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Prioritizing design for recycling criteria in Moroccan manufacturing

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Abstract: This study investigates the prioritization of Design for Recycling (DfR) criteria within Moroccan manufacturing Micro, Small, and Medium-sized Enterprises (MSMEs). Despite the potential of MSMEs to drive sustainable practices, a comprehensive understanding of key DfR criteria and their prioritization remains limited, particularly in emerging economies. These enterprises, often characterized by their adaptability and resource efficiency focus, are uniquely positioned to adopt sustainable practices like DfR. However, MSMEs, particularly in Morocco, face challenges in integrating DfR principles effectively. This is often due to a lack of awareness and understanding regarding key DfR criteria and how to prioritize them within their specific operational context. To address this gap, a context-specific, multi-level DfR criteria framework is developed, tailored for Moroccan manufacturing MSMEs. The Best-Worst Method (BWM), a robust multi-criteria decision-making technique, is employed to prioritize these criteria within a sample of eight Moroccan manufacturing MSMEs. Our findings reveal that materials compatibility and the use of recycled materials are paramount for optimizing recyclability. This prioritization is influenced by the unique challenges and opportunities within the Moroccan context, including limited recycling infrastructure and a reliance on informal recycling practices. This research provides practical guidance for Moroccan MSMEs seeking to integrate DfR principles into their design processes, contributing to sustainable manufacturing practices. Moreover, it establishes a methodological and theoretical foundation for future research on DfR implementation in emerging economies.

1 Introduction

Micro, small, and medium-sized enterprises (MSMEs) play a crucial role in driving economic growth, particularly in emerging economies [1]. Their inherent adaptability and resource efficiency make them well suited to embrace sustainable practices, such as Design for Recycling (DfR). However, integrating DfR principles into design processes can be challenging for MSMEs [2].

While DfR is a cornerstone of eco-design, much of the existing research focuses on theoretical frameworks or general principles [3-11]. This leaves MSMEs with limited actionable guidance for practical implementation. Moreover, there is a lack of understanding regarding the specific DfR criteria most crucial for these enterprises. This is particularly true in emerging economies like Morocco, where manufacturers must navigate a unique recycling landscape characterized by informal practices and infrastructural limitations.

This study addresses these gaps by developing and validating a context-specific framework of DfR criteria tailored to the needs of Moroccan manufacturing MSMEs. Drawing from existing literature and expert consultations, we meticulously assess and prioritize these criteria using the Best-Worst Method [12], a robust multi-criteria decision-making technique. This approach offers a practical roadmap for MSMEs seeking to enhance product recyclability in the design phase, thereby contributing to sustainable manufacturing practices. Additionally, our research provides a foundation for future investigations into DfR implementation across various contexts. The study has three primary objectives:

- Identify DfR criteria: Develop a comprehensive DfR decision framework tailored for manufacturing sectors.
- Assign weights to DfR criteria: Determine the relative significance (weights) of DfR criteria within the manufacturing context.
- Explore implications: Investigate the managerial, practical, and country-specific implications of this research.

To achieve these objectives, we conducted a comprehensive literature review on DfR and eco-design, extracting and synthesizing key criteria to form the foundation of our framework. This framework was further refined and validated through consultations with experts and practitioners. We then employed the BWM tool to evaluate the framework across eight Moroccan manufacturing firms, enabling us to prioritize the criteria and establish a strategic implementation pathway.

This paper makes several significant contributions to the field of DfR and sustainable manufacturing:

- Comprehensive framework: It develops a comprehensive, multi-level DfR criteria framework specifically tailored for manufacturing contexts. This framework offers a systematic decision-making tool, guiding practitioners in effectively integrating DfR principles into their product design processes.
- Methodological advancement: The study employs a novel application of the BWM, a robust multi-criteria decision-making technique, to assess and prioritize DfR criteria. This approach provides a rigorous, data-driven method for prioritizing DfR factors based on their relative importance.
- Empirical Insights: The research applies the proposed framework and methodology within the Moroccan manufacturing sector, revealing challenges and opportunities for MSMEs adopting DfR, improving understanding of sustainable manufacturing practices in this context.

