenarios (Schmidt et al., 2007) or increasing process efficiency (Kayo et al., 2012; Szabó et al., 2009). However, Sundin et al. (2001) conclude that the total material and energy use due to UK paper consumption can hardly be limited without addressing consumption itself. The urgency for demand reduction justifies exploring the challenging possibility of reducing demand by extending the life-time of paper products.

Method

The paper uses Material Flow Analysis to link specific practical interventions to reductions in total throughput. Material flow analysis is a systematic assessment of flows and stocks within a predefined system (Brunner and Rechberger, 2004). The results of MFA are commonly visually presented in Sankey diagrams, which have their origins in thermal engineering, and that provide a tool to compare actual flows with desired flows in a visually intuitive way (Schmidt, 2008).

MFA is useful insofar material flows are linked with environmental impacts. Depletion is proportional to material consumption and is very relevant for critical materials. Similarly, production forests take up space and reduce biodiversity at a rate proportional to virgin material demand for timber and paper. For other impacts, like toxicity and global warming potential, material flows are not necessarily good indicators, but such limitations can be compensated for by adding information on environmental impacts.

Extended use life is the delay between the time point when the product entered the market and the time point at which the product becomes waste. This has a number of implications in terms of waste management as waste arising will depend on the lifespan distribution of different products and the material composition of waste, especially for products with longer than average use-life and those that have undergone substantial design changes over the years (for example in the concentration of hazardous substances).

In addition, longevity or the extension of average use life has also other important implications in terms of potential savings of virgin raw materials and the transition to more circular models, where resources maintain their prime function for longer and are recycled at the end of the use life to recover valuable resources contained in them. Extending product life thus affects both virgin inputs, waste outputs, and material throughput of the economy.

Product life can be estimated using statistical distributions or simply average lifetimes. The former approach has been used both for WEEE (e.g. Bakker et al. (2014)) and for paper products (e.g. Hong et al. (2011)). For the purpose of forecasting waste arising of durable products, distributions are essential given the delay between the time the product is put on the market and the time when it becomes waste. For this paper, we use a mixed approach. For paper products, average lifetimes and estimated numbers of users or use-lives suffice. For EEE we use statistical distributions and a delay model.

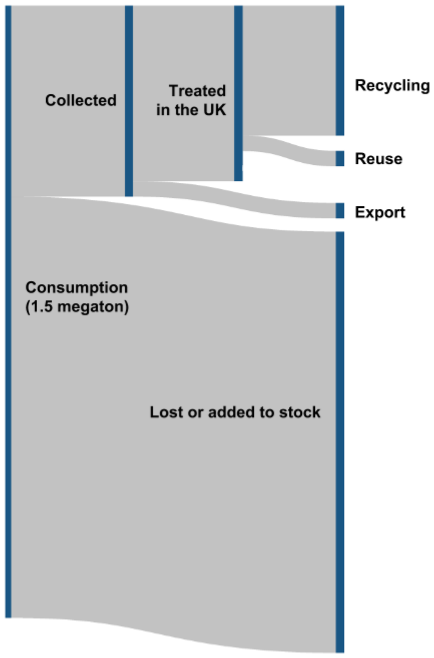

Figure 1 – Sankey Diagram of EEE/WEEE product flows in the UK in 2010 (Source: own elaboration based on Eurostat).

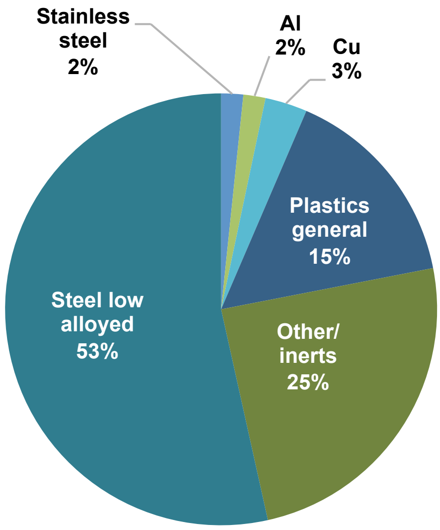

Figure 2 – WEEE Material composition in the UK 2010 for large household appliances (Source: own elaboration based on WRAP (2012) and Eurostat).

