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Metric Selection Framework: A Method for Optimizing Multidimensional Value Assessment of Resource Recovery Systems

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Keywords

metrics, complex value, resource recovery, sustainability, decision-making, value chain

Abstract

This article introduces the metric selection framework (MSF), developed as part of the CVORR+ methodology. CVORR+ is a systems-based evaluation toolkit designed to support complex sustainability assessment and decision-making. Within CVORR+, the MSF translates system analysis into decision-oriented, multidimensional metrics for monitoring, assessment, and evaluation of progress toward sustainability targets. Grounded in a value-focused decision-making approach, the framework combines expert elicitation with stakeholder engagement to ensure that metrics are system grounded, context specific, and practically relevant. Applied to England's plastic packaging system, the MSF reveals systemic inefficiencies, identifies leverage points for intervention, and informs policy design to support systemic value recovery. The case study demonstrates the heuristic and practical value of the MSF in capturing interdependencies across environmental, economic, social, and technical domains. Future developments will streamline

the translation from system conceptualization to metric development, ensuring that metrics are responsive to long-term monitoring and policy-making, remain aligned with technological and regulatory shifts, and enhance the robustness and transferability of CVORR+.

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1. INTRODUCTION

The pursuit of sustainability has become a central theme in global discourse, driving policy, industry, and academic agendas worldwide. Yet, since the 1987 Brundtland report (1), progress toward sustainable development has been uneven. Divergent definitions, varying interpretations of sustainability, and fragmented assessment methods continue to hinder coherent decision-making across value chains (2–4). These inconsistencies limit coordinated strategies to address global challenges, such as pollution, climate change, biodiversity loss, poverty and inequality, food and water security, and infrastructure resilience (5–9).

Resource and waste management exemplifies these tensions. The sector must urgently shift away from traditional end-of-pipe solutions that focus primarily on waste treatment to prevent pollution or on improving production efficiency alone. Such strategies are limited in effectiveness, especially when they neglect to address systemic impacts across social, economic, technical, and environmental dimensions of value chains. Instead, a comprehensive approach is needed that prioritizes resource recovery and value retention; aligns production, consumption, and management with planetary boundaries; and ensures that solutions consider interdependencies across all domains (3, 10, 11). Achieving this transition requires robust sustainability assessments that not only improve resource recovery efficiency but also embed circular economy principles and respond to evolving policy mandates (12, 13).

Over the past three decades, a proliferation of guidelines, standards, frameworks, and tools, including life-cycle assessment, triple bottom line, cost-benefit analysis, life-cycle costing, and

social life-cycle assessment, have generated useful insights (13, 14). However, critiques converge on their limited capacity to capture the holistic and interconnected nature of sustainability. Many of these approaches emphasize single dimensions (e.g., environmental or economic), treat others superficially (e.g., social), and overlook the interdependencies and feedback loops that shape system dynamics (SD) (4, 13–20). In particular, the technical dimension, which determines the feasibility and effectiveness of resource recovery, remains systematically underrepresented. This underrepresentation persists despite this dimension being central to value retention (through, e.g., reuse), loss (e.g., degradation or dissipation into waste), or creation (e.g., by repurposing or industrial symbiosis) in material, component, and product (MCP) systems, as exemplified by recent studies (12, 21–24).

In our 2017 systematic review, we showed that current frameworks rarely capture the complex, multidimensional value of MCP flows across value chains (13). This gap persists. Post-2017 literature identifies three core challenges: (a) a lack of explicit assessment of technical performance alongside environmental, economic, and social domains (19, 25–34); (b) reliance on a preselected set of static, universal, or generic metrics that fail to account for contextual variability (16, 35, 36); and (c) the absence of a systematic transparent process for selecting metrics that reflect stakeholder priorities and cross-domain trade-offs (27, 35, 37–40). These omissions constrain the ability of sustainability assessments to inform and guide decision-making in MCP systems and beyond (13), a challenge that resonates across sectors (41–45). Public health requires balancing cost-effectiveness with equity and accessibility (46); infrastructure planning must weigh resilience, social impact, and environmental performance alongside fiscal efficiency (47–52); and climate and energy policies must capture cobenefits for both air quality and public health (43). Even national well-being frameworks now incorporate multidimensional sustainability metrics, reflecting the broader shift toward holistic approaches to development (53).

To address these gaps, we introduce the complex value optimization for resource recovery (CVORR+) framework and its metric selection framework (MSF). CVORR+ provides a scientifically grounded, systems-based methodology that conceptualizes value as a multidimensional construct, coproduced through processes (flows of mass, money, and information) and structures (stakeholders, institutions, and networks) and operating within an enabling environment shaped by natural, technological, governance, market, and behavioral conditions (54). Building on this framework, the MSF offers a structured, context-sensitive process for selecting sustainability metrics across environmental, economic, social, and technical domains. Unlike prior approaches, it explicitly incorporates technical metrics and provides a systematic pathway to tailor metrics to specific MCP contexts. The intended audience for this framework includes practitioners, policy makers, designers, and resource and waste managers seeking to evaluate and improve sustainability performance in resource recovery and circular economy systems.

This article is organized as follows: Section 2 reviews value-focused decision-making approaches relevant to metric selection. Section 3 describes the development of the MSF as a decision-structuring tool, and Section 4 demonstrates its application through a worked example. Finally, Section 5 discusses implications for research and practice.

2. OVERVIEW OF SELECTED DECISION-MAKING APPROACHES

Robust sustainability assessment requires decision frameworks that treat value as an operational, multidimensional construct encompassing environmental, economic, social, and technical dimensions, simultaneously (27, 55). Political values, while integral to complex value, are not treated as a separate, directly measurable domain. Instead, they are captured indirectly through proxies (e.g., regulatory feasibility, governance capacity, or institutional stability) embedded across

the four measurable value domains. This approach ensures both feasibility and conceptual comprehensiveness, thereby supporting sound decision-making (56, 57).

Traditional assessment and evaluation approaches often rely on convenience-driven sets of predefined metrics, which may fail to reflect system-level priorities, resulting in incomplete or suboptimal evaluations (42, 58). This tendency highlights the need for frameworks that explicitly link problem framing and system goals to subsequent metric identification and selection, ensuring that the chosen metrics are both contextually relevant and decision oriented (38, 59, 60).

Value-focused thinking (VFT), articulated in 1996 by Keeney (60) and also known as an expert-driven approach, provides a structured, top-down method to define what truly matters in a decision context (61). VFT begins with the identification of high-level objectives, which are decomposed into subobjectives and then translated into measurable attributes. Candidate metrics are subsequently derived to operationalize these attributes, ensuring that measurement directly reflects the values embedded in the decision problem. This expert-driven approach is particularly effective at revealing latent or hidden objectives; at ensuring conceptual completeness across domains; and at producing metrics that are interpretable, relevant, and aligned with overall goals (60, 61). Key limitations of VFT are the potential underrepresentation of stakeholder perspectives and the risk of incomplete elicitation where expert input is constrained (62).

In contrast, alternative-focused thinking (AFT) prioritizes stakeholder-driven, bottom-up processes that begin with a predefined set of alternatives. Metrics are then selected to evaluate these alternatives, emphasizing local context, operational constraints, and stakeholder priorities (61, 62). While AFT enhances legitimacy and stakeholder buy-in, it may also constrain the decision space to existing options, potentially neglecting objectives that are not represented among known alternatives and overlooking innovative or optimal solutions (3, 19, 50). **Table 1** summarizes the characteristics, strengths, and limitations of these two approaches.

Table 1 Comparison of Keeney's decision-making frameworks: attributes, strengths, and limitations^a

Decision-making approach	Value-focused thinking	Alternative-focused thinking
Approach description	Articulates overall objectives, decomposes them into subobjectives, and derives attributes and metrics for measurement	Articulates predetermined potential alternatives, emphasizing local context constraints and stakeholder priorities, and derives metrics directly from alternatives for their evaluation
Type of approach	Top-down, expert driven	Bottom-up, stakeholder driven
Metric selection	Value based, directly linked to objectives and attributes	Focus based, directly linked to alternatives
Strengths	Reveals both explicit and hidden subobjectives Ensures that metrics align with system-level goals Supports complex system analysis Facilitates evaluation of alternatives	Captures context and operational relevance Increases stakeholder engagement and buy-in Produces operationally meaningful metrics
Limitations	May neglect stakeholder engagement Relies on expert judgement May dismiss broader systemic effects or unarticulated objectives	Constrains decision space to known alternatives May overlook latent or hidden objectives or innovative and optimal solutions May risk favoring existing options
Application examples	Health technology assessment (63); land acquisition (38); landscape ecology, conservation, and economics (62)	Organizational cost-saving strategies (64)

^aData are from Reference 60.

