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The Urgent Need for Better Methods

Van Dolderen, Dorien C.; Aghaeian, Soroush; Bakker, Conny A.; Balkenende, Ruud

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Design for Recycling of Electronics: The urgent need for better methods

1st Dorien C. van Dolderen
Department of Sustainable Design Engineering
Delft University of Technology
Delft, The Netherlands

2nd Soroush Aghaeian
Department of Sustainable Design Engineering
Delft University of Technology
Delft, The Netherlands

3rd Conny A. Bakker
Department of Sustainable Design Engineering
Delft University of Technology
Delft, The Netherlands

4th Ruud Balkenende
Department of Sustainable Design Engineering
Delft University of Technology
Delft, The Netherlands

Abstract— **Within a circular economy, prioritizing product integrity and durability is crucial for circular product design. However, in addition to efforts in strategies like reuse and repair, products inevitably require recycling. This paper critically assesses the current state of Design for Recycling guidelines and methods in the field of electronics, focusing on their *Efficacy* and *Effectiveness*.**

We conducted a literature review using Scopus, Web of Science, and Google Scholar. Following the methodology outlined by Hagen-Zanker and Mallett [1], we identified relevant literature and used snowballing to find additional sources. The search led to 16 articles (1993-2023) proposing methods, tools, guidelines, or frameworks targeting product designers and aimed at the design for improved recyclability of electronics. The final Design for Recycling methods and guidelines were assessed using an adapted version of the method evaluation framework [2] in the context of method content theory [3].

The inclusion of only 18 sources in the review, consisting of nine peer-reviewed and nine non peer-reviewed articles, indicated a limited development in the field since 1993. Many of the methods and guidelines presented were insufficient based on common recycling and design practices, they also lacked validation through recycling tests and were rarely tested with design practitioners.

The findings show an urgent need for a substantiated and validated Design for Recycling method, which helps lower the environmental impact of electronics, is tailored to design practitioners, and aligns with common recycling practices.

Keywords— Design, Recycling, Electronics, Guidelines, Methods, Literature review

I. Introduction

In the context of a Circular Economy, when alternative recovery strategies are no longer feasible, products need to be recycled to reclaim their materials. Especially in the case of electronic products, recycling is crucial due to the rapid innovation within this product category and their composition containing precious and critical raw materials with a high environmental impact.

Currently, the worlds of product design and recycling operate almost independently from each other [4], but products need to be designed with recycling in mind. Recycling is, however, a complex practice, making it difficult to understand the impact of design choices on the quality of the recycled materials. Efforts have been made to translate recycling processes into practical methods and guidelines for design practitioners, but an overview of their effectivity and applicability in practice is lacking.

This review aimed to evaluate existing methods on their representation in academic and grey literature, as well as their E*fficacy* and E*ffectiveness* [3]. Here *Efficacy* refers to the quality of a method in terms of the achieved result after using the method, i.e. achieved improvements in product recyclability. In contrast, *Effectiveness* refers to the quality of the method in terms of usability in design practice.

II. Method

Design for Recycling (DfR) methods were identified through a literature search following the approach outlined by Hagen-Zanker and Mallett [1] and evaluated according to an adaptation of the method assessment framework [2] in the context of method content theory [3].

A. Literature search

1) Search strategy

We performed a literature search using the databases Scopus, Web of Science and Google Scholar on 10-07-2023 with the aim of finding sources which present a method, tool, guide or framework supporting design for improved recyclability of electronics. Scopus and Web of Science cover various subject areas comprehensively, while Google Scholar supplements traditional database searches by capturing grey literature. Fig. 1 displays the full search strings.