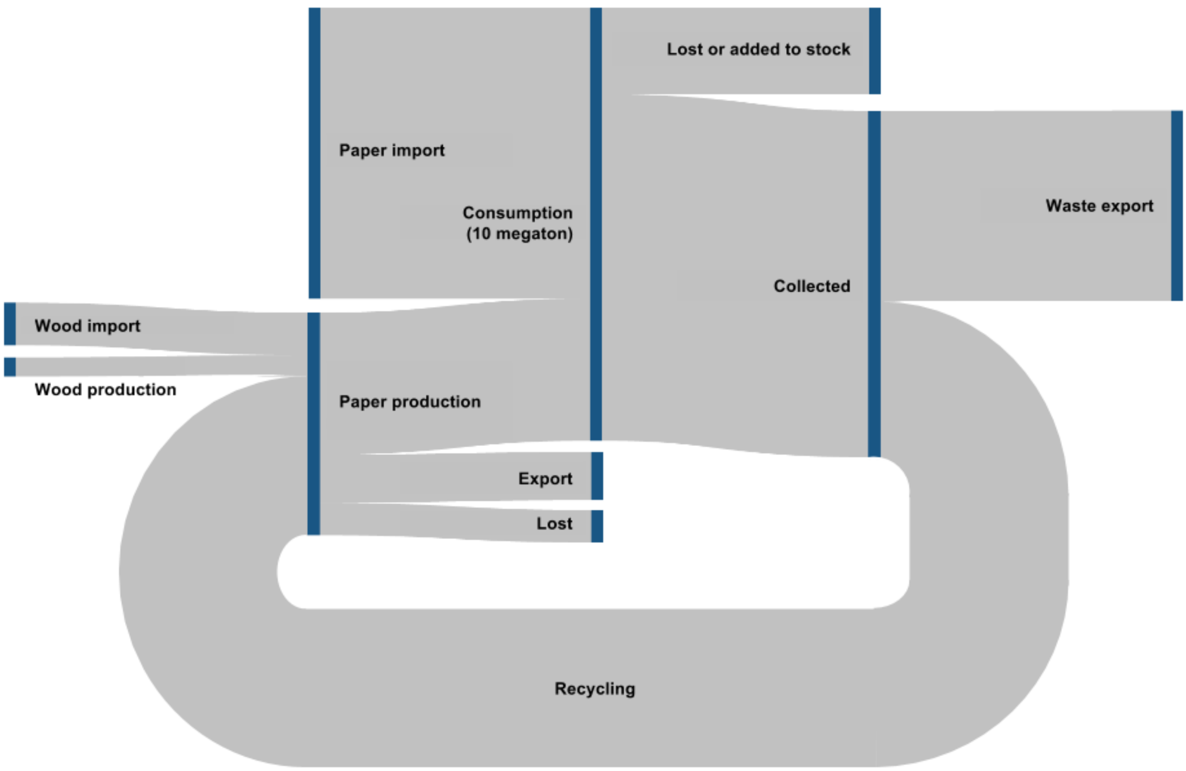

Figure 3 – Paper flows in the UK in 2012 (Source: own elaboration based on PPL (2012) and Eurostat).

Analysis

This section presents the findings from the MFA for EEE and paper and paper products. It subsequently discusses potential interventions for extending the life of products and calculates their impact on resource throughput. For EEE, the product flow is extremely diverse due to the variety of product categories and diversity of materials contained in products. In this case, we have departed from product data and converted into material streams based on average material composition of EEE. For paper, the MFA is more straightforward since most products are made mainly from paper only. Life extension however is much more challenging for paper than for EEE since many paper products are designed for single use and immediate disposal. The following section first presents the MFA and possible intervention for EEE and then for the case of paper and paper products.