This paper is organized as follows: Section 2 explores existing research on design for recycling criteria. Section 3 introduces the methodology and framework. Section 4 applies the framework to a real-world scenario. Section 5 analyzes the results. Section 6 concludes the paper.

2 Analysis of design for recycling criteria: a comprehensive review

2.1 Design for recycling

Growing environmental concern in the 1990s prompted a fundamental shift in product design, emphasizing the minimization of ecological impact. This shift is underscored by a 2021 European Commission report, which emphasizes the significant influence of the design phase on a product's environmental footprint [13]. Eco-design has emerged as a key solution, integrating environmental considerations throughout the entire product lifecycle. Its primary objective is to minimize environmental impacts without compromising performance or economic viability [14]. Design for Recycling is a critical pillar of eco-design, strategically addressing the product's end-of-life to facilitate material recovery and promote closed-loop systems. By optimizing products for recycling, DfR contributes to the broader objectives of a circular economy [15].

Guided by eco-design principles, which are aligned with waste management hierarchies such as the EU's Waste Framework Directive [16], manufacturers are increasingly integrating environmental considerations into their decision-making [14]. Eco-design emphasizes a preventative approach, prioritizing waste prevention, reuse, recycling, and resource recovery. DfR is a cornerstone strategy within this framework, optimizing products for recyclability from the design phase and promoting the use of recycled materials [17].

DfR has become a prominent research area within sustainability, with significant advancements in methodologies and tools empowering designers. Computer-aided tools now enable comprehensive assessments of material recyclability [18,19] and simulate end-of-life (EoL) scenarios to inform design choices [20,21]. Core DfR principles, such as material selection, disassembly considerations, and EoL strategies [15,22,23], are continually adapted to address sector-specific challenges. This is evident in research on the automotive industry [9], the packaging industry [7,24,25], and the emerging field of e-textiles [15], where waste prevention strategies are prioritized due to product complexity.

The recovery of critical raw materials (CRMs) is a vital aspect of DfR. Designers must integrate disassembly techniques and utilize specialized indices [26] to facilitate CRM extraction. However, research highlights systemic barriers that hinder DfR implementation, including limitations in recycling infrastructure, inadequate policy incentives, and fragmented stakeholder collaboration [2,6,11,25,27]. To fully realize the potential of DfR driving the transition to a circular economy, a deeper understanding of design criteria is crucial. This includes material selection, product architecture, EoL scenarios, and their interplay with existing recycling infrastructure and policy frameworks.

2.2 Review of design for recycling criteria

Design for Recycling (DfR) has garnered significant attention within the research community [17,18,20,27,28]. While core DfR principles, such as product architecture, material selection, and end-of-life considerations, are undeniably important, their practical effectiveness depends on contextual factors. Product characteristics, technological limitations, and recycling infrastructure all influence how DfR criteria should be prioritized [5,19,25,29].

A product's architecture significantly influences its recyclability. Simplicity, achieved by minimizing complexity and fastener use, facilitates disassembly [2,9,15,23,27]. Modularity, where products are composed of easily separable modules, facilitates targeted recycling of individual material streams [8,15,27]. Designing for disassembly ensures ease of access to components through non-permanent connections, preserving material integrity [11,18,26]. Standardizing parts and fasteners allows for the use of common disassembly tools, streamlining recycling procedures [7,11,18,20,21].

Material selection significantly influences the efficacy of DfR strategies. Choosing materials with well-established recycling pathways promotes efficient resource recovery [9,24]. Incorporating alternative materials like bioplastics, wood, or other sustainable options can offer environmental benefits [11,15]. When using multiple materials, ensuring compatibility is critical to avoid complications during recycling [2,3,8,18,19]. Using recycled content, where quality and performance allow, contributes to closed-loop material systems within a circular economy [4,23,27,30]. Minimizing or eliminating contaminants and hazardous substances is essential to avoid challenges within recycling systems [2,22,25]. Limiting material diversity and simplifying material choices improve a product's recyclability potential [9,11]. Market factors, such as the economic feasibility of using recycled materials, can also influence material selection decisions [2,28].

