Blockchain for a Traceable, Circular Textile Supply Chain: A Requirements Approach

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Globalized markets allow retailers to provide consumers with inexpensive garments, creating a reinforcing supply and demand dynamic. Buyers trade off traceability for low prices, resulting in opaque supply chains where natural biogeochemical cycles, social ethics, and principles of economic prudence are systematically transgressed—making textiles an unsustainable industry. Blockchain as a new technology provides an opportunity to increase traceability and, subsequently, sustainability. This study examines the feasibility of using blockchain in textile supply chain management to increase traceability and sustainability by examining the requirements for this kind of system from multiple stakeholder perspectives. It integrates different bodies of knowledge into a framework that stakeholders can use to holistically address sustainability issues in textile supply chains. Results demonstrate how innovative industry leadership, consumer behavior, policy, and technology all can converge to support a new paradigm of collaborative and sustainable textile supply chain management. This research is important because industrial blockchain use cases only solve traceability issues up to the product use phase—missing circular economy opportunities to recapture material value at the end of consumer use. The proposed framework can help stakeholders proactively design traceability and sustainability into systems by specifying appropriate requirements.

KEY WORDS

blockchain, circular economy, closed-loop, corporate social responsibility, feasibility, GDPR, life cycle, requirements, requirements engineering, supply chain, sustainable fashion, textiles, traceability

INTRODUCTION

Corporations are facing increasing obligations from government and customers to enhance the traceability of their products. A comprehensive survey of the textile industry designed to measure environmental and social impacts found that there is a large gap in the traceability of Tier 2 suppliers (processers), which ripples through the supply chain. Textile processors treat raw materials with chemicals and energy-intensive processes to get them ready for manufacture. Minimum industry standards require that companies are able to identify 50 percent of their Tier 2 suppliers, and best practice dictates 100 percent traceability (GFA and BCG 2017).

Supply chain traceability means corporations have the ability to follow material and production flows from raw material extraction until it reaches the customer (UNECE 2017). The ability to trace a product throughout its life cycle supports risk management, fraud mitigation, quality assurance, worker rights, informed management decisions, and establishes direct responsibility for each link in the product life cycle. To determine which phases in a particular product life cycle have the greatest impact, a life-cycle sustainability assessment (LCSA) can be carried out. LCSA is an approach that analyzes economic, environmental, and social impacts of a product throughout its life cycle including the extraction phase, production phase, use phase, and end of life. Unfortunately, due to overwhelming complexity in industrial systems, lack of firsthand data collection, data inconsistencies, and the tendency for supple chain partners not to collaborate, such analysis is subject to many limitations and uncertainties (Chkanikova and Kogg 2015).

Opaque supply chains prevent consumers and other stakeholders from obtaining information that may be of concern, such as environmental impacts, "sweat shop" working conditions, and product authenticity and safety (New 2010). While corporations may desire to have fully traceable products, most simply do not. Actors in a supply chain wishing to make educated and sustainable purchases must collaborate and innovate ways to share information safely and efficiently. To manage risks to all stakeholders—including noncompliance and reputational risks for corporations—products must be traced from raw material extraction to final products (or garments).

Addressing the problem of supply chain traceability requires collaboration among stakeholders and deploying technical solutions to aid the transition. Blockchain is a nascent technology with a lot of hype that promises to disrupt status quo operations in many industries and supply chains (O'Leary 2017). As a distributed (decentralized), immutable, verified, trusted, secure transaction ledger, blockchain platforms can record and store information pertaining to raw material harvest, production, product use, end of life, sustainability certifications, and vendor contracts. It is not a lynchpin solution; however, its distributed network protects consensus (verified, audited) data with cryptographic user keys and creates trust in a complex, dynamic, and interdependent system (Kshetri 2018). Radio frequency identification tags (RFIDs) and quick response (QR) codes also offer inconspicuous technological solutions that can enhance supply chain traceability (New 2010). Cutting-edge manufacturers have developed smart circuits that can be embedded into any textile and track data that users control (Lederer et al. 2018). Such technologies lay the foundation for industry collaboration and are beginning to engage users in a new way where the applications are only as limited as designers' imaginations.

