

Resource Recovery as a Supply Chain Resilience Strategy: From Linear Material Flows to Circular Waste-to-Value Systems

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 <https://doi.org/>

Abstract

Global supply chains have experienced repeated disruptions arising from pandemics, geopolitical conflict, extreme weather, transport bottlenecks and shortages of critical inputs. These events have exposed a structural weakness in supply systems organized predominantly around linear material flows: extraction, production, consumption and disposal. This conceptual review argues that supply chain resilience should not be understood only as the diversification of suppliers, increased inventories or relocation of production. It should also include the capacity to recover value from materials already circulating within economic systems. Drawing on circular economy, industrial ecology, resource recovery and supply chain resilience literature, the paper develops a waste-to-value resilience framework linking resource recovery with three dimensions of resilience: material resilience, economic resilience and systemic resilience. The framework positions reuse, repair, remanufacturing, recycling, urban mining, industrial symbiosis and design for recovery as complementary mechanisms for reducing dependence on vulnerable virgin-material supply chains. The paper further identifies policy, technological, market and information barriers that can prevent waste streams from functioning as reliable secondary-resource systems. The paper highlights how waste-to-value approaches are only capable of enhancing resilience if recovery solutions are built on the foundation of quality, traceability, sustainability, and social protection. The paper concludes by emphasizing that circularity should not be viewed as an environmental goal alone but as a strategic supply chain approach that reduces material exposure while creating more value.

Keywords: *waste-to-value; resource recovery; circular economy; supply chain resilience; industrial symbiosis; urban mining; secondary materials; material security*

1. INTRODUCTION

In the past, supply chains have been structured in terms of efficiency, savings, and availability of cheap virgin resources. In terms of efficient practices, organizations have been able to cut costs through just-in-time inventory, production that is close to each other geographically, single sourcing, and long-distance transport. These are all factors that may pose greater risks of disruptions to the system. The coronavirus pandemic, political unrest, transport disruptions, and climate changes have shown how fast a disturbance in one part of a network can spread through different stages of production and distribution. Thus, research into resilient supply chains has focused on creating a balance between vulnerability and adaptability (Pettit, Fiksel, & Croxton, 2010).

The pandemic period also stimulated the development of the concept of viable supply chains. According to Ivanov (2022), the modern supply chains should combine such features as agility, resilience, and sustainability; and they need to adapt their structure in accordance with changes in the external environment. The mentioned concept is especially important for material flows. In the case of the supply chain which relies almost exclusively on virgin materials located far away from the production place, it can still be fragile due to the interdependence of its suppliers.

The present paper proposes that waste and end-of-life materials should be considered part of the resilience architecture of supply chains. The argument is not that waste can replace virgin materials universally. Rather, discarded products, industrial by-products, packaging, obsolete equipment and other residual streams can constitute secondary material stocks that reduce dependence on external virgin inputs when they can be recovered economically and environmentally. This argument is consistent with the circular economy principle of maintaining products and materials at their highest possible value for as long as possible (Geissdoerfer et al., 2017).

The paper therefore asks three questions: (1) How does the linear supply-chain model create material vulnerability? (2) In what ways can resource recovery contribute to supply-chain resilience? and (3) What institutional, technological and market conditions are required for waste-to-value systems to function as reliable secondary-resource networks?

2. REVIEW APPROACH AND CONCEPTUAL SCOPE

This paper adopts a conceptual review approach. It synthesizes literature from four intersecting areas: supply-chain resilience, circular economy, industrial ecology, and resource recovery. It is not about calculating any recovery rate or assessing one specific waste stream but about constructing an analysis that shows how resource recovery can be considered a resilience capability.

This review starts from a systemic perspective. It does not analyze waste only in terms of its final disposal but also traces material flows through the stages of extraction, production, distribution, consumption, and post-consumption. This is crucial since there is potential for value loss during different stages of the lifecycle. According to Velenturf and Purnell (2017), the process of resource recovery must be considered within a broader transformation process when waste/resource management is reshaped around value.

The conceptual range of waste-to-value covers such approaches as reuse and repair, remanufacture, material recycling, urban mining, industrial symbiosis and designing for recovery. They vary in technical and economic terms, but there is one common aspect among them: they keep the value which otherwise would be lost from the system of production.

