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In search of standards to support circularity in product policies: A systematic approach

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ABSTRACT

The aspiration of a circular economy is to shift material flows toward a zero waste and pollution production system. The process of shifting to a circular economy has been initiated by the European Commission in their action plan for the circular economy. The EU Ecodesign Directive is a key policy in this transition. However, to date the focus of access to market requirements on products has primarily been upon energy efficiency. The absence of adequate metrics and standards has been a key barrier to the inclusion of resource efficiency requirements.

This paper proposes a framework to boost sustainable engineering and resource use by systematically identifying standardization needs and features. Standards can then support the setting of appropriate material efficiency requirements in EU product policy.

Three high-level policy goals concerning material efficiency of products were identified: embodied impact reduction, lifetime extension and residual waste reduction. Through a lifecycle perspective, a matrix of interactions among material efficiency topics (recycled content, re-used content, relevant material content, durability, upgradability, reparability, re-manufacturability, reusability, recyclability, recoverability, relevant material separability) and policy goals was created. The framework was tested on case studies for electronic displays and washing machines. For potential material efficiency requirements, specific standardization needs were identified, such as adequate metrics for performance measurements, reliable and repeatable tests, and calculation procedures.

The proposed novel framework aims to provide a method by which to identify key material efficiency considerations within the policy context, and to map out the generic and product-specific standardisation needs to support ecodesign.

Via such an approach, many different stakeholders (industry, academics, policy makers, non-governmental organizations etc.) can be involved in material efficiency standards and regulations. Requirements and standards concerning material efficiency would compel product manufacturers, but also help designers and interested parties in addressing the sustainable resource use issue.

1. Introduction

The aspiration of a circular economy is to shift material flows toward a zero waste and pollution production system. Sustainable resource use is considered a keystone of the European roadmap to 2050 (European Commission, 2011), and to target this transition, the European Commission proposed an EU action plan for the circular economy in 2015.

There are various ways in which the transition to a circular economy can be achieved – these could be revolutionary or evolutionary. In terms of the evolution of established policy, since 2009 the Ecodesign Directive has aimed to increase security of supply and contribute to sustainable development by establishing a framework for setting ecodesign[1] requirements (European Union, 2009a) for energy-related products (ErPs i.e. products that use or

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[1] Within this work, *Ecodesign* refers to the Directive 2009/125/EC, while *ecodesign* refers to the approach to designing products with special consideration for the environmental impacts of the product during its whole lifecycle.

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have an indirect impact on energy consumption). ErPs addressed by the policy account for a large proportion of current natural resource consumption (European Union, 2009a), and have to comply with ecodesign requirements in order to obtain the 'CE' marking, and therefore to be placed on the European market and move freely (European Union, 2009a).

The majority of implementing measures defined under the Ecodesign Directive to date regulate energy efficiency during the use phase. However, as energy efficiency of ErPs has improved with the implementation of this policy, the environmental impacts associated with other environmental life cycle phases have become relatively more significant (Dalhammar et al., 2014). As a result, the scope for tightening energy requirements has been reduced and attention has shifted to material efficiency. However, the absence of adequate metrics and standards has been a key barrier to the inclusion of material efficiency requirements.

International standards play a crucial cross-industry role, addressing areas such as rational production, international terminologies, safety and health protection, measurement, analysis, quality control and environmental protection (Grob, 2003). The need for standards related to material efficiency is clearly identified by Bundgaard et al. (2017) in their analysis of the processes and stakeholder interactions to better address material efficiency under Ecodesign Directive. Thus, the inclusion of requirements on material efficiency aspects in Ecodesign implementing measures could be greatly facilitated by availability of standards on: upgradeability; ability to extract key components for reuse; repair, recycling and treatment; calculation of recycled and re-used content in products; methods to identify components by their environmental impact; reusability, recyclability and recoverability indices (European Commission, 2015a).

The aim of this paper is to propose a novel framework to address material efficiency and therefore to support European policies in the transition to a circular economy. The framework can be used to map, plan and monitor the upcoming standardization activities. Our research was contextualized on the standardisation activities related to the Ecodesign Directive. Case studies are presented in order to demonstrate how a possible framework approach could involve different stakeholders (for instance industry, academics, policy makers, non-governmental organizations, etc.) to work systematically on material efficiency standards and support policies needed to promote sustainable engineering.

Starting from a literature review focused on standardisation, material efficiency and circularity in EU policies (section 2), the proposed framework is introduced in chapter 3 and tested in section 4, with two case studies represented by electronic displays and a household electric appliance. Finally, sections 5 and 6 are devoted to the discussion of the proposed systematic approach, with final remarks, opportunities and drawbacks.

2. Literature review: standards, products policies and circularity of products

We present an overview of standardization processes, including a review of existing material efficiency topics relevant to product policy, in order to 1) understand the role played by standardization in the scientific community and in technological progress, and to 2) contextualize material efficiency topics in product policy and the circular economy, and describe the standardization process.

2.1. Standards

Standardization is the result of scientific and technological activities, whose main objective is the collaborative production and dissemination of technical knowledge (Russell, 2005). Standardization includes terminology and definitions, requirements and guidelines for testing and for result assessment, measurements, verification and validation (Goluchowicz and Blind, 2011). According to ISO, standards refer to documents established by consensus and approved by a recognized body that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context. Moreover, standards should be based on the consolidated results of science, technology and experience, and aimed at the promotion of optimum community benefits (Ping, 2011). Standards are generally used by technicians, architects, designers and engineers as guidelines for conducting a test, checking minimum requirements or conformity, but also to support design development and innovation. Therefore, they are often jointly developed by standard organizations and groups of stakeholders, to maximize safety, health, quality, environmental protection and many relevant properties related to a specific product or service (Grob, 2003).

2.1.1. A brief history of standards

The process of developing and implementing technical standards began during the industrial revolution, with firm-level standardization; manufacturing devices, raw materials, workplace operating actions were standardized in order to allow new workers to be competent to their job immediately after simple training (Ping, 2011). However, the first systematic attempt at standardization took place in France during the Revolution and focused mainly on weights and measures: comparable weights and measures were a precondition for a functioning national and international system of commerce and trade which depended on a reliable common basis for exchange (Wenzlhuemer, 2010). As a result of industrialization, nations began to create institutions for standards research and development in the late nineteenth and early twentieth century and private standardization organizations began to be established to develop voluntary standards (Russell, 2005).

As standardization became the basis for technological and industrial innovation, these organizations appeared to be a mechanism for economic regulation, providing guidelines useful to coordinate industrial supply chains. The history of standardization and standards organizations was studied by Ping (2011), who also examined the driving forces behind the need to adopt a technical standard and the role of technical standards in the context of market economies. In another work, Russell (2005) discussed the central importance of standards for business and economics: standards can create intra-firm and inter-firm efficiencies, facilitating economies of scale in manufacturing and promoting interoperability between complementary products.

Nowadays the standardization portfolio is composed of private, national, regional and international standards. There are three principal international standards bodies: the International Electrotechnical Commission (IEC), the International Telecommunication Union (ITU) and the International Standard Organization (ISO). The European Union endorses the work of the three European standards organisations (ESOs): The Comité Européen de Normalisation (CEN, founded in 1961), the Comité Européen de Normalisation Électrotechnique (CENELEC, founded in 1973), and the European Telecommunications Standards Institute (ETSI, founded in 1988) (Wenzlhuemer, 2010). Table 1 shows how these organisations divide up the work of standardisation at a geographical and product scope level.

Within the EU there are agreements to recognise international standards and vice versa. Many CEN and CENELEC standards are identical to ISO and IEC standards – around 31% of CEN standards are identical to ISO due to the Vienna Agreement (ISO CEN, 2001), and around 60% of the CENELEC standards are substantially

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Table 1
Standardisation organisations.

	European Standards Organisations		
	CEN	**CENELEC**	**ETSI**
Product Scope	The main body for developing standards in Europe in all areas except telecommunications (ETSI) and electrotechnical (CENELEC).	Electrotechnical Standardisation[a].	Telecommunications Standards for Information and Communications Technologies (ICT), including fixed, mobile, radio, converged, broadcast and internet technologies.
	ISO	**IEC**	**ITU-T**
	International Standards Organisations		

[a] CENELEC coordinates closely with CEN via the CEN-CENELEC Management Centre (CCMC) on strategic matters of common interests.

identical to IEC due to the Frankfurt agreement (IEC CENELEC, 2016).

2.1.2. Standardization process

As reported by ISO (2015), a standard is generally developed by a panel of experts, within a technical committee. Adequate stakeholder participation is essential to standardization (Goluchowicz and Blind, 2011), therefore technical committees are formed by representatives of industry, non-governmental organizations (NGOs), governments and other stakeholders, appointed by standards organization members.

The development of a new standard is initiated by a request from industry, national members, governments or other stakeholders such as consumer groups. According to ISO (2015), standards development is a multi-stage linear process, formed by mandatory and optional stages, here summarized in Table 2.

2.1.3. The drive for standards

Recent studies have shown that the information and communications technology (ICT) sector (including both hardware and software producers) is strongly dependent upon standards (Blind et al., 2010): stakeholders of these industries perceive the main positive impacts of standards in terms of the ability to increase product variety and to develop new global outsourcing opportunities. On the supply side, ICT standards are indeed important for structuring relationships by facilitating world-wide procurement, outsourcing, production and even R&D. Firms usually do not innovate in isolation but in collaboration and interdependence with other organizations, hence standards can constitute incentives for innovation (Goluchowicz and Blind, 2011). The process has helped to develop best practice and good technical specifications and facilitates collaboration in multidisciplinary new complex fields such as relating to smart grids and energy efficiency. This consensus-based process has of course both strengths and weaknesses in that it is very robust and well accepted, but sometimes very slow (Jagu, 2015).

In recent works, researchers have used various methodologies to collect and structure views of stakeholders on international standards, and especially on trends for the future (Blind, 2008; Goluchowicz and Blind, 2011). Using in particular the Delphi methodology to survey a wide circle of experts, it was determined that the topics of efficiency of resources (including topics such as repair, recycling and recycled content), were characterized with a high priority in standardisation processes (Goluchowicz and Blind, 2011).