Many studies examine use cases where blockchain enhances supply chain traceability—for example, food tracking, port logistics, pharmaceuticals, and automotive supply chains (Deloitte 2017; Francisconi 2017). However, only a few studies broadly mention that the product traceability afforded by blockchain can facilitate keeping materials in closed-loop systems, avoiding landfills and incineration (Ellen MacArthur Foundation 2016; Project Provenance Ltd. 2015).

Although the need for transparency and efficiency in supply chains has been established, and blockchain has been proposed as a software solution (Benton et al. 2018), there is a gap in the extant literature indicating how blockchain could be used as a traceability mechanism to facilitate closed-loop supply chains. It is this gap that this article seeks to fill.

Literature Review

The need for supply chain traceability is often attributed to globalization as companies shift from in-house manufacture to global suppliers that have less expensive labor and varying raw material availability (Kumar, Hallqvist, and Ekwall 2017; Nakasumi 2017). General textile industry studies show that raw material production has the greatest impact on water use and is the third largest contributor to energy emissions (GFA and BCG 2017). A recent case study examines the benefits of implementing corporate transparency and concludes that efforts to make supply chains more transparent—sustainability reporting, certifications, and disclosure—can be beneficial in some instances, but will always be subject to trade-offs, so is not always an aspiration in and of itself (Egels-Zandén, Hulthén, and Wulff 2015). Nakasumi (2017) explores how blockchain applications can mitigate supply chain risks specific to manufacturers, but does not expand the analysis to how risks could be addressed systemically or holistically. Another recent article proposes a framework for a dual approach utilizing blockchain technology to address the shortcomings of current supply chain information systems—one that is private for enterprises and another public ledger (Wu et al. 2017).

A United Nations Economic Commission for Europe 2017 draft report on transparency in textile value chains emphasized that traceability is critical for legal compliance as well as corporate social responsibility (CSR). The report acknowledged blockchain's capacity to monitor supply chain transactions in real time; however, for these transaction records to be useful, life-cycle analysis (LCA) methods and standardization of key performance indicators (KPIs) should be advanced (UNECE 2017).

Confidence in worker safety and responsible chemical and material use throughout a product's life cycle cannot be taken for granted without adequate documentation. As corporations lose the ability to trace their supply chains, they face mounting pressure to assume responsibility and bridge the gap to achieve best standards (Kim and Davis 2016). Consumers are concerned with where their clothes are coming from in light of tragedies (Jacobs and Singhal 2017). In an effort to protect brand reputation, companies take on voluntary CSR standards that aim to improve the safety of workers upstream with agreements (Rahim 2017; Jacobs and Singhal 2017).

A 2017 report on the "Pulse of the Fashion Industry" recognizes efforts toward developing KPIs (GFA and BCG 2017). This report makes reference to the Higg Index, which is a tool that rates the social and environmental impacts of specific materials and processes used in garment manufacture from cradle to gate. This index is available to the public and is similar to other LCA tools, but specific to garment manufacture. The index platform allows companies to import their LCA data and virtually blend materials to see the potential impacts of their material and processing choices (GFA and BCG 2017).

There are companies offering a range of blockchain solutions for producers, retailers, and customers to increase product traceability and customer satisfaction. Platforms offer businesses a way to communicate their sustainability certifications and product sourcing information to customers, as well as manage their own data on the blockchain platform (Project Provenance Ltd. 2015). Such platforms offer businesses the opportunity to present supply chain information as a story that ends at the use phase. This study goes beyond those requirements and also addresses barriers to reuse, remanufacture, and recycle textiles at end of consumer use. Specific objectives include:

