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Review

Towards Recyclable Electronics: Criteria for High-Quality Design for Recycling Methods †

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Abstract

Electronics recycling aims at the recovery of materials from obsolete electronic products, containing valuable, harmful, and polluting materials. While product design can improve recyclability, a gap remains between design and recycling practices. This study assessed the quality of published Design for Recycling (DfR) methods for electronics to develop criteria for high-quality methods. A systematic review of 30 years of the literature identified 16 distinct methods, which were evaluated for completeness, practical applicability, and alignment with recycling practices. The review shows major gaps in method development and validation, with few methods being tested in design practice or validated by recycling experiments. Based on these findings, we propose criteria emphasizing aspects such as design practitioner involvement, integration with recycling practice, adaptability, and clear documentation. This study shows the need for practical and accessible methods that bridge the gap between design and recycling.

Keywords: recyclability; circular economy; method evaluation; product design; e-waste; material recovery

1. Introduction

In a circular economy, products and materials are kept in circulation to minimize waste and reduce demand for raw materials. Various value-retention strategies that can help preserve resources have been proposed, each with its own applications and implications [1]. Strategies such as reuse and repair are highly valued as they extend the life of products and maintain their integrity [2], but when products reach their final end-of-life (EoL) stage, recycling becomes essential. Recycling enables the recovery of materials when reuse and repair are no longer an option, thereby closing the loop of material use.

Recyclability is particularly important in the case of Electrical and Electronic Equipment (EEE). Obsolete EEE, often referred to as WEEE or e-waste, has reached enormous proportions and continues to grow rapidly. It has taken only 12 years to double to a mass of 62 million tons globally in 2022 [3]. In addition, WEEE is a complex mix of materials. It contains valuable and high-impact materials such as gold, which should be kept in circulation as much as possible. It also contains many critical raw materials with fragile supply chains and recycling them helps to reduce dependence on external factors related to mining and processing for sustainable development. In addition, E-waste contains toxic or hazardous components and materials that are dangerous if improperly handled. Examples

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include materials such as lead and mercury, which are harmful to human health and the environment, and components such as batteries, which can explode [3].

Product design decisions, such as material composition or fastener selection, can significantly affect the recyclability of electronics [4–7]. However, the fields of product design and recycling currently operate largely independently, leading to inefficiencies in recycling outcomes [7]. This is evident in a study which found a disconnect between design for circularity guidelines in research and policy, and the products that are actually developed in the EEE industry [8]. Recyclers face challenges in determining optimal processing methods due to the specific design choices made in products, especially given the diverse mix of product types, brands, and ages processed together [3,9]. This highlights the critical role of designers: their decisions can either support or obstruct recycling processes. Closer collaboration between design and recycling practice is therefore essential to ensure that design choices translate into improved recovery at end-of-life.

Efforts have been made to translate complex recycling processes into practical methods and guidelines that bridge the gap between design decisions and recycling outcomes [4,7,9–24]. A design method can be understood as a systematic approach that guides the design process by embodying and communicating a specific type of knowledge [25,26]. Such methods are typically formulations of best practices or principles developed through research [27], and they can range from rigorous and repeatable procedures to loose sets of recommendations [27,28].

Only a small portion of the methods developed in academia are widely applied [27,29,30], because they tend to be too complex, abstract and theoretical and do not fit the needs and practices of designers [27]. On top of that, the implementation and use of these methods are rarely reported or critically reflected upon in the academic literature [29,31]. Fakhredin [7] identified significant discrepancies between the goals of Design for Recycling (DfR) methods and the outcomes of manual disassembly and shredding tests on electronic products, showing that DfR methods are rarely used in design practice either.

Although existing DfR methods for electronics have been developed with good intentions, no study has systematically evaluated their quality or how well they meet the needs of design practice. Wu et al. [32] address a related question, reviewing DfR approaches across engineering products broadly and identifying a lack of dedicated methods and evaluation tools. Their review focuses on defining and categorizing these approaches rather than assessing method quality, and it is not specific to electronics or WEEE-regulated products. It remains unclear which characteristics separate DfR methods that succeed in practice from those that do not. This study addresses that gap in two ways: By assessing the quality of documented DfR methods using an established method-evaluation framework, and by deriving from that assessment a set of criteria for developing future DfR methods that better support design practice.

This study makes two contributions. It is, to our knowledge, the first application of Cash et al.'s Method Assessment Framework [28] to an existing body of design methods. It also offers a set of criteria for DfR method development based on a structured review of three decades of the literature, giving method developers concrete guidance for producing methods more likely to be adopted in design practice.

This paper is aimed at researchers developing Design for Recycling methods. It also addresses design researchers interested in Method Content Theory and method evaluation, providing a concrete case of their application.

2. Materials and Methods

While practical testing, interviews, and case studies are valuable for assessing methods in context, they are not feasible for examining a large set. For the current goal, a literature-

based assessment provides the most practical and consistent foundation. Within this review, we apply the Method Assessment Framework [28] within Method Content Theory [26], which offers a structured, theory-driven way to analyze and compare methods consistently.