2.2. Resource efficiency

According to the European Commission (2017a), resource efficiency means *using the Earth's limited resources in a sustainable manner while minimising impacts on the environment. It allows us to create more with less and to deliver greater value with less input*. Hence, resource efficiency can be improved by either reducing the amount of resources used to produce the output or by reducing the environmental impact associated with the output (Huysman et al., 2015). Bundgaard et al. (2017) recently published a paper devoted to the shift from energy efficiency towards resource efficiency within the Ecodesign Directive, which includes also other possible definitions of resource efficiency. Resources are objects of nature which are extracted by man from nature and taken as useful input to man-controlled processes (Udo de Haes et al., 2002). Taking into account these definitions, we consider resource efficiency as a

Table 2
ISO standard development process (ISO, 2015).

Proposal stage (mandatory)	The main objective of the first phase is to confirm that a new standard in the subject area is really needed. Then, the new work item is submitted to the committee by the project leader, highlighting possible complications (copyright, patents, etc.). The committee decides on how to proceed by voting.
Preparatory stage (optional)	The committee establishes a working group of experts (including the project leader) in charge to prepare the working draft. Once the last version of the working draft is ready, it is then sent to the committee that decides which stage to go to next (Committee stage or Enquiry stage).
Committee stage (optional)	The working draft is shared with the members of the committee. Comments and notes are usually added and the document circulates until consensus is reached on the technical content.
Enquiry stage (mandatory)	The draft standard is submitted to the central secretariat to be circulated among all of the organization members. Members decide on the standard approval by voting. If the standard is approved the project goes straight to publication, otherwise there could be a further process in case the draft standard has been significantly revised.
Approval stage (optional)	In case of main changes and comments, the draft standard is revised by the committee and then submitted again to the central secretariat for a second Enquiry stage.
Publication stage (mandatory)	If the draft standard is approved, the secretary submits the final document for publication. When the standard has passed through the Approval stage, the secretary may submit the project leader's responses to member body comments on the draft standard.

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combination of energy efficiency and material efficiency. Thus, material efficiency does not directly regard resources used to produce energy, nor energy used during the lifecycle of products.

2.2.1. Circular economy

Circular economy is a concept that lacks a scientifically endorsed definition (Ellen MacArthur Foundation, 2015). As for the concept of sustainable development, it is used in many contexts for different purposes, and also evolved rapidly over a relatively short period of time (Lawn, 2013). Circular economy can be identified as an approach to design bottom-up environmental and waste management policies, aiming at restorative and regenerative systems (Ellen MacArthur Foundation, 2015). The goal of a circular economy is to move from a linear understanding of consumption and production towards a circular model where products and materials continue to circulate instead of ending up as waste (Bundgaard et al., 2017). However, the implementation of circular economy worldwide still seems in the early stages (Ghisellini et al., 2015). Cradle to grave designs still dominate modern manufacturing (McDonough and Braungart, 2002).

In a Life Cycle Thinking perspective, the Ellen MacArthur Foundation (2015) introduces three main principles: 1) Preserve and enhance natural capital, 2) optimize resource yields, and 3) foster system effectiveness. Technological progress, therefore, should aim at preventing further diminutions of natural capital, but also at reducing the natural resources wasted in the transformation of natural capital to human-made capital (Lawn, 2013). However, as there is an unavoidable conflict between technological progress (economic development) and environmental protection, the greatest contribution to ecological sustainability may come from efforts to reduce demand (Rees, 2003). Daly (1991) hypothesized the collective ‘steady-state’ of humanity and nature, a theory that was further elaborated by other ecological economists (including concepts as population control and zero-growth in the global economy, as by Kopnina and Blewitt (2014)), but that has gained so far little effect in policy making (Rees, 2016).

On the other hand, emerging from the status quo are positive and concrete examples of resource efficiency are shown in new (circular) business model - namely initiatives, business opportunities and challenges for circular design, as reported by Bakker et al. (2014a). Strategies such as design for durability, design for ease of maintenance and repair, design for upgradability, design for disassembly and reassembly are considered key elements for the transition toward circularity of products. These strategies are creating new business opportunities, based on trust and compatibility, and are pushing competitors to reconsider their way to design products.

In a recent study, the Ellen MacArthur Foundation (2015) estimated that the circular economy and the technology revolution will allow Europe to grow resource productivity by up to 3 percent annually (€0.6 trillion per year by 2030 to Europe's economies and €1.2 trillion per year in non-resource and externality benefit). However it seems unrealistic to expect that this would be achieved via a radical shift to zero-waste philosophies. A gradual economic transition is necessary, in which bottom-up initiatives from open-minded stakeholders may provide the momentum for a more radical change in the future.

2.2.2. Material efficiency of products

Material efficiency standards will be of significant strategic importance in future. These will need to be consistent with the Life Cycle Thinking approach and avoid the optimisation of one lifecycle phase at the expense of another (for example, as has sometimes happened with a focus on energy use (Dalhammar et al., 2014)).

From the literature review conducted by Ghisellini et al. (2015), material efficiency emerged mainly contextualised within the principle of the waste hierarchy, or 3 Rs: Reduction, Reuse and Recycling. This is aligned with the waste hierarchy described in the EU action plan, establishing a priority order for prevention, preparation for reuse, recycling. A fourth R was introduced by McDonough and Braungart (2002), who recognised the importance of Regulations.

The Reduction principle essentially targets efficiency in the first life cycle phases (from design to production), aiming at minimizing resource consumption (energy and raw materials). Because of the first and second laws of thermodynamics, the amount of production waste that can be reduced via technological progress is limited, in a situation where the same quantity of products are produced. This is because 100% technical efficiency is physically impossible (Lawn, 2013). Whilst the ideal in terms of resource consumption would be a halt in the production of new products, this does not reflect the realities of the current economic system. Therefore, within the current infrastructure, most benefit can be achieved by using recycled materials in lieu of primary raw materials, by designing durable and lightweight products, and by using fewer harmful substances (Ghisellini et al., 2015). Reducing the use of precious materials prevents dependencies and reduces cost (Winkler, 2011), but also reductions in the amount of hazardous substances (Sakai et al., 2011) and critical raw materials (Tukker et al., 2016) have to be considered with the same relevance. Hazardous substances, precious metals and critical raw materials are hereinafter identified as “relevant materials”, in the context of this work. The concept of “doing more with less” (eco-efficiency) was however heavily criticized by McDonough and Braungart (2002), who do not consider it a strategy for success in the long term - underlining the urgent need to shift from a cradle to grave perspective to a cradle to cradle approach.

The Reuse principle refers to any operation by which products or components are used again for the same purpose for which they were conceived (European Union, 2008). Design for reusability and manufacturing with re-used content have been proved to avoid environmental impacts for a series of different items (Castellani et al., 2015).

The Recycling principle refers to operations by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. Recycling includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations (European Union, 2008). There are some complex considerations relating to recycling. McDonough and Braungart (2002) argued that the majority of recycling is actually downcycling, as it reduces the quality of materials over time. Recycling can be considered an energy consuming process to convert materials into a product they were not designed for, postponing their disposal or incineration by one or two product life cycles (McDonough and Braungart, 2002). The benefits of recycling materials tend to decrease until a cut-off point is reached where recycling is environmentally or economically too expensive (Ghisellini et al., 2015). Furthermore, the recycling process may introduce harmful additives that conventional products do not contain (McDonough and Braungart, 2002). But most important, there can never be 100% recycling of matter (Lawn, 2013), therefore the transition to a circular economy should prioritize prevention and preparation for reuse in order to target the elimination of waste.

In support of the 3Rs, there exist methods that could significantly contribute to the extension of the service life of a product. Design for durability and product lifetime extension are relevant considerations for waste prevention and can be key drivers for economy, as shown by Kagawa et al. (2006) for the automotive

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sector. Previous studies have assessed the environmental impacts of electronic products against their increasing energy efficiency over time, such as washing machines and dishwashers (Ardente and Mathieux, 2014a; Ardente and Talens Peiró, 2015), vacuum cleaners (Bobba et al., 2016), refrigerators and laptops (Bakker et al., 2014b), finding that product life extension is the preferred strategy for a series of products. This is partly because the share of the upstream impacts of an electronic device can be significantly reduced by ensuring a long and productive usage phase or by taking measures to extend its useful lifetime (Fitzpatrick et al., 2014; Prakash et al., 2012). Design for durability implies the selection of certain material grades and the analysis of failure risks (Prendeville et al., 2014), and tailored approaches are needed (Bakker et al., 2014b). Reparability is considered a key feature for lifetime extension and to reach highest material efficiency yields (Stahel, 2013). In addition, repair activities represent a business opportunity for the private sector.

Reuse, repair and remanufacture are activities characterized by local or regional system boundaries, limiting packaging and transport costs, and, if ownership is maintained, avoiding multiple transaction costs (Stahel, 2013). Design for remanufacturing aims to return a used product to its original specification. The factors that influence the integration of this method into a company design process were studied by Hatcher et al. (2013). A portfolio of design considerations were highlighted by Prakash et al. (2012) in the context of ICT, who recommended that the focus of mandatory product policy in this area should be expanded to include hardware upgrading, modular construction, recycling-friendly design, availability of spare parts, standardisation of components and minimum warranty periods.

Table 3 summarizes the different approaches analysed in this chapter, provides a classification of the aspects already targeted by the principles of the 3Rs, and shows which other ecodesign targets could be directly addressed (complementary topics).

2.3. EU policies and resource efficiency

Within the Roadmap to a Resource Efficient Europe (European Commission, 2011) a clear milestone is defined: waste shall be managed as a resource by 2020, with reuse and recycling being economically attractive options for public and private actors. Energy recovery shall be limited to non-recyclable materials and landfilling shall be virtually eliminated. The same important policy document suggests boosting the material efficiency of products by setting requirements under the Ecodesign Directive in terms of reusability/recoverability/recyclability, recycled content and durability (European Commission, 2011).