Epistemologically, VFT aligns with positivist scientific traditions that prioritize conceptual completeness, explicit methodologies, and quantitative rigor. Conversely, AFT draws on constructivist and participatory traditions that prioritize legitimacy, local knowledge, and stakeholder legitimacy (61, 62). Evidence from the literature suggests that hybrid frameworks combining VFT and AFT can capitalize on the strengths of both approaches, enhancing conceptual completeness and contextually relevant decision support (65).

Hybrid frameworks typically begin with a top-down value tree, which structures high-level objectives and ensures coverage across value domains. This structure is subsequently refined through bottom-up stakeholder engagement, generating practicable and contextually relevant metrics (63, 65). By integrating both approaches, hybrid frameworks reconcile completeness with relevance, producing context-sensitive, coherent, and policy-relevant metrics that support decision-making under uncertainty. Additionally, these frameworks require careful attention to knowledge governance as well as data collection and management, to ensure that metric sets remain scalable, comparable (where appropriate), and adaptable across spatial and temporal scales. Stakeholder engagement is guided but limited to feasible subsets of stakeholders, balancing representativeness with tractability.

Operationally, hybrid approaches are implemented through multicriteria decision analysis (MCDA), which translates objectives and attributes into measurable criteria and metrics, elicits stakeholder preferences, and makes trade-offs explicit under uncertainty (66, 67). MCDA supports both compensatory aggregation (e.g., multiattribute value theory, an analytical hierarchy process) and noncompensatory or outranking methods [e.g., ELECTRE (elimination and choice expressing the reality) and PROMETHEE (preference ranking organization method for enrichment of evaluations)]. The choice of method should follow the decision context, data availability, and stakeholders' tolerance for compensability. Detailed descriptions and comparisons can be found in existing literature (58, 66–68).

In CVORR+, MCDA is a bridging step that converts MSF-defined metrics into actionable evaluation indicators, guiding the selection of scoring scales and normalization procedures as well as weighting and integrating stakeholder preference. It also facilitates sensitivity and uncertainty analyses to test robustness and support iterative refinement. The detailed integration and operationalization of the MCDA into CVORR+ lie outside the scope of this review. The MSF introduced here is not an implementation or scoring tool; rather, it provides a structured foundation for rigorous metric development and selection by defining objectives, subobjectives, and attributes in a standardized manner. Essentially, the MSF guides subsequent data collection and informs evaluation through MCDA, ensuring robustness, transparency, and reproducibility in sustainability assessment.

3. METHODOLOGICAL NARRATIVE: DEVELOPING THE METRIC SELECTION FRAMEWORK

In this article, a framework is understood as a structured conceptual and methodological approach that systematically organizes components and their interrelationships to support transparent analysis and decision-making (69). Unlike models, which primarily seek to simulate or predict outcomes, frameworks structure thinking and action by clarifying what matters, how problems should be framed, and which elements must be considered during evaluation (69–71). A robust framework is therefore characterized by conceptual clarity, logical structure, and transparency (72). To be effective, it must also be accessible to stakeholders, adaptable across spatial and temporal contexts, and implementable with available methods and data (73).

The CVORR+ framework meets these criteria. CVORR+ is a systems-based analytical toolkit that integrates established methods, such as mass flow analysis (MFA), stakeholder theory, the

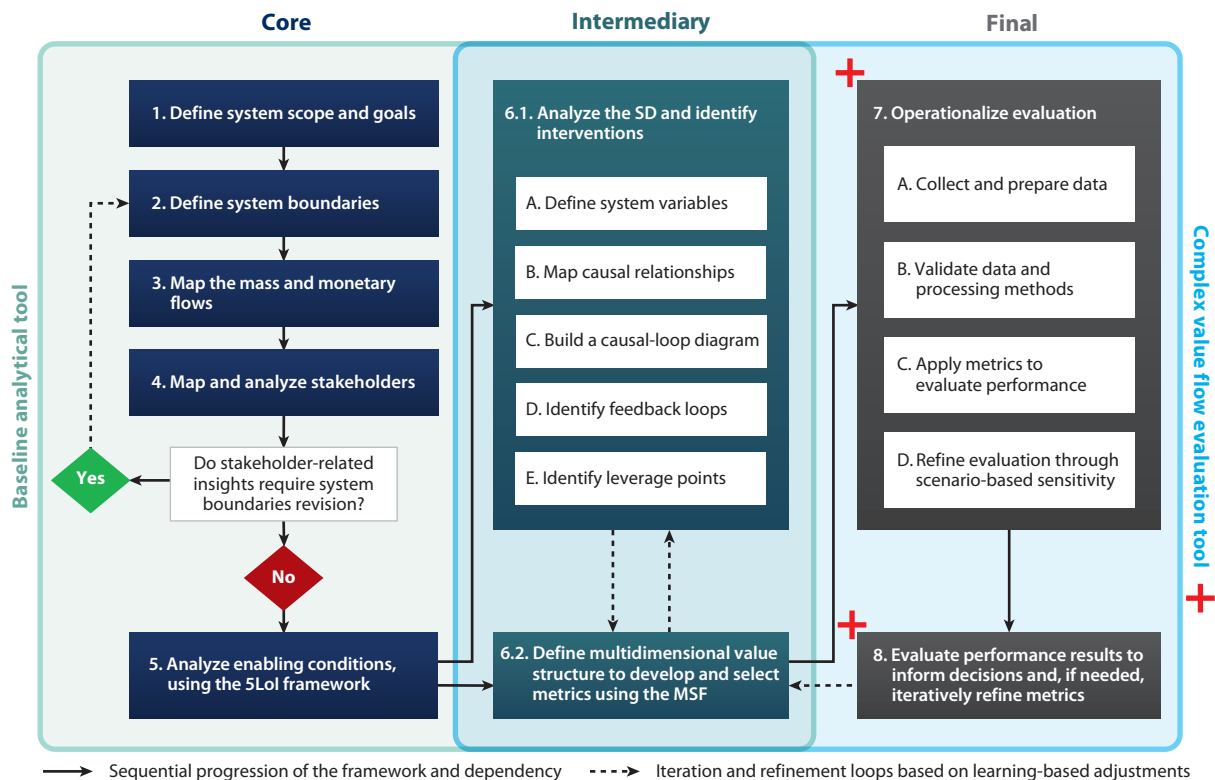


Figure 1

Overview of the CVORR+ framework. A system-wide assessment toolkit structured into three interconnected phases: the core phase (baseline analytical tool), the intermediary phase (SD and MSF), and the final phase (complex value flow evaluation tool). The core phase establishes the system scope, boundaries, mass and monetary flows, stakeholder configurations and enabling conditions through the 5LoI framework. The intermediary phase combines SD analysis and the MSF to identify causal relationships, feedback loops, leverage points, multidimensional value structures, and decision-relevant metrics. The final phase operationalizes evaluation by applying the metrics to assess system performance and support decision-making. The plus sign represents optional analytical extensions (data dependent). Solid arrows indicate primary process flow and dependencies, whereas dashed arrows represent iteration and refinement loops. Abbreviations: CVORR+, complex value optimization for resource recovery; MSF, metric selection framework; SD, system dynamics; 5LoI, five levels of information. Figure adapted from Reference 91.

Mendelow matrix, SD, and MCDA, with uniquely formulated components such as the CVORR-extended stakeholder analysis, the five levels of information (5LoI) framework, and the MSF (74, 75). Together, these elements streamline connectivity between methods, cut through complexity, ensure scientific rigor, and operationalize system insights coherently and credibly. CVORR+ was initially developed to evaluate complex value in MCP systems, with potential extensions to services, cities, and organizations.

