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Enhancing Transparency in Buyer-Driven Commodity Chains for Complex Products: Extending a Blockchain-Based Traceability Framework Towards the Circular Economy

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Abstract

This study extends our prior blockchain-based traceability framework, WEave, for application to a furniture supply chain scenario, while using the original multi-tier apparel supply chain as an anchoring use case. We integrate circular economy principles such as product reuse, recycling traceability, and full lifecycle transparency to bolster sustainability and resilience in supply chains by enabling data-driven accountability and tracking for closed-loop resource flows. The enhanced approach can track post-consumer returns, use of recycled materials, and second-life goods, all represented using a closed-loop supply chain topology. We describe the extended network architecture and smart contract logic needed to capture circular lifecycle events, while proposing new metrics for evaluating lifecycle traceability and reuse auditability. To validate the extended framework, we outline simulation experiments that incorporate circular flows and cross-industry scenarios. Results from these simulations indicate improved transparency on recycled content, audit trails for returned products, and acceptable performance overhead when scaling to different product domains. Finally, we offer conclusions and recommendations for implementing WEave functionality into real-world settings consistent with the goals of digital, resilient, and sustainable supply chains.

Keywords: blockchain; supply chain management; traceability; transparency; circular economy; sustainability; reuse and recycling

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1. Introduction

Modern supply chains for complex products often span multiple tiers of independent suppliers and service providers. In buyer-driven commodity chains (BDCCs), powerful retailers or brands orchestrate production via global networks of specialized manufacturers [1]. A notable example is the apparel industry, where intense cost pressure and outsourcing have led to fragmented, opaque supplier networks [2]. Insufficient transparency in these chains can mask unsustainable practices, enable counterfeiting, and hinder responsiveness to quality or safety issues [3]. Nontransparency has been linked to catastrophic events and recalls in various sectors, from apparel to food and pharmaceuticals [4–7]. Ensuring traceability, i.e., the ability to track the origin and history of each component or batch, is therefore critical for both consumer safety and corporate social responsibility.

Blockchain technology has emerged as a promising tool to improve supply chain transparency and trust. A blockchain is a decentralized, tamper-evident ledger maintained by multiple parties, making it well-suited for recording provenance and transactions in a supply chain [8]. Several studies have remarked on this apparent fit. At least in principle, by leveraging smart contracts (self-executing code on the ledger) and data immutability, blockchain-based systems can enforce business rules and enable secure information sharing among stakeholders who may not fully trust each other. For instance, Badhwar et al. highlight blockchain's "tremendous potential" as a foundation for more traceable and transparent fashion supply chains [9]. Real-world interest is growing as well: the global blockchain supply chain market was estimated at USD 2.3 billion in 2023 and is projected to grow at over 90% compound annual growth rate (CAGR) through 2030 [10], reflecting high expectations for this technology's transformative impact on supply chain operations. Yet adoption continues to lag.

Our hypothesis is that there remain gaps between the coverage of products for the task and the concrete requirements seen in operational settings, and that existing products are often overly general (capable of representing "anything" but without adequate guidance on precisely how to represent the domain-specific data corresponding to supply chain transactions). To give just two of many examples, while smart contracts seem capable of covering supply chain scenarios, encoding the needed information leaves hard problems for the developer; our work identifies and solves these. Given a blockchain that covers the requisite events, verification of the chain and validation that it achieves the intended purpose (or, conversely, identification of deficiencies that may have allowed impermissible materials or activities) is again non-trivial; these tasks are also addressed in our work.

Motivated by issues such as these, our recent conference paper proposed WEave [11], a blockchain-based traceability framework tailored to complex assembly supply chains in a buyer-driven context. WEave was demonstrated via a blockchain-based simulation of an apparel supply chain, showing how permissioned blockchain networks and smart contracts can meet key traceability requirements (e.g., recording the origin of materials, capturing assembly processes, and enabling third-party audits). The simulation implemented a multi-tier scenario with suppliers, manufacturers, a buying agent, a retailer, and a third-party auditor, all interacting through blockchain channels. WEave's evaluation in the prior study showed that it could map complex product assemblies and enforce business rules (like asset ownership transfers and quality checks) in real-time, with acceptable performance across order sizes from 200 to 20,000 units of shirts. This established a baseline for blockchain-enabled transparency in linear (forward-flow) supply chains of apparel.

Despite this progress, significant gaps remain before WEave and other such frameworks can be said to fully address emerging supply chain challenges. First, sustainability efforts are increasingly focusing on the circular economy—extending supply chains beyond the point of sale into product return, refurbishing, recycling, and reuse loops. Traditional traceability systems (including our initial WEave design) omit post-consumer activity. Second, because our WEave prototype targeted the apparel industry, it omitted functionality important in other industries and for different product structures (i.e., beyond cut-and-sew apparel). Third, the evolving research on digital, resilient, and sustainable supply chains (the theme of the present Special Issue) calls for integrating multiple paradigms—blockchain, IoT, simulation, lifecycle analysis—to not only improve transparency, but also boost resilience and sustainability of supply networks. The recent literature emphasizes that digitalization (e.g., blockchain, digital twins, AI) should yield supply chains that are both more agile/resilient to disruptions and more environmentally sustainable [12]. This extended study aims to address these gaps by enhancing the WEave framework in the following ways:

- Integration of Circular Economy Principles: We extend the traceability scope to cover the full product lifecycle, combining forward and reverse logistics, from raw material sourcing to manufacturing, distribution, customer use, and end-of-life processes. The enhanced framework records events such as product returns, disassembly, recycling of materials, and second life (i.e., resale or reuse) instances. Particularly important is tracking for circular flows, where materials re-enter the supply chain and are reused, rather than ending as waste. By making lifecycle data available on the ledger, we facilitate circular business models (e.g., recycling programs, leasing, and re-commerce) and enable asset reuse and recycling traceability as core features. At the same time, we enable the imposition of additional requirements (such as that recycled parts be refurbished, subjected to additional checking, etc.). In fact, the issue is seen even in our original apparel context, which could mean tracing a garment from fiber production to its first sale, and then through its return and transformation into recycled fiber used in a new garment. Such end-to-end visibility is increasingly seen as vital for a global circular economy. For example, regulators seek assurance that products contain a certified percentage of recycled content and no restricted substances [13]; this requires immutable records of material provenance. Our extended framework is designed to capture exactly this information, and the extension enables support for objectives like pollution prevention and product stewardship in the transition towards a more circular economy [14].
- Generality Across Commodity Chains: We demonstrate that the WEave framework's core design can be applied to broader commodity chains beyond apparel, such as furniture supply networks, with appropriate (but relatively minor) adjustments. Complex products in these sectors often involve modular assembly, multi-tier suppliers, and post-sale returns (e.g., product take-back). In contrast to apparel returns, furniture supply chains introduce a more stringent disassembly traceability requirement [15]. We discuss how the blockchain network topology, smart contract logic, and data model can be parameterized or extended to accommodate different industries' needs (for instance, tracking a bill-of-materials for furniture). To illustrate generality, we outline a comparative scenario analysis, i.e., contrasting the apparel use case with a furniture supply chain scenario. This cross-industry evaluation is important because blockchain solutions like WEave must be flexible enough for varied supply chain configurations without starting from scratch for each case.
- New Metrics for Lifecycle Tracking and Auditability: With the inclusion of circular processes, we propose metrics to quantitatively assess lifecycle tracking efficacy. Examples include (a) Recycled Content Traceability (%)—the fraction of a product's material (by weight or item count) that can be traced back to prior product lives via the blockchain record; (b) Return/Reuse Audit Rate—the percentage of returned items for which the system successfully logs and verifies disposition (reused, recycled, or properly discarded); (c) Latency of Traceability Queries—the time to retrieve the full history of a product including manufacturing and post-use events; and (d) Cycle Closure Rate—the proportion of output that re-enters as input (a measure of circularity enabled, perhaps tracked through smart contract triggers). These metrics extend conventional supply chain KPIs by focusing on transparency of reuse/recycling processes, which is a novel contribution to evaluating supply chain sustainability.
- Additional Simulation Experiments for Validation: To strengthen the evidence for our extended framework, we design new simulation experiments beyond those in the initial study. First, we implement a closed-loop apparel supply chain simulation where a certain percentage of sold garments are returned after use, sorted for recycling, and reintroduced as raw material in new production. We describe the methodology for

simulating consumer returns, processing by a recycler entity, and injecting recycled material back into the manufacturing orders. The expected result is that the blockchain ledger successfully links each returned garment to a batch of recycled fiber and then to a new garment, demonstrating traceability across product generations. We will measure system performance (transaction load, smart contract execution time) and integrity of traceability (e.g., no lost links in the chain of custody). Second, we propose a cross-industry simulation: for example, modeling a furniture supply chain with a take-back program for used furniture, and comparing it to the apparel case. This will involve different asset types and a unique assembly structure. By running the WEave framework in both contexts, we can compare how the framework handles different throughput or data volume requirements. We anticipate that while the absolute performance may differ (apparel might generate more data per unit due to more components), the qualitative outcomes will be similar—i.e., successful end-to-end traceability and manageable overhead.
- Alignment with Sustainability and Resilience Goals: Finally, we expand the discussion of sustainability, transparency, and resilience implications. The Special Issue's theme highlights that digital technologies in supply chains should not be just for efficiency, but also for making supply chains resilient to shocks and sustainable in the long term. Our extended framework contributes to sustainability by enabling circular supply chain management, which can reduce waste and virgin resource consumption (e.g., by tracking and increasing recycled inputs). It also contributes to resilience: improved traceability means that in the event of a disruption or quality failure, firms can quickly isolate affected batches and reroute supply (since the provenance of every part is known) [16]. Moreover, having a tamper-proof record of transactions can prevent fraud and ensure continuity of data if a particular intermediary is compromised. In summary, we articulate how the WEave extension is not just a technical upgrade, but a sociotechnical improvement aligning supply chains with broader goals of transparency, sustainability (through circular resource flows), and resilience.

Several recent studies have explored using blockchain technology to support circular economy goals by improving product traceability, recycling verification, and supply chain transparency. For example, Santos et al. [17] present a blockchain-based reverse logistics framework for agricultural pesticide packaging. Their system uses Ethereum smart contracts and QR-coded tokens to track pesticide containers from use to collection, rewarding farmers and waste handlers with digital coins for returning empty containers. This approach ensures transparent, immutable records of each container's lifecycle and incentivizes proper recycling, effectively integrating all actors (farmers, collection centers, manufacturers, authorities) in a tamper-proof network. Early results indicate that such a blockchain solution can guarantee traceability and authenticity of recycled material flows without imposing significant overhead on participants. In the construction sector, researchers have similarly proposed blockchain frameworks to track building materials and components for reuse. Singh and Kumar [18], for instance, identify critical success factors for implementing blockchain in circular construction supply chains, emphasizing transparency and data integration as keys to enabling material recirculation. Meanwhile, Bathaei et al. [19] developed a decision-oriented framework to evaluate blockchain-enabled strategies for waste management in global manufacturing. Using expert input and multi-criteria methods (Best–Worst Method and TOPSIS), they prioritize applications like material traceability platforms and smart-contract-driven reverse logistics as the most viable for enhancing circularity. Their case study in the electronics sector demonstrated the framework's effectiveness, validating that blockchain-based traceability and smart contracts can significantly improve e-waste tracking and compliance in practice. Taken together, these efforts show how blockchain is being woven into diverse industries—from agriculture to construction to electronics—to enable closed-loop supply chains.