2.1. Literature Review

To identify existing DfR methods, we conducted a systematic literature review using the databases Scopus, Web of Science, and Google Scholar, which were last updated in December 2024. The objective was to identify sources presenting methods, tools, guides, or frameworks aimed at supporting the design of electronics for improved recyclability. Scopus and Web of Science were selected for their comprehensive coverage across various subject areas, while Google Scholar was included to broaden the search and capture gray literature such as theses and practical design guides, which are common in the DfR field but often not indexed in the first two databases. The review followed the systematic review method as presented in [33]; an adaptation of established systematic literature review approaches (e.g., [34,35]) that preserves their core principles of rigor, transparency, and replicability while allowing more flexibility for snowballing and the gray literature. Table 1 presents an overview of the search strategies for each database.

Table 1. Literature search strategies for DfR methods for electronics, separated per consulted database.

Database	Search Type	Search String	Subject Area	Time Range
Scopus	Title, Abstract, Keywords	(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}) AND NOT ({reverse logistics} OR EV OR {electric vehicle})	Engineering Environmental science Materials science Business, management and accounting Decision sciences Multidisciplinary	2008–2024
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	2008–2024
Google Scholar	n/a	Design AND recycling AND electronics *	n/a	2008–2024

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

To be included in the review, sources had to present a DfR method, tool, guide, or framework aimed at product designers. Eligible methods needed to address design-

related product features that influence recyclability and provide guidance to designers on improving recyclability. The review focused on products covered by the EU WEEE Directive [36]. We excluded methods tailored to products outside of this scope, such as vehicles and batteries, as these have different recycling streams and require distinct DfR measures.

Three additional exclusion criteria were applied. First, manual disassembly remains relevant for specific high-value or hazardous parts, such as batteries or high-grade printed circuit boards, but rarely for the recycling of entire products at scale. Since this review focuses on design guidance for large-scale WEEE recycling streams, methods centered solely on manual disassembly fell outside its scope. In addition, we considered studies on topics related to DfR such as value chains, reverse logistics, policy, or recycling technologies to be outside the scope of this review. Finally, we excluded sources that only present product recyclability assessment methods without also providing guidance to product designers.

After the initial search, we removed duplicate records found in different databases. We then assessed the titles, abstracts, and full texts to determine eligibility based on the inclusion and exclusion criteria and progressively refined the literature selection (see Table S1 for the full screening decision log). Snowball sampling was used to identify additional relevant sources, including older records or gray sources that were not initially captured in the search. The screening process resulted in a final selection of the literature for review. Figure 1 illustrates the complete literature search and selection process, starting with 2519 records identified in the initial search and ending with 18 records (1993–2023) describing 16 methods selected for review.

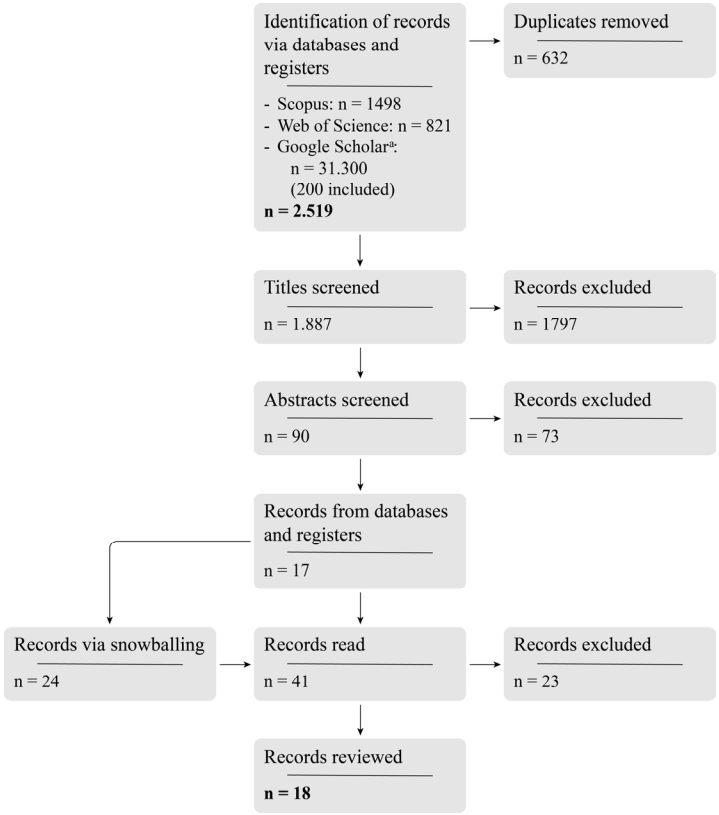


Figure 1. Flow diagram of the literature search and selection process. [a] In Google Scholar only the first 1000 results can be viewed, and the order of these is not disclosed [37]. It is recommended to focus on the first 200 results.

The high number of exclusions can be attributed to the broad use of the terms "design" and "recycling" across many different fields. The initial search returned sources ranging

from civil engineering to nanotechnology and materials science. Other papers focused on the design of new recycling technologies, the environmental or economic impacts of e-waste, consumer behavior, legislation, or alternative recovery strategies, while some concerned products outside the scope of consumer electronics. These factors explain the large reduction in records during the title and abstract screening stages.

The search and selection process required judgment calls that are difficult to fully standardize, characteristic of reviewing a fragmented field like DfR, where relevant work spans the academic and gray literature. Snowballing and gray literature searches are less systematic than structured database searches but were necessary to capture the practical guides and theses that are common in this field and often missed by database searches alone. This combination allowed us to bring together the most relevant sources on DfR methods currently available.