3.1. Overview of the CVORR+ Toolkit and Prerequisites for the Metric Selection Framework

CVORR+ is designed as a three-phase toolkit, illustrated in **Figure 1**, that reflects its integrated approach. It includes:

1. A baseline analytical tool that establishes the system context; maps mass and monetary flows and stakeholder configurations (using MFA, stakeholder theory, the Mendelow matrix, and

the CVORR-extended stakeholder analysis); and identifies key systemic drivers, barriers, and enabling conditions (via the 5LoI framework).

2. An intermediary phase in which the SD and MSF are embedded, translating system insights from the baseline analysis and, where undertaken, SD analysis into context-sensitive, value-driven metrics, and actionable interventions.
3. A complex value flow evaluation tool that applies the selected metrics using MCDA to evaluate system performance, assess trade-offs, and support decision-making.

This ordering sets CVORR+ apart from conventional siloed sustainability assessments by ensuring that metrics are selected on the basis of a comprehensive understanding of the system and its dynamic behavior, feedback loops, and value creation mechanisms, rather than being predefined.

The baseline analysis draws on three core building blocks: (a) processes (mapping mass and monetary flows and their interactions), (b) structures (identifying, mapping, and analyzing stakeholders and networks that shape system organization), and (c) values (capturing the norms, behaviors, priorities, and dynamics that influence decision-making). These building blocks operate across five interdependent subsystems (i.e., environmental, technical, political, economic, and social), of which conceptual assessment is operationalized through the 5LoI framework. The 5LoI framework generates insights about the system's structure, drivers, and barriers. From this baseline, two complementary analytical pathways can be followed: (a) the determination of how complex value is created, conserved, or destroyed across these subsystems, operationalized through SD in step 6.1 of the CVORR+ (**Figure 1**), and (b) the development of metrics through the MSF (step 6.2), informed directly by the baseline analysis outputs. The MSF can be used independently of SD; however, where SD is applied, its outputs should be used to inform and refine the MSF.

The SD approach serves a dual purpose: It maps interactions among system variables by revealing feedback loops and interdependencies while also identifying potential interventions for evaluation. SD is particularly well-suited for analyzing large-scale, complex systems, as it generates insights into system behavior over time, as well as the influence of systemic structural drivers, lock-in effects, and pathways for change (76). In CVORR+, SD is intentionally limited to causal loop diagrams (CLDs), although the method can be expanded to include stock-flow models, simulation runs, and scenario analysis (76).

CLDs provide a qualitative representation of system interrelationships, highlighting cause-and-effect relationships, feedback loops, leverage points, and cross-domain interactions. For instance, an increase in recycling rates leads to a reduction in reliance on landfill use and in greenhouse gas (GHG) emissions, revealing leverage points where interventions can increase benefits or create trade-offs (e.g., the introduction of a new recycling technology) (77). Moreover, CLDs illuminate how changes in one domain, for example, the technical domain [e.g., adopting chemical recycling or introducing extended producer responsibility (EPR)], can cascade into environmental, social, and economic domains and vice versa. CLDs play a pivotal role in supporting the MSF by visualizing cause-and-effect relationships and revealing lock-in mechanisms, thereby aiding the interpretation of subobjectives in relation to systemic structures when such analysis is undertaken. Rather than operating as a purely linear step between baseline analysis and MSF, CLDs function as an optional integrative refinement tool that enhances transparency in metric selection and optimizes decision-making. In this iterative process, preliminary metrics may be refined or expanded when SD is applied, as it reveals key feedback loops and potential intervention points (alternatives).

Table 2 Terminology adaptation from established decision-analysis concepts to CVORR+’s framing^a

Level	Definition in decision-analysis frameworks	CVORR+ framing
Overall objective	The overarching goal of the decision process; scope definition and problem framing	Optimize the system-wide complex value of a material, component, and product (i.e., resource/waste) system by conserving, creating, and avoiding destruction of value
Subobjectives	Thematic aims decomposing the overall objective; specify what value means in practice	Primary subobjectives: Domain-level aims (environmental, economic, social, and technical) are further decomposed into secondary subobjectives Secondary subobjectives: cause-and-effect expression of domain-level aims and stakeholder concerns
Attributes (conceptualizing subobjectives)	Conceptual performance measures that link subobjectives to measurable, understandable, and sensitive-to-change indicators	Conceptual performance measures that link secondary subobjectives to measurable, understandable, and sensitive-to-change indicators
Metrics (operationalizing subobjectives)	Operational measures that quantify attributes	Operational measures that quantify attributes
Alternatives (interventions)	Mutually exclusive courses of action, interventions, or system configurations compared in terms of objectives	Concrete interventions representing distinct system changes

^aData are from References 60 and 71.

3.2. Positioning and Purpose of the Metric Selection Framework

The MSF, embedded within the intermediary stage of the CVORR+ (Figure 1), operationalizes CVORR+’s overarching objective of maximizing complex value by providing a systematic pathway that links subobjectives to attributes and metrics. The MSF avoids collapsing diverse values into a single aggregated metric or index; instead, it maintains the incommensurability of value domains while enabling comparability across them. Table 2 shows how established decision-analysis terminology is adapted within CVORR+.

A key innovation of CVORR+ is the decomposition of subobjectives into primary and secondary. Primary subobjectives correspond to domain-level aims (environmental, economic, social, technical) informed by the baseline analysis. Political values, as mentioned above, are considered indirectly as proxies embedded across the four measurable value domains. Secondary subobjectives express specific cause-and-effect expressions of these goals, informed by the baseline analysis, and optionally refined through SD insights, particularly CLDs, which help elucidate feedback loops and mechanisms of value creation, retention, or loss. Attributes, the conceptual performance dimensions, serve as the bridge between secondary subobjectives and metrics.

Attributes are derived directly from the system’s values and structure. Their purposes are to retain the intent of the value statement and to reframe it in a form that is measurable, comparable, and sensitive to system change. This contrasts with approaches that define metrics on the basis of predefined attributes (47, 78–81). Such approaches can be suitable in some contexts, but in systems-based sustainability assessments, they risk misrepresenting system realities and neglecting interconnections that reveal critical dynamics and opportunities for value optimization (82).

This hierarchical flow ensures that metric selection is driven by value considerations rather than by available data, helping to avoid metric shopping and instead supporting more robust, transparent decision-making. Metric shopping refers to the practice of selecting indicators or

metrics opportunistically on the basis of data availability or convenience or to support a desired conclusion, rather than systematically deriving them from the underlying values, objectives, or system structure. This approach risks biasing assessments, misrepresenting system realities, and undermining the robustness and transparency of decision-making, because the metrics may not accurately reflect the multidimensional aspects of system performance or stakeholder priorities.

3.3. Designing the Metric Selection Framework

The design of the MSF explicitly combines the strengths of VFT and AFT. From VFT, the MSF inherits a top-down logic: starting with objectives and systematically decomposing them into sub-objectives, attributes, and candidate metrics to guarantee conceptual completeness (inductively). From AFT, the MSF incorporates a bottom-up process: engaging stakeholders to validate, refine, and contextualize metrics to ensure decision relevance and legitimacy (deductively). In practice, this hybridization is implemented in two sequential stages.

The first stage is the inductive stage (VFT oriented). Baseline analysis (steps 1–5) informs the development of primary and secondary subobjectives, which are subsequently translated into variables (step 6.1), attributes, and metrics (step 6.2). Specifically, insights from the baseline analysis can aid in the formulation of subobjectives grounded in the mechanisms of value creation, conservation, or loss; assigning them to one of the four measurable value domains; and consolidating overlaps or duplicates. This process includes the identification of recurring causal structures and the systemic drivers and barriers. Where SD through CLDs (step 6.1) is applied, the process of metrics development and selection may be further refined through the identification of reinforcing (positive) and balancing (negative) feedback loops, dominant cause-and-effect relationships, and potential leverage points (83). Step 6.1 is currently being refined and validated in ongoing work. This article applies a set of secondary subobjectives derived solely from the baseline analysis.

Each secondary subobjective expresses a systemic aspect that must be translated into an observable property of the system. In practice, a secondary subobjective could be associated with one or more attributes that capture its essential dimensions, which are then formulated into metrics. For example, in the environmental domain, a secondary subobjective is to reduce reliance on landfill, which translates into the attribute of waste diverted from landfill. This can then be measured through metrics such as percent of municipal waste diverted or tonnes per year diverted. Similarly, the secondary subobjective to reduce life-cycle GHG emissions maps to the attribute of life-cycle GHG intensity, with metrics such as kilograms of CO₂ equivalent per tonne of MCP. In the technical domain, a secondary subobjective could be improved recycle quality, which could be expressed as the attribute of purity of secondary materials, with metrics such as percent of contamination rate in sorted waste streams.