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Database	Search type	Search string	Subject area	Time range
Scopus	Title, Abstract, Keywords	(Design* OR DfR) AND (Recycl* OR OR {material integrity} OR {resource recovery}) AND (Method* OR guidelines OR tool OR model OR framework) AND ({electronic product} OR {electronic products} OR electronics OR device OR e-waste OR WEEE OR {electronic waste}) AND NOT ({reverse logistics} OR EV OR {electric vehicle})	Engineering Environmental science Materials science Business, management and accounting Decision sciences Multidisciplinary	2008-2023
Web of Science	Topic search	(Design* OR DfR) AND (Recycl* OR "material recovery" OR "material integrity" OR "resource recovery") AND (Method* OR guidelines OR tool OR model OR framework) AND ("electronic product" OR "electronic products" OR electronics OR device OR e-waste OR WEEE OR "electronic waste") NOT ("reverse logistics" OR EV OR "electric vehicle")	Engineering electrical electronic Environmental sciences Materials science multidisciplinary Engineering environmental Engineering electrical electronic Green sustainable science technology Engineering manufacturing Engineering multidisciplinary Engineering mechanical Engineering industrial Environmental studies Multidisciplinary sciences Management Business	2008-2023
Google Scholar	n/a	Design AND recycling AND electronics[a]	n/a	2008-2023

a. Google scholar does not allow nesting in parentheses and only very basic Boolean operators

Fig. 1. Literature search strategy

2) Inclusion and exclusion criteria

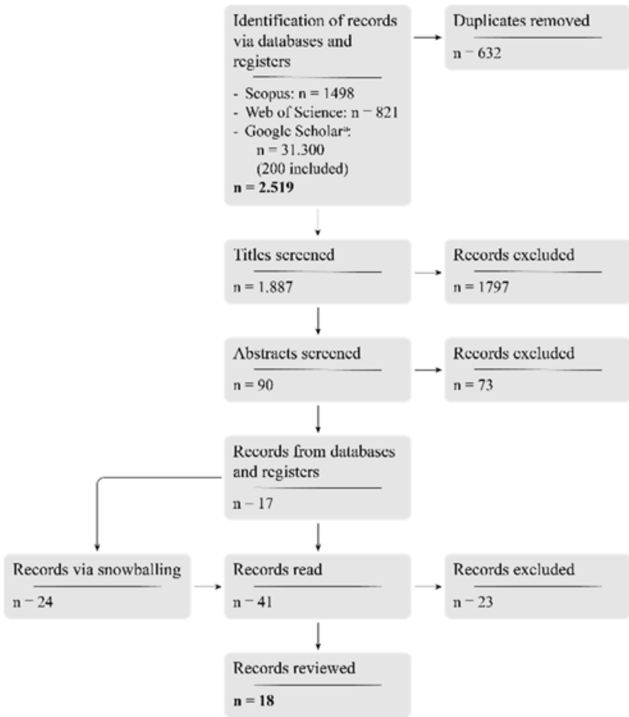
To be included in the review, sources had to present a DfR method, tool, guide, or framework specifically targeting designers. The approach should focus on enhancing recyclability through product design, as opposed to modifying recycling techniques or reverse logistics. Finally, the search was focused on improving the design of products included in the EU WEEE directive [5], which means methods helping to improve the recyclability of for example vehicles, were not in the scope of this review.

Sources solely focused on design for manual disassembly or dismantling were excluded from this review, as dismantling only represents an aspect of limited importance in recycling practice. Studies covering broader topics such as value chains were deemed overly expansive and were therefore also excluded. Case studies beyond the scope of Europe, along with sources discussing legislation, policy, management, or business models, were considered out of focus for this review. Lastly, sources only presenting a method for assessing a product's recyclability were excluded, as they lacked instructions for product design alterations.

3) Literature selection

From the initial search, first the duplicate records across the different databases were removed. Then the titles, followed by the abstracts and finally the full texts were assessed for eligibility based on the criteria mentioned earlier, with each consecutive step helping to narrow down the literature selection. Through snowballing, we found additional relevant sources. Despite the original search only considering records from 2008 to 2023, during snowballing older sources were evaluated as well. This approach led to a final selection of literature to review.