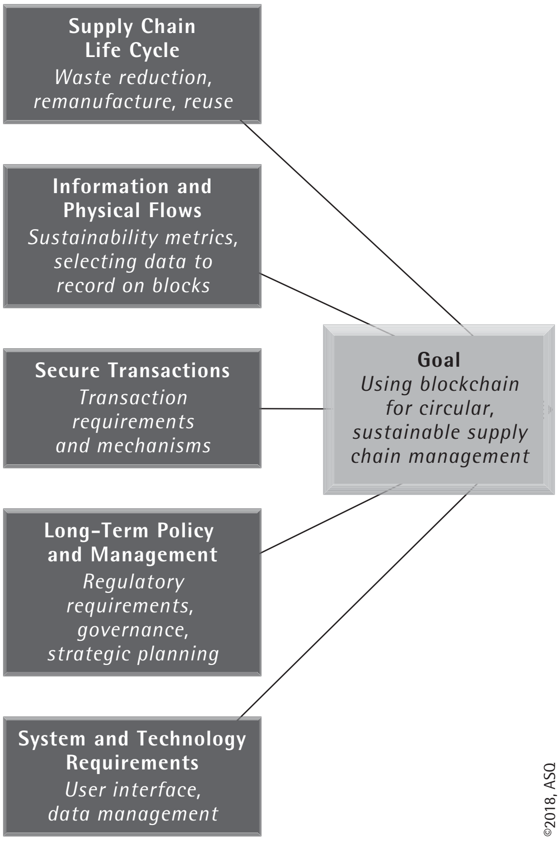
- Develop a framework integrating blockchain into textile supply chain management to understand how information flows could be captured and used by various stakeholders.
- Understand the system and policy requirements for long-term management of textile supply chains using blockchain.
- Understand how innovative industry leadership, consumer behavior, policy, and technology all can converge to support a new paradigm of collaborative and sustainable textile supply chain management. Use a case study to demonstrate implementation of the proposed framework.

Policy makers can use this framework to implement circular economy solutions (preserve resources) and facilitate compliance; businesses can use it for proactive supply chain management, and consumers can use it for education about the impacts of consumption, care, and disposal choices. All stakeholders can use this framework for long-term management, risk reduction, and to contribute to sustainability efforts.

METHODOLOGY

In this study, a framework was developed using the case-study methodology to employ blockchain for circular and sustainable textile supply chain management (see Figure 1). This framework is designed to account for the interests of all stakeholders in a textile supply chain and brings together five key aspects. First, the life cycle of a garment and a closed-loop supply chain were defined. Second, the sustainability metrics to be stored on the blockchain are described from a practical perspective. Next, transaction details are articulated to demonstrate