Proactive consideration of EoL scenarios is fundamental to DfR. Implementing standardized labelling systems for materials, fasteners, and components promotes efficient sorting and assessment within recycling facilities [2,24,26,27,30]. Aligning product designs with existing recycling systems and technologies optimizes resource recovery [2,5,18]. Adhering to current and anticipated recycling regulations is critical [6,25]. Providing clear information on disassembly, composition, and recyclability to end users and recyclers facilitates product recyclability at the EoL stage [21,28].

This review identifies core DfR criteria, which are interdependent and should be addressed holistically throughout the design process [22,27]. Based on an extensive literature review and discussions with industry professionals, this research proposes a three-dimensional DfR framework encompassing product architecture, material considerations, and EoL considerations. For ease of application, these dimensions are further divided into 14 sub-criteria, detailed in Table 1.

2.3 *Research gaps and highlights*

Existing research provides a valuable foundation for understanding DfR criteria, encompassing material selection [2], implementation frameworks [5,23], and tools for recyclability assessment [18,22,29]. However, a critical gap exists in empirically prioritizing these criteria within real-world manufacturing contexts, particularly in emerging economies. The lack of data driven weighting of individual criteria hinders designers seeking to optimize product recyclability from the outset.

Research suggests that existing DfR theories and conceptual models often are often difficult to apply directly to Micro, Small, and Medium-sized Enterprises (MSMEs) [2]. Considering the dominance of MSMEs in Morocco's economic landscape [31] and the intensifying pressure of global environmental regulations, proactive green design initiatives across all industry scales.

This study addresses these gaps by conducting a systematic survey of Moroccan manufacturing sector experts to prioritize DfR criteria, focusing on three key areas: product architecture, material considerations, and end-of-life considerations. The Best-Worst Method (BWM) will be used to establish a robust ranking of these criteria, revealing those most critical for designing products with optimized recyclability. This research offers a unique contribution by highlighting the specific challenges and potential solutions relevant to emerging economies. In these contexts, factors such as informal recycling practices and infrastructural limitations [25] must be integrated into early-stage design processes.

2.4 *Development of the design for recycling criteria framework*

This section outlines the two-stage development of a comprehensive Design for Recycling (DfR) criteria framework for the Moroccan manufacturing sector.

- Initial criteria identification: A thorough literature review of existing DfR studies was conducted, resulting in a preliminary list of 27 criteria.
- Criteria refinement and categorization: To ensure practical applicability, industry managers evaluated the initial list, suggesting omissions or redundancies. This feedback resulted in a final selection of 14 essential DfR criteria. Subsequently, through iterative discussions, the managers categorized these criteria into three main categories based on thematic similarities. The final sub-criteria categorization is presented in Table 1.

Table 1 Design for recycling (DfR) criteria and supporting literature

Main Criteria	**Sub-Criteria**	**Short description**	**References**
Product Architecture	Simple Design	Simplify design and use fewer fasteners.	[2,4,7,9,11,15,23,24,27]
	Modular architecture	Design modular products for targeted recycling.	[2,6,8,20,23,27,29,30]
	Design for Disassembly	Design for easy disassembly using accessible components and non-permanent connections	[2,3,6-9,11,15,18-20,23-27,29,30]
	Standardisation	Standardize parts and fasteners to streamline disassembly.	[3,7,18,20,21,23,28,29]
Material Consideration	Use of Recycled Materials	Prioritize recyclable materials with established recycling processes and high recycled content.	[2,4-11,15,19,20,23-30]
	Alternative Materials	Explore sustainable material alternatives.	[11,15,24]
	Materials Compatibility	Use compatible materials in mixed-material products.	[2,3,6-9,18,19,24,26-29]
	Avoid Contaminants	Minimize contaminants and hazardous substances.	[2-4,6-9,15,18,22-27,29]
	Materials Diversity	Simplify material selection by reducing the variety of materials used.	[3,5,7-9,11,15,18,23,25,27,28]
	Economic Convenience of Recycled Material	Evaluate the cost-effectiveness of recycled materials.	[3,4,6,19,21,24,25,28]