Fig. 2 displays the full literature search and selection process, from 2519 records identified in the initial search to 18 records (1993 – 2023) describing 16 methods selected for review.



a. In Google Scholar only the first 1000 results can be viewed, and the order of these is not disclosed [6]. It is recommended to focus on the first 200 results.

Fig. 2. Flow diagram of search and selection process

B. Synthesis

The reviewed records were evaluated based on the systematic review and assessment framework presented by Cash et al. [2]. This framework was designed to help evaluate any design method, for this review it was altered to more specifically apply to DfR methods. For this review we decided to focus only on the two main variables in the framework; *Efficacy* and *Effectiveness*.

1) Efficacy

Efficacy describes the method's performance from the perspective of the method as theory [3]. In the case of DfR methods, the evaluation of a method's *Efficacy* refers to the likelihood that application of the method in practice will result in improved recyclability of products. The relevant variables in the assessment framework are *Research basis* and *Efficacy validation.*

The variable *Research basis* covers the evidence behind a method e.g. speculation, literature, recycler visits or recycling tests. A proper *Research basis* is characterised by an identifiable connection between the presented method and recycling practice through collaborations with recyclers or recycling experiments.

The variable *Efficacy validation* covers the evidence of the method improving a product's recyclability e.g. calculations, simulations, recycling tests or case studies. *Efficacy* is properly validated through use of the method in product redesign and a comparison of recyclability with the previous version through recycling tests.

2) Effectiveness

Effectiveness describes the method's performance from the perspective of the method as a designed artefact [3]. In the case of DfR methods, this refers to the evaluation of their usability in design practice. The relevant variables in the assessment framework are *Method development* and *Effectiveness validation*.

The variable *Method development* covers the design process behind a method including strategies like research through design, experiments, case studies and expert practitioner interviews. 'good' method development is characterized by a combination of different strategies or multiple case studies.

The variable *Effectiveness validation* covers the proof of the method's usability in practice. The criteria used to evaluate *Method development* also apply to the evaluation of *Effectiveness validation*.

III. Results

Fig. 3 shows the evaluation of the 16 reviewed methods described in 18 sources. Nine sources are peer-reviewed and 11 are distributed free of access charges (open access).

A. Efficacy

Six out of the 16 methods have a properly reported research basis including descriptions of e.g. recycling tests or collaborations with recyclers. Most of the other methods are solely based on a review of existing literature, and the research basis of the three oldest methods is not reported.

One method [15, 16] has been properly validated in terms of its *Efficacy* through recycling tests of redesigned electronics. Others are validated through e.g. case studies showing how the method can be implemented in product design, or are not validated at all.

B. Effectiveness

For 3 methods the development process is properly reported including a description of a combination of different strategies like case studies and expert collaborations. For most methods the development process is not reported.

Two methods [16, 22] are properly validated in terms of *Effectiveness* through a collaboration with multiple companies or multiple case studies. For most methods the *Effectiveness* validation is not reported.

			Efficacy		Effectiveness	
			Research basis	**Efficacy validation**	**Method Development**	**Effectiveness validation**
Method	**Source**	**Type of source**	Green: Based on i.e. in depth collaboration with recyclers or recycling tests Yellow: Only based on literature	Green: Validated with a recycling test on a redesigned product Yellow: Validated through other strategies	Green: A combination of multiple strategies or multiple case studies Yellow: Only expert practitioner interview or a single case study	Green: A combination of multiple strategies or multiple case studies Yellow: Only expert practitioner interview or a single case study
[no name]	Beitz, 1993 [7]	Peer-reviewed Journal article Closed access	Not reported	3 examples improving products' disassemblability	Not reported	Not reported
[no name]	Dowie & Simon, 1994 [8]	Non peer-reviewed Report Open access	Not reported	Not reported	Not reported	Not reported
[no name]	Kriwet et al., 1995 [9]	Peer-reviewed Journal article Closed access	Not reported	Case study on a washing machine sub-assembly	Not reported	Not reported
IREDA	Xing et al., 2003 [10]	Peer-reviewed Journal article Open access	adapted to generic engineering design concept, guidelines from "current DfR research"	Case study on an air-conditioning unit, recyclability calculation	Not reported	Not reported