2.2. Method Assessment Framework

We evaluated the DfR methods in the context of Method Content Theory, which addresses how methods function in context, the elements of method content, and predictors of good method performance, bringing together knowledge on what constitutes the key elements of a method [26]. Method Content Theory defines a method as comprising five key elements: method framing, method rationale, method goal, method procedure, and method mindset. The theory explains how these elements function in context, predicting method performance based on their configuration and alignment with the design situation. The Method Assessment Framework operationalizes these elements, providing criteria and dimensions for systematically evaluating and comparing design methods. It examines how each element, such as procedure or rationale, contributes to the method's effectiveness and fit for purpose, enabling both qualitative and quantitative validation [28].

The Method Assessment Framework [28] evaluates five key building blocks (referred to in the source as "links in the chain of method development"): The initial motivation for the method, the nature of the method, its development process, the content of the method, and its claimed impact. Each building block includes specific elements that can be operationalized in different ways. For example, the *Context of need* element can be operationalized as *practice*, *education*, or *research*. According to Method Content Theory, weaknesses in any of the building blocks can undermine the overall strength of the method, while thorough coverage of all blocks indicates high method quality. Table 2 provides an overview of the framework's building blocks, elements and operationalizations, including explanatory prompts and a rubric used to compare different DfR methods.

For this evaluation, some elements and operationalizations were added or modified specifically for DfR methods, reflecting insights from the literature review. The original descriptions were often conceptual and high-level, so we specified how each element would apply in the context of DfR. For example, in *method framing*, we added variables that distinguish methods in practice, such as whether a method focuses solely on Design for Recycling or includes other end-of-life strategies, or the type of products it addresses (e.g., electronics or a specific category), and whether it aims to improve recyclability alone or considers multiple end-of-life destinations. In terms of research basis and validation, we also specified DfR-relevant approaches, such as recycler visits and recycling tests, to capture the practical evidence supporting method effectiveness. Adaptations from the original framework are highlighted in bold in Table 2. For methods that address multiple end-of-life recovery strategies, only the sections specifically related to Design for Recycling were reviewed.

Table 2. Method Assessment Framework from Cash et al. [28], and adapted by the authors to reflect DfR-specific prompts and operationalizations. Each building block includes specific elements that can be operationalized in various ways. The framework includes explanatory prompts and a rubric used to compare the methods. Text in bold indicates elements adapted or added specifically for this review, diverging from Cash et al.'s original framework [28].

Prompt	Element	Operationalisation	Rubric
Building block: Method motivation			
In which context is there a need for this method to be made/exist?	Context of need	Practice Education Research Not reported	Properly reported, the context of need should be practice. If the context is education, need sample, process sample and claim sample should align. Mentioned but lacking detail Not reported
Why is this method needed?	Need claims	Efficacy [a] Effectiveness [b] Dissemination [c] Not reported	Properly reported Mentioned but lacking detail Not reported
Where was the need for this method identified?	Need sample	Students Practitioners Both **Prior research** Not reported	Practitioners or both Students, also needs proper documentation. For claims on efficacy the sample should be proper prior research. Not reported
Building block: Method nature			
What type of method is presented?	Nature	Principle Approach Strict method Tool Template	No requirements.
What was the purpose of the developers of this method?	Purpose	Support practice Support education Support both Not reported	Purpose is to support practice and properly reported. Mentioned but lacking detail Not reported
Building block: Method development			
What is the method development process based on? What are the iterative steps in its development to ensure it aligns with design practice?	Development process supporting evidence	Expert practitioner opinion Research through design Single case Multi-case Experiment RCT Not reported	Multiple strategies Only developed through a single case study, expert opinion or one experiment. Not reported
With whom was the method developed?	Process sample	Students Practitioners Both	Practitioners or both Students Not reported
Building block: Method content			
What is the goal of a designer using this method?	Method goal	Specific goal(s) Prioritization or hierarchy **Not reported**	Properly reported Mentioned but lacking detail Not reported

Table 2. *Cont.*

Prompt	Element	Operationalisation	Rubric
Building block: Method content			
Which steps will help the designer in reaching their goal, how should these steps be completed and what is the purpose of these steps?	Method procedure	Specific steps How to complete steps Purpose of steps Not reported	properly reported (not just specific steps but also how to complete or the purpose of these steps) Mentioned only the steps Not reported
Is the method suited for designing new products, redesigning existing products, or assessing existing products?	**Method framing: Project**	**Design** **Redesign** **Assess** **Not reported**	Design and redesign Assess/evaluate Not reported
Who is the target audience of the method?	**Method framing: Audience**	**Design agency** **Specific company** **Specific team** **Students** **Not reported**	Specify the intended audience Intended audience is students Not reported
Which circular strategy does the method contribute to?	**Method framing: Strategy**	**Design for Recycling** **Design from Recycling** **Design for end-of-life** **Other** **Not reported**	Focus on Design for Recycling Focus on other strategies Not reported
What type of product is the method applicable to?	**Method framing: Product category**	**Products** **EEE** **Specific EEE category** **Not reported**	Focus on EEE Other focus Not reported
How does the method relate to the wider design process?	Method framing: Positioning	**Concept design** **Embodiment design** **Flexible** **Integrated in the entire design process** **Key decision moment** **Assessment** **Not reported**	Properly reported Mentioned but lacking detail Not reported
What is needed before this method can be used?	Method framing: Prerequisites	Resources Competences Information Not reported	Properly reported Mentioned but lacking detail Not reported
How can a designer evaluate their progress towards reaching the method goal?	**Success metrics**	Goal(s) success criteria Goal(s) end conditions Score Rationale for above criteria Support to reflect on progress/goal completion Not reported	Properly reported Mentioned but lacking detail Not reported
What are the underlying beliefs or intentions the designer needs when using the method?	Method mindset	Values and beliefs Working principles Not reported	Properly reported Mentioned but lacking detail Not reported