In the second stage, the deductive stage (AFT oriented), stakeholder engagement via participatory workshops or targeted interviews is employed to validate and refine attributes and metrics and may introduce new ones where appropriate. This process ensures that metrics are contextually feasible, scientifically defensible, and decision oriented, while capturing the dynamic nature of stakeholder needs, priorities, and interests (62, 66). It also strengthens legitimacy by embedding stakeholder perspectives into the framing of value, hence aligning institutional and organizational realities. All stakeholder suggestions are explicitly mapped back to the baseline analysis and, where available, SD representations through CLDs, to maintain systemic coherence, reconcile differences, and avoid siloed or disconnected metrics. Stakeholder engagement can be iterative, allowing metrics to be revised as system boundaries expand, new interventions are considered, or configurations of stakeholders (e.g., regulators, industries, consumers) change.

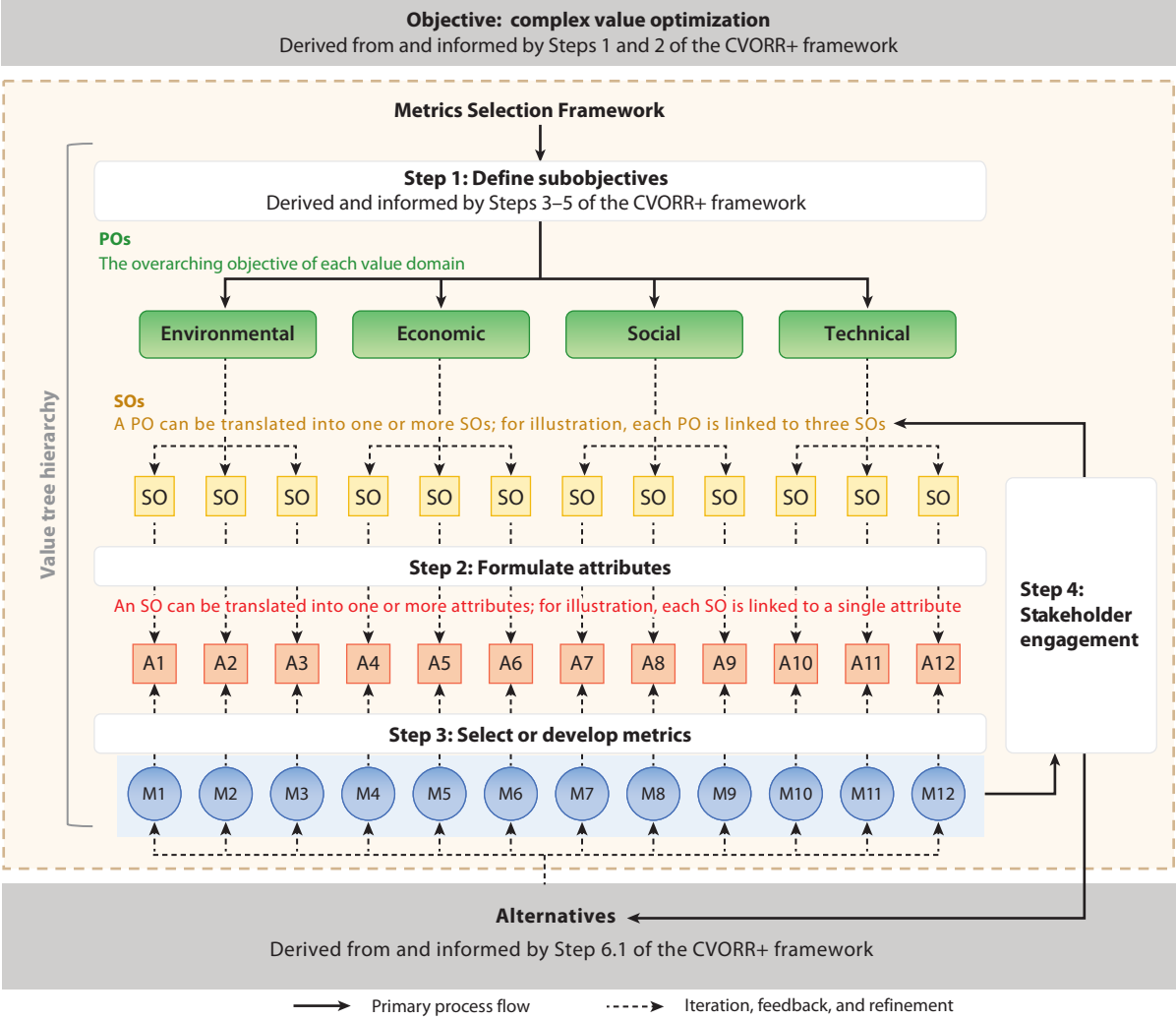


Figure 2 Conceptual architecture of the MSF embedded within the CVORR+ intermediary phase. The MSF illustrates how the baseline analysis (steps 1–5 in **Figure 1**) informs the hierarchical derivation of POs into SOs, attributes, and metrics across the environmental, economic, social, and technical value domains. The framework incorporates stakeholder engagement and iterative refinement to support the development of decision-relevant metrics. Where undertaken, SD analysis (step 6.1 in **Figure 1**) may further refine metrics, strengthen systemic alignment, and identify intervention-based alternatives through feedback loops and leverage points. These alternatives are subsequently evaluated using the metrics generated through the MSF, while also informing the need for metric adaptation and the development of additional metrics. Abbreviations: A, attribute; CVORR+, complex value optimization for resource recovery; M, metric; MSF, metric selection framework; PO, primary subobjective; SO, secondary subobjective.

The integration of these stages is shown in **Figure 2**, which illustrates the MSF as a four-step process as follows:

1. Derive primary and secondary subobjectives, documenting baseline analysis and CLD origins.
2. Translate each secondary subobjective into an attribute or attributes.

3. Generate candidate metrics for each attribute and screen the metrics developed for appropriateness and relevance using explicit criteria.
4. Pilot metrics through stakeholder engagement to finalize the metric set and prepare for MCDA input.

This protocol ensures replicability and provides practitioners with a prescriptive, traceable method for moving from systemic understanding to developing a defensible metric set. Where SD is undertaken, the resulting insights can be used to assess alignment between metrics, causal relationships, and intervention points, enabling refinement of metrics developed through the MSF (step 6.2) and the development of additional metrics where needed. The protocol also supports the evaluation of alternatives, as well as the monitoring, adaptation, and inclusion of new metrics under defined review cycles.

It is important to clarify that alternatives are not generated as part of the MSF, yet the MSF provides the lenses (i.e., the metrics) through which alternatives are assessed and monitored. Alternatives correspond to specific interventions that need to be designed to shift feedback loops in desirable directions, as informed by the causal structures defined through the baseline analysis and CLDs. For instance, reinforcing loops highlight where interventions can accelerate causal effects (e.g., strengthening recycling infrastructure to boost participation and reduce landfill dependency), while balancing loops illuminate lock-in dynamics that may require policy, market, or technical interventions (e.g., landfill taxes, extended producer responsibility). In this way, alternatives are grounded in systemic leverage points rather than ad hoc options (12). Stakeholders may also propose alternatives on the basis of local knowledge and data availability or flag barriers that may constrain implementation (e.g., infrastructural or policy related). This dual approach to the development of alternatives ensures they are both systemically justified and practically viable.