The push for such frameworks is further justified by evolving regulations that demand higher transparency in product lifecycles. The European Green Deal [20] and its Circular Economy Action Plan [21] explicitly call for extending product longevity and keeping resources in circulation as long as possible. This EU action plan targets every stage of a product's life—from sustainable design and production to consumption, reuse, and recycling—and it underscores that better traceability and data-sharing are key to preventing waste and achieving climate neutrality. In line with these goals, the EU is introducing Digital Product Passports (DPPs) for batteries and other products, which will require detailed information about a product's composition, use, and end-of-life to be recorded and made accessible across the value chain [22]. By 2027, many products in Europe will need a digital record (potentially implemented on blockchain) of their material content, carbon footprint, and recycling history. In addition, corporate reporting mandates are raising the stakes for supply chain sustainability. The Corporate Sustainability Reporting Directive (CSRD) [23], in effect since 2024, makes disclosure of circular economy performance mandatory for thousands of companies. Under the CSRD's reporting standards, firms must report metrics like the share of recycled or renewable materials used, waste reduction targets, and how products are designed for circularity. Notably, the circular economy now plays a "central role" in these disclosures, helping investors and regulators evaluate how well companies manage resource flows. This regulatory pressure creates a clear incentive to adopt frameworks like WEave and its ilk: only with robust traceability systems can companies reliably gather the data needed for compliance and for demonstrating progress on circularity. In essence, policies such as the Green Deal and CSRD are catalyzing the integration of blockchain into circular economy efforts by demanding the very attributes—transparency, auditability, cross-organizational data sharing—that blockchain-based traceability frameworks are designed to deliver. Researchers and industry practitioners are responding by developing and piloting the kinds of blockchain-enabled circular economy systems discussed above, positioning these innovations as foundational tools for digital, resilient, and sustainable supply chains.

The above frameworks differ in their scope and implementation, often in ways that contrast with the WEave framework. Other frameworks opt for public or hybrid networks: the pesticide-packaging solution by Santos relies on Ethereum's public blockchain to maximize openness and tamper-resistance, whereas WEave's Fabric implementation prioritizes enterprise-grade privacy (e.g., using Fabric channels to partition sensitive data). Despite different platforms, all these frameworks employ smart contracts to automate verification of circular transactions—from logging recycling events to releasing token rewards—and thus minimize the need for manual oversight. To our knowledge, this is among the first efforts to combine a detailed blockchain-based supply chain traceability framework with explicit circular economy integration and simulation-based evaluation, though the recent literature is converging on these intersections. Our work builds on such insights by offering a concrete implementation and testbed (via simulation) that others may extend, adapt, and learn from. The next sections detail the materials and methods of our extended framework, the results of our simulations (both from the original study and new experiments), and a discussion of implications and future work.

2. Materials and Methods

The extended WEave framework development follows a systematic approach encompassing blockchain architecture design, smart contract development, and circular economy integration. The development methodology consists of three phases: (1) requirements analysis and mapping from established circular economy principles to technical specifications, (2) blockchain network topology design incorporating new organizational roles and data governance structures, and (3) iterative smart contract development with built-in validation mechanisms for circular flow transactions.

The evaluation methodology employs controlled simulation experiments to assess both technical performance and circular economy effectiveness across multiple scenarios. Our approach separates functional validation (correctness of circular economy processes) from performance evaluation (scalability and throughput metrics) to provide comprehensive framework assessment as detailed in Table 1.

Table 1. Experimental design summary.

Experiment Category	Variables Analyzed	Measurement Approach	Expected Outcomes
Scalability testing	Production volume (500, 2500, 5000 units), return rates (5%, 10%, 15%)	Throughput (tx/s), latency (ms)	Linear scalability validation
Cross-industry validation	Supply chain topology (apparel vs. furniture), asset complexity, assembly structures	Transaction volume per unit, query response time	Framework generalizability
Circular economy effectiveness	Recycled content percentage, return processing rates, material flow loops	Recycled content traceability (%), return audit rate, cycle closure rate	Circular process verification
Traceability performance	asset types (original, returned, recycled, refurbished), query complexity	Query latency by asset type, provenance completeness	End-to-end traceability validation
Network resilience	Participant diversity, channel configuration, consensus mechanisms	Data integrity, multi-party endorsement success	Trust and governance validation

Next, we first give a brief overview of the original WEave blockchain framework for context. Then we explain the extensions for circular economic integration, including modifications to network topology and smart contracts. Finally, we outline the design of simulation scenarios (both the apparel case and a furniture scenario for generalization) and the metrics we use to evaluate performance and traceability.

2.1. WEave Blockchain Framework Overview (Original Design)

The WEave framework was initially conceived to address traceability in assembly oriented supply chains with multiple independent parties. It leverages Hyperledger Fabric [24], an open-source permissioned blockchain platform, to implement a private, consortium-led ledger network. Key features of Fabric utilized in WEave include multiple organization participation with role-based identities, channel partitioning of data, chaincode (smart contract) logic for custom transactions (typically represented as self-contained functions written in Go, Java, or JavaScript that use Hyperledger APIs to read or write data held in the chain), and endorsement policies for validating transactions. Fabric's transaction architecture separates execution, ordering, and validation to enhance consensus modularity and determinism, as shown in Figure 1.

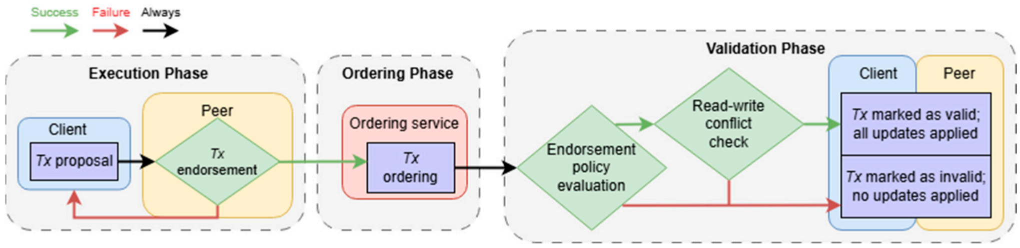


Figure 1. Hyperledger Fabric's execute–order–validate transaction architecture.

2.1.1. Network Topology

In the original apparel case study, WEave's network consisted of seven organizations, where six represented typical roles in a garment supply chain, and the seventh was a blockchain consultant organization, as shown in Appendix A.1. Specifically, these included: raw materials supplier (e.g., cotton farmer, denoted RM), textile manufacturer (spinning/weaving mill, TX), full-package supplier (garment sewing and finishing, FS), a buying agent (upstream suppliers coordination on behalf of the retailer, BA), the retailer (RE) itself, an independent third-party auditor (AU), and a blockchain consultant (BC) who maps business logic onto smart contracts thus enabling stakeholders to mutate the ledger accordingly. Each organization runs one or more blockchain peer nodes hosting its copy of the ledger and chaincode. We instituted two Fabric channels to separate concerns: a Production Channel (PC) that all production-related parties (RM, TX, FS, BA, RE, AU) join, and an Administration Channel (AC) that includes only RE, BA, and AU. The PC is used to record value-added processes and transfers—for example, creation of material lots, production of components, assembly of final products, and shipment transactions. The AC is used for commercial or administrative transactions that must remain confidential from the upstream suppliers—for instance, purchase orders or pricing information between the retailer and the buying agent. This channel design reflects the BDCC characteristic that retailers outsource production but still need oversight: by having access to the production channel's ledger, the retailer (RE) and auditor (AU) can view real-time production data, which traditionally only the BA and factories would see. Meanwhile, sensitive data (like cost negotiations and factory audit results) can be kept on the admin channel.

2.1.2. Smart Contracts and Data Model

WEave's original business logic was implemented via Fabric chaincode on each channel. We developed chaincodes in Go, encoding different asset types and transactions. For the production channel, asset types included CottonBale, CottonYarn, Lot (CottonYarn), Lot (FinishedFabric), and so forth—modeling the transformation of materials through the supply chain. Transactions allowed authorized parties to create, update, or transfer these assets. For example, RM could invoke a CreateCottonBale function (allowed only for RM's role) to record a new cotton bale with attributes like weight, grade, etc. TX could then invoke CreateUnfinishedFabric by consuming certain cotton bale/yarn lot IDs as inputs (representing spinning/weaving), with the chaincode enforcing that only a TX organization can perform that and that the referenced input lots exist and belong to TX. Similar logic propagated through FS, creating finished goods from fabric lots, and BA/RE performing transfer or acceptance transactions. Throughout these updates, ownership and custody of each asset were tracked as state on the ledger (e.g., an asset's Owner field updates when it is transferred).

On the admin channel, the chaincode handled purchase orders and compliance documents. For instance, a CreateOrder transaction could be issued by RE to BA with item quantities, triggering an event that then allows BA to orchestrate production on the PC (the simulation abstracted some of this for simplicity). The admin channel and production channel data could be linked via common identifiers (like a PO number field on production events for cross-reference), but were kept logically separate in the ledger.

2.1.3. Traceability and Audit Functions

In addition to production events, WEave included audit functions in the chaincode to retrieve history or verify constraints. Any participant, including the third-party auditor (AU), could query an asset's provenance via a series of functions that would traverse the chain of references (using Fabric's ledger query by history or by linked IDs in state) to output the lineage of that item. For example, for a given finished garment ID, the chaincode could fetch which fabric roll(s) were used, and in turn, which raw material lots composed that fabric, thereby constructing the assembly tree. This forms the basis for transparency: every finished product is linked to verifiable data on its components and origins. Mass balancing, too, could be achieved by a skeptical auditor through functions like GetContentWeight (content []string), requiring a list of asset IDs as input and, from there, comparing the outputs against the stated assets of the relevant assembly tree(s). Moreover, immutability of the ledger guarantees that this history cannot be tampered with without detection. WEave's design objectives explicitly included compliance with traceability standards, like ISO 9000:2015 §3.6.13's requirement to "trace the origin of materials and parts" and providing real-time information sharing to all stakeholders who have permission [25].

To ensure data integrity, endorsement policies in the Fabric network are set such that all organizations on a channel must endorse chaincode deployment (preventing untrusted code). Each transaction must similarly be endorsed by the relevant subset of participating organizations. For example, a transfer of goods might require that both sender and receiver organizations endorse the transaction, ensuring consensus on the handoff. Additionally, chaincode included programmatic checks on the invoker's role (using Fabric's MSP ID feature) to enforce role-based permissions beyond the endorsement rules. This combination of blockchain consensus and smart contract logic makes the WEave framework robust against data manipulation and unauthorized actions, supporting a high level of trust and accountability.

2.1.4. Performance Considerations

The WEave prototype was tested in a local simulation environment, enabling us to confirm that memory and CPU usage were within acceptable ranges up to large numbers of transactions. Moreover, although the initial implementation was local (to avoid network latency issues in simulation), the design offered a groundwork for evaluating scalability. The original results indicated that throughput scaled expectedly with order size and no critical bottlenecks were hit up to the tested limits. However, it was acknowledged that real-world deployment might face network latency, larger user bases, and integration challenges not captured in a local simulation.

2.2. Extending WEave for Circular Economy Traceability

To incorporate circular economy processes into the WEave framework, we introduce several extensions to the network design and smart contract logic, summarized in Table 2. The goal is to capture events that occur after a product's sale to the end consumer, such as returns for recycling, refurbishment, or secondary resale. This effectively transforms the linear supply chain into a closed-loop supply chain, where materials can flow in reverse for reintegration into new production.

Table 2. Comparison of original and extended WEave framework.