Electrical and Electronic Equipment (EEE)

Material flow analysis of EEE

The calculations of material flows are based on 1) category-specific and aggregated EEE/WEEE flows and 2) estimation of material content of EEE/WEEE on an aggregated level and by category. The main results are presented in Figures 2 and 3. Figure 1 depicts the material flows for the UK for 2010[2]. The lifespan distribution is not considered. The diagram shows a big discrepancy between the weights of the products put on the market and WEEE collected. Even in the absence of a lifetime distribution of products, this seems to point to a large quantity of materials that are either collected together with mixed household waste, exported as second hand goods, hoarded or just illegally dumped. Only in the first case, that WEEE undergoes appropriate treatment.
Figure 2 provides an idea of the material composition of EEE/WEEE for the category large household appliances, based on the combination of WEEE data and material composition data. Material composition data has been obtained from the literature and a WRAP study published in 2012 EEE (Huisman et al., 2007; Wrap, 2012). The data has been compared with other literature sources on material composition for other developed countries, significantly Japan, to check for consistency (Oguchi et al., 2013; Tasaki et al., 2007), although a sensitivity analysis has not been undertaken as it is out of the scope of this paper.
While the introduction of the WEEE directive has substantially increased the quality and availability of data on WEEE, there are still important gaps on the reverse loops of how recycled materials enter the productive system. Therefore, it is difficult to estimate how circular the system is even when recycling rates have increased substantially. Important uncertainty also exist about the fate of WEEE exported as second hand goods and their treatment and management in their final destinations, mainly Asia and Africa (Wang et al., 2013).

Interventions in the EEE cycle

Extending first use life: extending warranties

Extending the technical use life of large household appliances could bring important reductions in the throughput of the UK. It has been estimated that over two million fridges and freezers are discarded annually in the UK. Moreover, failure of compressors has been linked to premature obsolescence of fridges and reduction in average lifespan while other components with a high metal content are still fully operational when the fridge is discarded (Cooper et al., 2014). Extending first use life needs to consider the potential trade-offs between material saving and energy consumption, as it is expected that new appliances would be more energy efficient. Kim et al. (2006) have looked at the optimal life time of fridges taken into account this trade off. According to their analysis, optimal lifetimes for fridges ranged from 2-7 years for the energy objective and 2-11 years for the Global Warming Potential (GWP) based on Life Cycle Assessment (LCA) and dynamic programming. The focus here though is energy and GWP minimisation while other impacts linked to resource use are not considered in the optimisation model. Also, given that energy efficiency has improved substantially in recent years, it is expected that optimal life has increased as the marginal energy efficiency improvements are expected to reduce over time.

[2] Please note that in some cases data from 2009 has been used, as it is the last available for a number of variables.

In order to avoid potential trade-offs between energy and resource efficiency this intervention would have to consider introducing changes in the design of fridges and increasing modularity and upgradability. This intervention could significantly reduce demand of primary resources and waste generation. The main strategies directed towards extending the use life of fridges would have to consider not only trade-offs between material and energy efficiency but also changes related to the use of hazardous substances such as refrigerants.
Given that the average life of fridges is around 11-14 years (Bakker et al., 2014; Oguchi et al., 2013), further research is needed to assess the desirability of prolonging the use life of these type of appliances if we consider energy implications. However, if we consider that 8-10% of large household appliances break within the first 5 years due to early failure of some of the components (Oeko-Institut, 2015), extending warranties to five years for all large household appliances and ensuring the availability of replacements for a longer period of time could bring material savings of around 70 kilo-tonnes, and saving of approximately 4.5% of the total material throughout. This savings could be in the region of around 85 kilotonnes if we also consider small household appliances, and around 5.5% of the total material throughput.

Extending the total use life: upgradability of products

Another approach to extent the total life time of EEE would be extending the second use life of the appliance through repair, reuse and remanufacturing. Although there is very little research on the opportunities to increase reuse and repair of fridges, a recent study by WRAP considered that about 23% of the discarded appliances could be reused with very little repair. Again here the issue of the trade-offs between energy and resource efficiency need to be considered.
A number of studies have pointed to some sort of energy efficiency deterioration during use. Parts such as dirty coils and worn-out gaskets have been suggested to increase energy use, although maintenance programmes have brought only negligible energy saving improvements from cleaning or replacing these parts. Other parts that could explain the deterioration of energy efficiency during use may be insulation foams (Kim et al., 2006).

A 23% increase in the reuse of large household appliances such as fridges could bring material savings in the region of 160 kilo-tonnes, and about 10% of the material throughput. This though requires of the establishment of well-developed repair and reuse networks that provide guarantee to the consumer about the safety and performance of reused goods.