Method	Source	Type of source	Efficacy: Research basis	Efficacy: Efficacy validation	Effectiveness: Method Development	Effectiveness: Effectiveness validation
THEMA matrix	Castro et al., 2004 [11]	Peer-reviewed Journal article Closed access	Based on thermodynamic principles	Gives the example of a recyclability evaluation of a car based on material compatibility	Not reported	Not reported
Design For eXcellence (DFX) method for recyclability	Peters et al., 2012 [12]	Non peer-reviewed Conference paper Closed access[a]	Literature review, recycler visits, expert interviews	Recyclability calculation and expert opinion	Expert practitioners from Philips "were actively involved in the development of both the method and the tool"	Not reported
Guidelines and Design Strategies for Improved Product Recyclability	Hultgren, 2012 [13]	Non peer-reviewed Master's thesis Open access	Based on a previous tool [12] and a survey sent to recyclers to prioritize existing guidelines	Not reported	Expert practitioner interviews, product case studies on different product categories within Philips.	Expert practitioner interviews
WEEE wheel	Van Schaik & Reuter, 2012 [14]	Non peer-reviewed Book chapter Closed access	Thermodynamic principles, shredding tests and an analysis of a wide range of WEEE products	Recyclability calculations linked to CAD and LCA software	Not reported	Not reported
[no name]	Balkenende et al., 2014 [15]	Non peer-reviewed Conference paper Open access	Large batch recycling test on lamps, recycler visits	Redesigned lamps and displays, validated in recycling runs	Not reported	Not reported
	Fakhredin, 2018 [16]	Non peer-reviewed PhD dissertation Open access	Literature review, recycling tests on displays and lamps	Manual dismantling and shredding of redesigned displays, shredding and automatic sorting of redesigned lamps	Not reported	Multiple case studies with design practitioners
Product centric design for recycling	Van Schaik & Reuter, 2014 [17]	Non peer-reviewed Conference paper Open access	Metals processing, extractive metallurgy etc.	Case study on lamps, recyclability calculation + simulation	Not reported	Not reported
Design for multiple Life-Cycles	Go et al., 2015 [18]	Peer-reviewed Journal article Closed access	Literature review	Not reported	Not reported	Not reported
[no name]	Bovea & Perez-Belis, 2018 [19]	Peer-reviewed Journal article Closed access	Literature review	Applied to products including vacuum cleaners, hand blenders, kettles, irons etc., no recycling test	Not reported	Not reported
[no name]	Dimitrova et al., 2018 [20]	Non peer-reviewed, Report Open access	Literature review, disassembly trials[b], recycler interviews	Not reported	Not reported	Not reported
Re-Cycling	Leal et al., 2020 [21]	Peer-reviewed Journal article Open access	Literature review	Recyclability calculation of the fairphone 2	Not reported	Case study on the fairphone 2
[no name]	Shahbazi & Jönbrink, 2020 [22]	Peer-reviewed Journal article Open access	Literature review	Not reported	Co-developed with four companies through an action research approach.	Validated with four companies through an action research approach
Design for circularity guidelines	Berwald et al., 2021 [4]	Peer-reviewed Journal article Open access	Literature review, collaboration with stakeholders in entire WEEE value chain (including recyclers)	Not reported	Multi-stakeholder collaboration with entire WEEE value chain (Multiple case studies are implied)	Not reported
	Feenstra et al., 2021 [23]	Non peer-reviewed Report Open access	Literature review and "new learnings from the PolyCE project"	Not reported	Multi-stakeholder collaboration with entire WEEE value chain (development process is not reported)	Multiple products are redesigned using the method, the focus is however mostly on design from recycling, not design for recycling

a. The guidelines are also not described in this paper, they are specifically made for Philips and not accessible to the public.

b. A disassembly trial alone doesn't fully test a product's recyclability, as disassemblability is just one of the factors influencing recycling potential.

