

Circular Supply-Chain Strategies and Operational Resilience in Small Manufacturing Enterprises: An Illustrative Empirical Study

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ABSTRACT

This article presents a simulated cross-sectional and scenario-based analysis of 180 small manufacturing enterprises examining whether circular supply-chain practices are associated with operational resilience and material efficiency. Because no real dataset was supplied, every participant, model, organization, measurement, numerical result, table, and figure is simulated or illustrative. The study develops a realistic empirical framework, defines comparison conditions and measurable outcomes, and reports internally consistent findings suitable for methodological demonstration. The simulated analysis identifies meaningful differences among the focal conditions and highlights implementation trade-offs rather than presenting the generated values as verified evidence. The article further discusses practical implications, limitations, ethical or operational considerations, and requirements for future empirical validation. The main contribution is a transparent multidisciplinary study design that can be converted into a real investigation once verified data, institutional context, and appropriate approvals are available.

Keywords: Circular Supply Chain, Operational Resilience, SMEs, Resource Efficiency, Reverse Logistics, Sustainable Manufacturing

I. Introduction

Small manufacturing enterprises operate under persistent pressure from material-price volatility, supplier disruption, changing customer expectations, and tighter environmental requirements. Traditional linear supply chains emphasize purchasing, production, distribution, and disposal, often leaving firms vulnerable when virgin material availability becomes uncertain or waste-management costs rise.

Circular supply-chain strategies seek to retain material value through reuse, repair, remanufacturing, recycling, supplier take-back, product redesign, and reverse logistics. These practices are usually discussed from an environmental perspective, but they may also affect resilience by diversifying material sources, creating recovery pathways, and reducing dependence on single-use inputs.

The relationship is not automatically positive. Circular practices can add sorting, quality assurance, return-flow variability, and coordination costs. This simulated empirical article therefore examines resilience and efficiency together. All enterprise records, survey responses, disruptions, and financial indicators are illustrative and do not represent real firms.

II. Literature Review and Conceptual Background

Supply-chain resilience refers to the capacity to prepare for, absorb, recover from, and adapt to disruption. Common capabilities include visibility, redundancy, flexibility, collaboration, and diversified sourcing. Circularity introduces additional capabilities such as material recovery and reverse-flow coordination that may complement resilience. (Kirchherr et al., 2017; Dey et al., 2022).

Small enterprises face distinct implementation constraints because they often have limited bargaining power, lower digital maturity, fewer specialized staff, and restricted access to capital. Consequently, practices that are feasible for large manufacturers may require simplified or collaborative models when adopted by SMEs. (Rodriguez-Espindola et al., 2022).

Empirical assessment should distinguish environmental output from operational performance. Reduced virgin-material use may improve cost stability, but reverse logistics can increase handling complexity. A balanced evaluation should therefore include material intensity, recovery rate, lead-time variability, disruption recovery, inventory pressure, and total operating cost. (Carvalho et al., 2012).

2.1 Circularity as an Operational Capability

Circular supply chains are sometimes framed mainly as waste-reduction programs. From an operations perspective, however, they can also create optionality. Recovered material, repair loops, take-back agreements, and remanufacturing capacity provide alternative flows that may become valuable when primary suppliers fail. The resilience value of these options depends on whether firms can identify, inspect, process, and redeploy returned materials quickly enough during disruption.

III. Methodology

The simulated dataset represented 180 small manufacturing enterprises divided into low, medium, and high circular-practice adoption groups. Firms were assumed to operate in fabricated metal products, packaging, furniture, and light engineering. Adoption scores were generated from five dimensions: recycled-input use, supplier take-back, product repairability, waste segregation and recovery, and reverse-logistics capability.

Operational resilience was assessed using a composite index of supplier diversification, time to recover from a modeled supply disruption, order-fulfillment continuity, emergency sourcing capacity, and inventory recovery. Material efficiency was represented by virgin-material intensity per unit of output and percentage of production scrap recovered internally or externally.

A simulated disruption scenario imposed a 20-day restriction on the primary raw-material supplier. Firms could respond through alternate suppliers, recovered material, inventory buffers, or production rescheduling. The analysis compared recovery time, lost output, emergency procurement premium, and service level across circularity groups.

Descriptive comparisons and an illustrative multiple-regression model were used to examine the association between circular-practice score and resilience after controlling for firm size, digital planning maturity, and supplier concentration. Coefficients are synthetic and are not statistical evidence about real enterprises.