Remanufacturing, reuse and recycling of components

The third proposed intervention looks at extending the life of the components through remanufacturing and recycling of materials and use as a source of secondary materials. A study on appliance remanufacturing and energy savings estimated that total raw material processing and manufacturing of a mid-size fridge required 4,442 MJ to 6,847 MJ. Driven by legislative pressure. the energy consumption of fridges during the use phase have varied considerably ranging from 180 GJ for a model in 1974 to 50 GJ for a model in 2008 (Boustani et al., 2010)
The same studies concluded that remanufacturing would indeed have been a more energy consuming option since 1974 up to 2001. During this period, important increases in energy efficiency outpace energy savings associated to raw material processing in the remanufacturing. The study, however, also points that when comparing a 2001 and 2008 model, the energy savings of remanufacturing would break even with the energy savings associated to energy efficiency of newer models, given the slower pace of improvements in energy efficiency after a phase of substantial progress. This and the fact that the study does not account for other environmental impacts associated with end of life management opens up the viability of remanufacturing in coming years. A 20% increase in the remanufacturing of large household appliances could bring material savings of about 140 kilo-tonnes and about 9% of the total material throughput for EEE.

Paper and paper products

Material flow analysis of paper

The calculation of the paper flows is based on waste data, production and consumption data, and forestry data. Figure 2 shows the paper flows for the United Kingdom in the year 2010 including imports, exports and a recycling loop. The Sankey diagram uses the waste generation and treatment data from Eurostat, supplemented with industry statistics (PPL Research Ltd, 2012) and a government publication on forestry and paper (Forestry Commission, 2011). Most of the paper consumed in the UK is imported and some of the domestic production is exported. A roughly equal proportion of paper waste is exported and domestically recycled.

The Sankey diagram reveals a relatively large discrepancy between inputs and outputs to production. This is probably due to the inputs being measured as green tonnes (including water) of imported pulp and wood. Also, some of the paper waste generated in production might not be accounted as such but instead as mixed wastes. The small discrepancy between inputs and outputs of the consumption phase represent two things: additions to stock and unaccounted paper waste that may be found in "mixed waste" flows in Eurostat. The data does not allow distinguishing between the two options.

Interventions in the paper cycle

Lending and second-hand buying of books

Books are among the most popular goods to be shared or sold second hand. In Europe, around 7 out of 10 people indicate they would buy second hand books, CDs, DVDs, and video games (European Commission, 2014). At the same time, books are a leading example of the shared use model, with libraries being one of the most significant examples of sharing of consumer products. In 2010, around 4% of UK physical book sales were to public and higher education libraries (The Publishers Association, 2012).

According to a study by Maki (1999), as cited by (Heiskanen and Jalas, 2003), library books in Finland are used 60 times on average and constitute a saving of 32.000 tonnes of paper compared to the alternative of new sales. If libraries in the UK where to increase their stocks, the average amount of users may increase when it concerns top titles (which are currently easier to get by buying them) or if they expand into more marginal categories. Either way there is a large potential for dematerialization in the book sector through the extension of libraries.

If the number of 60 is valid, than total physical UK book sales could be reduced with 50% by only increasing the annual purchases of public libraries with about 20%, assuming privately held books are read only once. There are many reasons why this is hard to achieve in practice: many books are given as presents, there would be a rebound effect, and publishers (and writers) would have to move to a different business model for the supply to be feasible, effectively having to charge up to 60 times more per book to libraries to make it feasible.

The best weight estimate for an average paper book is suggested to be 600 grams (Borggren et al., 2011) and the total consumer sales in 2010 is estimated to be 339 million copies (The Publishers Association, 2012). Consumer books make up 1.8% of the total mass flow of paper in the United Kingdom. An increase of library stocks with 20% and an associated reduction of consumer book sales with 50% could thus reduce the overall paper flow with about 0.9%. The practical potential would however be much lower.

Un-printing office paper

For office paper, promising advances have been made regarding the "repairing" of paper through un-printing technology. Un-printing may involve the use of special ink or paper although a laser ablation process has been shown to work on regular paper and ink. The PrePeat technology from Sanwa Newtec (Sanwa Newtec, n.d.) from Japan substitutes paper by using rewritable PET sheets but is not considered further here since it is out of scope of a paper on paper.

Toshiba introduced a heat sensitive toner for their "e-blue" system in 2003 which allowed print to be removed from regular office paper at 140 degrees Celsius (Toshiba, 2003). The latest model still requires special ink and can make the paper reusable up to five or six times. Some of the old print remains visible however – a problem in case of confidentiality – and the toner is limited to the colour blue (Toshiba, 2013).