Fig. 3. Method evaluation according to an adaptation of the assessment framework presented by Cash et al. [2]

IV. Discussion

A. Interpretation of the results

Only 18 sources covering the period from 1993 to 2023 were found in the review, discussing a total of 16 Design for Recycling methods for electronics. This suggests limited development in the field, considering the substantial technological innovations in the electronics industry during this time. The rise in complexity and miniaturisation of components pose additional challenges to recycling processes.

Additionally, some of the reviewed methods incorporate recovery strategies beyond recycling or extend their scope to products other than electronics. We identified only 7 methods which purely focus on the Design for Recycling of electronics. Given the intricate nature of electronic devices, some methods appear overly broad. While these methods may convey the overall message, they might not offer the most practical guidance to design practitioners due to their lack of specificity.

1) Efficacy

The majority of sources report the research basis of the presented methods, often leaning heavily on a review of existing literature. It's noteworthy, however, that many guidelines originate from older sources without an explicitly reported research basis. Consequently, the reliability of the research basis for newer methods solely reliant on literature can be somewhat uncertain. Fortunately, six methods stand out for presenting a research basis grounded in e.g. extractive metallurgy, recycling tests or extensive collaborations with recyclers. This robust foundation significantly enhances the credibility and reliability of the content within these methods.

Unfortunately, there is a significant gap in the validation of these methods concerning their *Efficacy*. Only one method underwent practical application in a product redesign, with subsequent evaluation in a recycling test to assess its recyclability. While several of the reviewed sources present case studies, they often serve more as illustrative examples of how the method could be applied, lacking concrete evidence of improved recyclability in practice. Additionally, some methods rely on calculating a product's recyclability, but without comparison to practical experiments it is challenging to determine the validity of these calculations.

2) Effectiveness

The analysis revealed that only three methods had a well-documented development process in collaboration with design practitioners, and merely two methods underwent practical validation. This indicates a general lack of comprehensive reporting on the *Effectiveness* of design methods. As the successful integration of these methods into design practices is essential for enhancing the recyclability of designed electronics, the reporting of methods' *Effectiveness* requires more attention in the future.

3) Representation of methods in the literature

Several methods are solely found in scientific literature, with seven of them carrying access fees. This poses a barrier to accessibility for the design audience these methods are intended for. A strong presence in scientific literature is essential as it provides a platform for peer review, establishes a scientific foundation of methods, and enables further research into DfR. However, the representation of methods in more accessible "grey" guides is crucial for reaching designers effectively. The design for circularity guidelines presented by Berwald et al. [4] and Feenstra et al. [23] serve as a good example, appearing both in a peer-reviewed journal and in a practical guide tailored to design practitioners.

B. Limitations

1) Literature search

The literature search was conducted following a scientific review method [1]. Despite incorporating grey capture methods like Google Scholar and snowballing strategies, there is a possibility that "grey" guides explicitly aimed at designers as well as in-house methods of companies might have been overlooked. This shows the challenge of detecting such resources but also emphasizes the importance of effectively disseminating methods to ensure their visibility within the relevant community.

2) Method evaluation

This review primarily assesses the quality of a method's reporting, but we need to acknowledge that a method's *Efficacy* and *Effectiveness* may not be adequately addressed in the reported information. Good reporting does not automatically equate to high-quality methods, and conversely, a method's quality might not be accurately portrayed solely through its documentation. Furthermore, the method evaluation framework [2] cannot take into account secondary factors impacting method usage such as the embodiment or presentation of the method.

C. Further research

Given the potential uncertainty in the research basis of methods relying solely on literature, particularly with older sources lacking comprehensive reporting, delving deeper into the connections between individual DfR guidelines and current recycling practice is essential. Such an investigation would not only clarify the scientific basis of guidelines and methods but would also provide a comprehensive overview of existing gaps in research concerning the recyclability of electronics. This, in turn, would enable informed decision-making on investments in areas where further studies on recyclability and DfR are most needed, and help create better Design for Recycling methods.

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