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Material Selection Intelligence for Circular Product Design

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Abstract

Material selection is one of the earliest and most consequential decisions in product development because it influences technical performance, manufacturing routes, durability, repairability, environmental burden, disassembly, secondary-material compatibility, and end-of-life recovery. Conventional selection procedures have traditionally prioritized mechanical performance, cost, processing, and safety constraints. Circular product design requires a broader decision logic in which the preferred material is not merely capable of performing its initial function but is also compatible with strategies for prolonged use, component recovery, reuse, remanufacture, and high-value recycling. This study develops a simulation-based Material Selection Intelligence framework for circular product design without presenting hypothetical industrial data as empirical evidence.

The proposed approach combines engineering screening with circularity-oriented multicriteria decision analysis. Five dimensions are evaluated: functional fitness and durability, circular feedstock potential, compatibility with lifetime-extension strategies, end-of-life recoverability, and data and supply assurance. The framework is demonstrated through a hypothetical durable product enclosure using five candidate material families: virgin acrylonitrile butadiene styrene, recycled polypropylene, recycled acrylonitrile butadiene styrene, bio-based polyamide, and recycled aluminum. Simulated Circular Material Selection Intelligence scores range from 56.7 for virgin ABS to 87.1 for recycled aluminum, while recycled ABS achieves 78.8 and demonstrates a strong balance between technical continuity and circular feedstock use. The analysis shows that recycled content or low embodied impact alone should not determine selection. A material with favorable environmental characteristics can perform poorly in a circular system when its durability is inadequate, incompatible materials are permanently bonded to it, secondary-market quality is uncertain, or recovery infrastructure is absent.

Material-selection intelligence is therefore conceptualized as a transparent decision-support capability combining property databases, lifecycle information, recovery pathways, uncertainty, and product architecture rather than as an opaque automated ranking algorithm. The study concludes that circular material selection should optimize retained functional value across multiple potential lifecycles while maintaining engineering safety and manufacturing feasibility.

Keywords: material selection, circular product design, circular economy, recycled materials, design for recycling, material intelligence, durability, multicriteria decision making

1. Introduction

Material selection establishes a large portion of a product's technical and environmental trajectory before detailed manufacturing begins. Designers normally screen candidate materials against constraints involving stiffness, strength, thermal behavior, corrosion resistance, processing, mass, cost, safety, and geometry. The structured material-selection methodology associated with Ashby's engineering approach formalized the use of constraints, objectives, material indices, and property charts to identify technically suitable candidates from a large material space. Circular product development does not remove these engineering requirements; instead, it adds further questions concerning whether a material can remain in productive use, enter secondary cycles, be separated economically, tolerate repeated processing, and retain sufficient quality for future applications.

Circular economy scholarship similarly makes clear that circularity cannot be reduced to recycling alone. Circular strategies include slowing resource loops through durable design and life extension as well as closing loops through recovery and recycling. Bocken and colleagues distinguish product-life extension, resource recovery, long-life design, and related circular product strategies, while Kirchherr and colleagues' analysis of circular-economy definitions shows that reduce, reuse, recycling, and systemic change are recurring elements within the concept. The implication for product design is that material choice should support several possible recovery routes instead of assuming that all materials will reach a recycling facility at the end of one use phase.

A second challenge concerns measurement. Circular design decisions frequently involve trade-offs that are difficult to summarize using a single environmental variable. A low-carbon material may be less durable, a highly durable material may be difficult to recycle, and a technically recyclable polymer may have little practical circular value if it is contaminated, permanently joined to incompatible polymers, or lacks an established secondary market. Research reviewing circularity indicators has demonstrated that existing metrics capture different parts of the circular-economy concept and that no single indicator universally represents material flow, lifetime extension, reuse, disassembly, recycling, and value retention simultaneously. Saidani and colleagues reviewed a large set of circularity indicators, while Parchomenko and colleagues demonstrated substantial variation in the elements captured by different circular-economy metrics.

Material selection for circular design therefore requires decision intelligence rather than a simple environmental ranking. In this paper, intelligence refers to the systematic integration of engineering properties, lifecycle information, circularity criteria, supply data, and explicit decision rules. It can be implemented through conventional multicriteria methods, computational optimization, material databases, lifecycle-assessment tools, or machine-learning-supported data processing. Artificial intelligence and machine learning can assist with property prediction and large materials datasets, but their usefulness depends on reliable inputs and interpretable objectives; they should not replace the engineering definition of constraints or the transparent explanation of why one material has been preferred. Research on data-intensive materials development demonstrates substantial potential for machine learning across property prediction and materials discovery, but decision quality remains dependent on the quality and relevance of the underlying datasets.