Un-printing regular ink from regular paper is still in the research phase and can be done using ultraviolet (UV) radiation, infrared light (IR), or laser ablation (Leal-Ayala et al., 2011). The laser ablation process is considered best since it damages the paper least. The key parameter in the process is the fluence level (energy flow per unit of area), which should be below the ablative threshold of paper and above that of the toner.

The potential for un-printing to reduce material throughput seems very high. For the "e-blue" technology (Counsell and Allwood, 2007) estimate that un-printing could reduce energy use and carbon emissions with 86% and 95% per tonne of office paper. This reduction is realized because all other stages in paper production can be cut out. With the latest technology, that allows un-printing up to five times, the throughput of office paper could potentially be reduced with 80%.

The laser removal of ink has not been commercialized yet[3]. Estimates of the technical potential of the technology depend on the amount of damage done to the paper while the actual number of cycles greatly depends on practices and behaviour of office paper users. Paper may get spoilt, discarded at other locations, or crumpled and folded. Pushing the technical potential beyond that of the current Toshiba machine may not be of great use given these practical constraints.

The consumption of cut size paper is about 5% of total paper and board consumption (PPL Research Ltd, 2012) and about 75% of cut size paper is used in offices (Hekkert et al., 2002) where such technology could be easily installed. The share of paper suitable for un-printing is thus around 4% and un-printing could reduce the total paper flow about 3% if paper were to be un-printed about five times on average.

Extended use of paper packaging

Packaging contains, preserves, and presents the products it holds. Paper can hardly preserve goods like foods or shield them from water but can act to contain it and, importantly, helps presenting products in an instructive and attractive way. For purposes of preservation, paper may be combined with plastics or metals to ascertain water tightness and shut out air. Primary packaging comes with the product, while secondary packaging may refer to for instance bags and carrying boxes that could be used at convenience.

Paper packaging is a notoriously difficult to reuse since it is easily damaged in the process of use. Yet paper is a popular packaging material. About one third of the total packaging waste stream in the United Kingdom consists of paper (Eurostat, 2015d). For instance for white goods the share of paper in packaging material can range from 16% to 77%, with large appliances like freezers consistently featuring more than a kilogram of paper packaging per product (WRAP, 2007).

One way to increase the lifetime of packaging is by replacing paper packaging by more durable plastics packaging, especially in non-consumer environments. However, when consumers are involved, paper is often preferred because of its aesthetic qualities; research suggests that consumers associate paper bags more strongly with an attractive appearance than plastic bags (Prendergast et al., 2001). Based on the same survey in Hong Kong, the article suggest that paper bags are in fact more likely to be reused than plastic bags.

The potential for reuse of paper packaging is very difficult to assess. Uniquely shaped and printed paper packaging has little potential for reuse, generic boxes and board (from for instance furniture packaging and appliances) may in fact be reused for slightly varying purposes, and paper bags could be used many times to carry different things. The durability of the packaging is key, as well as the print, which could influence reuse depending on "fashionableness" of the depicted brand.

Most studies on environmentally friendly packaging however suggest the replacement of paper packaging by reusable plastic packaging. Such plastic packaging has lower environmental impacts when used once. A study of different types of shopping bags in China, Hong Kong, and India showed that paper bags had the highest life cycle carbon impact. At the same time, the authors point at reuse as an opportunity for significant reduction of carbon impacts (Muthu et al., 2011). As such, when it comes to carbon emissions, paper packaging can only compete with plastic alternatives if it is reused significantly more than plastic alternatives.

Discussion

The analysis has shown that material flow analysis can help identify the potential savings made through product life extension for the case of EEE and paper products. It also showed that data availability is limited, in particular for EEE. It is difficult to assess how many products and materials are actually being exported and what happens to the prod-

[3] The start-up Reduse is currently moving the technology to the market. www.reduse.co.uk

ucts at their final destination. For paper, data is better, but it remains difficult to gage how much paper ends up in landfill or is added to stock.
A limitation of the study concerns the actual environmental impact associated with the material flows. For paper, for instance the greenhouse gas emissions savings may not be exactly proportional to the energy and material savings (Counsell and Allwood, 2007). For other impacts, the discrepancy can be much larger. However, we have argued that for electrical appliances, the common focus on energy requirements may indicate optimal product life times to be shorter than they actually are when including resource considerations.
An important caveat in extending life times and reducing material throughput is demand substitution. When consumers do not buy a new fridge or paper bag, what else do they buy? And what is the impact of this alternative? This problem is often referred to as Jevon's Paradox or rebound from efficiency gains (Alcott, 2005). It basically shows that is not sufficient to partially limit resource use; an effective life time extension policy should also avoid a shift in consumer demand to other equally or more harmful purchases.