3.4. Attribute Taxonomy and Metric Selection Criteria

Attributes must effectively translate subobjectives into measurement dimensions that capture the unique structure and dynamics of MCP systems. They must balance contextual relevance to policy and stakeholder goals, specificity, and physical traceability. These requirements can be organized into a taxonomy, as follows:

- Contextually relevant attributes are those aligned with context-specific policy targets, regulatory priorities, capacity, transparency, and issues of concern arising from the baseline analysis. These attributes ensure that assessments remain consistent with policy agendas. Examples include direct CO₂ emissions (environmental), raw material prices (economic), job creation (social), public health (social), and regulatory compliance capacity (technical).
- MCP-specific attributes capture the embodied values and life-cycle characteristics of MCPs themselves, as well as adaptability and system trajectories over time, reflecting dynamics revealed in baseline analysis and CLDs. Examples include energy intensity (environmental), embodied carbon (environmental), accessibility to MCPs (social), user adoption rate (social), durability (technical), and resilience to supply shocks (economic).
- Mass-specific attributes are attributes tied to physical flows and material recovery goals. These are grounded in baseline mass and monetary flow analysis and are particularly relevant for regulatory compliance and performance monitoring. Examples include per capita demand for MCPs (social), recycling rates (technical/economic), landfill diversion (environmental), participation rate in recycling programs (social), mass recoverability (technical),

Table 3 List of criteria used for metric selection

Criterion	Definition	Fulfillment	References
Relevance (fit for purpose)	Must be directly linked to the defined subobjectives and can be generic (related to a general issue) or diagnostic (specific to a trend)	Explicitly linking metrics to specific subobjectives	44, 84–86
Nonredundancy	Avoiding overlapping attributes or metrics to maintain parsimony and clarity	Reviewing the pool of attributes	85–87
Operationality (simple to use)	Must be measurable with clear units and feasible data requirements	Applying the metrics in real-world or simulated scenarios	44, 84–87
Comprehensibility (easy to understand)	Easily interpretable and intuitively understood by both technical and nontechnical stakeholders	Providing clear explanations suitable for all stakeholders	44, 84, 86, 87
Scalability (sensitive to change)	Reproducible and consistent across system scales (static and dynamic) and over time	Testing reproducibility and consistency of metrics across system scales and over time	44, 86, 87
Preference neutrality	Maintaining holistic perspectives, fairness, and objectivity	By stakeholder review, bias analysis, scenario testing, and ensuring transparency to confirm fairness and objectivity	87

household-level or sector-level consumption of MCPs (social, economic), and secondary resource flows (technical, environmental, economic).

This taxonomy can lead to cross-domain attributes that explicitly capture synergies and trade-offs across the environmental, economic, social, and technical domains. Metrics operationalize attributes, and their selection is guided by explicit criteria. In much of the sustainability and decision-analysis literature, the terms “criteria” and “attributes” are often used interchangeably (47, 50, 56), which creates conceptual ambiguity. Here, we adopt a precise distinction: Criteria are the conditions that metrics must satisfy to qualify for selection, ensuring that they can meaningfully measure progress toward defined goals and objectives.

According to Mitchell (56), selection criteria must meet three fundamental requirements. They must (a) assess the status quo, enabling insights into the business-as-usual systems; (b) evaluate policy and interventions, allowing for measurement of the performance of current and future policies; and (c) monitor progress, tracking changes in enabling conditions and interventions over time. These requirements ensure that metrics support effective decision-making by linking system analysis to desirable states and policy goals. **Table 3** summarizes the essential properties that selection criteria must embody to be scientifically defensible and practically applicable.

Recent literature in sustainability science emphasizes that metrics should be (a) relevant to system values and assessment objectives and system boundaries, (b) distinct to avoid redundancy, (c) operational for measurement (quantifiable) and easy to apply with reasonable data demands, (d) comprehensible for users, (e) scalable and time consistent for longitudinal assessment (repeatable and comparable), and (f) preference neutral to ensure unbiased evaluation (44, 56, 84–87). These properties reinforce the MSF’s methodological rigor and ensure that metrics are both meaningful and deployable in decision contexts.

To ensure that these criteria are met, an approach following the principles of systematic evidence mapping is employed in which metrics are screened independently by multiple

researchers to promote objectivity and reduce bias. Additionally, collaboratively reviewing the pool of attributes and maintaining transparency throughout the process help confirm fairness and consistency, ensuring that the selected metrics are relevant, operational, comprehensible, scalable, and unbiased. Systematic validation processes are essential for ensuring that metrics are fit for purpose; therefore, a rigorous implementation of validation and review procedures is necessary to confirm full compliance. However, detailed application of these processes is beyond the scope of this article.

3.5. Stakeholders' Engagement in the Metric Selection Framework

The engagement of relevant stakeholders in the MSF ensures that metrics are not only technically valid (by those whose interests are materially affected by the system) but also legitimate (by those whose involvement is necessary for governance) and practically implementable (by those who hold essential data or expertise) (88). However, engaging all potential stakeholders can lead to overload and may blur governance responsibilities, requiring careful management to balance inclusivity with clarity.

Stakeholders are therefore prioritized by drawing on the baseline analysis, particularly on the stakeholder theory and the Mendelow matrix (75). Stakeholder theory categorizes stakeholders on the basis of their level and nature of involvement in the system into direct (e.g., directly participating in mass flows) and indirect (not directly involved in mass flows but potentially highly influential) and on the basis of their legal status. The Mendelow matrix further assists in pinpointing stakeholders with the highest levels of interest in system outcomes, regardless of their power within the system. As a result, stakeholder prioritization depends on the scope and primary goals of the analysis, as well as on its capacity to influence or implement change. For example:

- Strategic goals (policy design, infrastructure investment) require the involvement of decision-making authorities (local/national governments, regulators, financial institutions, industry) with the authority to adopt metrics and act upon analysis results or guide their implementation (researchers, consultants).
- Technical goals (e.g., measuring recovery efficiency) require representation by technical experts, analysts, data modelers, and engineers who design the methodology, run models, and interpret results and those who are involved in the installation and implementation of technological solutions (in industry, e.g., designers, manufacturers, utilities, contractors, and other service providers and technology suppliers).
- Multidimensional goals (social acceptance, environmental justice, economics) require wider representation involving both (a) contributors (e.g., industry, goods producers, enterprises, government, NGOs) to outcomes that hold data and knowledge and (b) affected stakeholders (e.g., consumers, communities, community-based organizations, trade associations) who are affected by outcomes or represent key societal values.

Stakeholder engagement is structured through consultation, workshops, focus groups, or advisory panels, but not all stakeholders may be equally involved in every stage. This flexibility is supported by Pohekar & Ramachandran (89), who explain that different groups of decision-makers (in their respective disciplines/business) can bring along different points of view that are often conflicting, as these points of view are highly dependent on the decision-makers' knowledge and preferences. These conflicting points of view can be resolved by providing a safe space for stakeholders to voice their concerns while keeping all stakeholders involved in the metric codevelopment and selection process (37, 89).

4. USING THE METRIC SELECTION FRAMEWORK: THE PLASTIC PACKAGING SYSTEM IN ENGLAND

The purpose of the MSF application was to develop metrics for assessing and monitoring progress in the plastic packaging (PP) system in England. The metrics were intended to support progress toward meeting the government's targets of achieving a 70% recycling rate for PP waste (PPW) and increasing the average recycled content in all PP to 30% by 2025 while also identifying broader environmental, economic, social, and technical benefits (90).

The CVORR+ baseline analysis provided the foundation for this process. Together with stakeholder-informed system scoping, it highlighted systemic inefficiencies and lock-ins that constrain value recovery. Stakeholder engagement was integral at multiple stages, from contributing insights to the baseline analysis and participating in the MSF operationalization to proposing alternatives (interventions) that are fully aligned with the CVORR+ philosophy.

4.1. From Objective to Subobjectives

The overall objective of the analysis was to increase PPW recycling rates, minimize value losses, and ensure progress toward national targets while retaining wider multidimensional benefits. The baseline analysis revealed several systemic lock-ins and inefficiencies. These included:

- poor source separation of PPW;
- high levels of littering and fly-tipping of PPW;
- prevalence of nonrecyclable PP types (e.g., multilayer, black plastics);
- high rejection rates at sorting facilities, specifically at material recovery facilities and plastic reprocessing facilities;
- reliance on exports to meet recycling targets;
- uneven distribution of revenues under the PRN (packaging recovery note) and PERN (packaging export recovery note) schemes;¹
- barriers to packaging design changes (e.g., color, labeling, and polymer types);
- uncertainty around the effectiveness of policy instruments in driving recycling, such as the PP tax;
- insufficient household participation in recycling schemes; and
- lack of public awareness around the importance of recycling and its contribution to recycling efforts.

These systemic insights were translated into four primary subobjectives (step 1 of the MSF), aligned with the CVORR+ value dimensions:

- Environmental: Reduce the environmental burden of PP.
- Economic: Increase the cost efficiency of the packaging system and avoid lost revenues.
- Social: Improve participation and trust in recycling efforts.
- Technical: Improve infrastructure capacity and throughput.