FIGURE 1 Framework model used in this study

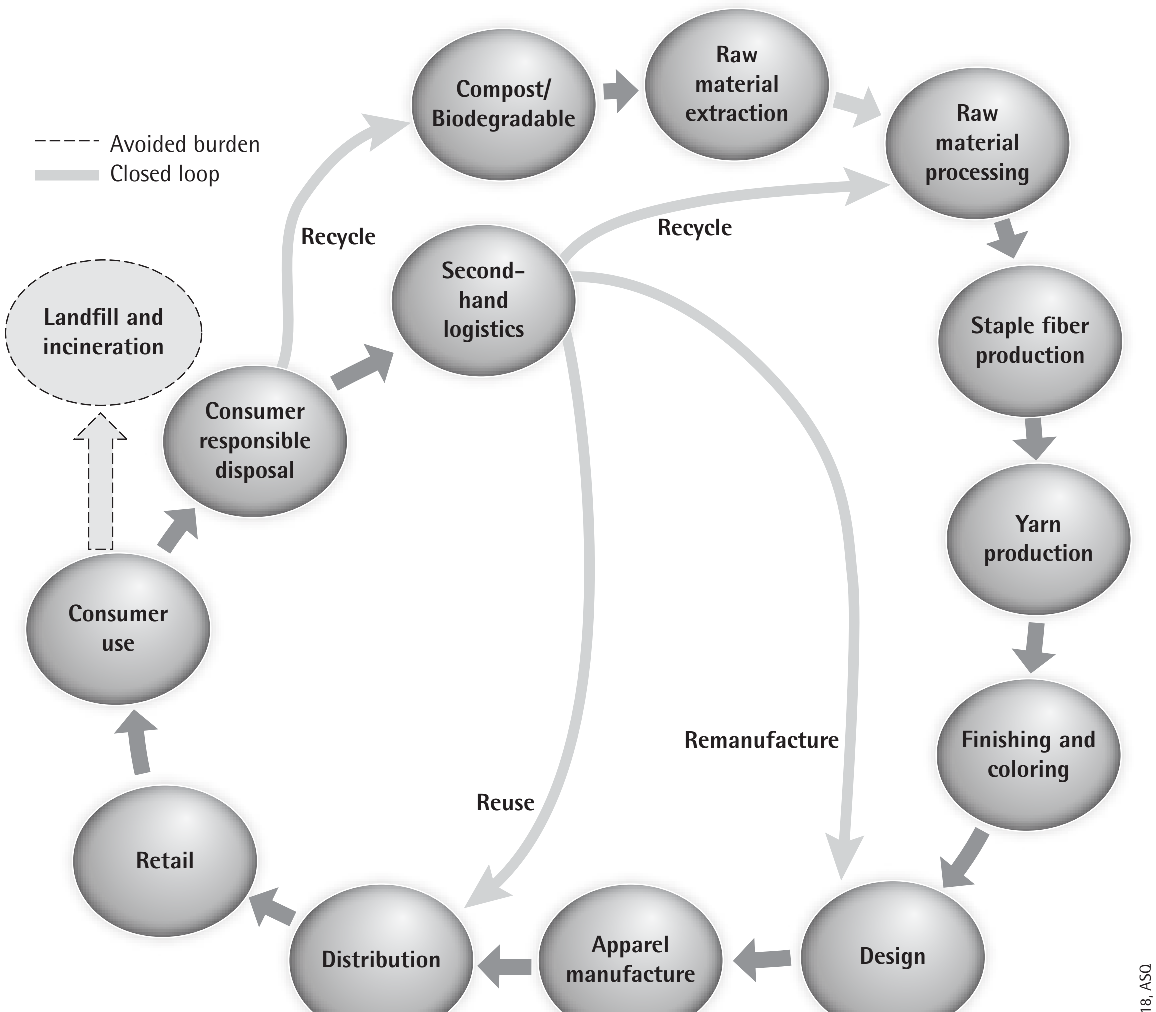


how assets can be securely exchanged. This is placed in the context of long-term goals to demonstrate why proactive environmental management is important. Finally, the system and technology requirements to engage customers and build an effective user interface are discussed.

Life-Cycle Supply Chain

By tracing the life cycle of an individual garment in terms of its components, opportunities for enhanced sustainability can be identified at various stages using integrated technology. In a typical textile supply chain there are dynamic and complex relationships between stakeholders. Integrated technology that uses decision support systems and tracing devices can mitigate sustainability challenges if implemented holistically in a collaborative environment (Nakasumi 2017; Ngai et al. 2014). Figure 2 shows a closed-loop textile life cycle that could be realized by integrating tracing mechanisms from a garment's incipiency; closing the loop through reuse, recycling, remanufacturing, and composting of textiles. The most preferred closed-loop system is textile reuse (and repair) because it avoids landfilling and incineration with the least extra supply chain steps and consequent energy demands (Ilgin and Gupta 2009). The second preferred option is textile remanufacture where second-hand garments in good condition are consigned by designers who draw up plans to deconstruct them and transform them into newly designed pieces (Dissanayake and Sinha 2015). Finally, textile recycling takes post-consumer or post-industrial waste and mechanically processes it to become feedstock for new fibers (composting is considered another form of

FIGURE 2 A closed-loop life cycle of textiles.



Adapted from (Muthu 2015)

recycling) (Muthu 2015; World Health Organization n.d.). These closed-loop systems can be catalyzed by emerging second-hand markets eager to capitalize on opportunities from traceable and recoverable resources. This is all premised on close stakeholder collaboration and the responsible disposal of garments by consumers (Muthu 2015) who are empowered by information availability.

Sustainability Metrics Recorded on Blocks

Managing the information stored on a blockchain system should be relevant to the economic, environmental, social, and functional metrics of individual garments. Storing economic information using blockchain-enabled smart contracts has been demonstrated to increase supply chain efficiency and can therefore result in cost savings for transacting supply chain partners (Chen et al. 2017). When economic information is captured using blockchain at each supply chain step, an auditable chain-of-command for materials and resources becomes available. Environmental metrics are important to track and store to holistically evaluate negative impacts and possible mitigation strategies, especially since environmental impacts accumulate throughout a textile's life cycle. Social aspects concerning garments can be made available in a transparent manner to ensure corporate codes of conduct are being upheld upstream and consumers have agency over the downstream impacts they cause. Functionality metrics are important to include on the blockchain for consumer and post-consumer ease of reference. All these parameters are suggested to be included practically (see Table 1). The specific parameters logged on the blockchain network will depend on which stakeholder is inputting the data. Materials and final garments will be traced at the unit level by each stakeholder in the system (Deloitte 2017). As information is captured at each step in the supply chain, the chain of command for products, their components, functions, and concomitant impacts will be compiled, creating traceability and opportunities for more sustainable decision making. Comprehensive management of these physical and informational flows can provide a range of assurances for all stakeholders.