Conclusions
This paper has studied the potential for using material flow analysis for assessing possible reductions in total material throughput through the extension of product life. In particular, it assessed the potential of increasing product longevity for the case of Electrical and Electronic Equipment (EEE) and paper products. The analysis shows that there is considerable potential for MFA in estimating the impacts of product life extension although more data is needed.
The paper first used data from different sources to give an overview of material inputs and outputs for both material/product categories. Subsequently, it drew on the literature for a selection of interventions and calculated the potential savings in the total material throughput. For EEE, a key issue was the idea of optimal life times based on pollution caused by the production and use of the product. For paper, a key issue are the practical limitations on reusing a material that is easily damaged and worn.
The conclusions are two-fold. First, it has been shown that certain interventions are likely to reduce material throughput for EEE and paper and could thus reduce environmental pollution. Second, the use of material flow analysis has proven fruitful in calculating the potential material throughput savings for the interventions. Further work should focus on the collection of more detailed data for mixed waste streams and EEE exports, demand substitution, and other product and material categories than EEE and paper.

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References

Alcott, B., 2005. Jevons' paradox. Ecol. Econ. 54, 9–21. doi:10.1016/j.ecolecon.2005.03.020

Allwood, J.M., Cullen, J.M., Milford, R.L., 2010. SUPPORTING INFORMATION Options for achieving a 50% cut in industrial carbon emissions by 2050. Environ. Sci. Technol. 44, 1888–94. doi:10.1021/es902909k

Bakker, C., Wang, F., Huisman, J., Den Hollander, M., 2014. Products that go round: Exploring product life extension through design. J. Clean. Prod. 69, 10–16. doi:10.1016/j.jclepro.2014.01.028

BIO Intelligence Service, 2014. Ex-post evaluation of certain waste stream Directives. Final report.

Borggren, C., Moberg, A., Finnveden, G., 2011. Books from an environmental perspective-part 1: Environmental impacts of paper books sold in traditional and internet bookshops. Int. J. Life Cycle Assess. 16, 138–147. doi:10.1007/s11367-011-0254-1

Boustani, A., Sahni, S., Gutowski, T., Graves, S., 2010. Appliance Remanufacturing and Energy Savings. Management.

Brunner, P., Rechberger, H., 2004. Practical handbook of material flow analysis. Int. J. Life Cycle ….

CEPI, 2012. Key Statistics European Pulp and Paper Industry.

Cooper, D.R., Skelton, A.C.H., Moynihan, M.C., Allwood, J.M., 2014. Component level strategies for exploiting the lifespan of steel in products. Resour. Conserv. Recycl. 84, 24–34. doi:10.1016/j.resconrec.2013.11.014

Counsell, T. a. M., Allwood, J.M., 2007. Reducing climate change gas emissions by cutting out stages in the life cycle of office paper. Resour. Conserv. Recycl. 49, 340–352. doi:10.1016/j.resconrec.2006.03.018

EC, 1999. DIRECTIVE 1999/44/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 25 May 1999 on certain aspects of the sale of consumer goods and associated guarantees 12–25.

Elshkaki, A., Van Der Voet, E., Van Holderbeke, M., Timmermans, V., 2004. The environmental and economic consequences of the developments of lead stocks in the Dutch economic system. Resour. Conserv. Recycl. 42, 133–154. doi:10.1016/j.resconrec.2004.02.008

European Commission, 2014. ATTITUDES OF EUROPEANS TOWARDS WASTE MANAGEMENT AND RESOURCE EFFICIENCY. Flash Eurobarom. 388.

Eurostat, 2015a. Generation of waste [env_wasgen] [WWW Document].

Eurostat, 2015b. Material flow accounts [env_ac_mfa] [WWW Document].