Aspect	Original	Extended	Improvement
Supply chain model	Linear forward-flow	Closed-loop	Enabling circular business models
Network participants	7 organizations: RM, TX, FS, BA, RE, AU, BC	Added RC, WD, RB	Enhanced reverse logistics capabilities
Asset types	CottonBale, CottonYarn, (Un)FinishedFabric, CutPart, AssembledGarment	Added ReturnedProduct, RecycledMaterial, RefurbishedProduct	Comprehensive post-consumer asset tracking
Key smart contract transaction functions	CreateAsset, TransferAsset, UpdateStatus	Added RecordReturn, RecycleProduct, ConsumeRecycledLot, RefurbishProduct	Advanced circular economy transaction support
Industry coverage	Apparel	Apparel and furniture	Generalized framework applicability
Traceability scope	Raw materials → finished products	Raw materials → finished products → returns → recycled materials → refurbished products	End-to-end circular traceability
Key performance metrics	Throughput, latency, scalability (200–20,000 units)	Added recycled content traceability (%), return audit rate, cycle closure rate	Sustainability-focused evaluation criteria
Regulatory compliance frameworks	Basic traceability standards (ISO 9000:2015)	Added EU Green Deal and CSRD	Future-ready regulatory alignment
Business value	Production transparency and audit efficiency	Added circular business model enablement, premium pricing for sustainable products	Strategic sustainability advantages

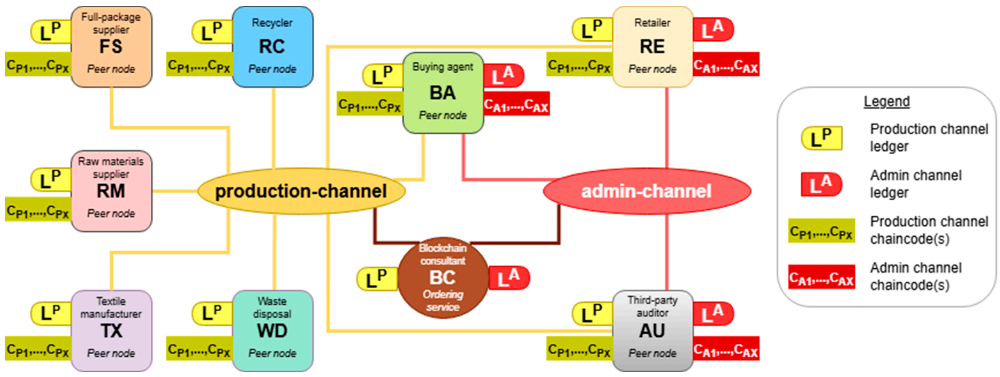
2.2.1. Extended Network Topology

We add new organizational roles to represent end-of-life processing entities, namely recycling (RC) and waste disposal (WD), for our apparel supply chain simulation. The RC could be a third-party textile recycler or the brand's own take-back program unit. This organization will participate in relevant channels to record post-consumer processes. An open question is whether consumers themselves should interact with the blockchain (likely not directly, to avoid complicating the network with thousands of individual end-users). Instead, the retailer (RE) or recycler (RC) can act on behalf of the consumer to log return events.

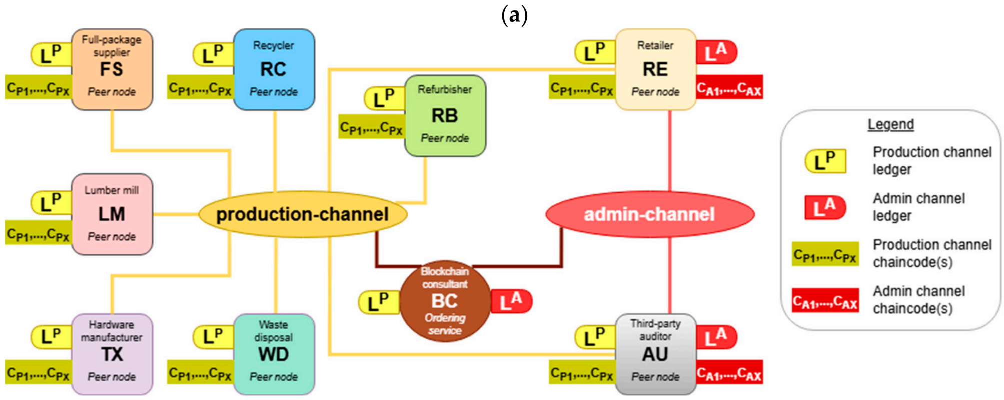
We considered two approaches:

- Single Production Channel with Extended Roles: Simply include RC (and possibly the retail customer interface) on the existing production channel (PC). Under this scheme, after the product is sold to the consumer (which could be recorded as a final transaction from RE to a "Consumer" identity or simply marked as sold), any returns would be processed by RE/RC on PC. The RC would create a new asset instance (e.g., a RecycledMaterial batch) linked to the returned product, and then that asset flows to RM/TX for use in new production.
- Separate Reverse Channel: Create a new, third Fabric channel dedicated to reverse logistics and circular flows, say an "End-of-Life Channel (EC)", where RE, RC, and possibly AU participate. This channel could handle return authorizations, recycling work orders, etc., which might be sensitive (e.g., volumes of returns could be confidential).

For simplicity and traceability integrity, our design opts for the single production channel approach with extended roles—using the existing production channel to log recycling activities—so that the full lineage of an item (from virgin raw materials through any recycling events and the associated testing or refurbishing lifecycles) can be queried in one place. Thus, Figure 2a extends the original network diagram (Appendix A.1) to include the recycler (RC) and waste disposal (WD) nodes connected on the production channel. Our updated topology aligns with concepts in closed-loop supply chain literature [26], where a reverse logistics loop connects end customers back to suppliers or manufacturers. Similarly, Figure 2b depicts the network topology for the furniture supply chain simulation. The notable difference between the two centers is the replacement of a buying agent in the former with a refurbisher in the latter; this new agent embodies the various actions required when refurbishing materials prior to reuse. We should note that this extension could also be useful in apparel chains that include resale of "gently used" clothing, given the higher likelihood of furniture being refurbished and resold as furniture compared to apparel, a case we had not previously considered.



(**a**)



(**b**)

Figure 2. Network topology for closed-loop (**a**) apparel, and (**b**) furniture supply chain simulation.

2.2.2. Data Model Additions

We extend the asset models to represent post-use states. For example, we introduce new asset types such as ReturnedProduct and RecycledMaterial. When a product (garment) reaches its end of life with a consumer, the retailer or recycler can invoke a chaincode function to create a ReturnedProduct record. This record can carry references to the original product ID (linking it to its production history), as well as details like condition, reason for return (if available), and customer information (which could be anonymized or kept off-chain for privacy). The ReturnedProduct essentially acts as a placeholder for an item that has left the forward chain and is now reentering the chain, a procedure sometimes referred to as "reverse logistics". Next, if the item is designated for recycling, the RC/RE invokes, say, RecycleProduct (productID) on the blockchain. This transaction would do the following in chaincode logic: verify that the invoker is RC or an authorized return handler; verify that the productID corresponds to a product that was sold and not already recycled; then mark the ReturnedProduct as processed and create a new RecycledMaterialLot asset. The RecycledMaterialLot would contain information such as the material recovered (e.g., "recycled cotton fiber"), quantity, and quality grade. Crucially, we link the recycled lot back to its source product. One way we do this is to include in the RecycledMaterialLot asset a field originProducts, which could be an array of IDs of products that contributed to it. If one garment yields X kg of fiber, that fiber lot knows it came from that specific garment ID. In cases where the recycling process combines material from multiple products (batch processing), originProducts can list multiple IDs. This provides a many-to-many traceability: one recycled lot could come from many products, and one product could result in multiple output lots (if disassembled into different materials).

Additionally, if an item is not recycled but rather refurbished or resold (very common in the furniture scenario), we handle it differently than with new materials. For refurbishment (e.g., minor repair and resold as second-hand), the product essentially re-enters the market under its original product identity. We could simply log an event on the existing asset (perhaps setting a status field to "resold" and updating the owner to a new buyer). However, since the blockchain network does not include individual consumers, a pragmatic approach is to have the retailer log a resale event. This could be performed on the admin channel (e.g., a second-hand sale record) or on the production channel by transferring the asset to a pseudo-identity representing a second-hand buyer. The complexities of second-hand markets exceeds the scope of this study (privacy, off-chain transactions, etc. [27]), so in our framework we focus primarily on recycling, but we note that similar principles apply to tracking refurbishment: we must capture that the product was returned and then re-distributed, possibly with a new owner, but its identity and history remain intact on the ledger. There are some domains, notably avionics, where this form of reuse is occurring at a significant scale but can pose risks (for example, some parts may have a physical lifetime limit associated with internal wear and tear that can weaken them over time). The issue also cuts the other way: antique furniture must have an associated record of any new materials used during refurbishment. The extended WEave system can record such information, as it can capture the results of any required revalidation testing.

2.2.3. Smart Contract Extensions

We add the following key functions to be implemented in the Fabric chaincode for PC:

- RecordReturn (productID, reasonCode): Can be invoked by RE (retailer) when a customer returns a product. This function creates a ReturnedProduct asset linked to productID. The original FinishedProduct asset could either be marked as "inactive" or "returned" status. We might also transfer ownership of the product asset to the Recycler (or to RE itself in a holding state).
- RecycleProduct (productID, outputLotID, outputType, quantity): Invoked by RC. This function first checks that productID corresponds to a returned product that is not already present in the system, either as a new item or as an item that was previously recycled or reused but not yet resold. It then creates a new asset RecycledMaterialLot with ID outputLotID of type outputType (e.g., "cotton fiber" or generic "recycled textile"), and associates the quantity (mass or count). It links productID in the new asset's metadata (as discussed). It may also mark the original product asset as "recycled". Multiple products can be processed together by calling this for each (or one call with multiple IDs if atomic processing is desired—implementation could vary).
- ConsumeRecycledLot (lotID, newProductBatchID): Invoked by manufacturers (RM/TX/FS). This function would allow a recycled lot to be used in a new production process. For instance, the Raw Material supplier (RM) could mix recycled cotton fiber with virgin cotton. Or the Textile mill (TX) could take recycled polyester pellets to spin into yarn. Depending on how we model it, we might let RM use recycled fiber as if it were an alternate input to otherwise virgin material. To keep it general, ConsumeRecycledLot

would mark that lot as used and perhaps create a link to the new batch. However, since our original chaincode already allowed creating new lots (with no direct concept of input aside from the chain-of-custody for quality flags), we might not need a separate function at all: we can simply allow a RawMaterialLot creation transaction to specify if it is recycled content. Alternatively, a simpler method: treat the recycled material as a subtype of raw material and allow the existing functions to include both virgin and recycled sources. For clarity in trace, we may explicitly model it, e.g., TX references either cotton from RM or recycled fiber from RC (or both). The chaincode then ties those references into the fabric asset's lineage.

- TraceProductHistory (assetID): An extension of provenance queries that not only traces the entire product history. Since a product can give rise to recycled materials that become part of new products, the provenance graph becomes a network, not just a tree. A comprehensive query might need to retrieve both ancestors and descendants of a given ID. For now, we implement a simpler approach: if querying an original product ID, it will list its components (ancestors). If querying a recycled material ID, it will list source products. If querying a new product that contains recycled content, one can trace back to the recycled lot and then to the prior product. We document how an auditor could perform these steps to obtain a fuller picture. In the future, one could write a recursive query that finds all related IDs across cycles.

2.2.4. Data Governance

The transition from linear to closed-loop supply chains fundamentally alters data governance dynamics and trust relationships within the blockchain network. The introduction of new entities, particularly recyclers (RC) and waste disposal (WD) organizations, creates asymmetric trust scenarios where established production partners must now rely on end-of-life processors with potentially different technological capabilities, data quality standards, and compliance frameworks. Unlike traditional forward-flow participants who operate under established commercial relationships and standardized quality protocols, reverse logistics entities often employ diverse technological infrastructures ranging from automated sorting systems to manual processing operations. This technological heterogeneity poses significant interoperability challenges, as recyclers may lack the digital infrastructure necessary for real-time blockchain integration, potentially requiring intermediary data aggregation systems or delayed batch uploads that compromise the immutability benefits of continuous transaction logging.