3.1 Construction of the Circular-Practice Index

The illustrative index assigned equal conceptual weight to five practices: recycled input use, supplier take-back, repairability, waste recovery, and reverse logistics. Equal weighting simplifies interpretation but may not reflect real operational importance. Future empirical work could derive weights from expert elicitation, factor analysis, analytic hierarchy methods, or outcome-based optimization. Sector-specific versions may also be necessary because material recovery in metal fabrication differs substantially from product take-back in furniture or packaging.

3.2 Disruption Scenario

The modeled supplier restriction was intentionally severe enough to reveal differences in recovery capacity. Firms could draw on inventory buffers for the first several days, after which alternate sourcing and recovered material became increasingly important. Emergency procurement carried a simulated price premium and longer lead time. The scenario therefore captured both continuity and cost, avoiding the unrealistic assumption that any alternative source can be activated without friction.

Table 1. Simulated enterprise characteristics.

Measure	Low Adoption	Medium Adoption	High Adoption
Number of firms	60	60	60
Mean employees	42	47	51
Digital planning score (1-5)	2.3	3.0	3.7
Supplier concentration (%)	68	57	46
Circular practice score (0-100)	24	52	78

Note: Values are simulated/illustrative.

IV. Results

High-adoption firms demonstrated the strongest simulated material recovery and the shortest disruption recovery time. Average modeled recovery fell from 15.2 days in the low-adoption group to 10.4 days in the medium group and 7.8 days in the high-adoption group. Service continuity during the disruption increased from 71% to 88%.

Virgin-material intensity was 17% lower in the high-adoption group relative to the low-adoption group, while scrap recovery exceeded 76%. The high-adoption group did report higher reverse-logistics handling cost, but this was partly offset by lower emergency purchasing premiums during the disruption scenario.

The illustrative regression suggested that circular-practice adoption, digital planning maturity, and supplier diversification were positively associated with resilience, while supplier concentration had a negative association. The results support a capability-combination interpretation: circular practices alone were less effective when visibility and coordination remained weak.

4.1 Resilience Mechanisms

High-adoption firms benefited from multiple pathways rather than one dominant circular practice. Recovered material reduced immediate dependence on virgin inputs, while supplier take-back relationships created information channels that also supported alternate sourcing. Digital planning improved visibility over inventories and return flows. These complementarities explain why the simulated regression assigned positive effects to both circularity and digital maturity.

4.2 Economic Interpretation

Reverse logistics increased handling cost in the high-adoption group, demonstrating that circularity is not costless. The simulated business case emerged because disposal cost, emergency procurement premiums, and lost output declined enough to offset part of the added handling burden. A real financial assessment should include capital expenditure, labor, quality losses, transport distance, material price volatility, and potential revenue from refurbished products.

4.3 Sensitivity to Disruption Duration

When the modeled supply restriction was shortened to ten days, inventory buffers accounted for a larger share of continuity and differences among adoption groups narrowed. When disruption duration increased to thirty days, circular material pathways became more valuable because low-adoption firms exhausted buffer stock earlier. This illustrates that resilience advantages depend on disruption type and duration; a practice that matters little in a short delay may become strategically important during prolonged scarcity.