Table 2. *Cont.*

Prompt	Element	Operationalisation	Rubric
Building block: Method content			
What is the evidence behind the content of the method?	Research basis	Logical speculation or inductive reasoning References to past findings **Expert interviews** Existing theory **Recycler visits** **Recycling experiments** **Not reported**	Based on proper evidence like recycling experiments or thorough collaboration with recyclers Only based on, e.g., the literature or interviews. Not reported
Building block: Method claims			
Does using the method lead to improved recyclability of products?	**Efficacy validation** [a]	**Calculation** Single case Multi-case **Recycling test** Not reported	Validated through a recycling test Validated through other means Not reported
Is the method usable in design practice?	**Effectiveness validation** [b]	Expert practitioner opinion Research through design Single case Multi-case Experiment RCT Not reported	Validated through multiple case studies Validated through a single case study, expert opinions or one experiment Not reported
Is the claimed evidence generalizable? To which products or product categories does it apply?	**Dissemination validation** [c]	**Products** **EEE** **Specific EEE category** **Not reported**	Generalizable to all electronics Generalizable to a specific EEE category Not reported
With whom was the method tested/validated?	Claim sample	Students Practitioners Both	With practitioners or both With students Not reported

[a] Efficacy; the likelihood that application of the method in practice will result in improved recyclability of products. [b] Effectiveness: The usability of the method in design practice. [c] Dissemination: The degree to which the method is generalizable for all products/electronics instead of just one type of electronics.

Each source presenting a DfR method was coded according to the Elements outlined in Table 2. This coding was carried out by a single researcher, which introduces a degree of subjectivity. To mitigate this, we established the rubric in advance to ensure consistency. In addition, we aimed for transparency by documenting the full process in Table S2, allowing readers to trace how the assessments were made.

3. Results

The review found only 18 sources covering the period from 1993 to 2023, discussing a total of 16 DfR methods for electronics. This suggests limited development in this field, given the significant technological innovations in the electronics industry during this period. The sources are also geographically concentrated: most originate from the European Union, particularly the Netherlands and Germany. Each reviewed method was assigned a number from 1 to 16 (Table 3); these numbers are used throughout this section to refer to specific methods.

Table 3. DfR methods evaluated using the Method Assessment Framework (refer to the complete evaluation in Table S2). Green indicates a solid and comprehensive description of the element, yellow indicates a weaker description, and white indicates there is no mention of the element or its operationalization in the source.

	Method	Motivation			Nature	Development				Content								Claims			
		Peer Reviewed	Context of Need	Need Claims	Need Sample	Nature	Purpose	Development Process	Process Sample	Method Goal	Method Procedure	Method Framing: Project	Method Framing: Audience	Method Framing: Strategy	Method Framing: Product Cat.	Method Framing: Positioning	Method Framing: Prerequisites	Goal Success Indication	Method Mindset	Research Basis	Claimed Outcomes + Evidence: Efficacy	Claimed Outcomes + Evidence: Effectiveness	Claimed Outcomes + Evidence: Dissemination	Claim Sample
1	Design for Circularity guidelines (Berwald et al., 2021) [4]				principle																		
	Design for Circularity guidelines (Feenstra et al., 2021) [9]				principle																		
2	Guidelines and Design Strategies for Improved Product Recyclability (Hultgren, 2012) [16]				Principle																		
3	Design For eXcellence (DFX) method for recyclability (Peters et al., 2012) [15]				Principle + tool																		
4 *	[no name] (Balkenende & Bakker, 2015) [19]				principle																		
	[no name] (Fakhredin, 2018) [7]				principle + tool																		
5	Re-Cycling (Leal et al., 2020) [23]				Tool																		
6	[no name] (Shahbazi & Jönbrink, 2020) [24]				principle																		
7	IREDA (Xing et al., 2003) [13]				template + principle																		
8	[no name] (Bovea & Perez-Belis, 2018) [21]				template																		
9	Product centric Design for Recycling (Balkenende et al., 2014) [18]				principle																		
10	[no name] (Kriwet et al., 1995) [12]				Principle																		
11	Design for Multiple Life-Cycles (Go et al., 2015) [20]				principle																		
12	WEEE wheel (van Schaik & Reuter, 2012) [17]				tool																		
13	THEMA matrix (Castro et al., 2004) [14]				tool																		
14	[no name] (Beitz, 1993) [10]				principle + tool																		
15	[no name] (Dimitrova et al., 2018) [22]				principle																		
16	[no name] (Dowie & Simon, 1994) [11]				Principle																		

* Method 4, described in [7,19], was co-authored by one of the authors of this paper; it was assessed using the same criteria and process as all others, and we flag this for transparency.