Four years later, the European Commission (2015c) published a new policy document that intends to be the milestone for the transition to a circular economy. The Communication “Closing the loop – An EU Action Plan for the Circular Economy” clearly identifies product design (and hence product policies) as one of the main pillars to implement a more circular economy in the EU. The Action Plan has created an important momentum to support the transition towards a more circular economy in the EU. This package included legislative proposals on waste, with long-term targets to reduce landfilling and increase recycling and reuse (European Commission, 2017b). In particular, it announced: the anticipated publication of the Ecodesign regulation on electronic displays, which will include material efficiency features; a mandate to European standardization organizations to develop standards on material efficiency (European Commission, 2015c); a more systematic analysis of material efficiency considerations in the preparatory studies carried out under the Ecodesign Directive; and options and actions for more coherent product policy framework.

The EU Action Plan has undoubtedly contributed to mainstreaming the concept of circular economy as a first step of a long-term endeavour. Ensuring a successful transition to the circular economy, however, requires efforts on many different fronts and does not stop with delivering on actions put forward by the Commission (European Commission, 2017b). The EU Action plan can be seen a way “to stimulate the transition of European businesses and consumers towards a circular economy, where resources are used in a more sustainable manner” (UNEP, 2016).

Ecodesign can also have an important contribution. Following political discussions on Ecodesign in 2016, the Commission confirmed the importance of smart product design and decided to focus efforts on the product groups with the highest potential in terms of energy and resource savings and further reinforce the evidence base for regulatory action. This resulted in the adoption on 30 November 2016 of the Ecodesign Working Plan 2016–2019 as part of the Clean Energy for All Europeans package (European Commission, 2016). The Commission also asked the European standardisation organisations to develop generic standards on the durability, reusability and recyclability of certain products. Joint working groups were then set up to develop around 20 horizontal standards (European Commission, 2017b).

2.3.1. Contribution of product policies to resource efficiency

As Geng et al. (2014) reported, many policies related to

Table 3
List of material efficiency targets.

	Targets	Reference
3Rs principle		
Reduction principle	Recycled content	(Ghisellini et al., 2015)
	Relevant material content	(Ghisellini et al., 2015; Winkler, 2011)
Reuse principle	Re-used content	(Castellani et al., 2015; Ghisellini et al., 2015)
	Reusability	(Castellani et al., 2015; Ghisellini et al., 2015; Hatcher et al., 2013)
Recycling principle	Recyclability	(Bakker et al., 2014b; Ghisellini et al., 2015; Winkler, 2011)
Complementary topics		
Lifetime	Durability	(Ardente and Mathieux, 2014a; Ardente and Talens Peiró, 2015; Bakker et al., 2014b; Fitzpatrick et al., 2014; Kagawa et al., 2006; Prakash et al., 2012; Prendeville et al., 2014)
	Upgradability	(Prakash et al., 2012)
	Reparability	(RREUSE, 2013; Stahel, 2013)
	Re-manufacturability	(Stahel, 2013; Winkler, 2011)
Waste reduction	Recoverability	(European Union, 2008)
	Relevant material separability	(Sakai et al., 2011; Tukker et al., 2016)

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environmental protection and resource efficiency have been developed by focusing on a single perspective (e.g. strategies for improving energy use efficiency, policies for improved resource efficiency, policies for climate change adaptation, policies for ecological restoration and biodiversity protection, policies to increase renewable and sustainable energy use, etc.). However, those policies were developed without an integrated and systematic approach, which simultaneously addresses all of the interconnected aspects.

Product policies offer a valuable opportunity to incite a preventative (at the design stage) and comprehensive assessment of the entire life cycle of any process as well as at the interactions between the process and the environment and economy in which it is embedded (Ghisellini et al., 2015). As already stated, product policies in the European Union context have so far mainly addressed energy efficiency during the use phase. Energy efficiency standards and labels for household appliances are among the most popular strategy to save energy and educate the consumers to use energy wisely (Mahlia and Saidur, 2010). The European Commission (2015a,b,c,d) expects a potential energy saving of around 1930 TWh by 2020 in the EU, thanks to energy labels and minimum energy efficiency standards. Other regions of the world undertake similar initiatives: for example, the Chinese government has been implementing national energy efficiency standards for household equipment. According to Tao and Yu (2011), the effect of the placement of high-efficiency refrigerators on the market during the period from 2003 to 2023 will potentially reduce residential energy consumption in China by 588–1180 TWh electricity, depending on sales share of efficient models.

However, if the objective is the improvement of the product's resource efficiency throughout its whole life cycle, the use phase cannot be the only target of efficiency measures. Moreover, when policies fail to sufficiently address other important aspects, they may have the unintentional effect of influencing manufacturers to optimize one visible performance criteria (e.g. energy use for a household appliance or an electronic device) at the cost of another (such as longer programme duration or a higher impact in the production phase) (Prakash et al., 2012; Sivitos et al., 2015). Therefore, in order to approach the sustainable design of a new product in a holistic manner, it is important that material efficiency aspects are taken into account in product policy. The potential impact of inclusion of these aspects in product policy is huge in terms of new jobs and potential cost savings (McAlister et al., 2015; Stahel, 2014). Relevant ecodesign principles, include design for resource reduction, use of renewable resources, design for reuse, recycling, recovery and adequate treatment for disposal, and design for dismantling (Gottberg et al., 2006; Mathieux et al., 2008; Cellura et al., 2012).

Regulations concerning the energy efficiency of products require the establishment of standards, especially those for conformity assessment (before the placement a product on the European market) against the defined requirements (Dworak and Zonneveld, 2015). The first step towards establishing energy efficiency requirements is to define a test procedure for testing and rating a product (Mahlia and Saidur, 2010). A test procedure is a well-defined protocol or laboratory test method to provide manufacturers, regulatory authority and consumers a way of consistently evaluating performance of products across different brands (Meier and Hill, 1997). Similarly, standards on material efficiency are necessary for the definition of material efficiency requirements in regulations. These are particularly needed to guide content relating to potential requirements, test procedures, thresholds, tolerance, and the verification procedure by Market Surveillance Authorities (MSA). Material efficiency performance of some product groups has been already analysed using the REAPro method (Resource Efficiency Assessment of Products, see (Ardente and Mathieux, 2014b), such as washing machines (Ardente and Mathieux, 2014a), electronic displays (Ardente and Mathieux, 2014b; Ardente et al., 2014), and servers (Talens Peiró and Ardente, 2015), for example. However adoption of requirements in regulations has so far been difficult due to the absence of appropriate metrics (European Commission, 2015c) and standards (Mathieux et al., 2014). Adoption of durability requirements on vacuum cleaners was only possible thanks to the existence of durability standards, initially developed for other purposes (McAlister et al., 2015). Nevertheless, further material efficiency requirements continue to be under discussion various product groups.

2.3.2. Standardisation mandate under the Ecodesign Directive

In line with foresight studies that had highlighted the extensive need for standardization activities to support material efficiency considerations ((Goluchowicz and Blind, 2011), see Section 2.1), the European Commission (2015b) issued a standardization request to European Standardization Organizations (ESOs), CEN, CENELEC and ETSI, with regard to ecodesign requirements on material efficiency aspects for ERPs in support of the implementation of the Ecodesign Directive. This request was one of the first follow-up actions of the Circular Economy action plan. The request is also consistent with Regulation (EU) No 1025/2012 on European standardization, a European guideline established with the goal of modernizing the standards process and to enable more standards to be produced, faster and with greater inclusivity.

This request was prepared by the European Commission, with inputs from a CEN/CENELEC task force on material efficiency, jointly implemented by CEN and CENELEC, reporting to the Ecodesign Directive coordination group. The material efficiency task force was composed of representatives from the standardization organizations, the design/manufacturing industry, the recycling industry, NGOs and the EC and national governments. The request has been accepted by CEN and CENELEC, and has been published with the reference M/543 (European Commission, 2015c). Joint working groups were set up to develop around 20 horizontal standards (European Commission, 2017b).

M/543 states that European standards should be prepared considering the following aspects:

1) Extending product lifetime;
2) Ability to re-use components or recycle materials from products at end-of-life;
3) Use of re-used components and/or recycled materials in products.

It also states that the European standards should covers topics such as "*upgrade-ability, ability to extract key components for reuse, repair, recycling and treatment; calculation of recycled and re-used content in products; methods to identify components by e.g. their environmental impact; reporting formats; reusability, recyclability and recoverability indices*" (European Commission, 2015a). Although precise topics are listed in the request (e.g. "*Definition of parameters and methods relevant for assessing durability, upgradability and ability to repair, re-use and re-manufacture of products*"), the request remains rather open on the content of the standardization deliverables: which metrics and which method for which topic? Which reporting format? Which verification procedure? When accepted, it will be up to ESOs to organize the work and to plan the timely delivery of standardization deliverables. An important feature of the request is that it is of a *horizontal* nature, meaning that it concerns standards that are applicable to several (if not all) product groups covered by the Ecodesign Directive. However, the horizontal standards to be developed may be complemented and enhanced by existing work on *vertical* (i.e. product group specific) harmonized standards. The deadline for adoption of the standards is fixed at 31.3.2019.

The literature review has provided deep insights into standardization activities with which many readers of this journal may not be familiar. Standards are necessary to ensure a smooth integration of enforceable material efficiency aspects in product policies, and the standardization mandate recently issued by the European Commission is a response to this need. In conclusion, the standardization work currently being commenced (the first meeting of the newly created CEN-CENELEC joint Technical Committee was held in September 2016) will need to collectively define what material efficiency of products means, and which metric/method/reporting format needs to be developed for each topic.

3. Proposal of framework linking material efficiency aspects with standardization activities

This section introduces a framework that aims at mapping and connecting material efficiency policy goals with material efficiency topics and with the necessary elements that can be developed in standards. This framework aims at providing an appropriate approach to policy makers, industry, academics and other relevant stakeholders in order to address material efficiency aspects in a robust, effective and comprehensive way.