3. SUPPLY CHAIN FRAGILITY IN A LINEAR MATERIAL SYSTEM

Three characteristics of conventional supply systems create particular vulnerability: geographic concentration, linearity and thin buffers.

Secondly, geographic concentration results in dependence on specific extractive zones, processors, manufacturing plants and transportation routes. Even when there is geographical diversity in the assembly of finished products, critical raw materials may continue to be geographically concentrated. The resilience of supply chains, as explained by Pettit et al. (2010), highlights this dichotomy.

The second issue that arises is the existence of asymmetry due to linearity. Materials become a part of the economy as virgin material, but once they have been used, they are often considered waste material rather than secondary material input. It thus becomes evident that a problem in virgin material extraction will cause shortage despite the fact that huge amounts of the same material are in waste products. The aim of the circular economy is to solve this problem by retaining products, components, and materials longer and by recapturing their value once their lifecycle is over.

Thirdly, thin buffers will increase disruptions. Just-in-time systems may lower inventory costs during stable times, but there is little margin for error when interruptions occur in transportation or manufacturing processes. Ivanov (2022) claims that viable and resilient chains of supply require adaptability in structure as opposed to one single configuration. Secondary material chains will help in

achieving such adaptability by providing another source of input which is not as susceptible to the same risk factors as virgin supply.

The implication is significant: supply-chain diversification should not be limited to adding more suppliers. It should also include diversification of material sources. A supply chain drawing on both virgin and recovered materials has a broader input portfolio than one dependent exclusively on primary extraction.

4. WASTE AS A SECONDARY RESOURCE STOCK

The prevailing paradigm of treating waste as an asset does not recognize its material worth. According to UNEP and the International Solid Waste Association (2024), waste management should shift from disposal to waste prevention and better management and circular economy in which materials are considered assets. This is also one of the challenges discussed by the Global Resources Outlook, which highlights rapid resource use growth as well as the fact that the circular economy model includes not only recycling but also reuse and maintenance of materials (UNEP & International Resource Panel, 2024).

From a supply-chain perspective, four characteristics make secondary material stocks strategically relevant.

4.1 Material concentration and accumulated stocks

Some of the products that have been disposed of have high concentrations of valuable materials, which are obtained due to past production processes. This means that products like electronic devices, automobiles, batteries, and other industrial products can be seen as stockpiles of materials. Urban mining is the concept that sees these material stocks as resources embedded in the built infrastructure as opposed to ore deposits.

4.2 Locational proximity

As opposed to many natural materials, waste tends to be more proximal to the production and consumption sites. Consequently, waste recovery can reduce the length of the material cycle. However, this will not negate the necessity for international trade, which may be used as a replacement when transportation channels are blocked. As Purnell (2019) argues, waste recovery infrastructure can turn into an integral part of resource management infrastructure, despite potential restrictions on its creation.

4.3 Diversification of input sources

Recovered materials provide a second material stream. In times when virgin materials are scarce or have volatile prices, firms having a relationship for recovery are less reliant on any one upstream stream. This is a resilience advantage but not an assertion that recovered materials are inherently cheaper or substitutable for virgin materials.

4.4 Retention of embedded value

High-value circular approaches would generally be those where the preservation of a product or its component parts would be better than a reduction to materials right away. The repair, reuse, and remanufacture of a product could allow for a greater amount of embedded energy and labor contained within the product to be utilized.

5. RESOURCE RECOVERY STRATEGIES FOR RESILIENT SUPPLY CHAINS

Resource recovery can be organized as a hierarchy of interventions across the material lifecycle.

Reusing and repairing products extend their life with relatively little additional processing. These processes minimize the need for new products, and thus minimize the frequency with which virgin materials need to be put into the process.

Remanufacturing is the process of making worn-out items usable again. Remanufacturing offers another source of supply for the components by retaining their inherent value in terms of manufacturing. This becomes pertinent in industries where the components have a long lifespan and contain considerable value in terms of materials and engineering.

The process of recycling divides materials and recycles them to be used as secondary raw materials. The efficiency of recycling depends on the system of collecting, the level of contamination, the quality of the materials, the technology used, and the availability of markets. For instance, Hahladakis & Iacovidou (2019) note that the process of closing material loops is fraught with many trade-offs.