The sources cover a range of publication types, including design guides, book chapters, conference proceedings, and journal articles. Only nine of the 18 sources have been peer-reviewed. Seven of the methods are only accessible through paywalled academic publications, which the design community often lacks the licenses to access. The types of methods also vary considerably. Some sources provide stand-alone guidelines intended to support specific aspects of the design process (**methods 1, 2, 4, 6, 9, 10, 11, 15** and **16**). Others present tools, such as tables detailing suitable connections for different processes or material combinations and their compatibility with recycling processes (**methods 12** and **13**). One source presents a structured template for the whole design process (**method 7**),

and several combine multiple approaches by integrating guidelines, tools, and templates (**methods 3, 4, 5, 8** and **14**).

Some of the methods reviewed include recovery strategies beyond recycling or extend their scope to products other than electronics. We identified six methods that focus exclusively on the Design for Recycling of electronics (**methods 1, 2, 3, 4, 9 and 12**). Table 3 shows the evaluation of DfR methods based on the Method Assessment Framework. A detailed assessment of each DfR method and its scoring is provided in Table S2 and the scoring rubric for each element is detailed in Table 3. Green cells indicate a solid and comprehensive description of the element, yellow cells indicate a weaker description, and blank cells indicate that the element or its operationalization is not mentioned in the source.

Methods with many green elements can be considered relatively complete, suggesting that the method described is of high quality [28]. Conversely, elements that are frequently left blank across sources reveal weaknesses in the methods and show areas for future improvement. The methods in Table 2 are ranked based on their completeness regarding the Method Assessment Framework. However, this approach assumes that all elements contribute equally to method quality, which is not necessarily the case. **Method 1** and **method 4** stand out because they are presented in more than one source.

The highest-ranked methods share key strengths. To begin with, they have been developed or tested with design practitioners, ensuring practical relevance (i.e., **1–4** and **6**). For instance, **method 1** was developed through collaboration with multiple stakeholders across the value chain, and this is reflected in the guidelines it presents. These guidelines are meant to capture the latest status of WEEE collection and are written in a practical way to be applied by product designers.

The highest-ranked methods also provide clear introductions to recycling practices, rather than assuming detailed prior knowledge (i.e., **1, 2 and 3**). Interesting to note, is that they all visualize the base process slightly differently, indicating that there is not one standard process to design for. The visualizations often also remain very high-level, sometimes not even specifying the different types of sorting techniques used to separate the fractions.

Method 1 also stands out for effectively integrating DfR principles into the broader design process, taking into account other product design requirements—for example, recognizing that the use of recycled plastics is not possible when a part needs to be transparent. Another key strength of, for example, **method 1** and **method 2**, is their well-explained design guidelines that are easy to understand and apply (an example is shown in Figure 2).

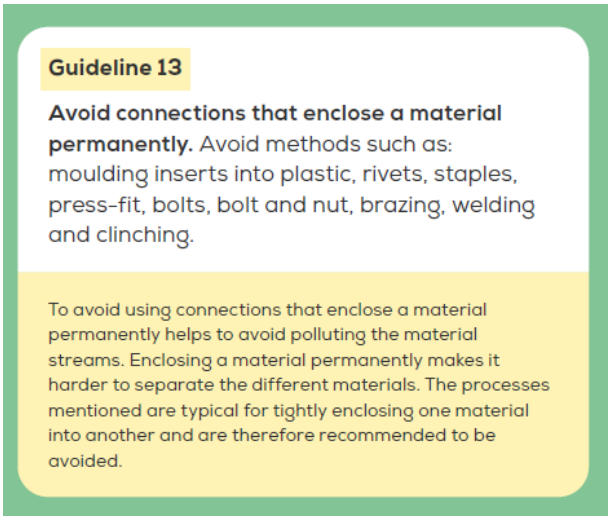


Figure 2. A guideline with substantiation from **method 1** [9].

DfR methods can be divided into two main approaches: quantitative recyclability tools which aim for measurable improvements, and qualitative guiding principles that offer broader recommendations. Some methods aim to calculate (**3**, **5**) or model (**12**) the recyclability of products. While these tools can help measure areas of improvement, they rely on extensive data about materials and recycling processes that are subject to change and sometimes unavailable. For example, **method 5** calculates recyclability using three variables: compatibility, diversity and recyclability of a product's materials. While compatibility remains relatively stable, the impact of material diversity on recyclability is less clear. Additionally, the recyclability of materials is influenced by location, technological advancements, market fluctuations and other external factors, making precise data difficult for designers to access. As a result, these tools provide useful recyclability scores but do not fully capture the complexities of real-world recycling. In the case of **method 5**, the score also does not take into account factors related to the geometry of the product, such as the connections between the materials.

Hultgren [16] (**method 2**) evaluated Peters' method [15] (**method 3**) for calculating product recyclability. She found the tool useful but overly complex and noted that weighing factors used in calculating the scores were largely based on assumptions. To address these issues, Hultgren simplified the method into a prioritized list of design guidelines informed by recycler feedback. Her approach removed scoring due to inconsistent data and instead focused on usability and the inherent tradeoffs in the design process. **Methods 1 and 4** are other examples of methods presenting guiding principles rather than scores.

Finally, some tools such as material combination tables based on thermodynamics (**4**, **12,** and **13**) and overviews of the likelihood of breakdown during shredding of different connection types (**4**) complement DfR methods. While they are valuable, these tools address only specific aspects of recyclability and are most effective when used as part of a broader method that considers the full complexity of product design and end-of-life processing. **Method 12** and **method 13** share an author (Reuter) and reflect a continued line of work on metallurgy-based recycling compatibility modeling, extending earlier thermodynamic material-compatibility analysis into a broader WEEE-focused framework.