End of Life Considerations	Identification and Labelling	Standardize labelling for materials and components.	[2,6-8,11,20,23,26,27,29,30]
	Recycling systems Consideration	Design adaptable products for evolving recycling technologies.	[2,5,6,7,11,19,21,24,29,30]
	Legislative Considerations	Comply with current and future recycling regulations.	[6,25,27]
	Information communication	Provide clear product information for end-of-life management.	[2,21,27,30]

3 Prioritizing DfR criteria: a best-worst method approach

Table 1 highlights the complex, multi-criteria nature of Design for Recycling, with each criterion encompassing various factors that demand careful consideration. Effectively evaluating and prioritizing these criteria is challenging due to their inherent complexity and the potential for inconsistencies in traditional Multi-Criteria Decision-Making (MCDM) methods that rely heavily on pairwise comparisons [32].

To address these limitations and ensure reliable outcomes, this study adopts the Best-Worst Method (BWM) [12]. BWM offers distinct advantages for DfR analysis, making it particularly well-suited for navigating the complexities of this domain:

- Reduced inconsistency: BWM minimizes inconsistencies inherent in traditional pairwise comparisons by focusing on comparisons between the "best" and "worst" criteria relative to all other criteria. This approach provides a more holistic and robust framework, going beyond simply identifying the most efficient alternative. By requiring experts to consider the best and worst criteria as reference points, BWM encourages more deliberate and consistent judgments.
- Streamlined process: BWM utilizes a vector-based approach, streamlining the assessment process and requiring fewer comparisons than matrix-based methods. This reduces the cognitive burden on decision-makers, making it more efficient and less prone to errors, especially when dealing with a large number of DfR criteria.
- Intuitive comparisons: BWM facilitates comparisons against a defined reference (the best and worst criteria), which aligns with intuitive decision-making processes. This makes it a user-friendly tool for practical DfR applications, enhancing the accessibility and understandability of the analysis for both experts and stakeholders.

The selection of BWM for prioritizing DfR criteria stems from its ability to systematically address complex, multifaceted factors while minimizing potential biases. BWM facilitates the structured integration of expert knowledge, which is crucial for understanding the nuances of DfR implementation, particularly within the Moroccan MSME manufacturing context. While expert evaluations may involve some subjectivity, BWM's emphasis on consistency, coupled with a diverse expert panel, mitigates biases and strengthens the credibility of the findings.

Furthermore, this confidence is further bolstered by the successful application of BWM in various real-world applications, including optimizing freight transportation [33], supplier selection [34], and evaluating risk in business continuity [35]. This diverse applicability underscores BWM's value as a robust and adaptable MCDM method across different industries.

The Best-Worst Method (BWM) involves a series of steps to identify the weights of criteria in a MCDM process.

Step 1. Identify Decision Criteria.

Identify the decision criteria $\{C_1, C_2, \ldots, C_n\}$ used to evaluate alternatives. These criteria will form the basis for making comparisons.

Step 2. Identify Best and Worst Criteria.

Select the most significant (best) and least significant (worst) DfR criteria from the identified set. This selection focuses solely on the relative significance of each criterion, independent of their specific values.

Step 3. Define Best-to-Others Preferences.

Pairwise comparisons are conducted employing a 9-point scale (1 = equal preference, 9 = extreme preference). These comparisons establish the best-to-others vector (BO) for the most significant (best) criterion, denoted as (1):

$$A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn}) \quad (1)$$

Here, a_{Bj} represents the preference of the best criterion B over criterion j, and $a_{BB} = 1$ (indicating equal preference for the best criterion itself).

Step 4. Define Others-to-Worst Preferences.

Similarly, using the same scale, determine the significance of each criterion over the least significant (worst) criterion. This information is captured in the others-to-worst vector (OW), denoted as (2):

$$A_W = (a_{1W}, a_{2W}, \ldots, a_{nW})^T \quad (2)$$

Here, a_{jW} represents the preference of criterion j over the worst criterion W, and $a_{WW} = 1$ (indicating equal preference for the worst criterion itself).