Urban mining builds on the concept of material recovery by including stockpiles of materials found in buildings, structures, transportation and waste products. This concept may be especially useful in relation to materials that are geographically constrained in their extraction from primary sources.

Industrial symbiosis connects separate production systems so that one firm's by-product, waste material, water or energy becomes another firm's input. Chertow (2000) emphasizes geographic proximity, collaboration and material exchange as central features of industrial symbiosis. From a resilience perspective, such networks can create local or regional material loops that complement conventional

supply chains.

Design for recovery shifts resilience upstream. Products designed for modularity, disassembly, repair and material identification are easier and less costly to recover at the end of their service life. Thus, resilience is partly determined before a product enters the market.

6. A WASTE-TO-VALUE SUPPLY CHAIN RESILIENCE FRAMEWORK

The central proposition of this paper is that resource recovery can contribute to three mutually reinforcing dimensions of supply-chain resilience: material resilience, economic resilience and systemic resilience.

Material resilience refers to the ability to reduce dependence on a single external source of virgin material. A firm with access to recovered inputs possesses an additional material channel. The value of this channel is greatest when it is geographically or operationally independent from the primary supply route. This corresponds to the resilience literature's emphasis on reducing vulnerability while developing adaptive capabilities (Pettit et al., 2010).

Economic resilience refers to the ability to withstand material-price volatility and preserve productive capacity. Recovery, reuse and remanufacturing can create secondary revenue streams and reduce exposure to some upstream price shocks. On the other hand, recovery may not always be economically feasible. Velenturf & Jopson (2019) observe that the economic case for resource recovery needs to account for the environment and society and not just profit making.

Resilience on the systemic level is related to the nature of structure and adaptation of the overall material network. Circular loops could potentially cut down on the length of the supply chain, make the flow of materials more transparent and provide an alternative route for connecting buyers and sellers. As stated by Ivanov (2022), the ability of supply chains to adapt their structure based on changes is crucial. Resource recovery offers one way to do that as materials can circulate within loops.

The framework can therefore be represented as:

Disruption → Virgin-material vulnerability → Recovery opportunity → Secondary material flow → Alternative input channel → Material, economic and systemic resilience.

Recovery does not need to occur for all streams of waste. Rather, recovery decisions should take into account feasibility in terms of technology, the environment, economics, material characteristics, socio-cultural context, and market considerations. Recovery needs to be viewed as resilience capacity if these conditions hold true together.

7. BARRIERS TO WASTE-TO-VALUE RESILIENCE

Several barriers can prevent waste streams from becoming reliable secondary-resource systems.

Infrastructure forms a key constraint. The collection, sorting, pre-processing and re-processing infrastructure requires investments and some waste streams may require sophisticated equipment. According to Purnell (2019), the capacity for infrastructure, regulation, finance, and information forms some of the major constraints to resource recovery systems.

Quality and contamination are important considerations as well. The secondary materials may differ in their composition and performance, rendering them unfit for certain high-performance purposes unless processed further. Standards need to be put in place to ensure the quality of the recovered materials.

A lack of market demand is yet another barrier. Unless firms are ready to buy recycled goods, the processes of recycling and collecting may turn out to be economically unfeasible. Market-based solutions such as mandatory recovery content and producer responsibility can aid in creating the demand.

Data and traceability have become crucial. The visibility of supply chains helps organizations determine the location of resources, their quality, and manage their recovery. Digital technology can help with this visibility. As Ivanov and Dolgui (2021) state, digital modeling of the supply chain is an effective method for disruption risk management through mapping and management of these risks. This logic can be transferred to secondary material flows as well; the visibility of materials makes their recovery more certain.

Lastly, safeguards must be in place from both social and environmental perspectives. While informal recycling may help generate incomes and yield a large percentage of recovery rates, the risks associated with the process can translate the environmental burdens onto marginalized communities. The waste-to-value approach should be considered from the perspective of environmental justice and safety for workers.

8. POLICY AND INDUSTRY IMPLICATIONS

A resilient waste-to-value system requires coordinated action across producers, governments, waste operators, logistics providers and consumers.