Eurostat, 2015c. Waste Electrical and Electronic Equipment (WEEE) [env_waselee] [WWW Document].

Eurostat, 2015d. Packaging waste [env_waspac] [WWW Document].

Fischer-Kowalski, M., Swilling, M., 2011. Decoupling: natural resource use and environmental impacts from economic growth.

Forestry Commission, 2011. UK Wood Production and Trade: First Release 1–12.

Guiltinan, J., 2009. Creative destruction and destructive creations: Environmental ethics and planned obsolescence. J. Bus. Ethics 89, 19–28. doi:10.1007/s10551-008-9907-9

He, W., Li, G., Ma, X., Wang, H., Huang, J., Xu, M., Huang, C., 2006. WEEE recovery strategies and the WEEE treatment status in China. J. Hazard. Mater. 136, 502–12. doi:10.1016/j.jhazmat.2006.04.060

Heiskanen, E., Jalas, M., 2003. Can services lead to radical eco-efficiency improvements? - A review of the debate and evidence. Corp. Soc. Responsib. Environ. Manag. 10, 186–198. doi:10.1002/csr.46

Hekkert, M.P., van den Reek, J., Worrell, E., Turkenburg, W.C., 2002. The impact of material efficient end-use technologies on paper use and carbon emissions. Resour. Conserv. Recycl. 36, 241–266. doi:10.1016/S0921-3449(02)00081-2

Hinterberger, F., Luks, F., Schmidt-Bleek, F., 1997. Material flows vs.natural capital': What makes an economy sustainable? Ecol. Econ.

Hischier, R., Wäger, P., Gauglhofer, J., 2005. Does WEEE recycling make sense from an environmental perspective? The environmental impacts of the Swiss take-back and recycling systems for waste electrical and electronic equipment (WEEE). Environ. Impact Assess. Rev. 25, 525–539. doi:10.1016/j.eiar.2005.04.003

Hong, S.J., Choi, Y.S., Kim, K.R., Kang, J.G., Oh, G.J., Hur, T., 2011. Material flow analysis of paper in Korea. Part I. Data calculation model from the flow relationships between paper products. Resour. Conserv. Recycl. 55, 1206–1213. doi:10.1016/j.resconrec.2011.08.002

Huang, K., Guo, J., Xu, Z., 2009. Recycling of waste printed circuit boards: a review of current technologies and treatment status in China. J. Hazard. Mater. 164, 399–408.

Huisman, J., Magalini, F., Kuehr, R., Maurer, C., Ogilvie, S., Poll, J., Delgado, C., Artim, E., Szlezak, J., Stevels, A., 2007. 2008 Review of Directive 2002/96 on Waste Electrical and Electronic Equipment (WEEE) - Final report. Comm. by Eur. Comm. Contract No 07010401/2006/442493/ETU/G4 1–347. doi:07010401/2006/442493/ETU/G4

Kayo, C., Hashimoto, S., Moriguchi, Y., 2012. Paper and Paperboard Demand and Associated Carbon Dioxide Emissions in Asia Through 2050. J. Ind. Ecol. 16, 529–540. doi:10.1111/j.1530-9290.2011.00419.x

Kim, H.C., Keoleian, G. a., Horie, Y. a., 2006. Optimal household refrigerator replacement policy for life cycle energy, greenhouse gas emissions, and cost. Energy Policy 34, 2310–2323. doi:10.1016/j.enpol.2005.04.004

Kleijn, R., Huele, R., Van Der Voet, E., 2000. Dynamic substance flow analysis: The delaying mechanism of stocks, with the case of PVC In Sweden. Ecol. Econ. 32, 241–254. doi:10.1016/S0921-8009(99)00090-7

Leal-Ayala, D.R., Allwood, J.M., Counsell, T. a M., 2011. Paper un-printing: Using lasers to remove toner-print in order to reuse office paper. Appl. Phys. A Mater. Sci. Process. 105, 801–818. doi:10.1007/s00339-011-6654-z

Muthu, S.S., Li, Y., Hu, J.Y., Mok, P.Y., 2011. Carbon footprint of shopping (grocery) bags in China, Hong Kong and India. Atmos. Environ. 45, 469–475. doi:10.1016/j.atmosenv.2010.09.054

OEKO-Insititut, 2015. ZWISCHENBERICHT: Analyse der Entwicklung der Lebens-, Nutzungs- und Verweildauer von ausgewählten Produktgruppen.