The present study develops a simulation-based framework entitled the Circular Material Selection Intelligence framework. The approach retains conventional engineering screening as the first decision gate and then evaluates surviving candidates through circularity-oriented criteria. A generic durable enclosure is used as an illustrative design context because such components can plausibly be produced from polymers or metals and can be designed for replacement, refurbishment, or material recovery. The numerical values presented in the analysis are deliberately hypothetical. They are intended to demonstrate a reproducible methodology and should not be interpreted as measured lifecycle inventories, verified material properties, or actual industrial sourcing conditions.

2. Objectives of the Study

2.1 To Integrate Engineering Performance With Circularity Criteria

The first objective is to develop a material-selection structure in which circularity does not override fundamental engineering fitness. Candidate materials must first satisfy mandatory technical constraints related to service temperature, structural performance, safety, manufacturing process, dimensional stability, and anticipated use conditions.

Once minimum technical requirements are satisfied, the framework evaluates circular attributes such as recycled or renewable feedstock, durability, repair compatibility, reuse potential, remanufacturing suitability, recoverability, and recycling compatibility. This staged structure reduces the risk of choosing a material that appears environmentally attractive but cannot deliver the required service performance.

2.2 To Convert Material Circularity Into a Transparent Decision Score

The second objective is to construct a transparent multicriteria index that enables comparison among technically feasible candidate materials. The index is designed to make weighting assumptions visible so that designers can understand why the ranking changes when strategic priorities change.

This approach responds to research showing that circularity indicators differ in purpose and scope and should therefore be selected according to the actual design question rather than adopted as universal measures. The framework emphasizes interpretability, sensitivity analysis, and traceable data sources rather than a single unexplained automated score.

2.3 To Examine How Material Intelligence Supports Multiple Product Lifecycles

The third objective is to evaluate material selection across more than the initial manufacturing cycle. A circular design should consider whether the material enables prolonged first use, part replacement, refurbishment, reuse in another product, reprocessing, or high-value recycling.

The objective therefore shifts attention from minimizing initial material impact toward maximizing retained functional value. Material selection intelligence should help designers distinguish between materials that merely originate from circular feedstocks and materials that remain compatible with repeated value-preserving cycles.

3. Review of Literature

3.1 Materials Selection From Performance Optimization to Circular Decision Making

Traditional engineering materials selection is based on identifying design requirements, translating them into constraints and objectives, screening infeasible material classes, and ranking feasible candidates using suitable property indices. Ashby's methodology provides a systematic basis for comparing large material families without allowing one property to dominate decisions arbitrarily. This structured approach remains highly relevant to circular design because it establishes a clear principle: sustainability criteria should be introduced without weakening the definition of functional constraints.

Environmental material selection has progressively added embodied energy, carbon footprint, resource scarcity, and other lifecycle variables. Morini, Ribeiro, and Hotza demonstrated that embodied energy and carbon footprint can be incorporated at early design stages to assist environmentally informed material decisions. Research concerning critical raw materials similarly shows that supply risk, material efficiency, substitution, and recycling can be integrated into mechanical-design selection methods.

Circular material selection extends these approaches by asking whether the material supports recovery strategies after and between use phases. Mesa, González-Quiroga, and Maury proposed a material-durability indicator combining chemical and mechanical durability with environmental burden, explicitly emphasizing lifespan extension rather than concentrating exclusively on recycling. Their work is important because circular product design can fail when a material achieves high recycled content but shortens useful life.

The literature therefore supports a two-part selection philosophy. First, a circular candidate must remain technically fit for purpose. Second, its broader system characteristics should favor long product life and high-value recovery. This distinction prevents the environmental profile of a material from being assessed independently of the component's actual engineering function.

3.2 Recyclability, Durability, and Product Architecture

Recyclability depends on considerably more than the intrinsic ability of a polymer or metal to be reprocessed. Product architecture determines whether a material can be separated economically and whether recovered fractions are sufficiently uncontaminated to enter secondary manufacturing. Research integrating high-recyclability material selection into computer-aided design has highlighted recycling infrastructure, material compatibility, hazardous constituents, contaminants, and disassembly requirements as essential design variables.