Each primary subobjective was systematically examined against the baseline analysis and its causal structures. Specific challenges or leverage points identified were reframed into 14 context-dependent secondary subobjectives, capturing specific, context-dependent expressions of value. This approach ensured that secondary subobjectives were grounded in mechanisms of value

¹For clarity, these schemes generate tradable certificates that act as evidence that PPW has been recycled or exported for reprocessing, respectively. Businesses with packaging obligations purchase these notes from accredited reproducers and exporters to meet their targets under the EPR scheme, with the revenue supporting the United Kingdom's packaging recycling infrastructure.

Table 4 Primary and secondary subobjectives for assessing and monitoring progress in increasing the plastic packaging system in England

Domain	Primary subobjectives	Secondary subobjectives
Environmental	Reduce the environmental burden of plastic packaging	Reduce environmental impacts
		Reduce virgin resource reliance
		Reduce reliance on export pathways
Economic	Increase the cost efficiency of the packaging system and avoid lost revenues	Minimize net system costs
		Maximize recovered value
		Minimize externalized costs
		Improve cost efficiency
Social	Improve participation and trust in recycling efforts	Increase household participation in recycling
		Ensure fairness in distribution of costs/benefits
		Build trust and acceptability
Technical	Improve infrastructure capacity and throughput	Improve sorting and reprocessing capacity
		Increase recyclate quality
		Promote design for recyclability

retention, creation, or loss. For example, the environmental primary objective of reducing the environmental burden of PP was decomposed into the following: Reduce virgin resource reliance, reduce reliance on export pathways, and minimize environmental impacts from mismanaged waste. All secondary subobjectives are summarized in **Table 4**.

The secondary subobjectives thus derived were then cross-checked with stakeholders to validate relevance and ensure that they captured both the strategic value dimensions and context-specific system challenges. The inductive derivation of subobjectives reflects the logic of VFT, while their subsequent refinement and validation with stakeholders illustrate the participatory grounding of AFT.

4.2. From Subobjectives to Attributes and Metrics

In line with steps 2 and 3 of the MSF, secondary subobjectives were translated into attributes and candidate metrics. The translation process followed the MSF logic, attribute taxonomy, and metric selection criteria. It included the identification of the core intent of each secondary subobjective on the basis of recurring causal themes, the translation of the intent into a measurable property of the system that serves as a proxy for tracking progress, and the development of candidate metrics to quantify the property using available data.

For example, the subobjective of reducing reliance on export pathways was expressed through the attribute of export dependency, with the corresponding metric defined as the percentage by weight of PPW exported as a proportion of total waste generated. Similarly, the subobjective of improving infrastructure capacity was represented by the attributes of sorting system efficiency and reprocessing efficiency, measured through percentage losses at material recovery and reprocessing facilities. MCP-specific attributes (e.g., raw material consumption, embodied carbon, water use, and additives) were included selectively to retain strategic focus and avoid metric overload.

Recurring themes from the baseline analysis and causal structures informed attribute development, linking systemic issues to operational metrics. These themes included the following:

- measuring the proportion of PPW reprocessed domestically;
- capturing postconsumer recycled plastic content in new packaging POM (placed on the market);

- tracking exports of PPW and risks of environmental leakage;
- quantifying energy recovery from PPW;
- quantifying cleanup and damage costs (remediation);
- quantifying costs avoided and revenues captured through improved recycling;
- monitoring household responses to design interventions and the deposit return scheme (DRS);
- monitoring household participation in recycling schemes (e.g., correct sorting);
- mapping cost and revenue allocation across the system;
- quantifying PPW losses and rejections in sorting facilities;
- monitoring colored plastics in recycling streams as a proxy for recyclate quality; and
- quantifying nonrecyclable PPW due to design characteristics (e.g., through the share of multilayer packaging).

This process was iterative, incorporating policy priorities (e.g., recycling rates), longer-term concerns (e.g., resilience, fairness, design for recyclability), and stakeholder validation. **Table 5** presents the resulting set of attributes and 16 initial candidate metrics. While not exhaustive of all possible system measures, these metrics provided a proof-of-concept demonstration of how the MSF translates systemic objectives into operational indicators. They also highlight the balance between short-term monitoring priorities (e.g., household participation rates) and long-term structural concerns (e.g., domestic reprocessing capacity), which is central to the adaptive design of the framework.

4.3. Stakeholder Evaluation of Attributes and Metrics

The next step in the MSF (step 4) involved testing the relevance, robustness, and decision-making utility of the proposed metrics through stakeholder engagement. A workshop was conducted with 12 experts who represented diverse perspectives from waste management (former and current industry actors), policy makers (government and regulators), and local technical experts in the social sciences, particularly human behavior and economics. Stakeholders were selected on the basis of a mapping exercise (detailed in Section 3.5) to ensure strategic expertise in PP system governance.

During the workshop, stakeholders evaluated each proposed metric for usefulness in assessing and monitoring the PP system in England, across short-, medium-, and long-term periods; for alignment with the metric selection criteria (see **Table 3**); and for practicality of data collection and measurement, given existing infrastructure, value chain logistics, and policy frameworks. The outcomes are provided below by value domain:

- Environmental metric (EM) evaluation. EM1 was extensively debated, with some stakeholders arguing that it belongs in the economic rather than the environmental domain, since energy recovery may not always yield environmental benefits. However, stakeholders acknowledged its relevance for monitoring the share of PPW diverted from landfill through incineration and mechanical–biological treatment (MBT) processes, and EM1 was retained under the environmental domain. Furthermore, it was argued that some incineration facilities may not meet the requirements for energy generation, whereas the solid recovered fuel/refuse-derived fuel generated from MBT is not well-tracked in the system. These conditions could bias results and overstate the contribution of recovery routes. As a result, stakeholders recommended reframing EM1 as tonnes PPW diverted to incineration and tonnes PPW diverted to MBT to align closely with monitoring performance. EM2 was strongly supported and ranked as a high-priority metric. Although some concerns

Table 5 List of attributes and metrics for measuring progress in PPW recycling for maximizing value recovery in England

Metric number (denoting domain)	Secondary subobjective	Attributes	Metrics ^a
EM1	Reduce environmental impacts	Energy recovery efficiency ^b	% (kWh/tonne PP) calorific value recovered as electricity/heat
EM2	Reduce virgin resource reliance	Reprocessing efficiency ^c	% wt PPW reprocessed domestically (as a proportion of overall waste generated)
EM3	Reduce virgin resource reliance	Postconsumer recycled content in packaging ^c	% wt in new PP produced
EM4	Reduce reliance on export pathways	Export dependency ^d	% wt of PPW exported relative to total PPW generated annually
EcM1	Minimize system costs	Cost efficiency/revenue captured ^d	£ saved per tonne diverted from landfill/leakage
EcM2	Maximize recovered value	Value of secondary plastic ^b	£/tonne recyclate sold domestically
EcM3	Maximize recovered value	Value of secondary plastic ^b	% PPW in domestic packaging production
EcM4	Minimize externalized costs	Cleanup and damage costs ^d	£/tonne PPW spent on environmental remediation
EcM5	Improve cost efficiency	Avoided cost losses ^b	% PRN revenue retained for domestic infrastructure
SM1	Increase household participation in recycling	Recyclable PP collected ^c	% wt of PPW entering the recycling waste stream, measured relative to total annual PPW generation and PP POM
SM2	Ensure fairness in distribution of costs/benefits	Inequality (in the distribution of costs/benefits) ^d	% (on £ share of system costs by producers versus consumers)
SM3	Build trust and acceptability	Social acceptability and convenience ^d	Qualitative score: survey based
TM1	Improve sorting and reprocessing capacity	Sorting system efficiency ^c	% wt output/input of PPW at MRFs
TM2	Improve sorting and reprocessing capacity	Sorting system efficiency ^c	% wt output/input of PPW at PRFs
TM3	Increase recyclate quality	Recyclate composition/quality ^b	% wt (tonnes of colored PPW in overall PPW sorted for reprocessing)
TM4	Promote design for recyclability	Recyclability of PP POM ^b	% wt of multilayered packaging POM

^aExpressed annually.

^bMCP specific.

^cMass specific.