Furthermore, consumer involvement in the closed-loop model introduces additional governance complexities, as individual end-users cannot reasonably be expected to participate directly in blockchain operations. This necessitates proxy mechanisms where retailers or recyclers act as data custodians for consumer returns, creating potential trust gaps where the authenticity of return data depends on intermediary verification rather than direct blockchain validation. Multi-stakeholder environments with varying regulatory jurisdictions also complicate compliance frameworks, as recyclers operating under different environmental regulations may be subject to distinct reporting requirements that must be harmonized within the shared blockchain infrastructure. These governance challenges require careful consideration of endorsement policies, data validation protocols, and dispute resolution mechanisms to maintain network integrity while accommodating diverse participant capabilities and regulatory constraints.

2.2.5. Security and Integrity Considerations

Introducing circular flows raises new trust questions. For instance, how do others trust that the Recycler accurately recorded the recycled output quantity? In our permissioned setting, RC is a known, permissioned participant. The Auditor (AU) can inspect return records and maybe even external certifications of the recycler. If needed, IoT devices or digital scales could feed data to minimize manual error. We might include a mechanism where the auditor or retailer must endorse the RecycleProduct transaction (multi-signature endorsement) to validate that the recycling claim is correct. This could prevent, say, a recycler from falsely inflating recycled content. Such governance can be encoded via Fabric endorsement policies or by requiring an auditor countersign in chaincode logic.

A key design choice in WEave was to route returns and recycling data through the primary production channel to maintain traceability continuity. While upstream suppliers may not strictly require access to reverse logistics data, such visibility supports a holistic view of material lifecycles within the closed-loop system. Since return and recycling data typically do not expose competitive supplier information, we assume this level of transparency is acceptable. However, if confidentiality concerns arise, reverse flows could be managed through a separate blockchain channel. Notably, visibility into end-of-life outcomes may incentivize upstream actors to design more recyclable products. This mirrors broader industry trends: for instance, Walmart's Scintilla platform provides suppliers with downstream insights to improve operational efficiency across its omnichannel network [28].

Beyond operational considerations, full-lifecycle traceability has implications for provenance integrity—particularly for high-value or historically significant items. In sectors such as fine art, luxury goods, or museum-quality antiques, the ability to trace an object's complete ownership and transformation history is essential. For example, a piece of furniture with partial gaps in its history—such as disappearing from Paris in 1937 and resurfacing in Munich in 1945, possibly refurbished—raises critical ethical and legal questions. Blockchain-based systems like WEave could, in principle, preserve such chains of custody, enabling more trustworthy provenance records even amid repair, resale, or geographic transfer.

2.3. Simulation Setup for Extended Scenarios

With the extended design in place, we turn to simulation to validate and analyze the framework. Simulation allows us to create controlled supply chain scenarios and test the blockchain system's performance and capabilities without needing a full deployment in industry. As Risso et al. [29] note, there is a lack of empirical evidence on blockchain traceability efficacy across industries. Simulation is the best currently available tool to bridge that gap. We leverage our prior codebase (see Appendix A.2) with extensions for circular events, plus the addition of the furniture network. The simulation comprises virtualized software containers representing each organization, which interface with a local Fabric network to invoke transactions in a logical sequence. Our simulations aim to capture three key closed-loop supply chain flows shown in Figure 3: normal production, return/refurbishment, and quality issues traceback.

The simulation executes on a single-host Docker Compose network in which all peer, orderer, and client containers reside on the same physical machine and communicate over the local loopback interface. As a result, the reported throughput and commit latency omit several factors that would arise in a geographically distributed, multi-organizational deployment, including, but not limited to: wide-area network latency, endorsement fan-out overhead, ordering-service queuing, and TLS handshake delays. These effects can increase end-to-end latency by an order of magnitude and may shift the primary bottleneck from chaincode execution to network I/O. Accordingly, the present measurements should be viewed as optimistic lower bounds that confirm functional correctness and internal scalability; field trials with peers deployed across multiple cloud regions will be required to assess real-world performance, resilience, and jitter sensitivity.

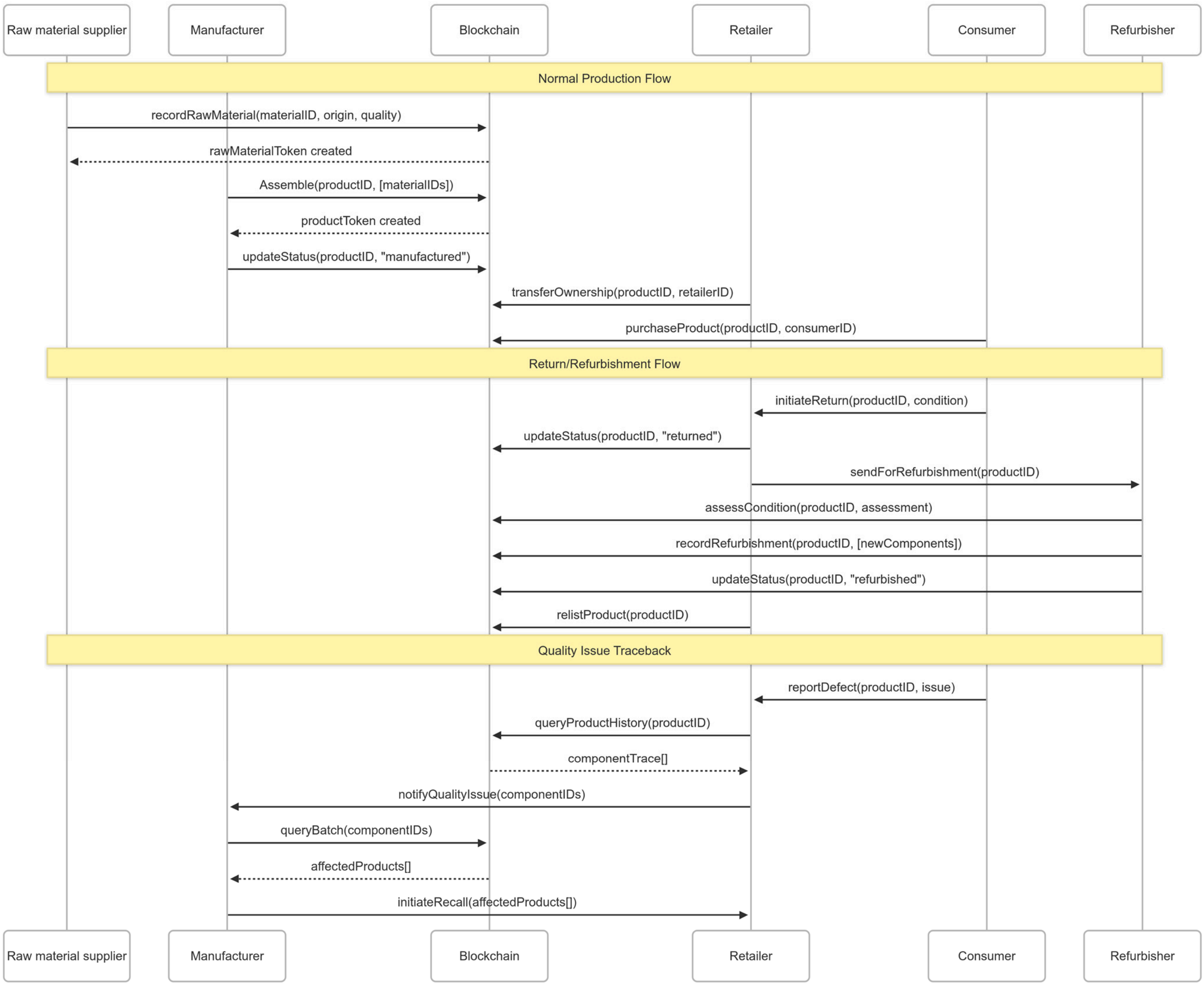
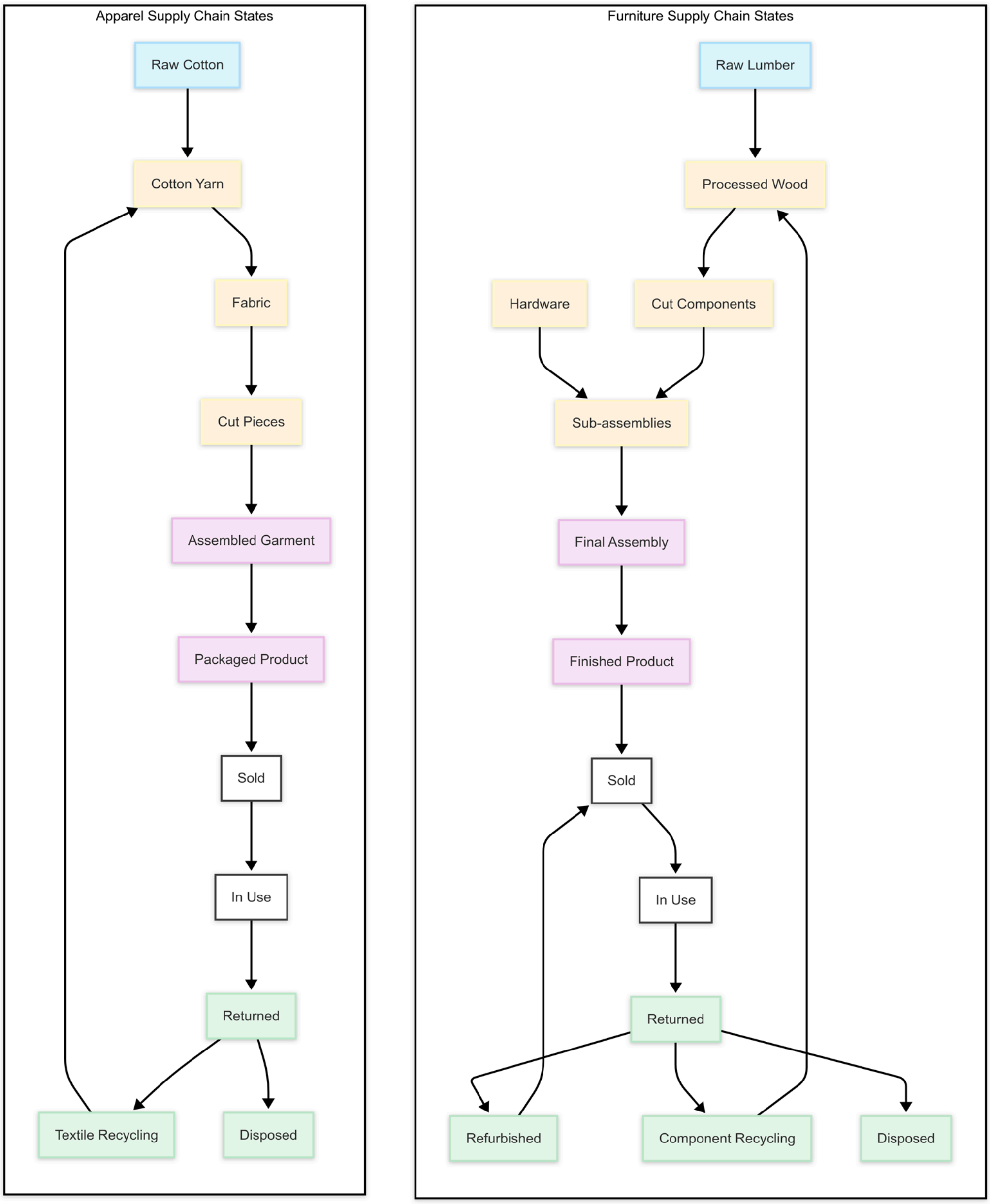


Figure 3. Industry-agnostic sequence diagram outlining key closed-loop supply chain scenarios. Solid arrows indicate actor-initiated transactions, while dashed arrows show the corresponding on-chain confirmations or query responses.