3.1. Connecting material efficiency policy goals with topics

Material efficiency aspects have to be considered by adopting a lifecycle perspective. The literature analysis identified three main high level *policy goals* concerning material efficiency of products, which were recently confirmed by the standardization request: "reduce embodied impact"; "extend life time"; "reduce residual waste". The literature review also identified nine main *topics* related to material efficiency, namely "Recycled content", "Re-used content", "Relevant material content", "Durability", "Upgradability", "Reparability", "Re-manufacturability" "Reusability, Recyclability, Recoverability", "Relevant material separability". Each of the three material efficiency policy goals is connected with the relevant material efficiency topics, as depicted in Fig. 1. For example, being able to measure the *content* of a product in *recycled materials*, *re-used component* or *relevant materials*, can be used to set targets to reduce the embodied impacts of products. Defining clearly *reparability* can enhance requirements that would contribute to increase the expected lifetime of products. Defining *recyclability/recoverability* indices or criteria (and associated thresholds) can contribute to reductions in residual waste. Moreover, defining better aspects such as *durability* or *re-manufacturability* can contribute to the implementation of several of the policy goals. In Fig. 1, each policy goals is linked to the appropriate life cycle stage of the product (bottom of the figure) to emphasize the life cycle features of material efficiency.

3.2. What comprises a standard on material efficiency: framework approach

The framework aims at mapping and connecting material efficiency *policy goals* with material efficiency *topics* and with the necessary elements that can be developed in standards. In the proposed framework, in addition to the three policy goals and the nine material efficiency topics, the following building elements are suggested:

- *Potential requirements*: Material efficiency requirements (and associated thresholds) should "improve performance" or "supply of information" with regard to material efficiency (EUR-LEX, 2009). Regulatory requirements should be verifiable by MSA and should not impose excessive administrative burdens on manufacturers (European Union, 2009a);
- *Metrics*: Each material efficiency topic needs to be associated with appropriate metrics (expressed in appropriate units) so that performance can be measured. The metrics can be used as a foundation for regulatory requirements. In the case of information requirement, the metric can be a Boolean value (yes/no) corresponding to the presence or absence of required documentation;
- *Tests*: Testing procedures should be defined in standards so that conformity to requirements can be verified, in particular by MSAs. Procedures should aim for repeatable and reliable laboratory tests;
- *Calculations*: Depending upon the requirement, conformity may be verified by calculation procedures rather than or in conjunction with testing. For example "energy efficiency indices" in the context of energy efficiency. Calculations should be defined in standards, in order to provide robust and reliable results;
- *Reference tables*: Databases (or data tables) might be necessary, for example to support calculations. These need to be defined in a standardized way;
- *Reporting/information format*: Formats to report information by manufacturers should be defined in a standardized way to allow smooth calculation and/or quick verification of requirements by MSA.

These elements are represented and connected together in Table 4. The framework relates material efficiency policy goals and topics with specific standardization needs such as potential, metrics, tests, calculation, database and reporting format. The following rules for connecting these elements are proposed:

- for each material efficiency topic, at least one potential requirement is proposed together with one or several appropriate metric(s);
- for each requirement and metric, either a test and/or a calculation method is defined;
- calculation method and test can be supported by reference tables to be agreed on;
- reporting format might have to be standardized, either to comply with information requirement or to enhance efficient information flows between manufacturers and MSAs.

4. Case studies

This section aims to illustrate and test the proposed framework on several material efficiency aspects and potential requirements for two energy using product groups; electronic displays, and washing machines for household use.

4.1. Electronic displays

Material efficiency performance of this product group, which comprises televisions and computer displays, is well documented in the scientific literature - for example in (Mathieux et al., 2008; Nelen et al., 2014; Peeters et al., 2014, 2013). Moreover, some ecodesign opportunities for displays have been reported and discussed in various papers (Mathieux et al., 2001; Peeters et al., 2015; Ryan et al., 2011; van Schaik, 2014). Electronic displays is a product group targeted by several EU product policies, including the Ecodesign Directive (European Union, 2009b), Energy Labelling (European Union, 2010a) and the EU Ecolabel (European

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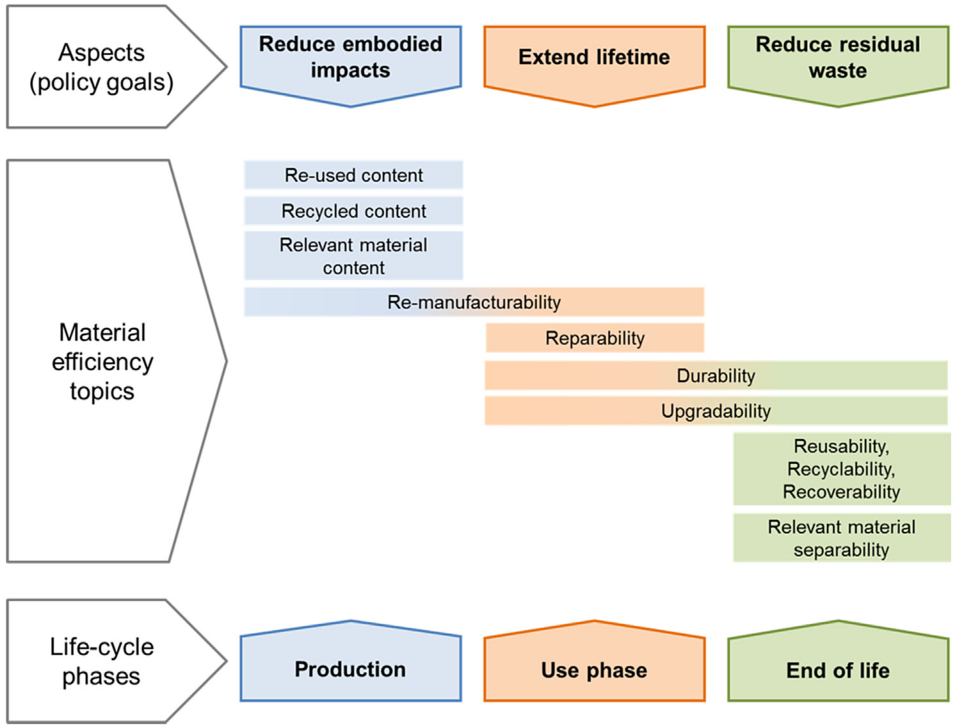

Fig. 1. Connection of policy goals, product life cycle phases and material efficiency topics. Material efficiency topics can overlay more than one policy goal.

Table 4
Overview of the proposed framework for material efficiency. The framework connects materials efficiency policy goals, potential requirements and topics with specific standardization needs (metrics/calculations, tests, database/tables and reporting/information) for each material efficiency aspect.

	Key framework elements	Necessity	Example
Policy drivers (defined via EC assessment studies)	Policy goals	Necessary	Extend product lifetime
	Topics	Necessary	Durability
	Potential requirements	Necessary	Minimum durability requirement for a given product
Standardisation needs	Metric	Necessary	Definition of a minimum number of stress cycles a product shall withstand
	Test	And/or	Definition of the endurance test (sequence of operations to conduct the stress cycle)
	Calculation		–
	Reference tables	Optional	–
	Reporting format	Optional	Development of a template to report results

Commission, 2009). The revision of the EU Ecodesign regulation on this product group has been underway (including the integration of computer displays in addition to televisions): the proposal for an implementing regulation under Ecodesign on television and displays is one of the first actions of the EU Action Plan for the Circular Economy (EC, 2015b). To support this, several analyses concerning the potential benefits and feasibility of material efficiency requirements under this piece of legislation have been published recently (Ardente and Mathieux, 2014a; 2012; Ardente et al., 2014, 2013). This section builds on these analyses and discusses the practicality of material efficiency requirements, in relation to the availability of appropriate standards. It uses the framework presented in Section 3.2 as a foundation for an analysis grid. This section has been fuelled by discussion with stakeholders held during the policy process, including manufacturers (represented by Digital Europe, but also Bang&Olufsen), recyclers (in particular European Electronics Recycler Association), NGOs (in particular ECOS[2]), academics (KU Leuven) and representatives of Market Surveillance Authorities of several Member States of the European Union.

Which material efficiency requirements are potentially relevant for displays?

The analysis published by Ardente and Mathieux (2014b) showed that the following potential material efficiency requirements are not only are relevant from an environmental life cycle perspective for electronic displays, but could also potentially be regulated under Ecodesign:

- ***[R1]*** *Declaration of content of critical raw materials* (in particular indium in the display panel);
- ***[R2]*** *Recyclability of plastic parts (with a focus also on the content of flame retardants)*;
- ***[R3]*** *Dismantlability criteria for some key components* (including the printed circuit boards, mercury containing components, the display panel and some plastic parts).

These three proposed requirements for displays relate to the policy goals defined in Fig. 1 in terms of 'Reduce embodied impacts' (for R1 above) and 'Reduce residual waste' (R2 and R3 above).

[2] http://ecostandard.org/.

4.1.1. Mapping standardization needs for electronic displays

These three material efficiency requirements (referred to from now on as R1 to R3) can be further examined and connected to existing and potential standards, using the framework presented in Section 3. Table 4 provides a refinement for the electronic displays product group, associating material efficiency policy goals and topics with other elements (i.e. metrics, calculation, etc.). Underlined cells are those for which authors clearly identify a standardization need.

For R1 which belongs to the topic 'Relevant material content' that sits under the 'Reduce embodied impacts' policy goal, it is foreseen that each manufacturer make an annual declaration of the quantity of indium contained in its products. When computed at the product group level (i.e. summing figures from all product families and all manufacturers), this information would be very useful to recyclers to be able to predict flows of indium that would arise from displays at the end of life, and hence to plan necessary investments in treatment facilities. For such a requirement, there is a clear need for the definition of a standardized electronic template to be developed to facilitate reporting for manufacturers and analysis for policy makers. Furthermore, MSA could verify the declaration by measuring the quantity of indium contained in any product put on the market using common characterization devices, such as a mass spectrometer, and using a verification procedure.

R2, under the 'Reduce residual waste' policy goal addresses the topic of 'Recyclability', aiming at ensuring minimum recyclability/recoverability rates for plastic parts. R2 can build on the metrics/calculations and on reporting formats contained in existing standards, i.e. ISO 22628 (BSI, 2002) for automotive products and IEC/TR 62635 (2015) for electric and electronic equipment. Some adjustments are still necessary in order to be able to calculate a recyclability/recoverability index for a proportion of the product (i.e. plastic parts) rather than the whole product. Standardization work is also necessary to define a common database of recycling/recovery rates of plastic materials to be used for the calculations. A standardised test method using common scales and mass spectrometers would enable MSAs to verify manufacturer declarations, hence ensuring that recyclability rates satisfy thresholds defined in the Ecodesign regulation.