Step 5. Calculate weights.

BWM employs an optimization model to calculate the weights of each criterion (w_1^*, w_2^*, ..., w_n^*) This model minimizes the maximum absolute difference between two sets of comparisons {$|w_B - a_{Bj}w_j|$, $|w_j - a_{jW}w_W|$}.

A minimax model is formulated to achieve this minimization (3).

$$\min \max_j \{|w_B - a_{Bj}w_j|, |w_j - a_{jW}w_W|\} \quad (3)$$

Subject to,
$\sum_j w_j = 1 \qquad w_j \geq 0$, for all j

Model (3) can be solved by transforming it into the subsequent linear programming formulation (4):

$$\text{Min } \xi^L \quad (4)$$

Subject to,
$|w_B - a_{Bj}w_j| \leq \xi^L$, for all j
$|w_j - a_{jW}w_W| \leq \xi^L$, for all j
$\sum_j w_j = 1 \qquad w_j \geq 0$, for all j

Model (4) being linear and possessing a unique solution implies upon solving it, optimal weights (w_1^*, w_2^*, ..., w_n^*) and an optimal value ξ^L will be derived.

The consistency ratio ξ^{L*} is calculated to indicate the consistency of the comparison system. A Value closer to zero implies higher consistency [12].

4 Practical applications: the case of moroccan MSMEs

4.1 MSMEs in the Moroccan context

MSMEs are recognized for their critical role in driving economic expansion and development in both industrialized and developing nations. They contribute significantly to wealth creation and employment [1]. In Morocco, MSMEs hold a particularly prominent position, constituting nearly 99% of the economic sector [31]. Notably, microenterprises represent the vast majority 88% of all businesses within this sector [31].

Despite their economic importance, MSMEs are significant contributors to global pollution, generating an estimated 60-70% of it [1]. This necessitates the adoption of sustainable practices within the sector. While classification criteria for MSMEs vary by country, Morocco uses a turnover-based system. This system categorizes businesses into microenterprises (annual turnover ≤ 3 million dirhams), very small enterprises (3-10 million dirhams), small enterprises (10-50 million dirhams), medium enterprises (50-175 million dirhams), and large enterprises (> 175 million dirhams). This nuanced approach facilitates targeted support policies for SMEs and allows businesses to assess their growth potential [31].

Despite their substantial environmental footprint, MSMEs often lack comprehensive strategies to address sustainability challenges [1]. This research seeks to address the gap by equipping MSME decision-makers with a robust understanding of DfR criteria. By strategically integrating DfR into their product design process, MSMEs can enhance product recyclability and contribute to broader sustainable manufacturing goals.

4.2 Application of the BWM

To evaluate the practicality of the proposed framework, we engaged in comprehensive discussions with ten experts from eight Moroccan manufacturing MSMEs spanning diverse sectors. These MSMEs were carefully selected to represent a variety of industries. Participants held key positions such as senior design engineer, industrial manager, and product engineer, all of whom play significant roles in the design phase. All participants had at least a decade of operational experience, ensuring a diverse spectrum of perspectives.

Following these discussions, experts from each company participated in a structured evaluation process. Prior to engagement, participants were provided with a briefing outlining the research objectives and detailed clarifications of each criterion. A preliminary refinement phase was conducted, followed by pairwise comparisons using the BWM. Experts identified the most and least important main criteria, which were designated as the “best” and “worst” criteria, respectively. They then compared the “best” criterion against all other criteria, indicating their preferences. Next, they compared all criteria against the “worst” criterion. This process was repeated for the sub-criteria. Individual ratings across all ten experts were aggregated to determine the final rankings of both main and sub-criteria. Table 2 summarizes the identified “best” and “worst” criteria for all ten respondents.