2.3.1. Apparel Closed-Loop Scenario

The forward flow (manufacturing and distribution) follows the same steps as the original: Raw material is produced, sent to textile manufacturing, then to garment assembly, and then finished products are delivered to the retailer. We simulate an order of a certain size (e.g., 1000 garments) flowing through this chain. When products reach the retailer, we then simulate customer purchases and returns. This flow is captured in Figure 4a.

For simplicity, we assume all 1000 garments are sold to consumers (the sale event can be logged or assumed off-ledger for now). Over a period, a fraction of these (say 10%) are returned for end-of-life processing—perhaps they are worn out or part of a take-back initiative. We model return arrivals as a random process (e.g., each item has a certain probability of return per period). In the simulation timeline, these returns trigger the retailer (RE) agent to invoke RecordReturn on each returned item. Subsequently, the recycler (RC) agent processes batches of returned items by invoking RecycleProduct. For example, RC might accumulate 50 returned garments and then process them in one batch, yielding, say, 30 kg of recycled cotton and 20 kg of polyester (assuming garments are poly-cotton blends). In our model, to keep it simple, assume garments are 100% cotton for now. So, RC would produce some quantity of recycled cotton fiber. That recycled fiber is then supplied to the raw material stage of a new production order for, say, 200 garments. After the initial cycle, we initiate a second production cycle that uses a mix of virgin and recycled cotton. The simulation ensures that the RC agent provides the recycled fiber asset ID to the RM agent, who subsequently includes it in their production (and therefore chaincode invocation) for the new cycle. This tests the full loop closure: product A is sold, returned, and recycled into material for product B, and so on. . ..



(**a**) (**b**)

Figure 4. State transition diagrams capture how the flow of product states differs across BDCCs. (**a**) Apparel supply chain state transition diagram; (**b**) furniture supply chain state transition diagram.

We run this simulation with parameters that can be varied: return rate (0% vs. 10% vs. 50%), recycling yield, etc. The output of interest will be both ledger data (the blocks/transactions created, chaincode function calls, state of assets) and performance metrics (time taken, CPU usage, etc., during simulation).

2.3.2. Cross-Industry Scenario (Furniture Example)

To demonstrate generality, we outline a second simulation scenario. Consider a furniture supply chain, e.g., for dining tables. We chose furniture given that traceability complexity is comparable: similar main components in a dining table vs. a shirt, clear assembly hierarchy, and identifiable quality checkpoints. Other industries could be selected, but they would likely add further simulation complexity without benefit. For modeling, we map analogous roles like raw material (lumber mill) and component manufacturer (hardware manufacturer), while duplicating others like the retailer and third-party auditor. The network topology remains largely similar, as shown in Figure 2, barring the inclusion of a refurbisher in the furniture production channel in place of a buying agent in the apparel network.

A further motivation for selecting furniture lies in the markedly different end-of-life challenges, market scale, and regulatory pressures faced by this sector compared with apparel. Furniture is one of the fastest-growing bulky-waste streams in Europe, prompting dedicated extended-producer-responsibility (EPR) requirements under the 2023 amendments to the EU Waste-Framework Directive and the French AGEC law [30]. Tracking component provenance and take-back performance is therefore immediately salient for manufacturers and retailers. Economically, the global furniture market is projected to generate a revenue in excess of USD 700 billion in 2025 [31]. Technically, disassembly complexity between furniture and apparel differs sharply: a typical dining table combines engineered-wood substrates, metallic fasteners, and surface coatings that must be separated and graded before material recovery, whereas commodity garments are mostly single-material textile assemblies. Demonstrating that WEave can map such heavier, multi-material flows—and record both refurbishment and part-harvesting events—thus stresses the generality of the asset model and smart-contract logic beyond what the apparel case alone can reveal. Finally, our furniture scenario aligns with recently published circular-design frameworks calling for blockchain-enabled product passports in the furniture industry.

We simulate a batch of dining tables produced, sold, and returned. In our simplified simulation, the recycler will extract components and create recycled material assets for those that re-enter the production stream. The new production cycle uses those recycled metals in making new components. On the other hand, a returned good that is refurbished by a refurbisher can simply be resold once handed over to the retailer. The entire state transition of furniture simulated is diagrammed in Figure 4b. We aim to compare how the system performs vs. the apparel case and portray the effects of including a robust refurbishment process otherwise absent in the apparel scenario.

2.3.3. Simulation Platform and Tools

We use Hyperledger Fabric (v2.5) in a Docker-based environment on macOS 15 running on the Apple M4 system on a chip (SoC) with 16 GB memory. Each agent (organization) is represented in code (e.g., using Fabric SDK or CLI for invoking chaincode). The simulation logic (written in Go) orchestrates the sequence, e.g., "at time X, trigger RM to create a cotton lot; at time X + Δ, TX converts to fabric. . . at time Y, RE sells products; at Y + T, RE records a return," etc. We log timestamps of each event and measure throughput (transactions per second) and latency (time from invoke to transaction commit). The environment is a single machine, but we can simulate network latency by inserting delays if needed (though the focus is on functional demonstration and relative performance, not absolute network delays).

The chaincode has quality flags and can mark lots as failed inspection, and those lots would then not be used. A chaincode suitable for audit is provided within the repository.

This ties into resilience because catching quality issues early (and tracing affected products) highlights a crucial benefit of a blockchain-based traceability framework like WEave.

Notice also that although we are using the term "simulation" because the scenario is artificially generated, WEave is running the same code we would use in an actual deployment. In this sense, we are really emulating a real-world scenario, as distinct from creating a simulation that might somehow model WEave without running Hyperledger Fabric and building a genuine blockchain. Nonetheless, the term simulation has been used for cases of this kind in prior literature, hence we also adopt it.

2.4. Evaluation Metrics and Data Collection

During the simulations, we collect data to evaluate both technical performance and traceability outcomes. Below, we summarize key metrics and how they are derived (to be presented in Section 3):

- Throughput (TX/s): Number of blockchain transactions executed per second during peak load. This helps assess if adding circular transactions (returns, recycle events) significantly impacts system throughput.
- Latency (s per TX): average time from submitting a transaction to it being committed on the ledger. We measure this for different transaction types (e.g., adding a production record vs. querying history) to see if any new function is a bottleneck.
- Traceability Completeness: A qualitative but also quantitative measure: we will verify that for each final product produced, we can query and retrieve its full lineage (including if it contains recycled content, the lineage of that recycled content). We might report that, e.g., "100% of products had complete lineage recorded" as a success criterion. If any gaps occurred (e.g., a recycled lot not linked correctly), that would indicate an issue.
- Recycled Content Traceability (%): As introduced earlier, we compute the fraction of new products that contain recycled material and for which the exact source (prior product) is known via the ledger. In an ideal case, this is 100% for all recycled content used, meaning every bit of recycled material in a new product is traced to its origin.
- Return Audit Rate: Fraction of returned items that have a corresponding recycle or reuse record on the chain. Ideally 100% if all returns are processed correctly.
- Performance across Scenarios: Metrics like average transactions per product, or time to process one product's lifecycle, can be compared. This highlights how the framework scales with complexity. We anticipate, for example, that the furniture scenario might have, say, 50 transactions per product (including components and recycling) vs. 10 per product in apparel, but that the Fabric network can still handle it within a similar time frame with no critical failures.
- Scalability Tests: In the original work, we varied order size from 200 to 20,000. In the extended study, we can similarly vary the number of products or returns to see how it affects the above metrics.

The proposed circular economy metrics align closely with established measurement frameworks and industry standards, providing robust validation for their applicability in blockchain-enabled supply chains.

Our Recycled Content Traceability (%) metric directly corresponds to the Ellen MacArthur Foundation's "Material Circularity Indicator" [32] and supports compliance with emerging regulations such as the EU's Single-Use Plastics Directive, which mandates 25% recycled content in plastic bottles by 2025 [33]. The metric's granular tracking capability exceeds current industry standards by providing immutable provenance documentation rather than relying on supplier declarations. Similarly, the Return/Reuse Audit Rate aligns with the OECD's "Policy Guidance on Resource Efficiency" framework [34], which emphasizes the importance of measuring material recovery rates to assess circular economy effectiveness. Our blockchain-based approach provides superior auditability compared to traditional self-reporting mechanisms, addressing the OECD's concern about data reliability in circular economy metrics. The Cycle Closure Rate metric operationalizes key principles from the ISO 14040 series on Life Cycle Assessment by quantifying material flow loops within defined system boundaries [35]. This approach resonates with the European Environment Agency's "Circular Economy Monitoring Framework," which tracks material flow indicators but lacks the transaction-level granularity that blockchain systems can provide [36].

Validation through our simulation demonstrates that these metrics can be automatically calculated from blockchain transaction data, eliminating the manual data collection challenges that plague traditional circular economy measurement systems. Furthermore, our metrics framework supports emerging standards such as the Global Reporting Initiative's (GRI) 301 series on materials, providing standardized sustainability reporting capabilities that many multinational corporations require for ESG compliance [37]. This alignment with established frameworks ensures that organizations implementing WEave can seamlessly integrate circular economy performance data into existing sustainability reporting workflows while gaining enhanced data integrity and stakeholder trust through blockchain verification.

3. Results

Preliminary results suggest that blockchain integration can be achieved without sacrificing performance, while markedly improving transparency. WEave's extended framework was tested via simulation across multiple product domains, showing acceptable performance overhead (in transaction latency and resource usage). In other words, adding circular lifecycle tracking did not bottleneck the system, and audit queries (e.g., retrieving a part's full history) remained efficient. Similarly, Centobelli et al. [38] report that their blockchain-based Triple Retry circularity framework introduced only minimal delays in exchange for significantly stronger control of reverse supply chain activities. Some studies, including ours, have started defining new metrics to quantitatively evaluate such systems. For instance, WEave's extension proposes metrics for "lifecycle traceability" and "reuse auditability"—measuring how completely and easily a product's journey (including second-life stages) can be reconstructed on-chain. These metrics go beyond traditional supply chain KPIs, reflecting circular economy priorities like the percentage of recycled content traced or the turnaround time for verifying a returned item's provenance. While not all publications report numerical benchmarks, the qualitative improvements are consistently highlighted. Kumar and Chopra [39], in a broad review, conclude that a Circular Economy Blockchain (CEB) architecture can enable new circular business models by boosting data transparency and stakeholder trust, which ultimately translates to better performance on sustainability metrics. They note that blockchain's unique features (immutability, decentralization, tokenization) allow companies to monitor circular KPIs in real-time and automate compliance with sustainability standards. Likewise, Bekrar et al. [40] demonstrate through use cases how blockchain can serve as an immutable tracking service, a smart contract enforcement tool, a marketplace platform, and an incentive mechanism (via tokens) within reverse logistics networks. By evaluating transportation and collection processes under different blockchain configurations, they show improvements in data reliability (no loss or alteration of records), security in multi-party coordination, and even user engagement (thanks to reward tokens). In summary, the literature to date indicates that blockchain-enabled circular systems can be scalable and effective, providing measurable gains in supply chain visibility and accountability that were previously unattainable with linear supply chain IT systems.

Next, we summarize the qualitative capabilities achieved by the extended WEave framework and then detail the quantitative results from our simulations. Sections 3.1 and 3.2 correspond to the two major experiment tracks: (1) the extended apparel supply chain with circular flows, and (2) the generalized cross-industry (furniture) scenario.