Circular product architecture also places a strong emphasis on slowing material cycles. Bocken and colleagues identify long-life products, product-life extension, reuse, repair, refurbishment, and remanufacturing among important circular design strategies. Sauerwein and colleagues further demonstrate that manufacturing and design choices should be assessed according to their support for multiple product lifecycles rather than evaluated solely according to end-of-life recycling.

Durability is therefore both a material property and a systems property. Mechanical resistance, ultraviolet stability, chemical resistance, moisture behavior, fatigue resistance, thermal aging, and surface degradation determine whether a material can survive the intended environment. Yet product architecture determines whether a durable component can actually be retained, repaired, or separated. Mesa and colleagues' material-durability work shows why durability and environmental impact must be examined jointly, while product-family circularity research demonstrates the importance of material flow, component reuse, reconfiguration, and functional performance.

Recycled content must likewise be interpreted carefully. Ford and Fisher's consumer-electronics case study demonstrated that recycled ABS can be technically feasible for an enclosure application when the design accommodates material-specific characteristics. Such findings support recycled polymers as credible design materials rather than automatically inferior substitutes, but they also emphasize that substitution requires property verification and design adaptation.

3.3 Circularity Indicators, Data Quality, and Material Intelligence

Circularity measurement remains fragmented because indicators address different scales and strategic questions. Elia, Gnoni, and Tornese found that circular-economy assessment methods vary in their ability to represent specific circular strategies. Saidani and colleagues subsequently developed a taxonomy to help users choose indicators based on decision needs, while Parchomenko and colleagues identified substantial variation among circular-economy metrics in the elements they capture.

This evidence argues against treating one circularity score as an objective property of a material. Circularity is partly relational. Aluminum may be highly recyclable in a product system possessing effective separation and secondary-metal infrastructure but less valuable if permanently bonded to incompatible materials. A polymer with technically lower recycling yield may provide better overall circular performance if it enables a much lighter, repairable, and longer-lived product.

Material intelligence must therefore include information quality. Circular selection depends on credible recycled-content declarations, supplier consistency, contaminant limits, processing history, recovery routes, secondary-material quality, and geographically relevant recycling capability. Circular design decisions become less reliable when database values are treated as universal constants without accounting for supplier, grade, processing route, or regional infrastructure.

Computational intelligence can support this complexity by screening databases, performing multicriteria ranking, estimating missing properties, and testing sensitivity to uncertain inputs. However, its contribution should be subordinate to transparent design logic. The appropriate role of digital intelligence is to help designers process complex evidence efficiently while preserving traceability between data, assumptions, constraints, and the final selection

4. Research Methodology

4.1 Simulation-Based Circular Material Selection Design

The study adopts a simulation-based multicriteria methodology. The hypothetical product is a durable non-safety-critical enclosure requiring moderate structural stiffness, impact resistance, manufacturability at production scale, acceptable appearance, and compatibility with mechanical disassembly.

Five candidate material families are considered: virgin ABS, recycled polypropylene, recycled ABS, bio-based polyamide, and recycled aluminum. These candidates are not asserted to be directly interchangeable in every real enclosure design. Their purpose is to demonstrate how materially different alternatives can be compared after design adaptations have established basic functional feasibility.

The method uses two decision gates. Gate 1 screens candidates against mandatory technical constraints. Gate 2 compares feasible candidates using circularity-oriented criteria. A candidate failing Gate 1 is removed regardless of its circularity score, thereby preventing sustainability ranking from overriding safety or functionality.

4.2 Circular Material Selection Intelligence Index

A Circular Material Selection Intelligence Index (CMSII) is developed using five weighted dimensions. Scores range from 0 to 100, with higher values representing a stronger hypothetical fit with the circular-design objectives of the illustrative enclosure.

Table 1: Criteria and weighting structure of the Circular Material Selection Intelligence Index

Criterion	Design interpretation	Weight
Functional fitness and durability	Ability to satisfy service performance while resisting relevant mechanical, thermal, chemical, and environmental degradation	0.25
Circular feedstock potential	Availability of credible recycled or renewable feedstock and potential to reduce virgin-resource dependence	0.20
Lifetime-extension compatibility	Suitability for repair, part replacement, refurbishment, reuse, and prolonged component service	0.20
End-of-life recoverability	Ability to be identified, separated, processed, and returned to useful material cycles with practical recovery infrastructure	0.20
Data and supply assurance	Confidence in supplier information, grade consistency, traceability, secondary-material quality, and supply continuity	0.15

The weighting structure is illustrative. A medical, aerospace, packaging, construction, or consumer-electronics product would require a different set of priorities and possibly additional criteria concerning toxicity, food contact, fire performance, criticality, or regulatory restrictions.