There is considerable variation in the completeness of the reporting of the methods, and as a result in their overall quality. Some methods, such as method **16**, are very incomplete, only describing the elements of *purpose* and *prerequisites* completely. Others, such as **method 1**, are relatively comprehensive and only lack descriptions for a few elements.

Method 4 is described by two scientific sources, showing that even when multiple sources describe the same method, they may focus on different elements. **Method 1** is another example, described in both a journal article [4] and a non-peer-reviewed design guide [9]. The latter stands out for its comprehensive reporting, illustrating that such a medium can be effective. Design guides can provide more space for detailed descriptions and practical explanations tailored to designers, complementing the more concise reporting typical of scientific publications.

Method motivation and *method nature* are the most extensively documented building blocks. This shows that developers often prioritize explaining why they are creating a method and what kind of method they are presenting. While *method content* is sometimes well documented, there is significant variation among its elements. Developers often address *method framing*, including who should use the method, when it should be used, what types of projects it is appropriate for, and where it fits into the design process. While the method's *goal* and *research basis* are also typically addressed, the *procedure* needed when using the method is often overlooked. This lack of clarity about the specific steps needed to use a method can affect its usability. The building blocks of *method development* and *method claims*, which are critical indicators of a method's credibility, are often poorly

described. These building blocks provide insight into a method's alignment with recycling practices–for example, whether it is grounded in a strong research base or tested through recycling experiments. They also highlight the method's usability in design practice and its integration into the broader design process.

Only three methods (**1**, **2**, and **6**) documented their development process in collaboration with design practitioners, and only two methods (**4** and **6)** were validated in real-world design practice. This is an indication of a general lack of comprehensive reporting on the usability of DfR methods in actual design settings.

Most sources provide some form of evidence of their method's alignment with recycling practices. However, many contain guidelines that are based on older references and can lack clear justification. This casts doubt on the reliability of newer methods that rely only on the older literature for their research base. Six methods (**1**, **3**, **4**, **9**, **12**, and **13**) drew on extractive metallurgy, recycling trials and/or collaboration with recyclers as their evidence base. This connection to current recycling practices strengthens their reliability.

Only one of the methods (**4**) has been validated through testing in recycling practice to assess its effectiveness in improving product recyclability. It was applied in a product redesign and its impact was measured through recycling experiments comparing the old and new designs. Although several sources include case studies (**5**, **8**, **9**, **10**, **12**, and **13**), these are often illustrative examples rather than concrete evidence of improved recyclability in practice. Some methods rely on recyclability calculations to measure their impact (**3**, **7**, **9**, and **12**), but without practical validation, their reliability remains unclear. In addition, the results of these validations do not always translate broadly, as methods that claim to apply to all electronic products are typically tested on only one type.

Finally, only a few methods (**1**, **4**, **9**, and **12**) provide a clear and detailed overview of the recycling processes behind their assumptions. This is important because recycling processes vary across regions and companies and are continually updated to accommodate changing material streams. While many sources acknowledge the importance of shredding in recycling (**3**, **4**, **12**, and **15**), some still emphasize design-for-disassembly guidelines, which overlook the dominance of mechanical disintegration in large-scale recycling.

4. Discussion

This section discusses the findings of the review. Section 4.1 considers the trade-off between quantitative and heuristic DfR methods and presents the criteria this review proposes for developing higher-quality methods. Section 4.2 reflects on the Method Assessment Framework itself, including how it performed in this domain and how the reviewed methods compare to Cash et al.'s findings on design methods more broadly. Section 4.3 discusses the limitations of this review and directions for future research.

4.1. Criteria for Future DfR Method Development

Our analysis identified two main approaches in DfR methods: quantitative recyclability scores and qualitative design guidelines. Recyclability scores offer a way to compare designs and track improvements but rely on extensive data that may be unavailable or subject to change, making them less adaptable and harder to apply throughout the design process. **Method 5's** data limitations and Hultgren's simplification of **method 3** [15,16] illustrate this trade-off directly. This tension is visible in Wu et al.'s review [32] as well. They call for an automated, data-driven design system to keep DfR "minimal in human bias," but their own review names insufficient data as the field's biggest limitation, the same thing their proposed system would need most. The trade-off between quantitative and qualitative approaches reflects a broader difference between systematic and heuristic methods: While systematic approaches can generate precise and repeatable outcomes, they also tend to

demand more time, effort, and data, and may even lower motivation when users perceive them as less effective [38]. In contrast, heuristic design guidelines are easier to use, more applicable across design phases, and less sensitive to shifts in recycling practices, making them more likely to be taken up in practice. Since methods that are time-consuming or not adaptable to context, existing processes, available inputs, or user needs are generally less likely to be adopted [29], this raises the question of whether systematic approaches to DfR are inherently less suited for design practice. While both approaches have their place, it is important to reflect on the intended goal before choosing a method: whether the aim is to evaluate recyclability with measurable outputs or to provide actionable guidance that fits within real-world design practice. A hybrid method, combining heuristic guidance with systematic scoring, could serve both needs. However, systematic scores risk conveying false precision when based on incomplete design-stage data. None of the methods reviewed here attempted this combination, and whether it can be done without overstating reliability remains an open question.