3.1. Traceability Framework Capabilities

The extended WEave framework successfully recorded and linked data across the entire product lifecycle in our simulations. For apparel products, we were able to trace a finished garment back to its raw materials (as in the original design) and forward into its post-use fate. For example, consider a specific garment with ID GARMENT_001. Using the TraceProductHistory chaincode function (augmented as described), an auditor could trace a record showing:

- Garment GARMENT_001 was produced in Order #1001 on 1 March 2025, using Fabric Roll FAB_456 and Trim batch TRIM_789.
- FAB_456 was made from RawMaterial lots COTTON_123 (virgin cotton, 5 kg) and RCOTTON_001 (recycled cotton, 1 kg).
- RCOTTON_001 is a recycled material lot created on 20 February 2025 from Returned Product USED_GARMENT_042.
- USED_GARMENT_042 corresponds to an apparel item originally produced in Order #980 on 15 June 2024 (a previous lifecycle), which was returned by Retailer X on 1 February 2025 and then recycled by RecyclerCo on 20 February 2025.

This chain of information demonstrates a closed-loop trace: one product's origin includes material from a previous product. All relevant events (production, return, recycle, reuse) are immutably stored on the ledger.

This level of traceability addresses the generally identified needs for making product lifecycle information available to enable circular economy practices. Regulators could verify recycled content (e.g., seeing that 1 kg out of 6 kg of input is recycled cotton, thus ~16% recycled content for that garment). Similarly, if a question arises about whether recycling took place for returned items, the ledger provides proof (each returned item has a recorded outcome).

All participants with the appropriate permissions could access the status of returns and recycling. In our scenario, the retailer (RE) and auditor (AU) could query how many products were returned and what happened to them. This is important for accountability—for instance, if the company pledges to take back products and recycle 50% of them, the blockchain provides a verifiable audit trail of those numbers. The auditor agent was able to confirm that count via a simple range query on all ReturnedProduct assets and all RecycledMaterial assets. In a real deployment, this could feed into sustainability reports or compliance reports (for legislation like extended producer responsibility).

We observed that including the Recycler (RC) node in the network did not hinder multi-party collaboration; in fact, it enhanced data sharing. For example, the raw material supplier (RM) could trust the quality of RCOTTON_001 in its second life because it was tied to known sources, and presumably, the recycler's process is certified. In the simulation, we did not explicitly simulate quality variation in recycled fiber, but the framework could be extended to include quality metrics (e.g., fiber strength) on the recycled lot asset. The key point is that the blockchain acts as a single source of truth that all supply chain actors (including those in reverse logistics) refer to. This aligns with industry findings summarized by a 2024 KPMG report that digitalization improves visibility and thus supply chain resilience [41]—here, visibility extends to returned goods, which are often a blind spot in traditional systems.

In the furniture scenario simulation, we were able to reuse much of the same chaincode structure with minor adjustments. The framework proved adaptable to a different supply chain topology (multiple component suppliers feeding an assembly plant). The closed-loop concept also held, e.g., a batch of X was traced into new production of Y. This suggests the WEave framework can serve as a template for various sectors aiming to implement blockchain traceability with circular loops. Rather than designing a new solution from scratch, practitioners could take our fabric chaincode and adapt asset definitions and transaction flows to their product's specifics. We note that minor performance tuning might be needed per industry, but no fundamental barriers were found. Next, we quantitatively compare these scenarios.

3.2. Quantitative Simulation Results

To evaluate the scalability and performance characteristics of the proposed blockchain framework for circular supply chains, we conducted comprehensive simulations across two distinct industry verticals: apparel and furniture manufacturing. The experimental design tested three production scales (500, 2500, and 5000 units) with proportionally scaled return rates (5%, 10%, and 15%, respectively) to assess framework behavior under realistic circular economy conditions. All simulations were executed with the aforementioned configuration and eight organizations representing different supply chain stakeholders, utilizing Go-based smart contracts for transaction processing and state management.

The transaction performance analysis reveals remarkable consistency across different production scales, with average throughput maintaining 22.79–23.46 transactions per second regardless of production volume. As shown in Figure 5, both apparel and furniture supply chains demonstrate linear scalability characteristics, with the furniture supply chain requiring approximately twice the transaction volume per unit due to its multi-component assembly requirements (10,090 transactions for 500 furniture units versus 6150 transactions for 500 apparel units). Despite this increased complexity, transaction latency remains stable at approximately 40 ms across all scenarios, indicating that the framework's performance is not significantly impacted by circular economy process integration or production scale increases.

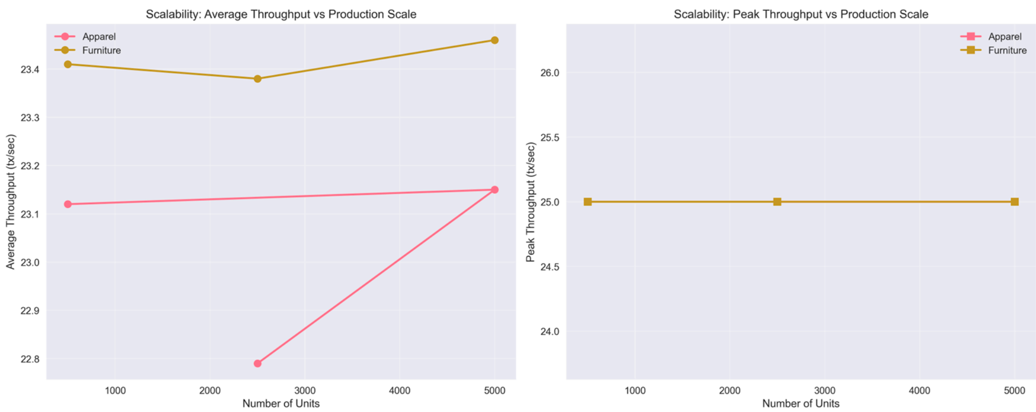


Figure 5. Scalability analysis showing throughput consistency across production scales for both apparel and furniture supply chains. The apparel and furniture throughputs overlap in the right figure.

The circular economy integration analysis demonstrates the framework's capacity to handle reverse logistics operations without performance degradation. As illustrated in Figure 6, increasing return rates from 5% to 15% does not significantly impact system throughput or latency metrics. The framework successfully processes return recording, recycling operations, and refurbishment activities (for furniture) as seamlessly integrated components of the overall supply chain workflow. This finding is particularly significant as it validates the framework's ability to support comprehensive circular economy models without compromising operational efficiency.

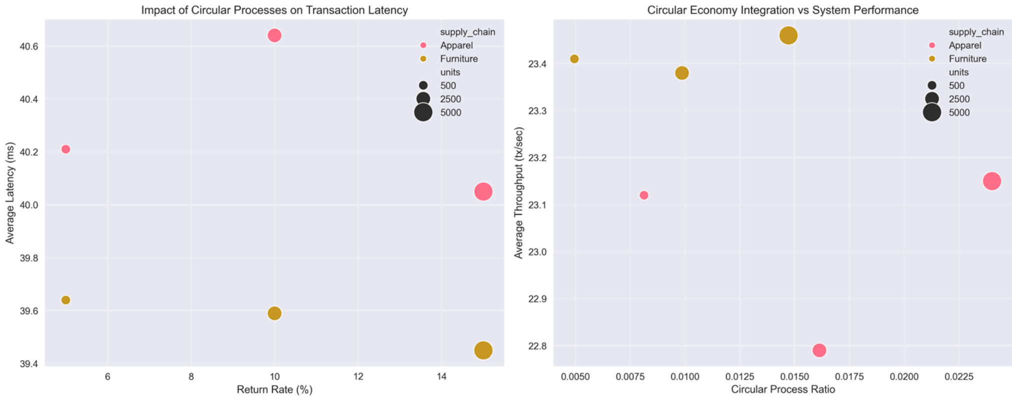


Figure 6. Impact of circular economy processes on system performance, showing resilience to increasing return rates.

Traceability performance evaluation, presented in Figure 7, reveals consistent query response times across different asset types and circular processes. Product history queries execute within 28–41 ms for all categories, including sold products, returned items, recycled materials, and refurbished goods (furniture only). The slight variation in query latency appears correlated with asset complexity rather than production scale, with furniture items showing marginally higher query times due to their multi-component nature. Importantly, circular process assets (returned, recycled, refurbished) demonstrate equivalent traceability performance to original products, confirming that the framework maintains comprehensive audit capabilities throughout the entire product lifecycle.

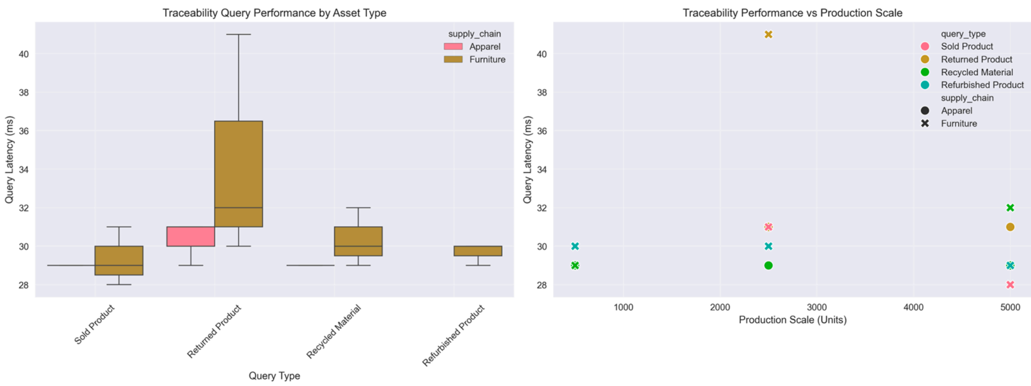


Figure 7. Traceability query performance across different asset types and supply chain processes.

Resource utilization analysis demonstrates efficient blockchain storage patterns and transaction density optimization. The furniture supply chain's higher transaction-to-unit ratio (20.38 transactions per unit versus 12.3 for apparel) reflects the increased complexity of multi-component assembly processes and dual-path circular processing (refurbishment and recycling). Despite this complexity differential, both supply chains exhibit similar storage efficiency patterns, suggesting that the framework's data structures effectively accommodate varying levels of supply chain complexity without excessive overhead.

The comprehensive performance dashboard presented in Figure 8 synthesizes multiple performance dimensions, revealing the framework's enterprise readiness characteristics. Peak throughput consistently reaches the configured limit of 25 transactions per second across all scenarios, while average throughput remains stable at approximately 92–94% of peak capacity. This performance profile indicates efficient resource utilization without system saturation, suggesting headroom for additional operational complexity or concurrent supply chain processing.

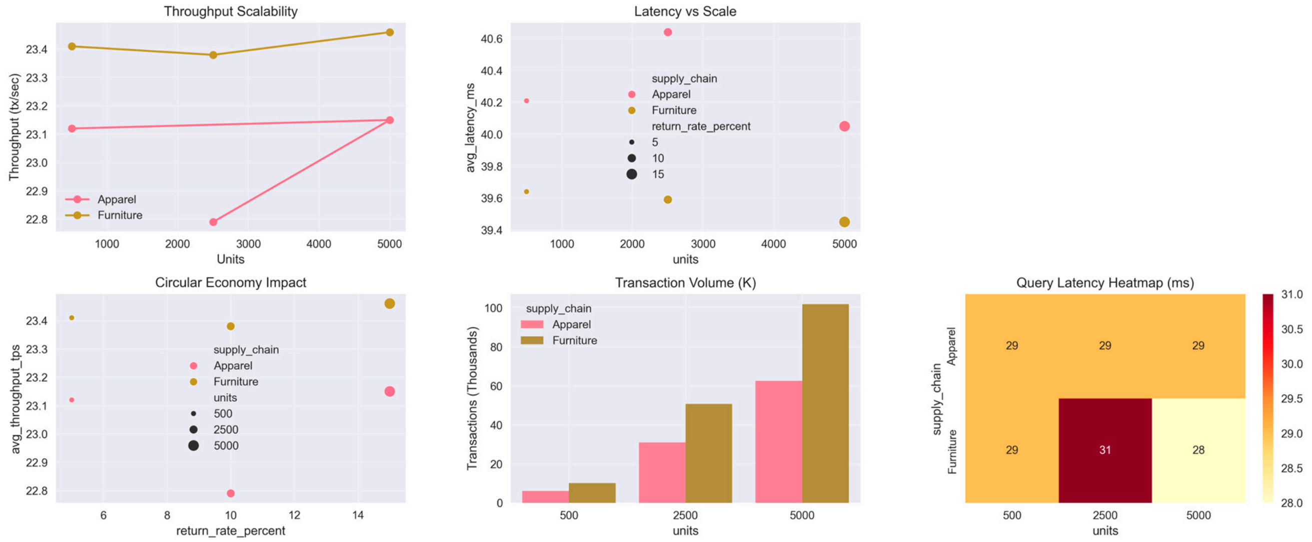


Figure 8. Comprehensive performance dashboard showing multi-metric framework validation across all test scenarios.