Finally, R3, also under the 'Reduce residual waste' policy goal addresses the topic of "Relevant material separability", ensuring a degree of dismantlability of key display components (e.g. PCB and display panel). This could, for example, be implemented using time as a metric, as time for dismantling is a good proxy of the dismantling efforts and costs and should therefore be minimized (Ardente et al., 2014). Using such a metric would require that a repeatable standardized method for measuring the time for dismantling is developed. General principles of such a method (including operating conditions, measurement devices, tolerances, etc.) could be developed in a generic way, to provide a foundation approach across product groups, as already initially discussed by (Mathieux et al., 2014). An alternative to the measurement of the time for dismantling could be the development of a method to calculate a time score or rating for dismantling, based on measurable parameters of the product, for example as suggested by Vanegas et al. (2016). The adoption of R3 would also necessitate the definition of a standardized template for manufacturers to report recommended dismantling sequences, to be used by recyclers or MSA. Some standardization work in this area is actually on-going, for example with the development of the so-called 'oManual', in the context of (IEEE 1874, 2013), a standard for storing and transmitting procedural manuals. Alternative ways of declaring/verifying the compliance with this requirement include uploading visual media detailing dismantling processes (e.g. videos) or a declaration of a certified recycler.

In summary, Table 5 systematically maps standardization needs to support potential material efficiency for the 'electronic displays' product group. For these three exemplary requirements [R1-3], it has been shown that standardization activities are necessary, with regard to metrics/calculations, test procedures, databases/tables to support calculations, or reporting/information templates. It is important to note that all standardization needs identified in Table 5 are in fact *horizontal* in nature, meaning that they are needed for several product groups, not only for electronic displays. For example, a template for reporting product content of relevant materials could also be used for a product group like washing machines, but with a focus on neodymium in permanent magnets (Ardente et al., 2012). Recyclability requirements could be applied to other product groups such as imaging equipment (Ardente et al., 2012). As several categories of Waste Electric Electronic Equipment are collected and treated together, a database of recycling/recovery rates for plastic materials can be developed for use across several product groups. Likewise, as dismantlability of key components could be a consideration for many other product groups, including washing machines (Ardente et al., 2012), dishwashers (Ardente and Talens Peiró, 2015) or enterprise servers (Talens Peiró and Ardente, 2015), the need for reporting template is clearly *horizontal*. Such horizontal standards should obviously be complemented by vertical (i.e. product specific) elements.

4.2. Washing machines

The second case study selected to illustrate the framework is represented by the washing machine product group. It deals in particular with requirements and standards aiming at contributing to the policy goal of 'extending lifetime'. The (household) washing machine product group is addressed by the Ecodesign Directive, through Commission Regulation n. 1015/2010 (European Union, 2010b). This case study is timely as the Preparatory study to review the Ecodesign regulation was begun in 2015 (JRC, 2016). The washing machine product group is considered a relevant energy-related product (RREUSE, 2013) and has been previously selected as one of the most suitable product groups for the application of material efficiency and waste management methods (Ardente and Mathieux, 2012; Tecchio et al., 2016).

Based on a survey in the Dutch context, Bakker et al. (2014a,b) observed that the median lifespans of washing machines had changed over time, resulting in a decrease of the lifetime expectancy, from 12.1 years in 2000 to 11.7 years in 2005. Furthermore, many household products, including washing machines, are simply treated as waste rather than being repaired and/or reused, resulting in a negative consequence for the environment (McCollough, 2009). Statistics on reparability of washing machines were recently published by Tecchio et al. (2016). While some products will become obsolete relatively rapidly (as consumers may decide to upgrade and replace an item before the end of its working lifetime), this is not usually the case with washing machines, because they are technologically more stable than consumer electronics products such as mobile phones or televisions (Ricardo-AEA, 2014a). As a result, 90% of washing machine sales are primarily due to replacements after product failures (VHK, 2014). It has been found that washing machine lifetime extension could lead to environmental benefit for some environmental impact categories, such as global warming, abiotic depletion, human toxicity and acidification, despite lower energy efficiency compared to new equipment (Ardente and Mathieux, 2012; Tecchio et al., 2016).

Although the important contribution of durability to the development of a circular economy is recognised (Ricardo-AEA, 2014b), as a stand-alone concept has not yet been specifically addressed within European product policies. The average lifetime

Table 5
Illustration of the framework for three potential material efficiency requirements for the electronic display product group.

Policy Goal	Material efficiency topic	Potential material efficiency requirements	Metrics [unit]	Tests	Calculation	Reference Tables	Reporting/information
Reduce embodied impacts	Relevant material content	R1. Declaration of content in indium	Quantity of indium contained in the display [kg]	Verify truthfulness of declaration using chemical analysis			Template for reporting to be developed
Reduce residual waste	Recyclability/ Recoverability	R2. Minimum recyclability/recoverability of plastic parts	Recyclability/recoverability index of a subset of a product to be developed (based on (IEC/TR 62635, 2011) and (ISO 22628, 2002)) [%]	Verify truthfulness of declaration using mass check and chemical analysis		Common database of recycling/recovery rates of plastic parts to be developed	Existing template from (IEC/TR 62635, 2011) and (ISO 22628, 2002)) to be adapted to a sub-set of a product
Reduce residual waste	Relevant material separability	R3. Minimum dis-assemblability of key components	Time necessary for disassembly [s]		Calculated time with a specific algorithm (to be developed)		Template for dismantling sequence to be developed

Legend: when a cell is underlined, it means that standardization activities are necessary.

of a washing machine depends upon many factors, and can be between 9 and 20 years (if several geographical areas are considered (Prakash et al., 2015)). While a standardized procedure to test the minimum lifetime of the whole washing machine does not yet exist, safety standards already include minimum endurance requirements for washing machine parts. The horizontal standard IEC 60335-1 specifies endurance tests for automatic controls, switches and internal wiring of household appliances and the vertical standard IEC 60335-2-7 concerns openings and braking mechanisms of washing machines, specifically (IEC 60335-1, 2010; IEC 60335-2-7, 2012).

There are therefore opportunities to implement durability related requirements within the framework of the Ecodesign Directive. In terms of testing lifetime, tests have become very lengthy, since devices are not prone to fail (Tucci et al., 2014), therefore engineers in the manufacturing industries have developed accelerated tests to acquire reliability information quickly (Escobar and Meeker, 2007). Examples of accelerated life tests and accelerated degradability applied to washing machines are available in literature and are mostly focused on mechanical resistance and washing performance (De Carlo et al., 2013; Stamminger et al., 2017; Tucci et al., 2014). Reparability is another possible focus with high potential to extend the lifetime of products whilst maintaining added value within the economy, as opposed to, for example, recycling, which requires destruction of products (BIO by Deloitte, 2015). Voluntary standards already take into account features such as design for repair and spare parts availability (ONR 192102, 2014), but repair operators are identifying the lack of instructions and technical information availability as the key obstacle to the repair of fridges, dishwashers and washing machines (RREUSE, 2013). Design for durability and reparability are identified by Prakash et al. (2016) as two strategies to counter obsolescence of washing machines, through life-time requirements and standardisation.

Which material efficiency requirements are potentially relevant for washing machines?

The product lifetime is dependent upon many factors, such as stress, abrasion, maintenance, technological change, fashion, shift in values and other external environmental influences (Prakash et al., 2015). Clearly, the product should achieve a minimum lifetime performance, appropriate to technological progress, especially if newer products have significantly better energy performance (Bundgaard et al., 2017, 2015). Based on the outcomes of the study developed by Tecchio et al. (2016), an extended lifetime for washing machines can have environmental benefits when assessed from a life cycle perspective. Product longevity can be facilitated by the extended availability of components for replacement in the event of repair (ONR 192102, 2014). Requirements based upon component availability have been implemented in standards proposed in other product groups (NSF 426, 2013), and this is considered as one of the key options to stimulate reparability of washing machines (RREUSE, 2013). As in the previous case study, minimum dismantlability of some key components could be regulated, in order to ensure the reparability of the whole device. To allow proper functioning after reparation, only reversible operations should be allowed for this dismantling process, which would therefore be referred to as 'disassembly'.

Two potential material efficiency requirements are proposed as relevant for washing machines as they could reduce the environmental impacts from a life cycle perspective, and could be potentially regulated under the Ecodesign Directive:

- *[R4] Minimum durability (lifetime expectancy);*
- *[R5] Minimum reparability.*

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Both R4 and R5 directly relate to the 'extended lifetime' policy goal. Furthermore, R4 also contributes to the 'reduce residual waste' policy goal, because prolonging the lifetime of a device also delays its end-of-life management.

4.2.1. *Standardization needs for material efficiency aspects of washing machines*

For R4, washing machine manufacturers could declare the level of durability for each new washing machine launched on the market. The durability assessment could be expressed in a declaration of the achievement of minimum endurance requirements. Manufacturers could also benefit from such a requirement, by the establishment of a shared metric to demonstrate robustness and reliability from one design to another. Although some standardized endurance tests are available (IEC 60335-1, 2010; IEC 60335-2-7, 2012), these were conceived for safety reasons and only concern specific parts of the device rather than the product as a whole. Therefore, a standard procedure for measuring durability and performance stability over time would need to be defined, as well as a template for reporting. Such a procedure should limit cost and time for testing bodies (Stamminger et al., 2017), so that MSA are able to appropriately verify declarations of manufacturers by examination of washing machine samples.

R5 aims at ensuring a minimum disassemblability of weak components contained in washing machines. Weak components are those that have the highest failing rates and can be identified by analysis of failure statistics (Tecchio et al., 2016). Ardente and Mathieux (2012) associated environmental benefits with the improved disassemblability of components such as printed circuit boards, motors and LCD screens. Time for dismantling is a possible metric useful for R5 (Vanegas et al., 2017), provided that the process is reversible, meaning that the device should be reassembled and able to function after the repair. As discussed in the electronic display study, such a metric would require a repeatable standardized approach for measuring the time for disassembly, and associated standards.