4.3 Decision-Intelligence Workflow and Uncertainty Treatment

The first computational step defines technical constraints and rejects infeasible grades. The second normalizes circularity attributes to a common scale. The third applies the CMSII weights. The fourth performs sensitivity testing by changing criterion weights and identifying whether the preferred material remains stable.

Data confidence is treated explicitly because circular-material databases frequently combine generic environmental datasets, supplier declarations, laboratory values, and regional recovery information. A nominally strong candidate with uncertain recycled content or inconsistent mechanical performance can therefore receive a lower data-assurance score.

The framework can be implemented in a spreadsheet, CAD-linked decision-support environment, lifecycle-design platform, or software application. Machine learning could later support property prediction or missing-data estimation, but any estimated value should be distinguishable from verified supplier or test data. The framework does not permit an automated model to silently replace missing evidence with unverified assumptions.

5. Analysis

5.1 Comparative Material Ranking for the Simulated Enclosure

The simulation produces a clear difference between a traditional virgin-material option and alternatives offering stronger circular characteristics. Virgin ABS receives a CMSII of 56.7. Its technical fitness and supply assurance are modeled as strong, but the candidate scores poorly on circular feedstock because the scenario assumes virgin resin. Its recoverability remains moderate rather than negligible because ABS is technically thermoplastic, but practical recovery depends heavily on product separation and available recycling streams.

Recycled polypropylene reaches 69.9. The candidate benefits from secondary feedstock and favorable recoverability, but the simulated technical-fitness score is lower because the illustrative enclosure has been assumed to require tighter stiffness, finish, and dimensional performance than the selected recycled PP grade provides without additional design modification.

Recycled ABS reaches 78.8. Its principal advantage is continuity with an established enclosure-material family while providing substantially stronger circular feedstock performance. The result is conceptually consistent with published evidence demonstrating the feasibility of recycled ABS in consumer-electronic housing when product design accounts for relevant material characteristics.

Table 2: Simulated circular-material evaluation for the illustrative product enclosure

Candidate material	Functional fitness & durability	Circular feedstock	Lifetime extension	Recoverability	Data & supply assurance	CMSII
Virgin ABS	82	20	62	45	72	56.7
Recycled PP	70	75	70	72	60	69.9
Recycled ABS	82	88	76	78	66	78.8
Bio-based PA	86	72	80	55	72	73.7
Recycled aluminum	90	92	82	92	76	87.1

Note: All scores are simulated values created solely to demonstrate the proposed decision framework. They are not verified properties, lifecycle scores, or commercial material ratings.

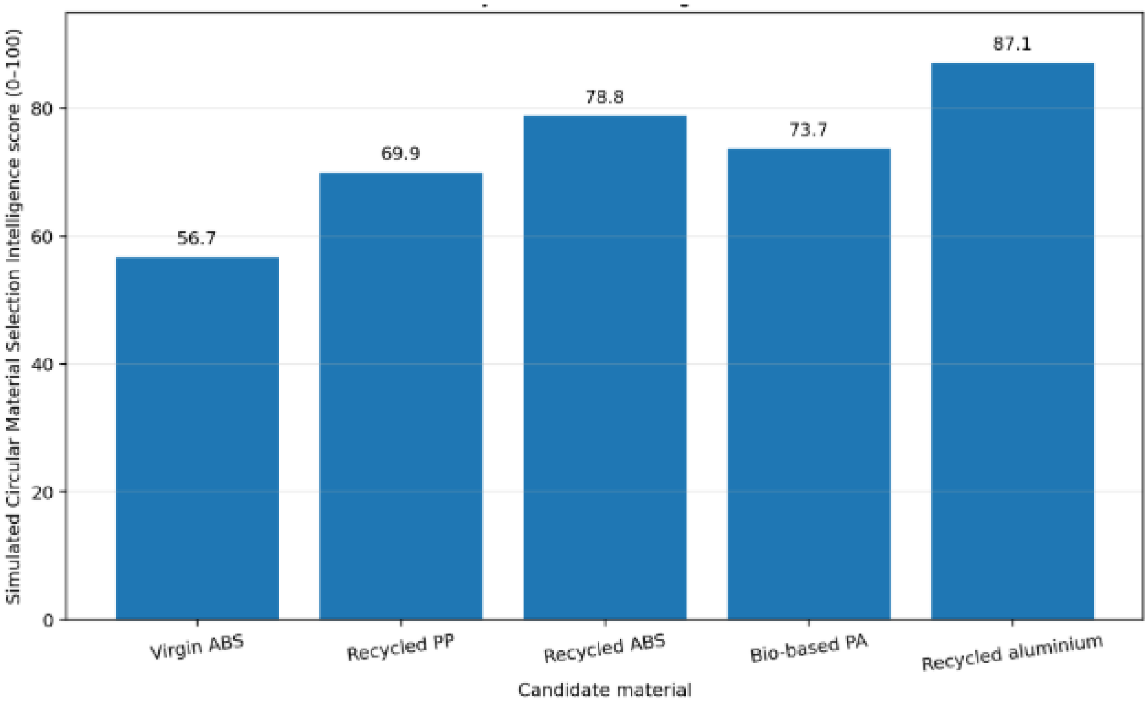
Bio-based polyamide achieves 73.7. It receives high technical and lifetime-extension scores but a lower recoverability score in the simulated context because the assumed local recovery system is less mature than for metals and widely collected commodity thermoplastics. The result illustrates that renewable origin and circular recovery are separate characteristics.