Table 2 Best and worst criteria identified by the respondents

Criterion	“Best” by Respondents	“Worst” by Respondents
Product Architecture (PA)	**2, 7**	**3, 4, 6, 8, 9, 10**
PA1: Simple design	3, 4, 10	5, 8
PA2: Modular architecture	5, 8, 9	2, 6, 7
PA3: Design for disassembly	1, 2, 6, 7	3, 4
PA4: Standardization		1, 9, 10
Material Consideration (MC)	**1, 3, 4, 5, 6, 9, 10**	
MC1: Use of recycled materials	1, 3, 4, 5, 8, 9	
MC2: Alternatives materials		7, 10
MC3: Materials compatibility	2, 6, 7	
MC4: Avoid contaminants	10	
MC5: Materials diversity		1, 3, 4, 5, 8, 9
MC6: Economic convenience		2, 6
End of Life Considerations (EoL)	**8**	**1, 2, 5, 7**
EoL1: Identification and labelling	1, 2, 3, 4, 5, 6, 7, 10	
EoL2: Recycling systems consideration	8	3, 4, 6, 7
EoL3: Legislative consideration	9	1, 2, 5
EoL4: Information and communication		8, 9, 10

The BWM method uses pairwise comparisons to ascertain the relative importance of criteria. To illustrate, Table 3 presents Respondent 1's preferences for the "best" main criterion compared to other main criteria, as well as their preferences for each main criterion compared to the designated "worst" criterion. These pairwise comparisons were conducted using a 9-point scale (detailed in Table 4).

Table 3 present Respondent 1's pairwise comparisons using the Best-Worst Method (BWM). These comparisons establish preferences for the "best" main criterion relative to other main criteria (Best-to-Others vector, or BO), and for each main criterion compared to the "worst" criterion (Others-to-Worst vector, or OW).

Table 3 Pairwise comparison of main criteria by respondent 1

BO	**PA**	**MC**	**EoL**
Most important: Material Consideration (MC)	4	1	8
OW	**Least important: End of Life Considerations (EoL)**		
PA	3		
MC	8		
EoL	1		

For example, in the BO vector (Table 3), the value of 4 at the intersection of Material Considerations (MC) and Product Architecture (PA) signifies that MC is considered "Somewhat to considerably more significant" than PA. The diagonal entries (e.g., MC and MC) are automatically assigned a value of 1, denoting equal importance. Similarly, in the OW vector (Table 3), the value of 8 at the intersection of MC and EoL considerations reflects Respondent 1's judgement that MC is "Highly to exceptionally more significant" than EoL considerations.

Table 4 BWM scale for pairwise comparisons

Term	**Scale**
Equally significant	1
Equivalent to somewhat more significant	2
Somewhat more significant	3
Somewhat to considerably more significant	4
Considerably more significant	5
Considerably to highly more significant	6
Highly more significant	7
Highly to exceptionally more significant	8
Exceptionally more significant	9

After evaluating of the main criteria, Respondent 1 undertook pairwise comparisons of the sub-criteria within each category using the same 9-point scale (1-9). The results of these comparisons for Product Architecture, Material Considerations, and End-of-Life Considerations are presented in Tables 5-7. Weights for both the main criteria and their associated sub-criteria were then calculated using equation (4). Table 8 summarizes these calculated weights for Respondent 1.

This process of pairwise comparison and weight calculation was repeated for each of the ten respondents. The final weights for the main criteria and sub-criteria were then calculated by averaging the individual weights across all respondents. Table 9 presents these final averaged weights.

Table 5 Pairwise comparison for PA sub-criteria by respondent 1

BO	**PA1**	**PA2**	**PA3**	**PA4**
Most important: Design for disassembly (PA3)	2	3	1	8
OW	**Least important: Standardization (PA4)**			
PA1	5			
PA2	4			
PA3	8			
PA4	1			

Table 6 Pairwise comparison for MC sub-criteria by respondent 1

BO	**MC1**	**MC2**	**MC3**	**MC4**	**MC5**	**MC6**
Most important: Use of recycled Materials (MC1)	1	6	5	4	8	3
OW	**Least important: Materials diversity (MC5)**					
MC1	8					
MC2	2					
MC3	5					
MC4	6					
MC5	1					
MC6	4					