Regardless of which form a method takes, certain characteristics determine whether it succeeds in practice. Based on the review, we can derive key characteristics of an effective DfR method, which can also serve as recommendations for the development of future methods in this field. These characteristics include not only the technical and practical aspects of the method but also its documentation and communication, which are important for ensuring accessibility and applicability by designers. Although 16 methods may seem limited, this reflects a near-complete inventory of DfR methods developed specifically for electronics with actionable design guidance, rather than a small sample of a much larger set, and the criteria below are grounded in patterns that recurred consistently across nearly all 16 methods, not in a few isolated cases. We derive the following criteria for future DfR method development:

1. **Make the method clear and well-defined.**

According to Daalhuizen and Cash's Method Content Theory [26] a good design method is "defined" when it is complete, logically coherent, and unambiguously described. This means that the documentation of the method should be comprehensive and address all building blocks outlined by Cash et al. [28] in the Method Assessment Framework (Table 2): It should include details about the initial motivation for the method, the nature of the method, its development process, the content of the method, and its claimed impact.

2. **Provide comprehensive explanations supported by evidence.**

DfR methods need to be rooted in recycling practice to improve the recyclability of products. Evidence from metallurgy, shredding tests, and collaboration with recyclers is essential, as it provides a link to the capabilities and limitations of current processes. Clear explanations of guidelines or other aspects of a method also strengthen their connection to recycling practice and help designers understand its relevance and impact. Such descriptions also improve a method's *predictability* [26], as they will help designers understand how altering one variable will impact others as well as the outcomes of using the method. This criterion is derived from the element *research basis* from the Method Assessment Framework [28] and Daalhuizen and Cash's Method Content Theory [26].

3. **Validate through recycling tests.**

Ideally, a DfR method is validated through recycling trials, where products redesigned using the method are tested in real-world recycling processes. These tests determine whether the method actually improves recyclability, which is the core objective of DfR. However, such tests require significant time and resources and may not be feasible for every method developer. If direct recycling tests are not possible, validation through calculations

based on previous recycling tests or evaluation by recycling experts is recommended. In addition, methods intended for a wide range of products should ideally be tested across different product types to confirm their versatility. This criterion is derived from the element *method claims* from the Method Assessment Framework [28].

4. **Develop and test with design practitioners.**

Methods are more likely to be used in practice if they are developed with input from design practitioners. Developers need to recognize that methods will only be adopted if designers can understand and use them, and if the methods can be adapted to different contexts, needs, abilities, and to the broader method ecosystem in which they are applied [27]. Collaboration during development and testing in design environments ensures that methods are aligned with design workflows, making them more useful and easier to adopt. This criterion is derived from the elements of *method development* and *method claims* of the Method Assessment Framework [28].

5. **Ensure the method is adaptable to evolving recycling practices.**

As electronics design, legislation, and recycling technologies evolve, static DfR methods risk becoming outdated. For example, the miniaturization of components has reduced the concentration of valuable materials like gold in e-waste, impacting the funding of recycling processes. In addition, recycling is becoming more automated, and legislation continues to impose stricter restrictions on hazardous materials in new products. Recycling practices also vary significantly by region, depending on available infrastructure, labor costs, and regulatory frameworks. A DfR method should not only be updateable but also account for these context-specific variations to remain effective. Concretely, this means building the method with a modular structure where possible, so that individual guidelines or parameters can be updated without revising the method as a whole, and establishing a clear update cycle (e.g., revisiting recyclability data or material assumptions every few years) rather than treating the method as a fixed, one-time publication.

6. **The method effectively reaches and engages designers.**

According to Daalhuizen and Cash [26], a good design method is accessible, understandable, and credible to designers. While academic publications are important for documenting the method's research basis and enabling further development by academic and professional communities, a practical "Design for Recycling Guide" can translate research into tools suited for everyday design work. For example, the design for circularity guidelines (**method 1**) were published in both a peer-reviewed journal [4] and a practical guide [9], effectively communicating DfR principles to both scientific and design audiences. This aligns with the findings of Matschewsky et al. [29]: methods are currently often presented in a format not optimized for use by practitioners, which is why a proper form of communication needs to be considered in method development. Open access publication further ensures that these methods are widely available and more likely to be adopted.

7. **Address tensions with other Design for End-of-Life strategies.**

Ideally, a DfR method should address and provide guidance on the tensions between different Design for end-of-life strategies, such as Design for Recycling, Design for Reuse, and Design for Repair. Methods cannot be seen in isolation; they are part of an ecosystem of design methods that interact, share inputs, and feed into one another throughout the design process [27]. In a circular economy, recycling is only one of many recovery strategies, and each product's likely EoL must be evaluated before choosing the ones to focus on. DfR is not a stand-alone activity but part of a broader design process that must balance competing requirements across multiple recovery pathways. An effective DfR method should help designers manage this complexity by clarifying potential trade-offs. While

some of the reviewed methods include other recovery strategies, they focus on overlaps rather than conflicts. For example, **method 6** provides a table linking guidelines to different circular design strategies, but it does not address how to handle situations where improving recyclability may come at the expense of repairability, or vice versa. None of the reviewed methods explicitly explore these tensions or provide actionable guidance on how to address them in the design process.