^dContextually relevant.

Abbreviations: EcM, economic metric; EM, environmental metric; MCP, material, component, and product; MRF, material recovery facility; POM, placed on the market; PP, plastic packaging; PPW, plastic packaging waste; PRF, plastic reprocessing facility; PRN, packaging recovery note; SM, social metric; TM, technical metric.

were raised regarding overlaps with existing recycling efficiency definitions, stakeholders agreed that EM2 should be retained as proposed, as it offers a direct measure of systemic value recovery. EM3 was supported in principle, since it aligns with policy targets. However, its feasibility was questioned due to globalized supply chains and limited producer transparency. Despite these challenges and measurement difficulties, stakeholders recommended retaining EM3 for long-term consideration. EM4 was considered useful for capturing system leakage, although stakeholders noted difficulties associated with tracking destinations, political feasibility, and environmental standards across receiving countries. Additional suggestions/refinements included incorporating EMs associated with carbon emissions, resource use, and explicit addition of a leakage intensity EM.

- Economic metric (EcM) evaluation. EcM1, -2, -4, and -5 were strongly supported as useful in capturing avoided costs and potential revenues from improved recycling and for quantifying savings linked to recycling interventions. EcM3 was deprioritized. While EcM3 was acknowledged as useful, stakeholders considered it too difficult to quantify reliably and too uncertain to support long-term monitoring. Additional suggestions/refinements included adding basic EcMs (e.g., turnover, employment in PPW management) and misalignments in costs and revenues across producers, governments, and households.
- Social metric (SM) evaluation. SM1 was strongly supported, with recognition of trade-offs between quantity (higher participation) and quality (reduced contamination). A suggested refinement was to disaggregate by household participation for granularity by adding another metric. SM2 was supported, but stakeholders recommended renaming it to distributional equity to avoid emotive connotations. They highlighted its importance for monitoring fairness in cost–benefit allocation under the EPR reforms. SM3 (acceptability) was deprioritized, as it was considered to be dependent on political leadership and policy framing rather than measurable household behavior. SM3 (convenience) was also deprioritized, as it was found to be too difficult to operationalize robustly. Additional suggestions/refinements included adding SMs for tracking the success of local initiatives (e.g., improved council recycling rates, as percent of councils with above-national-average PPW recycling rates), job creation/loss in the sector (e.g., net jobs created per 1 kilotonne of PPW recycled domestically), quality of work (permanent versus temporary contracts), and labeling clarity (e.g., percent of weight PP POM with clear polymer codes and recycling route). The labeling clarity was considered more appropriate to the technical domain and was situated there.
- Technical metric (TM) evaluation. TM1 and TM2 were strongly supported, with a recommendation to rename them as percent of losses in sorting facilities for precision. TM3 was acknowledged as a useful metric in the short term, but it may lose its relevance with advances in design for recycling. Stakeholders advised retaining it as a metric requiring adaptive monitoring. TM4 was also supported but flagged as limited by industry investment and functionality constraints, and eventually, stakeholders suggested deprioritizing it. Additional suggestions/refinements included adding TMs on recycling by polymer type (at least polyethylene terephthalate, polyethylene, and polypropylene) and a resilience capacity metric, namely percent of domestic demand met by UK reprocessing capacity.

The workshop outcomes were triangulated with the CVORR+ baseline analysis to ensure that all revised and newly suggested metrics were system grounded. The triangulation approach ensures methodological rigor by preventing the introduction of ad hoc or politically biased metrics while still incorporating practitioner knowledge and lived expertise. This process resulted in a refined and expanded set of 30 metrics, presented in **Table 6**.

Table 6 Final list of revised metrics^a developed in step 4 of the metrics selection framework

Domain number	Secondary subobjective	Attributes	Metrics
EM1	Reduce environmental impacts	Energy recovery potential from incineration	Tonnes PPW to incineration/year
EM2	Reduce environmental impacts	Energy recovery potential from MBT	Tonnes PPW to MBT facilities/year
EM3	Reduce environmental impacts	Life-cycle GHG intensity	kg CO ₂ eq/tonne PP
EM4	Minimize plastic packaging leakage and litter	Leakage intensity	Tonnes of littered PPW/year
EM5 (EM2 in Table 5)	Reduce virgin resource reliance	Reprocessing efficiency	% wt PPW reprocessed domestically (as a proportion of overall PPW generated)
EM6 (EM3 in Table 5)	Reduce virgin resource reliance	Postconsumer recycled content in packaging	% wt in new PP produced
EM7	Reduce virgin resource reliance	Virgin feedstock dependency	Tonnes of virgin PP/tonnes POM (per year)
EM8 (EM4 in Table 5)	Reduce reliance on export pathways	Export dependency	% wt of PPW exported relative to total PPW generated annually
EcM1	Minimize net system costs	Cost efficiency/revenue captured	£ saved per tonne diverted from landfill/leakage
EcM2	Minimize net system costs	Life-cycle system cost	£/tonne net cost of PP POM
EcM3 (EcM2 in Table 5)	Maximize recovered value	Value of secondary plastic	£/tonne recyclate sold domestically
EcM3 in Table 5	Maximize recovered value	Value of secondary plastic	% PPW in domestic packaging production
EcM4	Minimize externalized costs	Cleanup and damage costs	£/tonne PPW spent on environmental remediation
EcM5	Improve cost efficiency	Avoided cost losses	% PRN revenue retained domestically
EcM6	Improve cost efficiency	Avoided cost losses	% cost allocation producer versus government versus households
SM1	Increase household participation in recycling	Recyclable PP collected	% wt of PPW entering the recycling waste stream, measured relative to total annual PPW generation and PP POM
SM2	Increase household participation in recycling	Household participation rate	% households participating in recycling schemes
SM3	Increase household participation in recycling	Local government recycling effectiveness	% councils with above-national-average PPW recycling rates
SM4 (SM2 in Table 5)	Ensure fairness in distribution of costs/benefits	Distributional equity	% (of £ share of system costs by producers versus consumers)
SM3 in Table 5	Build trust and acceptability	Social acceptability and convenience	Qualitative score: survey based
SM5	Support jobs and well-being in the sector	Employment creation/loss	Net jobs created per 1 kilotonne of PPW processed domestically
SM6	Support jobs and well-being in the sector	Employment quality	% of workforce in recycling sector on permanent versus temporary contracts
TM1	Improve sorting and reprocessing capacity	Sorting system efficiency	% wt losses of PPW at MRFs

(Continued)

Table 6 (Continued)

Domain number	Secondary subobjective	Attributes	Metrics
TM2	Improve sorting and reprocessing capacity	Sorting system efficiency	% wt losses of PPW at PRFs
TM3	Increase recyclate quality	Recyclate composition and quality	% wt (tonnes of colored PPW in overall PPW sorted for reprocessing)
TM4	Increase recyclate quality	Recyclate composition and quality	% wt (tonnes of recovered polyethylene terephthalate as a proportion of total polyethylene terephthalate POM)
TM5	Increase recyclate quality	Recyclate composition and quality	% wt (tonnes of recovered polyethylene as a proportion of total polyethylene POM)
TM6	Increase recyclate quality	Recyclate composition and quality	% wt (tonnes of recovered polypropylene as a proportion of total polypropylene POM)
TM7	Increase recyclate quality	Recyclate composition and quality	% wt (tonnes of other polymer types recovered as a proportion of PP POM)
TM8 (TM4 in Table 5)	Promote design for recyclability	Recyclability of PP POM	% wt of multilayered packaging POM
TM9	Promote design for recyclability	Packaging labeling transparency	% wt PP POM with clearly labeled recycling identification codes and/or instruction
TM10	Strengthen system resilience	Domestic capacity coverage	% demand met by UK reprocessing capacity

^aBlue font, revised on the basis of stakeholder suggestions; green font, new metrics; orange font, pending future consideration; gray font, deprioritized. Abbreviations: EcM, economic metric; EM, environmental metric; GHG, greenhouse gas; MBT, mechanical–biological treatment; MRF, material recovery facility; POM, placed on the market; PP, plastic packaging; PPW, plastic packaging waste; PRF, plastic reprocessing facility; PRN, packaging recovery note; SM, social metric; TM, technical metric.