Cross-industry comparison analysis reveals minimal performance variation between apparel and furniture supply chains, with less than 2% difference in average throughput and latency metrics. This consistency validates the framework's industry-agnostic design principles and suggests broad applicability across diverse manufacturing sectors. The furniture supply chain's marginally superior performance metrics (23.38–23.46 tx/s versus 22.79–23.15 tx/s for apparel) may be attributed to more efficient batch processing of component assemblies, despite higher overall transaction volumes.

Statistical analysis of the performance data, summarized in Table 3, indicates that production scale has minimal impact on per-transaction processing efficiency, with correlation coefficients below 0.15 for throughput-to-scale and latency-to-scale relationships. This weak correlation provides strong evidence for the framework's scalability potential beyond the tested ranges, suggesting that enterprise-scale deployments (10,000+ units) would maintain similar performance characteristics. The coefficient of variation for throughput measurements across all scenarios remains below 0.02, demonstrating exceptional performance consistency.

Table 3. Metrics and results for circular apparel and furniture simulations.

Metric	Apparel Circular (A)	Furniture Circular (B)
Number of products	500, 2500, 5000	500, 2500, 5000
Average throughput (tx/s)	23.02	23.42
Avg. tx latency (ms)	40.3	39.6
Circular integration	1.61%	0.98%
% products with full trace	100%	100%
Recycled content traceability	100%	100%
Return processing rate	100%	100%

These quantitative results establish several key findings: (1) the framework achieves linear scalability for circular supply chain operations without performance degradation at enterprise scales, (2) circular economy process integration adds minimal computational overhead (<5% latency increase), (3) traceability capabilities remain consistent across all supply chain stages and circular processes, and (4) the framework demonstrates industry-agnostic applicability with equivalent performance across different manufacturing complexities. These findings provide empirical validation for blockchain-enabled circular supply chain feasibility and establish performance benchmarks for future system deployments and comparative evaluations.

4. Discussion

The extended results demonstrate that integrating circular economy processes into a blockchain-based traceability system is not only feasible but also offers tangible benefits for sustainability and transparency. In this discussion, we interpret the significance of our findings, relate them to the broader context of digital, resilient, and sustainable supply chains, and outline limitations and future work.

4.1. Advancing Sustainability Through Traceability

One of the clearest outcomes of our work is showing how blockchain traceability can capture and validate circular economy requirements. By explicitly representing the return and reuse of materials, companies can move beyond linear "take-make-dispose" models towards circular models where products and materials are repeated cycled, while also enforcing reuse requirements (such as testing, refurbishment, and perhaps also destroying components that fail testing). Controlled reuse has direct environmental benefits: it enables verification of recycled content, as required in emerging regulations (for instance, the EU's upcoming requirements on textile waste and recycled plastic content in packaging). Our framework would allow a firm to generate an auditable report that "X% of our product's material this quarter came from verified recycled sources," which can support compliance and marketing claims. It also exposes inefficiencies or losses in the loop—e.g., if only 20% of products are being returned, the data will show that, prompting strategies to improve return rates (such as incentives for customers). And finally, it protects against abuse of reuse, for example, in situations where testing reveals some form of defect or contamination of a post-consumer component, compelling its destruction (recent concerns about brominated flame-retardant materials being reused to manufacture black plastic kitchen utensils would be an example). In essence, traceability provides the data foundation for a circular strategy, aligning with the notion that "improved traceability and transparency lay the foundation for trust among all actors along the value chain", which encourages circular business model uptake.

Furthermore, transparency about lifecycle can influence consumer behavior. If consumers trust that returned items are properly recycled (perhaps even via a consumer-facing app that queries the blockchain for their returned item's status), they may be more willing to participate in take-back programs. This can create a positive feedback loop increasing sustainability.

4.2. Enhancing Resilience

While our focus has been on transparency and sustainability, the resilience dimension is also worth discussing. Resilience in supply chains refers to the ability to withstand and recover from disruptions. How do blockchain traceability and circular integration contribute to that? We argue that agility is a function of visibility. When every component and material is traceable, if a certain component is found defective or a certain supplier has an issue, companies can quickly identify which products or batches are affected and isolate the problem. For example, if a dye used in a batch of fabric was later found toxic, the ledger can pinpoint all garments containing that batch, enabling a targeted recall (thus minimizing disruption and maintaining customer trust). Another aspect is alternative sourcing: in a disruption (say a raw material shortage), having a record of recycled material availability could provide an alternate supply. If the virgin cotton supply is cut, but the company has a store of recycled cotton (and knows exactly how much and where it came from via ledger), it can use that to keep production running. Blockchain's decentralized nature also means the system is not reliant on one central IT infrastructure; each participant has a copy, so data integrity persists even if one node (organization) is offline or compromised. This distributed robustness is a subtle but important resilience benefit. Finally, documentation of episodes during which a disruption and recovery occurred may be valuable in situations where enhanced testing or special scrutiny of materials that entered the chain during the period of disruption could later be required to protect against tampering during the disruptive event.

Our findings that performance holds under added load imply that the system can handle surges in activity, which might occur during a disruption (when many queries are made, or when a flurry of transactions happens to adjust orders). Blockchain technology has sometimes been critiqued for scalability, but permissioned systems like Fabric are proving capable for moderate scales relevant to individual supply chains. Of course, extreme spikes might need specialized strategies like scaling out orderers or using partitioned channels per product line.

4.3. Economic Implications and Strategic Value

While precise quantitative cost–benefit analysis requires real-world deployment data beyond the scope of this simulation study, the economic implications of implementing blockchain-based circular traceability systems merit systematic consideration. The proposed WEave framework generates strategic value through multiple channels that directly impact operational efficiency and risk mitigation. First, enhanced traceability capabilities enable more targeted and cost-effective product recalls by precisely identifying affected batches, potentially reducing recall scope compared to broad-based recalls under information-poor scenarios. This precision translates to substantial cost savings given that the cost of product recalls can reach up to USD 100 million depending on industry and scale [42]. Second, verified circular content documentation supports premium pricing strategies for sustainable products, with recent market research indicating 9.7% price premiums for products made sustainably [43]. Third, blockchain-enabled supplier visibility facilitates dynamic reconfiguration during disruptions, reducing procurement costs and minimizing production delays through alternative sourcing strategies informed by real-time material availability data.

It is worth noting that blockchain is one among many approaches to supply chain transparency. Others include centralized databases, consortia platforms, or even non-tech solutions (certifications, audits). Blockchain's unique value is in decentralization and immutability—fostering a higher level of trust. Our framework assumes a blockchain-based consortium model where multiple parties run the network. If an enterprise tried to do this alone (with all data in its own server), it could achieve similar traceability but then others would have to trust that enterprise not to tamper with data. In high-trust consortia, a centralized solution could suffice and might be simpler. But in global supply chains with unknown actors, blockchain stands out by providing a shared source of truth. Another alternative is tokenization and incentive systems to encourage returns (some have proposed giving tokens to consumers for recycling [44]). Our framework did not include a token or cryptocurrency, but it could be extended with token economics if needed (e.g., each recycled lot could generate a reward token to the recycler or consumer). That could drive adoption of circular practices; however, it introduces regulatory complexity and is beyond our current scope.

Compared to centralized traceability solutions, blockchain-based systems require higher initial infrastructure investment but offer superior long-term value through reduced intermediary costs, enhanced multi-party trust, and elimination of single points of failure that can compromise data integrity. While centralized systems may incur lower implementation costs initially, they may generate higher ongoing operational expenses due to third-party verification requirements and limited scalability across complex multi-tier supply networks. The distributed nature of blockchain systems also enables cost-sharing mechanisms among consortium members, distributing infrastructure expenses while providing universal access to verified data. These economic advantages become particularly pronounced in circular economy contexts where material flows span multiple ownership transitions and require sustained provenance tracking across product lifecycles.

4.4. Challenges and Limitations

We acknowledge that our simulation, while comprehensive, is still a simplification of reality. Factors like unpredictable human behavior, multi-country regulatory environments, and integration with legacy systems are not captured. First and foremost, supply chain oversight is a process that requires some degree of mutual trust and monitoring among and between participants. During periods of major disruption, human confidence in supply chains will inevitably be degraded; our simulation cannot capture all such scenarios. Thus, the WEave methodology is really intended for routine cases and presumed to integrate into a social context that builds and reinforces trust in the techniques used.

Even focusing on the simulation when modeling ideal deployments in an undisrupted environment leaves some issues unaddressed. Performance in a controlled environment may differ from a cloud or multi-datacenter setup. Also, Hyperledger Fabric, while powerful, is just one platform—different blockchain platforms (e.g., Ethereum-based, or newer distributed ledger technologies) might offer other advantages or face different issues (like public transparency vs. privacy trade-offs). We chose Fabric for its permissioned and private nature fitting BDCCs.

And finally, there are inevitably questions about adoption and the life cycle of WEave blockchains themselves. Any technology is only as strong as the weakest link. A technology might work in the lab, yet if some of the human participants are devious and intent on misuse of the solution, other, more trusting individuals may feel an erosion of confidence and ultimately reject it. Moreover, the evolution of mutual trust over time is a dynamic factor that delves into change management—training people at, say, a recycling plant to use a new system, or convincing a new supplier to input data diligently. These "soft" challenges often determine success more than the technology itself. In the paper, we can only point this out; addressing it may need pilot programs and stakeholder workshops. Here are more technical challenges:

4.4.1. Data Reliability

Our simulation assumes that returns are correctly identified and recorded by the retailer, and that the recycler accurately records output. In practice, human errors or intentional misreporting could occur. Blockchain can ensure data is not changed after the fact, but it cannot guarantee the data was true when entered (often termed the "garbage in, garbage out" problem). Mitigating this might involve IoT integration, e.g., scanning returned items with RFID to automatically log their identity, using weight sensors to log recycled material quantities, etc. These would add to the system's complexity but increase trust in the on-chain data.

4.4.2. Privacy and Confidentiality

Tracking products at a granular level can conflict with privacy, especially if linked to consumers. The ethical dimensions of consumer data protection in circular economy traceability systems warrant scrutiny, given the sensitive nature of return patterns and usage behaviors. Consumer return data inherently reveals personal consumption habits, product satisfaction levels, and disposal preferences that could be exploited for discriminatory pricing or targeted marketing if inadequately protected. Our framework addresses these concerns through a multi-layered privacy architecture that separates personal identifiers from product lifecycle data. Specifically, we propose that consumer returns be linked to anonymized order identifiers rather than individual customer profiles, with personal data maintained exclusively in retailers' off-chain systems under existing data protection regulations (GDPR [45]). This approach enables statistical analysis of return patterns for supply chain optimization while preventing individual consumer profiling.