Recycled aluminum receives the highest CMSII of 87.1. The material benefits from strong modeled durability, high secondary-feedstock potential, and well-established theoretical recyclability. The ranking does not imply that recycled aluminum is universally preferable for enclosures. Product mass, forming processes, joining, surface finishing, electricity mix, alloy compatibility, cost, and structural design can change the comparison substantially.

5.2 Circularity-Oriented Material Intelligence Ranking

The comparative ranking demonstrates the importance of evaluating several lifecycle characteristics simultaneously.

Graph 1: Simulated Circularity-Oriented Ranking of Candidate Materials



The graph places recycled aluminum first, followed by recycled ABS, bio-based polyamide, recycled polypropylene, and virgin ABS. The difference between virgin and recycled ABS is particularly instructive because the basic polymer family remains similar while feedstock circularity changes substantially. Published circular-design research supports the use of recycled polymers where performance can be retained, but also emphasizes that material selection should remain linked with product architecture and multiple lifecycle strategies rather than material origin alone.

The graph also demonstrates why the bio-based candidate does not automatically rank above every recycled material. Renewable feedstock can reduce dependence on fossil-derived virgin resources, but circular design additionally requires durability, recovery, reuse, and reprocessing pathways. Circular product design should therefore avoid treating "bio-based," "recycled," "recyclable," and "low carbon" as interchangeable labels.

5.3 Sensitivity of Material Selection to Circular Design Strategy

The preferred candidate changes when design priorities change. If the product is intended for very long first-life use with repairable components, greater weight can be assigned to durability and lifetime extension. Under such a scenario, high-performing durable materials can outrank options having greater recycled content but weaker long-term stability.

If the product is designed for short use followed by controlled closed-loop recovery, feedstock circularity and recoverability become more influential. A company operating a take-back program may therefore rationally select a different material from a manufacturer selling into an uncontrolled market where end-of-life collection is uncertain.

Material criticality can also alter ranking. Research integrating critical-raw-material risk into material selection shows that supply risk and recycling opportunity can be incorporated directly into design decisions. A high-performing material dependent on a constrained or volatile supply system may deserve a lower strategic score when substitution or recovery is difficult.

This sensitivity confirms that material-selection intelligence should not generate one universal ranking independent of product system. Its purpose is to formalize the relationship between material data and a clearly stated circular strategy.

6. Discussion

6.1 Circular Material Selection Is a Systems Decision

The principal finding is that circular material selection cannot be reduced to identifying the material with the lowest initial environmental burden. Product circularity emerges from the interaction among material properties, component architecture, joining technology, maintenance, collection, secondary processing, and business model.

Bocken and colleagues' design framework makes this systemic relationship explicit by connecting product design with slowing and closing resource loops. Kirchherr and colleagues similarly demonstrate that circular economy requires a broader systemic shift than isolated recycling activity. The present framework translates that systems perspective into the material-selection stage.

An enclosure produced from a highly recyclable polymer may still perform poorly in a circular system if it is bonded permanently to incompatible materials. A more difficult-to-recycle material may deliver higher overall value when it enables repeated component reuse. Circularity should therefore be assessed at the level of the material–component–product system, not as a label attached to the material in isolation.