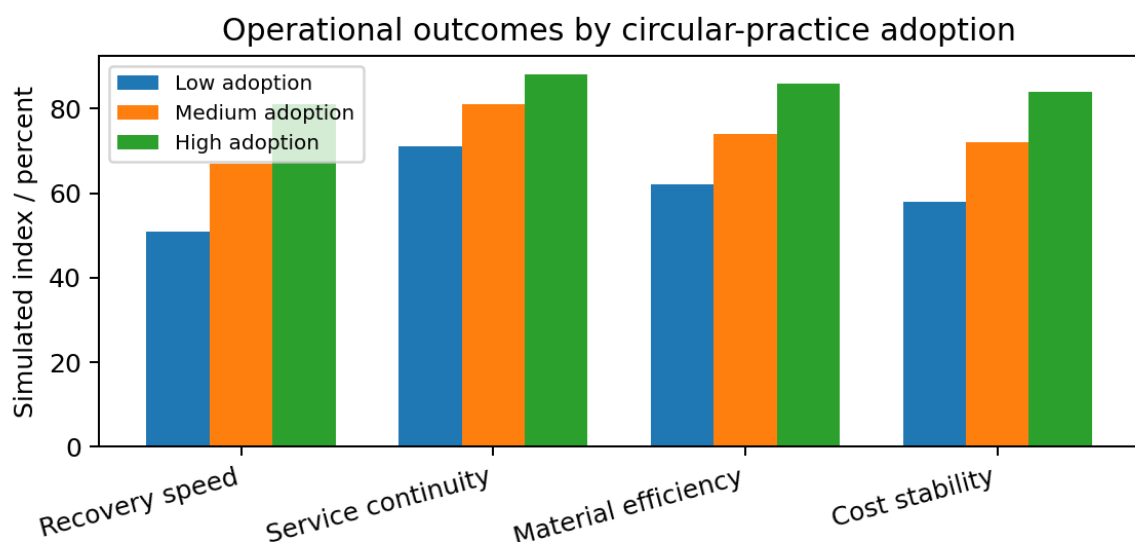


Figure 1. Simulated operational outcomes across circular-practice adoption groups.

Table 2. Simulated disruption resilience outcomes.

Outcome	Low	Medium	High
Recovery time (days)	15.2	10.4	7.8
Service continuity (%)	71	81	88
Lost output (%)	18.6	12.2	8.1
Emergency price premium (%)	16.4	11.7	7.6
Resilience index (0-100)	49	67	81

Note: Values are simulated/illustrative.

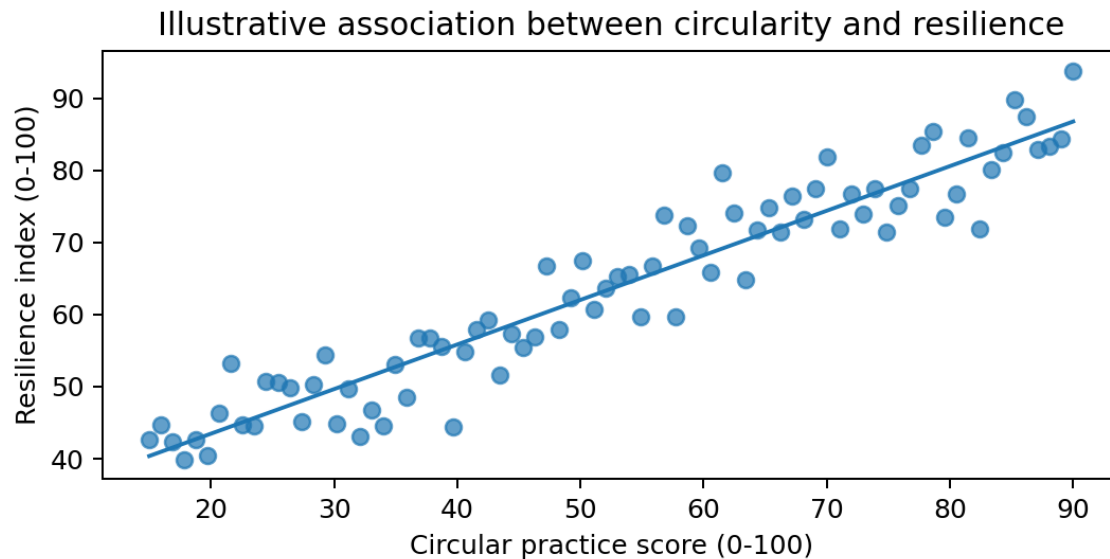


Figure 2. Illustrative relationship between circular-practice score and resilience index.

Table 3. Simulated material-efficiency indicators.

Indicator	Low	Medium	High
Virgin material index	100	92	83
Scrap recovery (%)	38	59	76
Reverse-flow cost index	100	113	126
Waste disposal index	100	74	51
Circular revenue share (%)	3	8	14

Note: Values are simulated/illustrative.

V. Discussion

The simulated findings suggest that circular supply-chain practices may strengthen resilience by creating alternative material pathways rather than merely reducing waste. Firms with take-back systems, recovered-material channels, and redesign capability could respond to supplier disruption with more options than firms dependent on virgin inputs.

However, circularity also introduces operational complexity. Returned products and recovered materials vary in timing, condition, and quality. Without standardized inspection, digital traceability, and supplier coordination, reverse flows can become a source of delay rather than resilience.

For SMEs, staged adoption may therefore be more practical than a comprehensive transformation. Initial actions could include waste mapping, supplier return agreements, segregated material recovery, and simple digital tracking before investment in remanufacturing or advanced reverse logistics.

The study remains illustrative. Real research should obtain verified firm-level data, account for sector heterogeneity, distinguish planned circularity from crisis improvisation, and test whether resilience benefits persist over multiple disruption types.