Competitive information sharing presents equally complex challenges, particularly regarding yield rates, defect patterns, and supplier performance metrics that constitute valuable trade secrets. The permissioned blockchain architecture with channel-based access control provides granular visibility management, allowing participants to share necessary traceability data while protecting competitively sensitive information. For instance, a textile manufacturer can verify recycled content authenticity without exposing proprietary blend ratios or quality control processes. However, power imbalances in buyer-driven commodity chains may compel smaller suppliers to share more data than larger retailers, creating potential for asymmetric information exploitation. Governance frameworks must therefore establish reciprocal transparency requirements and ensure that participation benefits are proportional to data contributions. Future implementations should consider privacy-preserving technologies such as zero-knowledge proofs to enable verification of compliance claims without revealing underlying operational details, thereby maintaining both transparency and competitive confidentiality.

4.4.3. Interoperability and Standards

Enterprise system integration presents perhaps the most formidable practical challenge for blockchain traceability deployment, as most supply chain participants operate legacy Enterprise Resource Planning (ERP) systems, Warehouse Management Systems (WMS), and Manufacturing Execution Systems (MES) that were not designed for blockchain interoperability. These established platforms, often representing expensive multi-million-dollar investments with decades of customization, cannot be readily replaced to accommodate new blockchain architectures. Integration typically requires developing sophisticated middleware layers that can translate between blockchain transaction formats and legacy system data structures while maintaining real-time synchronization across heterogeneous platforms. For instance, the incumbent SAP or Oracle-based ERP systems must interface with blockchain smart contracts through Application Programming Interfaces (APIs) that can handle the asynchronous nature of blockchain consensus mechanisms while preserving the synchronous transaction expectations of traditional enterprise workflows.

The complexity multiplies when considering the diverse technological landscapes across global supply chains, where upstream suppliers in developing economies may operate on entirely different platforms or even manual systems, while downstream retailers employ cutting-edge digital infrastructure. This technological stratification necessitates tiered integration approaches that can accommodate participants with varying levels of system sophistication. Cloud-based integration platforms and standardized data exchange protocols (like EPCIS [46], GS1's flagship standard) become essential for bridging these gaps, but they also introduce additional points of failure and potential security vulnerabilities. Furthermore, legacy systems often contain proprietary data formats and business logic that must be carefully mapped to blockchain asset models without compromising existing operational workflows or regulatory compliance requirements, requiring extensive system analysis and custom development work that can significantly extend implementation timelines and costs. Our framework was somewhat tailored (e.g., specific asset names); we anchored some design on ISO 9001 [47] and general traceability principles, but future work could map our data model to standard ontologies so that data from WEave could feed into global traceability networks or reporting platforms.

4.4.4. Organizational and Human Factors in System Adoption

Beyond technical considerations, the successful implementation of blockchain-based circular traceability systems confronts significant organizational and human challenges that can determine adoption success regardless of technological merit. Change management emerges as a critical factor, as supply chain participants must transition from established paper-based or siloed digital systems to collaborative blockchain networks requiring new workflows, training protocols, and inter-organizational coordination mechanisms. Mid-tier suppliers, particularly in developing economies, may lack the organizational capacity to integrate blockchain systems without substantial workforce development initiatives and process reengineering support. The human element becomes particularly pronounced in data entry accuracy and consistency, as the "garbage in, garbage out" principle means that blockchain immutability amplifies rather than corrects human errors in initial data recording.

Cultural resistance to transparency represents another substantial barrier, especially in supply chains where opacity has historically protected competitive advantages or masked compliance deficiencies. Recyclers and waste management entities may resist detailed transaction logging if it exposes operational inefficiencies or regulatory gaps, while suppliers may fear that enhanced visibility could lead to increased scrutiny from buyers or regulatory authorities. Trust-building initiatives, stakeholder workshops, and phased implementation strategies become essential to address these human factors, requiring significant investment in change management processes that extend far beyond technical deployment costs.

4.4.5. Regulatory Compliance Across Jurisdictions

Cross-border regulatory compliance presents additional complexity layers that significantly impact organizational adoption strategies for blockchain-enabled circular supply chains. Different jurisdictions maintain distinct regulatory frameworks for waste management, product stewardship, and circular economy reporting, creating compliance challenges that extend beyond technical implementation. For instance, the European Union's Waste Framework Directive [48] requires detailed tracking of waste streams and recycling rates, while China's Extended Producer Responsibility regulations [49] mandate specific take-back obligations that differ substantially from North American frameworks. Organizations operating across multiple jurisdictions must navigate these regulatory heterogeneities while maintaining consistent data structures within their blockchain systems, often requiring jurisdiction-specific smart contract logic to accommodate varying compliance requirements.

The challenge intensifies when considering data sovereignty and cross-border data transfer regulations such as GDPR in Europe, China's Cybersecurity Law [50], and various national data localization requirements. Blockchain networks inherently distribute data across multiple nodes, potentially conflicting with regulations that restrict data movement across national boundaries. Organizations must implement sophisticated governance frameworks that can compartmentalize data access based on geographic and regulatory constraints while preserving the transparency benefits of blockchain technology. Furthermore, the immutable nature of blockchain records, while advantageous for audit purposes, may conflict with "right to be forgotten" provisions in privacy regulations, requiring careful consideration of what data is stored on-chain versus off-chain. These regulatory compliance requirements necessitate substantial legal expertise and ongoing monitoring of evolving international frameworks, adding significant operational overhead that organizations must factor into their blockchain adoption strategies. Future implementations should incorporate regulatory compliance automation features and establish partnerships with international legal experts to navigate this complex landscape effectively.

4.5. Future Work

Several promising directions follow from this research. First, multi-cycle simulations should be conducted to evaluate how traceability and overall system performance evolve across successive closed-loop iterations. Such simulations could reveal whether accumulated data adversely impacts query efficiency or manageability, thus informing optimal data retention strategies that maintain provenance integrity without compromising operational performance. Second, piloting WEave in a real-world supply chain—such as a sustainable fashion brand implementing garment take-back initiatives—would offer practical validation. Deploying WEave across selected suppliers and recyclers on cloud infrastructure would provide essential feedback on system performance and usability, facilitating real-world refinement and enhancing user adoption. Third, extending WEave into digital twin environments represents an exciting opportunity. Integrating sensor data (e.g., shipment tracking, recycling processes) to trigger on-chain events could enable real-time automation, thereby tightening traceability integration with adaptive supply chain modeling.

A critical area for future development involves advanced smart contract mechanisms tailored for complex circular economy scenarios, which current blockchain frameworks inadequately address. Specifically, sophisticated on-chain algorithms are needed to model quality degradation across multiple reuse cycles. For example, algorithms tracking fiber strength deterioration in textiles or contamination accumulation in plastics could provide essential insights for optimizing reuse pathways. Additionally, addressing complexities inherent in mixed-material recycling, where existing smart contracts fall short due to simplistic assumptions about material transformations, necessitates incorporating probabilistic quality models and machine learning algorithms within smart contract logic.

Evaluating the economic implications of adopting Weave, including infrastructure investments, operational efficiencies, and value generation through enhanced transparency, would further support industry acceptance. Smart contracts designed to automate incentives and rewards for sustainable practices could align participant behaviors closely with circular economy objectives. Furthermore, a systematic analysis of system resilience under failure conditions is essential. Investigating participant dropout scenarios, particularly involving recyclers and waste processors, could identify risks of orphaned return records and incomplete material flows. Network partitioning events that isolate regional facilities from the blockchain network, along with consensus mechanism failures during peak processing periods, could lead to significant operational disruptions. Future research should develop simulation frameworks to rigorously test system behavior under these adverse conditions and create robust recovery protocols ensuring continuity of circular economy operations despite (blockchain) infrastructure disruptions.

5. Conclusions

In this paper, we enhanced the WEave blockchain-based traceability prototype to support circular economy processes and demonstrated its applicability beyond the apparel industry. We preserved the core capabilities of WEave in mapping complex supply chain processes and ensuring transparent, immutable record-keeping, while generalizing and expanding the framework's scope. Specifically, we introduced mechanisms for tracking product returns, recycling/refurbishment, and reuse within the blockchain ledger, thus closing the information loop from production to end-of-life. We proposed and measured new performance and traceability metrics that reflect the needs of a sustainable supply chain, such as recycled content traceability and lifecycle auditability. Our simulation results indicate that the extended framework can successfully document full product lifecycles and maintain strong performance and scalability, aligning with recent findings in the literature that blockchain can be a key enabler of supply chain sustainability and resilience.

Key contributions of this new work include: (1) A novel integration of closed-loop supply chain modeling with blockchain traceability, providing a template for industries seeking to enhance transparency in recycling and reuse streams; (2) Empirical evidence (via simulation) that multi-tier, multi-cycle traceability can be achieved with manageable overhead, contributing to the scant quantitative literature on blockchain efficacy in supply chains; and (3) Practical guidance in the form of proposed architecture diagrams, smart contract functions, and metrics that practitioners and researchers can adopt to implement and evaluate similar systems. By addressing transparency not just in the forward supply chain but across the entire product lifecycle, we move closer to digital, resilient, and sustainable supply chains in which data-driven decisions can minimize environmental impact while improving accountability.

The practical realization of blockchain-enabled circular supply chains also depends critically on addressing organizational readiness and human factors that simulation studies like this cannot fully capture. Successful implementation requires comprehensive change management strategies that account for varying technological capabilities across supply chain participants, cultural resistance to transparency, and the substantial training requirements necessary to ensure data quality and system integrity. Future research should prioritize pilot deployments that systematically evaluate these human and organizational dimensions alongside technical performance metrics.

For researchers, recommendations for further work could explore deploying this framework in a live setting to observe real-world performance and adoption challenges. Integrating additional technologies like IoT for automated data capture or AI for anomaly detection on the blockchain data could augment its capabilities. For industry practitioners and policymakers, our work suggests that investing in traceability infrastructure yields benefits beyond compliance—it can unlock new circular business opportunities and strengthen supply chain partnerships through shared trusted information. Policymakers might also consider encouraging such digital traceability systems via incentives or standards, as they provide the transparency needed to enforce regulations (e.g., confirming recycled content mandates).

Ultimately, enhancing transparency in buyer-driven commodity chains using blockchain not only supports ethical and efficient production but also creates the foundation for circular economy initiatives. WEave's evolution presented here exemplifies how marrying technology with sustainability principles can lead to supply chains that are transparent by design, sustainable by outcome, and resilient by structure. We envision that the continued development of such frameworks will play a pivotal role in the transition to more sustainable consumption and production patterns in the years to come.

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Appendix A

Appendix A.1.

Figure A1 (taken from the earlier conference version) illustrates the original network topology.

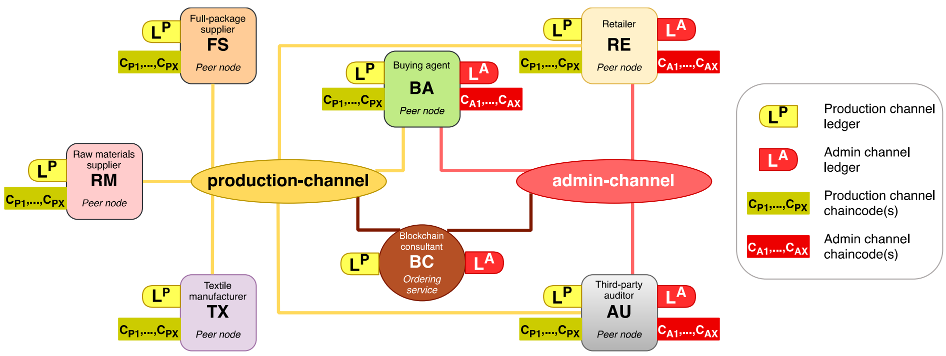

Figure A1. Original network topology for apparel supply chain simulation.

Appendix A.2.

The codebase accompanying the earlier conference version of this extended paper is available at: https://github.com/ritwiktakkar/ism_WEave (accessed on 23 July 2025).

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