In summary, as for the previous case study, Table 6 has mapped the standardization needs to support potential material efficiency for washing machines, by focusing on two exemplary requirements [R4-5], concerning durability and reparability. Standards are clearly necessary, especially for test procedures and reporting/information templates. As recalled in the previous example, dismantlability of key components could be a consideration for many other product groups and a template for reporting durability assessment is needed for several ErPs concerned by the Energy Labelling Directive 2010/30/EU. Once again, there is potential for a more effective approach if standards are established at a *horizontal* level, to provide consistency in approach across different product groups.

5. Discussion

This paper has shown that a framework approach to addressing the material efficiency of products can provide an effective means of mapping policy goals to material efficiency topics in order to develop potential requirements and understand the standardisation needs to support these requirements. This should of course be integrated within product group studies that include a review of the scientific literature, existing standards etc. In the wider ecodesign context, such an approach could be used in work programme studies to consider which priority products hold the most potential to be addressed by material efficiency measures.

It is interesting to note that much of the standardisation activity necessary could be horizontal in nature (i.e. of a generic nature, applied across product groups). In particular, the case studies highlighted that potential requirements relating to dismantlability of key components could be facilitated a strong generic standards foundation. This reinforces the important contribution that standardisation deliverables provided in the context of mandate M/543 will have to this area. Indeed, it suggests that there could be a potential for ESOs to carry out a framework analysis of different product groups in order to identify common elements that can successfully be addressed by horizontal standards, and ensure that the outputs of M/543 make the most effective contribution to the area of material efficiency. However, it is important to note that whilst the relationship between the policy makers and ESOs is key to this standardisation work, there is also a substantial contribution that can be made by academia. Focus is only just shifting to the material efficiency area, and there are many unknowns, particularly in the areas of testing, databases and calculations. Researchers can make substantial contributions to these areas by carrying out studies to propose and refine approaches and resolve many of the uncertainties in the area – thus providing a robust foundation for standards and speeding up the standards development process. This is especially important for the generic standards in the context of M/543 as the currently proposed delivery timelines are relatively tight as far as standardisation processes are concerned (by March 2019), and resources limited.

The focus of this paper has been upon the potential for standards to support potential material efficiency requirements in the context of the Ecodesign Directive. Indeed, the provision of robust standards is key to the effectiveness of the Ecodesign regulation as a whole, by supporting effective market surveillance (Braungardt et al., 2014). However, there is also potential for the framework to support other policy initiatives, such as the EU Ecolabel, which could also draw on some of the generic standardisation deliverables established for ecodesign, but perhaps with different thresholds or verification requirements. Equally, it is also important that any

Table 6
Illustration of the framework for two potential material efficiency requirements for the washing machine product group.

Policy Goal	Material efficiency topic	Potential material efficiency requirements	Metrics [unit]	Tests	Calculation	Reference tables	Reporting/information
Extend the expected lifetime and reduce embodied impacts	Durability	R4. Declaration of expected lifetime	Number of washing cycles [n]	<u>Standardized endurance test</u> (tdb [a]) based on both mechanical resistance and performance measurements according to IEC 60456			<u>Template for reporting</u> to be developed (e.g. a logo compatible with the energy label)
Extend the expected lifetime	Reparability	R5. Minimum disassemblability of key components	Time necessary for disassembly [s]	<u>Measured time during a standardized test</u> (tbd)			<u>Format for dismantling sequence</u>

Legend: when content is <u>underlined</u>, it means that standardization activities have to be started.
[a] To be developed.

standards developed take into account the wider policy context – for example, they will need to ensure consistency with WEEE legislation. They should also allow sufficient flexibility to ensure that the ability of manufacturers to innovate is not inadvertently restricted (Braungardt et al., 2014) – for example by including a degree of flexibility to account for the introduction of innovative new materials. Moreover, beyond this policy context, any front-runner company will be able to use the standardised methods to promote in a trustful way the performances of its products towards its customers.

Clearly, there comes a point where standards need to include product specific considerations. This is particularly the case for testing methods and may also be the case for calculations, which could be defined at a general level and adapted for the product specific aspects in an additional standard (note – product specific standards would require to be developed under a separate mandate as they would not be included in the work programme for M/543).

A particular issue to be taken into account is that further research is required in the field of material efficiency, in terms of lifecycle evaluations, product testing, reference table population and material efficiency indices development. Even though the primary goal of this work was to support Ecodesign Directive regulations in the transition to a circular economy, the framework is flexible enough to be used also with other policies (such as the regulation on the EU Ecolabel (European Union, 2010c) or the mandate for standardisation in the field of WEEE (European Commission, 2013)), or even future legislative proposals with a long-term vision for the elimination of waste.

6. Conclusions

Sustainable use of resources underpins the roadmap to a resource efficient Europe and the EU action plan for the circular economy. Within this context, the material efficiency of products can be boosted by setting policy regulations, that aim to address topics such as durability, upgradability, reparability, reusability, as well as recoverability and recyclability, trying to prioritize those aspects that eliminate, or at least minimize, loss of materials and waste generation. Requirements and standards dealing with material efficiency would compel, but also facilitate, the integration of sustainable resource use in the product design process in a structured and systematic way.

The motivation of this work arose from the need for robust and effective standards that would enable a solid foundation from which to move towards the circularity of products. One of the reasons for the relative lack of ecodesign requirements related to material efficiency in the implementing measures adopted so far is the absence of adequate metrics and standards for assessing material efficiency aspects identified in previous product specific Ecodesign implementing measures. Another more general reason is that radical changes proposed to shift from the paradigm of “sell more, sell faster” have gained little traction, perhaps also because those theories are often correlated to concepts such as population control and zero-growth at a global scale. Engineers and designers are often accustomed to traditional cradle-to-grave approaches and the shift to new business models may be seen burdensome and threatening, as remarked by McDonough and Braungart (2002). Nonetheless, the EU Action Plan discusses the waste hierarchy, which “establishes a priority order from prevention, preparation for reuse, recycling and energy recovery through to disposal, such as landfilling” (European Commission, 2015b). Enhanced recycling is clearly seen as an important step towards a more circular economy. However, as stated in the International Resource Panel report, “governments are becoming increasingly aware of the benefits of moving upwards through the resource management hierarchy, and seeing [recycling] policy not just as a fixed target, but as a transition path” (UNEP, 2016). It can be concluded that policy goals such as “reduce embodied impacts” and “extend lifetime” will become more and more important while the transition to a circular economy will be implemented. Positive and concrete examples of circular business models already exist. Strategies such as design for durability, design for ease of maintenance and repair, design for upgradability, design for disassembly and reassembly are creating new business opportunities, pushing competitors to reconsider their way to design products. Thus, sustainable design may be the inspiration for new policies and the driver for the transition to a circular economy.

The framework proposed in section 3 represents the novel element of the study and aims at providing a method by which to identify key material efficiency considerations relevant for policies to support sustainable engineering, and map out the generic and product specific standardisation requirements (such as adequate metrics, tests, calculation procedures, reference tables and structured templates for results). The involvement of policy makers and ESOs is necessary to develop standards, taking into account the full range of possible material efficiency considerations, in order to ensure that future policies deliver effectively on circular economy goals.

The potential outcomes of this work include an active contribution to the systematic preparation of over-arching (horizontal) and product-specific (vertical) harmonized standards, in order to address the initial problem highlighted in this work: the need of standards to effectively deal with material efficiency of products.

Further work is required to strengthen the technical foundations of the framework, to provide guidance for a wider set of products, systems and services, and to extend the framework to other policies.

Disclaimer

The views expressed in the article are personal and do not necessarily reflect an official position of the European Commission.

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References

Ardente, F., Mathieux, F., 2014a. Environmental assessment of the durability of energy-using products: method and application. J. Clean. Prod. 74, 62–73. http://dx.doi.org/10.1016/j.jclepro.2014.03.049.

Ardente, F., Mathieux, F., 2014b. Identification and assessment of product's measures to improve resource efficiency: the case-study of an Energy using Product. J. Clean. Prod. 83, 126–141. http://dx.doi.org/10.1016/j.jclepro.2014.07.058.

Ardente, F., Mathieux, F., 2012. Integration of resource efficiency and waste management criteria in European product policies - second phase - report 2. http://dx.doi.org/10.2788/72577.

Ardente, F., Mathieux, F., Recchioni, M., 2014. Recycling of electronic displays: analysis of pre-processing and potential ecodesign improvements. Resour. Conserv. Recycl 92, 158–171. http://dx.doi.org/10.1016/j.resconrec.2014.09.005.

Ardente, F., Mathieux, F., Sanfélix Forner, J., 2012. Integration of Resource Efficiency and Waste Management Criteria in European Product Policies - Second Phase - Report 1-Analysis of Durability. http://dx.doi.org/10.2788/72577.

Ardente, F., Mathieux, F., Talens Peirò, L., 2013. Environmental Footprint and Material Efficiency Support for Product Policy - Report on Benefits and Impacts/costs of Options for Different Potential Material Efficiency Requirements for