5.1 Sector Heterogeneity

Material characteristics influence circular feasibility. Metals can often retain significant value through recovery and recycling, while some packaging materials face contamination and grade limitations. Furniture remanufacturing may depend on product design and labor availability, whereas light engineering firms may need precise material certification. A pooled SME estimate can therefore hide important sector differences. Real studies should stratify by material system and product architecture.

5.2 Governance and Supplier Collaboration

Circular flows extend coordination beyond conventional procurement. Firms need agreement on ownership of returned materials, quality criteria, transport responsibility, data sharing, and financial incentives. Supplier collaboration may reduce uncertainty but can also create dependence if reverse channels rely on a

small number of partners. Contract design and shared digital records can help clarify responsibilities while preserving flexibility.

5.3 Quality Control in Reverse Flows

Recovered materials and returned products require acceptance criteria that protect downstream process quality. In real operations, inspection cost can rise rapidly when incoming condition is highly variable. Firms may therefore need supplier certification, standardized grading, quarantine areas, and traceability records. The resilience benefit of circularity is strongest when substitute material is not only available but also usable without lengthy rework or validation.

VI. Practical Implications

For management, industrial engineering and sustainability, the simulated findings emphasize that implementation decisions should be based on multiple performance indicators rather than a single headline metric. Stakeholders should define what constitutes success before selecting an intervention, model, or technology.

A staged evaluation is preferable to immediate large-scale deployment. Pilot testing can reveal measurement errors, operational constraints, unintended consequences, training needs, and cost drivers that are difficult to represent in synthetic data. Data governance and transparent documentation should be designed at the same time as the technical intervention.

Decision makers should also evaluate distributional effects. Average improvements can coexist with poor outcomes for particular subgroups, locations, operating conditions, or resource-constrained settings. Future real-world work should therefore report heterogeneity and uncertainty wherever data permit.

6.1 Managerial Decision Framework

Managers can evaluate circular projects using a portfolio of indicators: recovery rate, virgin-material reduction, disruption recovery time, quality loss, working-capital effect, reverse-logistics cost, and service continuity. Projects that improve environmental metrics while creating unacceptable operational fragility should be redesigned rather than labeled successful. Conversely, modestly more expensive recovery systems may be justified if they materially reduce disruption exposure.

6.2 Measurement for Future Field Studies

A real empirical study should collect longitudinal data before, during, and after disruption rather than relying only on manager perception. Useful records would include purchase orders, lead times, inventory transactions, scrap weights, recovery yields, service levels, production downtime, and emergency freight. Combining operational records with interviews could distinguish planned circular capability from ad hoc responses.

VII. Limitations

The primary limitation is the exclusive use of simulated data. The reported means, percentages, model outputs, correlations, and visualizations were generated to be internally coherent and should not be interpreted as measurements from real participants, structures, firms, campuses, or urban areas.

The simulation also simplifies contextual complexity. Real systems contain measurement error, missing data, institutional constraints, behavioral adaptation, extreme events, and interactions that may alter effect size or even reverse apparent relationships. The present numerical patterns are therefore hypotheses and design examples, not validated estimates.

Finally, citations are intentionally marked as placeholders where source verification has not been performed. A submission-ready version should replace every placeholder with verified, topic-specific literature and should align methods with the ethical, regulatory, and technical standards relevant to the final study setting.

VIII. Conclusion and Future Work

The simulated analysis indicates that circular supply-chain adoption can be associated with faster disruption recovery, higher material recovery, and lower dependence on virgin inputs when supported by

digital planning and supplier diversification. Future empirical studies should measure implementation cost, quality risk, long-term profitability, and sector-specific constraints.

The next stage should replace simulated observations with verified data, predefine inclusion and exclusion rules, document preprocessing, specify uncertainty analysis, and compare results against domain-appropriate benchmarks. Where human participants or sensitive data are involved, formal ethics review and data-protection procedures would be required before real data collection.

Declarations

Data availability: All numerical data, results, tables, and figures in this manuscript are simulated/illustrative for article-development purposes.

Ethics statement: No real human participants, animals, organizations, field sites, or operational systems were studied in this simulated demonstration.

Conflict of interest: No conflict of interest is claimed for this illustrative manuscript.

Funding: No external funding or grant support is claimed.

Author affiliations: Institution names are intentionally left as placeholders and should be replaced only with verified author information before publication.

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