Stakeholder evaluation highlighted the need for adaptive monitoring, whereby some metrics may be phased out and new metrics may need to be added as technologies, policies, and stakeholder priorities evolve. Furthermore, this stage demonstrates how the MSF integrates technical system analysis with participatory validation, ensuring that metrics are both scientifically robust and decision relevant.

4.4. Outcomes of the Metric Selection Framework Application

The application of the MSF to the PP system in England generated a refined set of 30 metrics that are system grounded and stakeholder validated, providing a practical basis for monitoring progress toward national targets while also addressing broader environmental, economic, social, political, and technical concerns. This demonstrates the MSF's capacity to translate systemic inefficiencies into operational indicators that capture both immediate priorities and long-term structural concerns, illustrating the adaptive nature of the framework and its ability to evolve in response to changing contexts.

While the MSF made explicit the pathway from subobjectives to metrics, stakeholder engagement proved essential in refining the selection and ensuring completeness of metrics. This highlights the strength of using the hybrid approach that combines VFT with AFT. Expert elicitation alone, even when scientifically robust, proved insufficient to capture the full range of system-level dynamics, implementation constraints, and sector-specific realities. The AFT

process brings in real-world expertise and preferences based on sectoral experience, which enhances the feasibility and legitimacy of the outcomes. It also reveals that, while experts may consider certain metrics useful, practical experience is critical to ensure that such metrics are measurable and actionable. This was evident in the deprioritization of several metrics due to data limitations or low actionability as well as in the reframing of others to align with emerging priorities and bridge language barriers across sectors. Such iterative refinement underpins the MSF's role as a bridge between systemic analysis and decision support, balancing conceptual completeness (via VFT) with contextual and participatory legitimacy (via AFT).

Finally, several of the proposed metrics have been incorporated into the resources and waste strategy, particularly for monitoring plastic waste recycling, and are now embedded within a broader set of national metrics under development. By grounding metric development in systemic analysis and value-focused subobjectives, the MSF strengthened the government's capacity to evaluate policy options and anticipate unintended consequences. Beyond individual metrics, the MSF also proved valuable as an evidence-based tool for diagnosing inefficiencies and informing interventions. These insights directly informed four UK government-proposed measures: reforms to EPR schemes and associated revenue structures, the introduction of the DRS, upgrades to domestic recycling infrastructure, and increased consistency in household waste collection across councils (simpler recycling).

4.5. Limitations

While the MSF effectively captures systemic interactions and lock-ins, the case study application highlighted several limitations that require further refinement. The demonstration was intentionally scoped to illustrate the methodological pathway from subobjectives to attributes and metrics, rather than to provide a fully detailed technical account of PP recycling in England. As such, important distinctions, including the need for granularity to differentiate across material types, recycling pathways, and life-cycle fates, were not fully developed. For example, distinguishing between closed-loop and open-loop recycling, or unpacking the dynamics of specific polymers, would significantly enhance the explanatory power of the framework, although such refinements are constrained by methodological and data challenges.

In addition, although stakeholder validation of the MSF enhances relevance by capturing stakeholder needs and context-specific challenges, it also introduces subjectivity that may affect metric selection and reduce direct comparability across contexts or over time. However, this subjectivity is deliberately constrained through transparent documentation, explicit metric screening criteria, triangulation with system analysis, and adaptive review cycles that support robustness testing and enable the controlled evolution of metrics.

Moreover, dimensions such as fairness in cost distribution, household behavior, and the institutional design of policy instruments emerged as critical for value recovery but remain only partially integrated into the MSF. Similarly, structural lock-ins arising from technical complementarities, economies of scale, and quasi-irreversible investments across collection, sorting, reprocessing, and export pathways should be explicitly incorporated into attribute and metric formulation. Without such considerations, the MSF risks underrepresenting financial viability, investment risks, and organizational dependencies that are central to strategic decision-making.

Finally, the procedure for deriving and refining secondary subobjectives can be further strengthened through systematic integration of insights from CLDs, where SD analysis is undertaken, enabling causal relationships and feedback mechanisms to directly inform and cross-validate decision support metrics. Addressing all these limitations will be critical for advancing the MSF from proof-of-concept applications toward a widely applicable and adaptable tool for decision-making in complex resource recovery systems.

5. CONCLUSIONS

The CVORR+ MSF advances multidimensional decision analysis in three ways. First, it avoids collapsing diverse values into a single aggregated metric or index. For example, in macroeconomic evaluation, GDP is often used as a convenient aggregate metric of economic activity or as a proxy for national performance, yet it collapses sustainability performance into a single aggregate metric. This obscures critical trade-offs between economic growth, environmental protection, social equity, and long-term societal resilience. The MSF therefore maintains distinct value dimensions to support transparent, decision-relevant analysis to make visible welfare effects, distributional outcomes, and ecological costs. Second, it explicitly derives primary and secondary subobjectives from the baseline analysis, while allowing SD insights, such as feedback mechanisms, trade-offs, and intervention points identified through CLDs, where undertaken, to further refine and strengthen metrics development and interpretation. Third, it translates secondary subobjectives into attributes and metrics through a transparent and structured process. Together, these features operationalize systemic analysis for decision-making.

The PP case study provided a proof of concept for how the MSF can move beyond unstructured metric selection toward a structured, replicable process that links system understanding, stakeholder input, and policy priorities. By integrating subobjectives, attributes, and metrics, the MSF enabled the identification of systemic inefficiencies and supported the development of robust, policy-relevant metrics. Several metrics are already being considered in national monitoring and evaluation frameworks, highlighting the MSF's immediate policy relevance. Simultaneously, further integration of SD insights into the refinement and cross-validation of metrics remains essential for strengthening replicability, systemic coherence, and generalizability.

Taken together, these outcomes illustrate both the promise and the challenges of developing metrics for multidimensional value recovery. The MSF provides an adaptable pathway for operationalizing systemic analysis in decision-making, catalyzing a shift in both policy and system thinking while recognizing that metrics alone cannot resolve the structural constraints of resource recovery systems. Future work will extend the validation of the MSF across MCP contexts and governance settings, embedding it more firmly within value-focused decision-making approaches. In doing so, the MSF contributes not only to improved monitoring and evaluation but also to a broader cultural shift: moving beyond waste management to systemic value recovery.

SUMMARY POINTS

1. The metric selection framework (MSF), embedded in the CVORR+ systems-based approach, translates system analysis tailored to material, component, and product (MCP) systems and contexts into evidence-based, decision-oriented metrics, thereby avoiding arbitrary metric selection.
2. The MSF integrates subobjectives, attributes, and metrics through value-focused thinking, ensuring the multidimensional representation of value domains (i.e., environmental, economic, social, technical).
3. The MSF leads to the selection of metrics that are contextually aligned with the sustainability problem, and stakeholder engagement (alternative-focused thinking) validates subobjectives, refines attributes, and ensures that metrics are both system grounded and practically feasible.

4. The MSF strengthened intervention design through a proof-of-concept application in England's plastic packaging system, producing metrics already under policy consideration.
5. The MSF is not only a structured, transparent, and replicable tool for decision-oriented, contextually sensitive metric selection but also a means to catalyze a shift from waste management toward systemic value recovery, with potential for generalization across MCP systems.

FUTURE ISSUES

1. Causal loop diagrams can be used to enhance the systemic consistency and contextual completeness of metrics within the full operationalization of the MSF, thereby strengthening its replicability and generalizability.
2. Pathways for integrating MSF outputs into ongoing monitoring and policy frameworks should be strengthened, ensuring long-term uptake by decision-makers.
3. Adaptive metrics that can evolve with technological innovation, policy shifts, and market changes while maintaining long-term relevance need development.
4. Analyses should be extended to account for investment risks, financial viability, cross-border flows, export dependencies, and variable environmental and governance standards abroad.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

AUTHOR CONTRIBUTIONS

E.I. was involved in conceptualization, methodology, formal analysis, investigation, resources, data curation, writing (original draft, review, and editing), visualization, supervision, and project administration. S.G. was involved in conceptualization, methodology, investigation, writing (review and editing), and visualization. P.P. was involved in conceptualization, methodology, formal analysis, and writing (review and editing). N.E. was involved in conceptualization, methodology, formal analysis, and writing (review and editing).

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AI-assisted text was reviewed, edited, and fact-checked by the authors, who take full responsibility for the accuracy, interpretation, and conclusions of the article.

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