Electronic Displays. http://dx.doi.org/10.2788/28569.
Ardente, F., Talens Peiró, L., 2015. Environmental Footprint and Material Efficiency Support for Product Policy - Report on Benefits and Impacts/costs of Options for Different Potential Material Efficiency Requirements for Dishwashers. http://dx.doi.org/10.2788/28569.
Bakker, C., den Hollander, M., van Hinte, E., Zljstra, Y., 2014a. Products that Last - Product Design for Circular Business Models.
Bakker, C., Wang, F., Huisman, J., den Hollander, M., 2014b. Products that go round: exploring product life extension through design. J. Clean. Prod. 69, 10–16. http://dx.doi.org/10.1016/j.jclepro.2014.01.028.
BIO by Deloitte, 2015. Study on Socioeconomic Impacts of Increased Reparability.
Blind, K., 2008. Regulatory foresight: methodologies and selected applications. Technol. Forecast. Soc. Change 75, 496–516. http://dx.doi.org/10.1016/j.techfore.2008.02.004.
Blind, K., Gauch, S., Hawkins, R., 2010. How stakeholders view the impacts of international ICT standards. Telecomm. Policy 34, 162–174. http://dx.doi.org/10.1016/j.telpol.2009.11.016.
Bobba, S., Ardente, F., Mathieux, F., 2016. Environmental and economic assessment of durability of energy-using products: method and application to a case-study vacuum cleaner. J. Clean. Prod. 137, 762–776. http://dx.doi.org/10.1016/j.jclepro.2016.07.093.
Braungardt, S., Molenbroek, E., Smith, M., Williams, R., Attali, S., McAlister, C., 2014. Impact of Ecodesign and Energy/Tyre Labelling on R&D and Technological Innovation [WWW Document] (Accessed 2.15.16). http://www.ecofys.com/files/files/fraunhofer-ecofys-2014-impact-of-ecodesign-energy-labelling-on-innovation.pdf.
BSI, 2002. BS ISO 22628:2002 Road Vehicles - Recyclability and Recoverability - Calculation Method.
Bundgaard, A.M., Mosgaard, M.A., Remmen, A., 2017. From energy efficiency towards resource efficiency within the Ecodesign Directive. J. Clean. Prod. 144, 358–374. http://dx.doi.org/10.1016/j.jclepro.2016.12.144.
Bundgaard, A.M., Remmen, A., Zacho, K.O., 2015. Ecodesign Directive Version 2.0: from Energy Efficiency to Resource Efficiency. København K: Miljøstyrelsen.
Castellani, V., Sala, S., Mirabella, N., 2015. Beyond the throwaway society: a life cycle-based assessment of the environmental benefit of reuse. Integr. Environ. Assess. Manag. 11, 373–382. http://dx.doi.org/10.1002/ieam.1614.
Cellura, M., Longo, S., Mistretta, M., 2012. Life Cycle Assessment (LCA) of protected crops: an Italian case study. J. Clean. Prod. 28, 56–62. http://dx.doi.org/10.1016/j.jclepro.2011.10.021.
Dalhammar, C., Machacek, E., Bundgaard, A., Zacho, K.O., Remmen, A., 2014. Addressing Resource Efficiency Through the Ecodesign Directive: A Review of Opportunities and Barriers. Edition: TemaNord 2014:511. Nordic Council of Ministers 2014, pp. 22–238. ISBN: 9789289327206.
Daly, H.E., 1991. Steady-state Economics: with New Essays. Island Press.
De Carlo, F., Borgia, O., Tucci, M., 2013. Accelerated degradation tests for reliability estimation of a new product: a case study for washing machines. Proc. Inst. Mech. Eng. Part O J. Risk Reliab 228, 127–138. http://dx.doi.org/10.1177/1748006X13500650.
Dworak, C., Zonneveld, N., 2015. WEEE-check – a tool for designers. In: Global Cleaner Production & Sustainable Consumption Conference Accelerating the Transition to Equitable Post Fossil-Carbon Societies 1–4 November 2015. Sitges, Barcelona, Spain.
Ellen MacArthur Foundation, 2015. Growth within: a Circular Economy Vision for a Competitive Europe.
Escobar, L.A., Meeker, W.Q., 2007. A review of accelerated test models. Stat. Sci. 21, 552–577. http://dx.doi.org/10.1214/088342306000000321.
European Commission, 2017a. Resource Efficiency - Environment - European Commission [WWW Document] (Accessed 2.9.17). http://ec.europa.eu/environment/resource_efficiency/index_en.htm.
European Commission, 2017b. COM(2017) 33 Final Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the Implementation of the Circular Economy Action Plan.
European Commission, 2016. COM(2016) 773-Communication from the Commission - Ecodesign Working Plan, pp. 2016–2019.
European Commission, 2015a. C(2015) 9096 Annexes 1 to 2. http://dx.doi.org/10.1007/s13398-014-0173-7.2.
European Commission, 2015b. COM(2015) 614 Final. Communication from the Commission to the European Parliament, the Councli, the European Economic and Social Commitee and the Committee of the Regions. Closing the Loop - an EU Action Plan for the Circular Economy.
European Commission, 2015c. M/543 C(2015) 9096 Commission Implementing Decision of 17.12.2015 on a Standardisation Request to the European Standardisation Organisations as Regards Ecodesign Requirements on Material Efficiency Aspects for Energy-related Products in Support of the Imp. http://dx.doi.org/10.1017/CBO9781107415324.004.
European Commission, 2015d. Energy Efficient Products - European Commission [WWW Document] (Accessed 9.21.15). http://ec.europa.eu/energy/en/topics/energy-efficiency/energy-efficient-products.
European Commission, 2013. M/518 Mandate to the European Standardisation Organisations for Standardisation in the Field of Waste Electrical and Electronic Equipment (Directive 2012/19/EU (WEEE)).
European Commission, 2011. COM(2011) 571 European Commission - Communication: Roadmap to a Resource Efficient Europe doi:COM(2011) 571 final.
European Commission, 2009. Commission Decision of 12 March 2009 Establishing the Revised Ecological Criteria for the Award of the Community Eco-label to Televisions (Notified under Document Number C(2009), p. 1830.
European Union, 2010a. Commission Delegated Regulation (EU) No 1062/2010 of 28 September 2010 Supplementing Directive 2010/30/EU of the European Parliament and of the Council with Regard to Energy Labelling of Televisions.
European Union, 2010b. Commission Regulation (EU) No 1015/2010 of 10 November 2010 Implementing Directive 2009/125/EC of the European Parliament and of the Council with Regard to Ecodesign Requirements for Household Washing Machines.
European Union, 2010c. Regulation (EC) No 66/2010 of the European Parliament and of the Council of 25 November 2009 on the EU Ecolabel.
European Union, 2009a. Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 Establishing a Framework for the Setting of Ecodesign Requirements for Energy-related Products.
European Union, 2009b. Commission Regulation (EC) No 642/2009 of 22 July 2009 Implementing Directive 2005/32/EC of the European Parliament and of the Council with Regard to Ecodesign Requirements for Televisions.
European Union, 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives. LexUriServ. Do doi:2008/98/EC.; 32008L0098.
Fitzpatrick, C., Hickey, S., Schischke, K., Maher, P., 2014. Sustainable life cycle engineering of an integrated desktop PC; a small to medium enterprise perspective. J. Clean. Prod. 74, 155–160. http://dx.doi.org/10.1016/j.jclepro.2014.03.042.
Geng, Y., Fujita, T., Park, H., Chiu, A., Huisingh, D., 2014. Call for papers: towards post fossil carbon societies: regenerative and preventative eco-industrial development. J. Clean. Prod. 68, 4–6. http://dx.doi.org/10.1016/j.jclepro.2013.12.089.
Ghisellini, P., Cialani, C., Ulgiati, S., 2015. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. http://dx.doi.org/10.1016/j.jclepro.2015.09.007.
Goluchowicz, K., Blind, K., 2011. Identification of future fields of standardisation: an explorative application of the Delphi methodology. Technol. Forecast. Soc. Change 78, 1526–1541. http://dx.doi.org/10.1016/j.techfore.2011.04.014.
Gottberg, A., Morris, J., Pollard, S., Mark-Herbert, C., Cook, M., 2006. Producer responsibility, waste minimisation and the WEEE Directive: case studies in ecodesign from the European lighting sector. Sci. Total Environ. 359, 38–56. http://dx.doi.org/10.1016/j.scitotenv.2005.07.001.
Grob, G.R., 2003. Importance of ISO and IEC international energy standards and a new total approach to energy statistics and forecasting. Appl. Energy 76, 39–54. http://dx.doi.org/10.1016/S0306-2619(03)00045-X.
Hatcher, G.D., Ijomah, W.L., Windmill, J.F.C., 2013. Integrating design for remanufacture into the design process: the operational factors. J. Clean. Prod. 39, 200–208. http://dx.doi.org/10.1016/j.jclepro.2012.08.015.
Huysman, S., Sala, S., Mancini, L., Ardente, F., Alvarenga, R.A.F., De Meester, S., Mathieux, F., Dewulf, J., 2015. Toward a systematized framework for resource efficiency indicators. Resour. Conserv. Recycl 95, 68–76. http://dx.doi.org/10.1016/j.resconrec.2014.10.014.
IEC 60335-1, 2010. IEC 60335-1:2010+AMD1:2013 CSV Consolidated Version Household and Similar Electrical Appliances - Safety - Part 1: General Requirements.
IEC 60335-2-7, 2012. IEC 60335-2-7:2008+AMD1:2011 CSV Consolidated Version Household and Similar Electrical Appliances - Safety - Part 2-7: Particular Requirements for Washing Machines.
IEC CENELEC, 2016. IEC-CENELEC Frankfurt Agreement.
IEC/TR 62635, 2015. IEC/TR 62635:2015 Guidelines for End-of-life Information provided by Manufacturers and Recyclers and for Recyclability Rate Calculation of Electrical and Electronic Equipment.
IEEE 1874, 2013. IEEE Standard for Documentation Schema for Repair and Assembly of Electronic Devices. http://dx.doi.org/10.1109/IEEESTD.2014.6712032.
ISO, 2015. Standards Development - ISO [WWW Document] (Accessed 8.4.15). http://www.iso.org/iso/home/standards_development.htm.
ISO CEN, 2001. Agreement on Technical Co-operation between ISO and CEN (Vienna Agreement).
Jagu, C., 2015. Improving European Union Ecodesign Standardization, Eco-friendly Innovation in Electricity Transmission and Distribution Networks. Elsevier Ltd. http://dx.doi.org/10.1016/B978-1-78242-010-1.00003-3.
JRC, 2016. Product Groups - Current Criteria Development and Revision Projects [WWW Document] (Accessed 12.12.16). http://susproc.jrc.ec.europa.eu/product_bureau/projects.html.
Kagawa, S., Tasaki, T., Moriguchi, Y., 2006. The environmental and economic consequences of product lifetime extension: empirical analysis for automobile use. Ecol. Econ. 58, 108–118. http://dx.doi.org/10.1016/j.ecolecon.2005.06.003.
Kopnina, H., Blewitt, J., 2014. Sustainable Business: Key Issues. Routledge.
Lawn, P., 2013. Globalisation, Economic Transition and the Environment: Forging a Path to Sustainable Development. Edward Elgar Publishing.
Mahlia, T.M.I., Saidur, R., 2010. A review on test procedure, energy efficiency standards and energy labels for room air conditioners and refrigerator-freezers. Renew. Sustain. Energy Rev. 14, 1888–1900. http://dx.doi.org/10.1016/j.rser.2010.03.037.
Mathieux, F., Froelich, D., Moszkowicz, P., 2008. ReSICLED: a new recovery-conscious design method for complex products based on a multicriteria assessment of the recoverability. J. Clean. Prod. 16, 277–298. http://dx.doi.org/10.1016/j.jclepro.2006.07.026.
Mathieux, F., Rebitzer, G., Ferrendier, S., Simon, M., MFroelich, D., 2001. Ecodesign in the European Electr(on)ics Industry – an analysis of the current practices based