Extended producer responsibility can motivate producers to consider end-of-life recovery during the design and marketing of their products. Design considerations related to modularity, recoverability and material identification and disassembly can reduce future recovery costs.

In terms of investment into regional recovery infrastructure, it is possible to develop some buffers that will support existing stock and supplier diversification measures. In such a way, governments and industries need to consider recovery infrastructure within the context of their resilience strategy rather than waste management costs.

Certification and standards are needed to build trust in recycled materials. Standards will lower transaction costs and help recycled materials integrate into existing manufacturing processes.

Another way to secure stable demand is through procurement policies. Governments and corporations can set minimum recovered material requirements when it is feasible. This could contribute to stabilizing the secondary materials markets.

Lastly, digital traceability will link up waste collection, transportation, processing, and manufacturing. Systems such as material passports, tracking technologies, and information systems will increase the visibility and management of secondary resource flows. Such efforts align with the trend towards increased visibility of supply chains and network management.

9. DISCUSSION

At its very core, what makes this study unique is the way in which it transforms the challenge of going from waste to value not into an environmental management issue but into a supply chain resilience issue. While circular economy research has focused almost entirely on resource use and its environmental implications, supply chain resilience research has concentrated on disruption and post-disruption challenges.

This synthesis also makes clear where the argument's limitations lie. Waste can't be used indefinitely to replace virgin resources. The process of recovery depends on the amount and type of stock that is in place. It also depends on rates of recovery, throughput, and product lifetime. Some materials break down as part of the recycling process or even get dispersed through use. In other words, a robust system will still involve virgin resources along with recycled ones.

This theory further builds on the concept of supply chain redundancy. Traditionally, supply chain redundancy involved having more than one supplier, stock or production facility. The waste-to-value principle brings into focus material redundancy, whereby the same productive process utilizes both primary and secondary materials. This form of redundancy can simultaneously support sustainability and resilience when recovery processes are environmentally sound.

The framework further suggests that circularity and resilience should not be treated as separate organizational objectives. A circular intervention that reduces virgin-material dependence may also improve resilience; a resilience intervention that merely increases stocks of virgin material may improve short-term continuity without reducing long-term resource vulnerability. The strongest strategies are therefore those that address both dimensions simultaneously.

10. LIMITATIONS AND FUTURE RESEARCH

This paper is conceptual and does not test the proposed framework using firm-level data, material-flow analysis or life-cycle assessment. The three dimensions of resilience are therefore analytical categories rather than empirically validated indicators. Future research should operationalize the framework through quantitative measures such as the proportion of secondary inputs in total material demand, recovery lead time, geographic independence of recovered supply, price sensitivity, carbon intensity and continuity of recovered-material availability.

Future studies could also compare specific waste streams, including electronic waste, plastics, industrial residues, construction materials and end-of-life batteries. Such studies would help identify where waste-to-value strategies provide the strongest resilience benefits and where technical or environmental constraints limit their usefulness. Scenario modelling could examine how secondary-resource availability changes the impact of disruptions to ports, mines, processing facilities or international trade corridors.

Furthermore, there is a need for research on the relationship between informal recovery networks and formal logistics systems. In many developing countries, informal workers undertake considerable efforts in terms of collecting and recovery. It is thus crucial to understand how such systems can be incorporated effectively and ethically into circular logistics systems.

11. CONCLUSION

Supply-chain disruptions in recent times have shown that efficiency without flexibility leaves the system vulnerable. The typical solution has been supplier diversification, buffer inventories, and

geographic restructuring of the system. This is essential, but it does not solve the issue of dependency on virgin flows of materials.

A supplementary approach would be to see waste and end-of-life products as secondary resource inventories. Reuse, repair, remanufacturing, recycling, urban mining, and industrial symbiosis can help create alternative material flows and lessen reliance on potentially fragile upstream sources. These benefits may be looked at from three perspectives: material resilience, economic resilience, and systemic resilience.

This means that the paradigm shift of waste to value brings about a paradigm shift in the strategic questions. In addition to the traditional questions on the means through which organizations can gain access to more resources or even alternate suppliers, another question that organizations may be able to ask is: which resources are already within the organization's economic systems and what ways can the organization employ to make the best out of the existing resources. The move from the linear flow of material into circular flows is not only environmentally imperative but also strategically important.

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