The same argument applies to recycled content. Increased recycled content is desirable where quality and performance remain suitable, but a recycled material that significantly shortens product life can create additional replacement demand. Durability-oriented selection methods demonstrate why mechanical and environmental performance must be integrated rather than optimized separately.

6.2 The Role of Data and Computational Intelligence

The amount of information required for circular material selection can exceed what a designer can manage efficiently using conventional catalog review alone. Material properties, embodied impacts, recycled-content availability, chemical restrictions, cost, criticality, recycling compatibility, and supplier quality can create a high-dimensional decision problem.

Digital material intelligence can assist by connecting property databases with lifecycle and circularity indicators. Rules can automatically remove candidates that violate technical constraints, after which multicriteria algorithms can rank feasible alternatives. Sensitivity analysis can then show whether the preferred material is robust to changes in weighting.

Machine learning provides additional capability where property data are incomplete or relationships are nonlinear. Research on AI across the materials-development lifecycle demonstrates the ability of data-driven models to predict properties and process large materials datasets. However, circular product design requires additional caution because circularity variables are often contextual rather than purely intrinsic. A model may estimate tensile strength effectively but cannot infer the existence of a reliable local recycling market from chemistry alone.

Consequently, material-selection intelligence should remain explainable. The system should show which criteria determined the ranking, where each value originated, which inputs are estimated, and how uncertainty affects the result. Designers should be able to identify whether one material won because of technical performance, recycled content, durability, recovery infrastructure, or a particular weighting choice.

6.3 Design Implications for High-Value Circularity

Circular design generally retains more value when products, components, and materials are kept at the highest feasible level of functionality. Recycling can recover material value, but repair, reuse, refurbishment, and remanufacturing can preserve substantially more of the manufacturing effort embedded within components. Product-design strategies for circular economy therefore emphasize lifetime extension alongside material recovery.

Material selection should support these higher-value loops. Durable surfaces, stable mechanical properties, reversible joining compatibility, repairability, and resistance to service degradation can be more circular than easily recyclable materials that fail prematurely. Conversely, excessive durability achieved through inseparable multi-material structures or hazardous additives can obstruct recovery.

Designers should also recognize the difference between theoretical and practical recyclability. Theoretical recyclability asks whether a material can technically be reprocessed. Practical recoverability asks whether it can be identified, separated, collected, processed economically, and converted into a secondary material with sufficient quality and demand. Research on recyclability-oriented design explicitly identifies material compatibility, contamination, disassembly, and infrastructure as important elements of recovery performance.

The most advanced material-intelligence systems should therefore eventually connect materials databases with product bills of materials, joining information, disassembly sequence, expected product life, recovery networks, and supplier data. Such integration would allow circular product design to progress from retrospective environmental evaluation toward proactive material-system optimization.

7. Conclusion

Material selection is a strategic entry point for circular product design because decisions made at this stage influence not only initial manufacturing but also durability, repair, reuse, remanufacture, disassembly, and eventual material recovery. Circular selection should therefore begin with conventional engineering fitness and extend into lifecycle and recovery criteria rather than replacing technical design with environmental scoring.

The Circular Material Selection Intelligence framework developed in this study demonstrates how functional performance, circular feedstock, lifetime-extension compatibility, recoverability, and data assurance can be integrated transparently. In the simulated durable-enclosure example, recycled aluminum obtains the highest CMSII at 87.1, followed by recycled ABS at 78.8. Virgin ABS ranks lowest at 56.7 largely because the hypothetical scenario gives substantial weight to secondary feedstock and recovery. These numerical results are illustrative and are not intended as universal material rankings.

The analysis also demonstrates that apparently sustainable material labels can conceal important trade-offs. Recycled content does not guarantee durability, bio-based origin does not guarantee recyclability, and technical recyclability does not guarantee practical recovery. The preferred circular material is the candidate that delivers the required engineering function while remaining compatible with the highest-value realistic recovery pathways available to the product system.

Future empirical research should validate the framework using industrial bills of materials, measured material properties, verified recycled-content data, lifecycle inventories, supplier traceability information, disassembly studies, and region-specific recovery infrastructure. Sensitivity and uncertainty analysis should accompany any automated ranking. With appropriate data governance and engineering validation, material-selection intelligence can become a practical design capability that helps engineers move from selecting materials for a single manufactured product toward selecting materials for a sequence of retained-value product and material lifecycles.

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