on cases studies – an analysis of the current practices based on cases studies. J. Sustain. Prod. Des. 1, 233–245. http://dx.doi.org/10.1023/A:1024670630297.
Mathieux, F., Recchioni, M., Ardente, F., 2014. Measuring the time for extracting components in end-of-life products: needs for a standardized method and aspects to be considered. Procedia CIRP 15, 245–250. http://dx.doi.org/10.1016/j.procir.2014.06.033.
McAlister, C., Mathieux, F., Ardente, F., Tecchio, P., 2015. Horizontal standards: the missing link to ensure minimum performance of products from a material efficiency perspective?. In: Global Cleaner Production & Sustainable Consumption Conference Accelerating the Transition to Equitable Post Fossil-Carbon Societies 1-4 November 2015. Sitges, Barcelona, Spain.
McCollough, J., 2009. Factors impacting the demand for repair services of household products: the disappearing repair trades and the throwaway society. Int. J. Consum. Stud. 33, 619–626. http://dx.doi.org/10.1111/j.1470-6431.2009.00793.x.
McDonough, W., Braungart, M., 2002. Cradle to Cradle: Remaking the Way We Make Things, First. ed. North Point Press, New York.
Meier, A.K., Hill, J.E., 1997. Energy test procedures for appliances. Energy Build. 26, 23–33. http://dx.doi.org/10.1016/S0378-7788(96)01022-5.
Nelen, D., Manshoven, S., Peeters, J.R., Vanegas, P., D'Haese, N., Vrancken, K., 2014. A multidimensional indicator set to assess the benefits of WEEE material recycling. J. Clean. Prod. 83, 305–316. http://dx.doi.org/10.1016/j.jclepro.2014.06.094.
NSF 426, 2013. NSF 426 – Environmental Leadership Standards for Servers Draft Document.
ONR 192102, 2014. ONR 192102 Gütezeichen für langlebige, reparaturfreundlich konstruierte elektrische und elektronische Geräte 1–22.
Peeters, J.R., Vanegas, P., Duflou, J.R., Mizuno, T., Fukushige, S., Umeda, Y., 2013. Effects of boundary conditions on the end-of-life treatment of LCD TVs. CIRP Ann. - Manuf. Technol. 62, 35–38. http://dx.doi.org/10.1016/j.cirp.2013.03.092.
Peeters, J.R., Vanegas, P., Tange, L., Van Houwelingen, J., Duflou, J.R., 2014. Closed loop recycling of plastics containing Flame Retardants. Resour. Conserv. Recycl 84, 35–43. http://dx.doi.org/10.1016/j.resconrec.2013.12.006.
Peeters, J.R., Vanegas, P., Van den Bossche, W., Devoldere, T., Dewulf, W., Duflou, J.R., 2015. Elastomer-based fastener development to facilitate rapid disassembly for consumer products. J. Clean. Prod. 94, 177–186. http://dx.doi.org/10.1016/j.jclepro.2015.01.081.
Ping, W., 2011. A Brief History of Standards and Standardization Organizations: a Chinese Perspective. East-west Center Working Papers. Economics series; no.117.
Prakash, S., Dehoust, G., Gsell, M., Schleicher, T., Stamminger, R., 2016. Einfluss der Nutzungsdauer von Produkten auf ihre Umweltwirkung: Schaffung einer Informationsgrundlage und Entwicklung von Strategien gegen „Obsoleszenz“, Öko-Institut e.V. http://dx.doi.org/10.1017/CBO9781107415324.004.
Prakash, S., Dehoust, G., Gsell, M., Schleicher, T., Stamminger, R., 2015. Einfluss der Nutzungsdauer von Produkten auf ihre Umweltwirkung: Schaffung einer Informationsgrundlage und Entwicklung von Strategien gegen „Obsoleszenz“ | Umweltbundesamt.
Prakash, S., Schischke, K., Stobbe, L., 2012. Timely Replacemet of a Notebook under Consideration of Environmental Aspects. Federal Environment Agency. http://dx.doi.org/10.1073/pnas.0703993104.
Prendeville, S., O'Connor, F., Palmer, L., 2014. Material selection for eco-innovation: SPICE model. J. Clean. Prod. 85, 31–40. http://dx.doi.org/10.1016/j.jclepro.2014.05.023.
Rees, W.E., 2016. Denying Herman Daly: why conventional economists will not embrace the Daly vision. In: Beyond Uneconomic Growth: Economics, Equity and the Ecological Predicament. Edward Elgar Publishing.
Rees, W.E., 2003. Economic development and environmental protection: an ecological economics perspective. Environ. Monit. Assess. 86, 29–45. http://dx.doi.org/10.1023/A:1024098417023.
Ricardo-AEA, 2014a. The Durability of Products: Task 1 Report Standard Assessment for the Circular Economy under the Eco-innovation Action Plan Task 1 – Selection of Products.
Ricardo-AEA, 2014b. The Durability of Products: Task 2 Briefing Standard Assessment for the Circular Economy under the Eco-innovation Action Plan.
RREUSE, 2013. Investigation into the Repairability of Domestic Washing Machines, Dishwashers and Fridges.
Russell, A.L., 2005. Standardization in history: a review essay with an eye to the future. In: The Bolin Group, T.S.E.F.G. (Eds.), The Standards Edge: Future Generations. Sheridan Press, Ann Arbor, MI, pp. 247–260.
Ryan, A., O' Donoghue, L., Lewis, H., 2011. Characterising components of liquid crystal displays to facilitate disassembly. J. Clean. Prod. 19, 1066–1071. http://dx.doi.org/10.1016/j.jclepro.2011.01.009.
Sakai, S., Yoshida, H., Hirai, Y., Asari, M., Takigami, H., Takahashi, S., Tomoda, K., Peeler, M.V., Wejchert, J., Schmid-Unterseh, T., Douvan, A.R., Hathaway, R., Hylander, L.D., Fischer, C., Oh, G.J., Jinhui, L., Chi, N.K., 2011. International comparative study of 3R and waste management policy developments. J. Mater. Cycles Waste Manag. 13, 86–102. http://dx.doi.org/10.1007/s10163-011-0009-x.
Sivitos, S., Spiliotopoulos, C., Stamminger, R., Toulouse, E., 2015. Don't just press the button! – why appliance settings increasingly matter for efficiency delivery and rulemaking. In: ECEEE 2015 Summer Study on Energy Efficiency.
Stahel, W., 2014. European Commission Interview: Reuse Is the Key to the Circular Economy [WWW Document] (Accessed 10.8.15). http://ec.europa.eu/environment/ecoap/about-eco-innovation/experts-interviews/reuse-is-the-key-to-the-circular-economy_en.htm.
Stahel, W.R., 2013. Policy for material efficiency—sustainable taxation as a departure from the throwaway society. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 371 http://dx.doi.org/10.1098/rsta.2011.0567.
Stamminger, R., Tecchio, P., Ardente, F., Mathieux, F., Niestrath, P., 2017. Enhancing circular economy through extending the lifetime of products: towards a durability test for washing machines. Submitt. to Resour. Conserv. Recycl.
Talens Peiró, L., Ardente, F., 2015. Environmental Footprint and Material Efficiency Support for Product Policy - Analysis of Material Efficiency Requirements of Enterprise Servers. http://dx.doi.org/10.2788/409022.
Tao, J., Yu, S., 2011. Implementation of energy efficiency standards of household refrigerator/freezer in China: potential environmental and economic impacts. Appl. Energy 88, 1890–1905. http://dx.doi.org/10.1016/j.apenergy.2010.11.015.
Tecchio, P., Ardente, F., Mathieux, F., 2016. Analysis of Durability, Reusability and Reparability - Application to Washing Machines and Dishwashers. http://dx.doi.org/10.2788/630157.
Tucci, M., Carlo, F. De, Borgia, O., Fanciullacci, N., 2014. Accelerated life tests as an integrated methodology for product design, qualification and production control: a case study in household appliances. Prod. Manuf. Res. 2, 112–127.
Tukker, A., van Bueren, E., van Raak, R., Spork, C., 2016. Towards a Circular Products Initiative in the EU - Report of the Leiden-Delft-Erasmus Centre for Sustainability.
Udo de Haes, H., Finnveden, G., Goedkoop, M., Hauschild, M., Hertwich, E., Hofstetter, P., Jolliet, O., Klopffer, W., Krewitt, W., Lindeijer, E., 2002. Life cycle impact assessment: striving towards best practice. In: Proceedings.
UNEP, 2016. Resource Efficiency: Potential and Economic Implications. A Report of the International Resource Panel.
van Schaik, A., 2014. Handbook of Recycling, Handbook of Recycling. Elsevier. http://dx.doi.org/10.1016/B978-0-12-396459-5.00022-2.
Vanegas, P., Peeters, J., Cattrysse, D., Duflou, J., Tecchio, P., Mathieux, F., Ardente, F., 2016. Study for a Method to Assess the Ease of Disassembly of Electrical and Electronic Equipment. Method Development and Application to a Flat Panel Display Case Study.
Vanegas, P., Peeters, J.R., Cattrysse, D., Tecchio, P., Ardente, F., Mathieux, F., Dewulf, W., Duflou, J.R., 2017. Method to assess ease of disassembly for eco-design and treatment cost evaluation. Submitt. to Resour. Conserv. Recycl.
VHK, 2014. "Omnibus" Review Study on Cold Appliances, Washing Machines, Dishwashers, Washer-driers, Lighting, Set-top Boxes and Pumps.
Wenzlhuemer, R., 2010. The History of Standardisation in Europe, European History Online (EGO).
Winkler, H., 2011. Closed-loop production systems—a sustainable supply chain approach. CIRP J. Manuf. Sci. Technol. 4, 243–246. http://dx.doi.org/10.1016/j.cirpj.2011.05.001.