Oguchi, M., Kameya, T., Yagi, S., Urano, K., 2008. Product flow analysis of various consumer durables in Japan. Resour. Conserv. Recycl. 52, 463–480. doi:10.1016/j.resconrec.2007.06.001

Oguchi, M., Sakanakura, H., Terazono, A., 2013. Toxic metals in WEEE: Characterization and substance flow analysis in waste treatment processes. Sci. Total Environ. 463-464, 1124–1132. doi:10.1016/j.scitotenv.2012.07.078

PPL Research Ltd, 2012. Trade statistics covering the UK paper and board market.

Prendergast, G., Ng, S.W., Leung, L.L., 2001. Consumer perceptions of shopping bags. Mark. Intell. Plan. 19, 475–482. doi:10.1108/EUM0000000006217

Reck, B.K., Graedel, T.E., 2012. Challenges in Metal Recycling. Science (80-.). 337, 690–695. doi:10.1126/science.1217501

Sanwa Newtec, n.d. Rewritable Printer [WWW Document].

Schmidt, J.H., Holm, P., Merrild, A., Christensen, P., 2007. Life cycle assessment of the waste hierarchy--a Danish case study on waste paper. Waste Manag. 27, 1519–30. doi:10.1016/j.wasman.2006.09.004

Schmidt, M., 2008. The Sankey diagram in energy and material flow management: Part I: History. J. Ind. Ecol. 12, 82–94. doi:10.1111/j.1530-9290.2008.00004.x

Schuelp, M., Hagelueken, C., Kuehr, R., Magalini, F., Maurer, C., Meskers, C., Mueller, E., Wang, F., 2009. Recycling from e-waste to resources. United Nations Environ. Program. United Nations Univ. 120.

Sundin, E., Svensson, N., McLaren, J., Jackson, T., 2001. Materials and Energy

Flow Analysis of Paper Consumption in the United Kingdom, 1987-2010. J. Ind. … 5, 89–105.

Szabó, L., Soria, A., Forsström, J., Keränen, J.T., Hytönen, E., 2009. A world model of the pulp and paper industry: Demand, energy consumption and emission scenarios to 2030. Environ. Sci. Policy 12, 257–269. doi:10.1016/j.envsci.2009.01.011

Tasaki, T., Oguchi, M., Kameya, T., Urano, K., 2007. Screening of metals in waste electrical and electronic equipment using simple assessment methods. J. Ind. Ecol. 11, 64–84. doi:10.1162/jiec.2007.1309

The Publishers Association, 2012. The UK Book Publishing Industry in Statistics 2012.

Toshiba, 2003. Toshiba's “e-blue(TM)” Decolorable Toner and Erasing Machine Set to Boost Paper Recycling at Offices in Japan [WWW Document]. Press release. URL http://www.toshiba.co.jp/about/press/2003_12/pr0201.htm (accessed 2.11.15).

Toshiba, 2013. FriXion feeds new Toshiba erasable printer [WWW Document]. Press release. URL http://www.eid.toshiba.com.au/downloads/Eco_Launch_OCT2013/Press Releases/StationaryNews_Article_04NOV13.pdf (accessed 2.11.15).

Van Nes, N., Cramer, J., 2006. Product lifetime optimization: a challenging strategy towards more sustainable consumption patterns. J. Clean. Prod. 14, 1307–1318. doi:10.1016/j.jclepro.2005.04.006

Wang, F., Huisman, J., Meskers, C.E.M., Schluep, M., Stevels, A., Hagelüken, C., 2012. The Best-of-2-Worlds philosophy: Developing local dismantling and global infrastructure network for sustainable e-waste treatment in emerging economies. Waste Manag. 32, 2134–2146. doi:10.1016/j.wasman.2012.03.029

Wang, F., Huisman, J., Stevels, A., Baldé, C.P., 2013. Enhancing e-waste estimates: Improving data quality by multivariate Input-Output Analysis. Waste Manag. 33, 2397–2407. doi:10.1016/j.wasman.2013.07.005

WRAP, 2007. A feasibility study of reusable transport and storage systems for large kitchen appliances.

Wrap, 2012. Electrical product material composition.