4.2. Reflecting on the Method Assessment Framework

We evaluated the methods using the Method Assessment Framework [28], which proved valuable for its detailed yet comprehensive approach to assessing methods as a whole. The framework could be easily adapted to the specific needs of Design for Recycling methods and allowed for the consideration of a wide range of factors that influence method quality. Adding recycling-specific elements and operationalizations gave us a more holistic view of each method. However, using documentation as a proxy for method quality has its limitations, as the available documentation may not fully reflect how the method functions in practice. Some details might be missing, or the way a method is actually used could differ from how it is described. Since testing all these methods directly is not feasible, we have to rely on their documentation instead. In addition, the framework overlooks secondary factors that can influence method use, such as how the method is presented or embodied. To the best of our knowledge, this study is the first to apply the framework to existing design methods. Demonstrating its practical application using a subset of DfR methods provides concrete examples of the different method elements and their operationalization.

Our evaluation of DfR methods showed clear patterns across the different building blocks. Method motivation and method nature are generally well described, while the development process is almost never reported. Method content and method claims fall somewhere in between. In the case of method claims, developers typically focus on measurable results in terms of efficacy, with much less attention to usability and effectiveness in practice. There are large differences between methods, but the overall picture aligns with Cash et al.'s [28] review of general design methods. They found that the development process is often poorly described, with a general lack of reporting and evidence, and that method claims in general design methods focus on efficacy but often lack supporting validation. The one area where DfR methods perform somewhat better is in describing method motivation, perhaps because the lack of recyclable products provides a tangible and urgent motive for developing such methods.

Although the framework treats all building blocks and elements as equal, their relevance may vary in practice. Some elements, like *procedure* and *mindset*, are rarely reported but may not significantly impact method quality. For instance, detailed procedures may not be necessary for methods offering only guidelines, and the *mindset* element, such as 'Attention and awareness for recyclability in product design' described by [16], may not always be essential. For DfR methods, a clear description of aspects like product applicability, the method's fit within the design process, and its target audience are more critical. These factors enable designers to determine whether a method aligns with their specific context and DfR objectives. While the framework treats all elements as equal, some may be more important than others. A method that looks complete could still miss key details, while a simpler one might cover the most critical points.

Overall, we found the Method Assessment Framework highly useful, but it is important to evaluate and adapt it to the specific set of methods under review. In our case, tailoring it to DfR methods increased its relevance and depth. If we view methods as designed artifacts [26], then the Method Assessment Framework can also be seen as a

method in its own right, and is adaptable to specific needs and contexts, just like any other design method [30].

4.3. Limitations and Future Research

As with any review of this kind, some judgment calls were involved in screening and coding, and here this was done by a single researcher. As a result, no inter-rater reliability metrics are available, and the assessment reflects a single perspective. To address this, a full record of these screening and coding decisions is provided in Table S1, allowing readers to trace how each judgment was made. Furthermore, the study was time-bound, covering the period until December 2024, so more recent methods are not included here. However, since the proposed criteria come from patterns across three decades of the DfR literature, a handful of newer methods is unlikely to change the overall picture.

Future research could focus on developing a DfR method based on the criteria proposed in this paper. In this study we focused on method content, as it is relatively static in nature and independent of contextual factors, which makes it a suitable starting point for evaluation. However, method use is influenced by a complex set of contextual factors [27,38,39], and outcomes are directly shaped by how a method is staged within the design process [40]. A future DfR method should therefore be developed and validated with designers, for example through the evaluation approaches described in [27,30]. It should also be developed and validated with recyclers, through interviews with recycling experts and recycling tests on a range of products. Existing guidelines need this same kind of validation with both designers and recyclers, since many currently lack clear traceability or supporting evidence. Recycling practices also change over time and vary by region. Further research into these temporal and regional differences would help ensure new methods remain aligned with the actual recycling industry. Finally, examining trade-offs between recycling and other recovery strategies, such as repair and reuse, would help create more circular products overall. Together, these research directions would help ensure that future DfR methods could close the gap between design and recycling.

5. Conclusions

This review shows that current Design for Recycling methods for electronics are not yet capable of bridging the gap between design and recycling. Across the 16 methods reviewed, development processes were almost never documented, validation through recycling tests was rare, and design practitioners were rarely involved.

Based on these findings, we developed seven criteria for developing better DfR methods: methods should be clearly defined, backed by evidence, validated through recycling tests, developed with design practitioners, adaptable to changing recycling practices, well communicated to designers, and able to address tensions with other end-of-life strategies. Meeting these criteria will not guarantee a method gets adopted, but their absence across three decades of the DfR literature is a likely reason so few methods make it from paper to practice.

Turning these criteria into method development starts with treating them as a checklist from the outset, not something to fix in hindsight. That means documenting the development process and evidence base, testing draft methods with design practitioners before publishing, and validating results through recycling trials, expert input, or data-based calculations when full trials are not possible. This study also shows that Cash et al.'s Method Assessment Framework [28] is an effective way to compare design methods even within a specific field, rather than only across design methods in general.

If these criteria are taken up by method developers, the benefits extend further downstream. Designers would have access to better and more reliable DfR methods, and

recycling practitioners would see product designs that better align with recycling processes. Recycling is considered a last resort among circular strategies, behind reuse and repair. Even so, every product needs to be recycled at some point in its life, so better DfR methods are essential to building a next generation of genuinely circular electronics.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18168225/s1, Table S1: Title and Abstract Screening Decision Log; Table S2: Method Assessment Framework.

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Abbreviations

The following abbreviations are used in this manuscript:

EoL	End-of-Life
EEE	Electrical and Electronic Equipment
WEEE	Waste Electrical and Electronic Equipment
DfR	Design for Recycling

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