Table 7 Pairwise comparison for EoL sub-criteria by respondent 1

BO	**EoL1**	**EoL2**	**EoL3**	**EoL4**
Most important: Identification and labelling (EoL1)	1	2	5	2
OW	**Least important: Legislative consideration (EoL3)**			
EoL1	5			
EoL2	4			
EoL3	1			
EoL4	4			

Table 8 Weights of main and sub-criteria for respondent 1

Main Criteria	Local weights	Sub Criteria	Local weights Sub-criteria	Global Weights	Ranking
PA	0.194	**PA 1**	0.270	0.052	7
		PA 2	0.180	0.035	9
		PA 3	0.494	0.096	4
		PA 4	0.056	0.011	12
MC	0.722	**MC 1**	0.438	0.317	1
		MC 2	0.091	0.066	6
		MC 3	0.110	0.079	5
		MC 4	0.137	0.099	3
		MC 5	0.041	0.030	10
		MC 6	0.183	0.132	2
EoL	0.083	**EoL 1**	0.519	0.043	8
		EoL 2	0.305	0.025	11
		EoL 3	0.053	0.004	14
		EoL 4	0.122	0.010	13

5 Discussion and analysis of results

The substantial weight accorded to material considerations (MC) underscores the paramount importance of material selection in determining a product's recyclability. This aligns with the global emphasis on material-centric DfR practices and the principles of a circular economy. Effectively managing the flow of materials throughout the product lifecycle, from raw material sourcing to end-of-life processing, is crucial for achieving circularity. The high rankings of criteria like “use of recycled materials” (MC1) and “material compatibility” (MC3) further solidify this commitment to optimizing material flows. This emphasis also reflects the realities of the Moroccan recycling industry. Limited infrastructure and dependence on informal sorting necessitate a focus on readily identifiable, compatible materials with established recycled content sources. By prioritizing such materials, Moroccan MSMEs can ensure their products seamlessly integrate into the existing recycling ecosystem.

While product architecture is significant, its lower emphasis compared to material considerations suggests that extensive design overhauls might be constrained within the surveyed companies. These constraints could arise from various factors: limited production capacity, where smaller production runs may not justify investments in complex product architectures; compliance with external market demands, which may impose strict design specifications that limit flexibility; and technological limitations, where existing manufacturing setups may not be easily adaptable to intricate designs. However, the prioritization of “modular architecture” (PA2) and “design for disassembly” (PA3) is noteworthy. This aligns with trends in emerging economies, where customization, faster time-to-market, and easier repairability are increasingly valuable.

This seemingly forward-thinking approach within the Moroccan MSME context could be attributed to market adaptation. Modular designs may be more suitable for smaller production runs or accommodating custom orders, supporting a thriving informal sector of product repair and refurbishment in Morocco. This highlights the role of the informal sector in extending product lifespans. The lower emphasis on extensive product architecture overhauls might contrast with developed economies, where larger manufacturers generally have greater flexibility for design innovation. This difference could be influenced by technological constraints and limited investment capacity of Moroccan MSMEs. Furthermore, the need to adapt their designs to the realities of an informal recycling sector appears particularly important for Moroccan MSMEs.

The relatively lower weight given to “recycling systems consideration” (EoL2) and “legislative considerations” (EoL3) indicates that MSMEs perceive limited influence over these broader life cycle aspects. This underscores the need for collaborative initiatives between stakeholders to optimize the reverse logistics processes associated with DfR. This includes:

- Manufacturers: Implementing DfR principles to facilitate efficient sorting and processing within the reverse logistics flow.
- Policymakers: Establishing clear regulations and developing recycling infrastructure.
- Recycling industry: Investing in sorting technologies and fostering formal recycling channels.

Such collaborative efforts should prioritise infrastructure enhancement by upgrading sorting and processing facilities to handle a wider range of materials, standardised labelling by implementing clear and consistent labelling systems to guide consumers and recycling operators, and incentivising responsible practices by establishing financial or regulatory incentives to encourage eco-friendly design and responsible consumer behaviour.

The emphasis on material considerations aligns with global trends. However, Moroccan MSMEs demonstrate a unique approach to DfR, focusing on adapting to the limitations of the existing recycling infrastructure and prioritizing materials that readily integrate into this system.

Additionally, the prioritization of "Modular Architecture" (PA2) and "Design for Disassembly" (PA3) within the constraints of production capacity suggests a strategic approach that balances practicality with potential benefits for repairability and market adaptation. Further comparative studies exploring DfR priorities across MSMEs in developed and emerging economies would provide valuable insights into how economic context, supply chain dynamics and recycling infrastructure influence these priorities.

Table 9 Aggregate weights of DfR criteria for all the respondents

Main Criteria	Local weights	Sub Criteria	Local weights Sub-criteria	Global Weights	Ranking
PA	0.237	**PA 1**	0.275	0.065	8
		PA 2	0.294	0.070	7
		PA 3	0.294	0.070	6
		PA 4	0.137	0.032	13
MC	0.539	**MC 1**	0.298	0.161	1
		MC 2	0.118	0.064	9
		MC 3	0.198	0.107	2
		MC 4	0.169	0.091	4
		MC 5	0.077	0.042	12
		MC 6	0.140	0.075	5
EoL	0.224	**EoL 1**	0.459	0.103	3
		EoL 2	0.211	0.047	10
		EoL 3	0.210	0.047	11
		EoL 4	0.120	0.027	14

6 Conclusion and future research

This research contributes to the theory and practice of Design for Recycling (DfR), particularly within the context of Moroccan manufacturing MSMEs. By introducing the Best-Worst Method (BWM) for prioritizing DfR criteria, this study offers a rigorous, data-driven approach applicable across diverse economic contexts. The multi-level DfR framework developed serves as a valuable tool for both researchers and practitioners, enabling structured evaluation and comparison of DfR initiatives. Furthermore, by focusing on the unique context of Moroccan MSMEs, this study addresses a crucial knowledge gap and provides insights into the specific challenges and opportunities these manufacturers face in emerging economies. This nuanced understanding enhances the practical relevance of existing DfR frameworks and underscores the need for globally inclusive approaches to sustainable design.

The prioritized DfR criteria identified offer manufacturers a clear roadmap for implementation. The emphasis on material considerations, such as the use of recycled materials and material compatibility, aligns with the strengths of Morocco's existing recycling infrastructure and provides a strategic pathway for immediate improvements in product recyclability. Additionally, the focus on modular architecture and design for disassembly reflects the specific technological landscape and market demands in Morocco, suggesting proactive strategies for optimizing recyclability within these constraints.

At a national level, this research highlights the potential for developing cross-sector DfR guidance. By combining the proposed framework with sector-specific knowledge, tailored guidelines can be created to address the distinctive challenges faced by various industries within Morocco's manufacturing sector. This study also underscores the need for a comprehensive national dialogue on DfR practices in Morocco. The findings provide a foundation for policy discussions focused on developing robust recycling infrastructure, establishing consistent labeling standards, and incentivizing responsible end-of-life product management.

While this study offers valuable insights, it is essential to acknowledge its limitations. The sample size, while representative of diverse manufacturing sub-sectors and augmented by the inclusion of an engineering consulting firm working with numerous MSMEs, may still limit the generalizability of findings to the broader MSME population in Morocco. Future research with larger and more diverse samples would enhance the generalizability and provide a more comprehensive understanding of DfR prioritization across different MSME contexts. Additionally, applying other MCDM techniques alongside the BWM could further validate the criteria prioritization and offer a more robust analysis.

Further research could delve deeper into the long-term implications of DfR implementation, considering factors such as technological advancements and policy changes. This would involve exploring future trends and potential disruptions that could affect the feasibility and effectiveness of the prioritized DfR criteria. Such an analysis would contribute to a more comprehensive understanding of the long-term implications of DfR strategies and enhance their practical value.

This research paves the way for extensive exploration and implementation of the DfR criteria prioritization framework within Morocco's manufacturing sector. By addressing the identified limitations and fostering interdisciplinary collaboration, future research can further advance sustainable manufacturing practices, benefiting not only Morocco but also contributing valuable insights to the global discourse on DfR in emerging economies.

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