TABLE 1 Categorical metrics of information to include on individual blocks

Metric	Information to include on block
Economic	a. Smart contract—executed transactions (e.g., payments and deliveries) [3, 4, 7, 8] b. Bank access to network [3] c. Insurance information [1] d. Age of material or resource e. Market resources and commodities prices
Environmental	a. Relevant environmental certifications (e.g., EU Ecolabel, FSC certification, chemical certifications like OEKO-TEX, GOTS, Cradle to Cradle) [5] b. LCA impact data c. Higg MSI impact data [6] d. Raw materials used [2] e. Chemicals used f. Amount of water used g. GHG emissions h. Waste, byproducts, and coproducts produced i. Biodegradability, compostability
Social	a. Relevant certifications (e.g., Fair Trade, GOTS, OEKO-TEX, SA8000) b. Living wages (120 percent of minimum wage) [6] c. Worker age and hour restrictions; freedom to organize [6] d. Gender equality [5] e. Responsible care instructions [5] f. Responsible disposal instruction [5]
Functional	a. Intended use [2] b. Capabilities (e.g., heating, cooling, data tracking, water resistant, antimicrobial, UV protection) [9] c. Design for *X* (e.g., environment, disassembly; privacy) [10] d. Warrantee information [1] e. Repair information f. Quality control information

[1] (Marr 2018);
[2] (Project Provenance Ltd. 2015);
[3] (Francisconi 2017);
[4] (Jeppsson and Olsson 2017);
[5] (Muthu 2015);
[6] (GFA and BCG 2017);
[7] (IBM Corporation 2018);
[8] (Ethereum Blockchain App Platform 2018);
[9] (Kiekens et al. 2014);
[10] (Fabiano 2017)

Economic metrics

A smart contract is a coded document detailing the terms of an agreement that executes automatically once terms such as payments and deliveries are verified and met (He et al. 2016; Jeppsson and Olsson 2017). Bank access to network implies that a financial institution involved in the supply chain is granted access to the blockchain network via the smart contract in order to read and write information such as letters of credit, and processing payments between parties as stipulated in an agreement (Francisconi 2017). Insurance information can be stored on a blockchain network so it is easily accessible to stakeholders who require this information from their supply chain partners (Marr 2018). The age of a material or resource is important to include because of the cascading value of materials (Ellen MacArthur Foundation 2016). By knowing the age of components, value can be ascribed by second-hand markets. Links to market prices of resources and commodities allows a variety of procurement decisions to be compared in real time.

Environmental metrics

Storing relevant environmental certifications on the blockchain network makes this information easily accessible to stakeholders who require or are interested in this information. LCA and the Higg Material Sustainability Index (MSI) are tools for assessing the environmental and social impacts that result from product design, material, and processing choices (Sustainable Apparel Coalition 2018b). Access to these impact data allows all actors across a supply chain—from raw material producers to consumers—to see the full impact of their choices with reference to specific calculations that can serve as a basis for exploring alternative procurements. Tracking waste, byproduct, co-product, information allows second-hand markets to compete for these resources. Degradability/Compostability information enables consumers to responsibly dispose of garments.

Social metrics

Storing relevant social certifications on the blockchain network makes this information easily accessible to stakeholders who require or are interested in this information. Living wages are defined as having the ability to meet basic necessities without working excessive overtime (OECD 2018). By proactively monitoring worker age, hour restrictions, freedom to organize, and gender equality metrics, brands can reduce reputational risks and advertise their commitment to human rights and equity (GFA and BCG 2017; Muthu 2015). Responsible care and disposal information can empower consumers to understand their impacts in this system and modify their behavior (Muthu 2015).

Functional metrics

Storing the type of textile and its capabilities adds an extra layer of transparency and ease of information access for stakeholders. There could be market demand for certain types of textiles (denim, UV protection, antimicrobial, and so on), in which case quickly accessible and tracked materials would facilitate second-hand markets. If a product is designed for disassembly, it may command a higher market price from second-hand markets. Warranty, repair, and quality control information will be useful to customers and retailers by enhancing efficiency and consumer protections. Storing these metrics encourages customer loyalty (good for retailer) and customers to take advantage of warranty and repair programs to extend the life of products (good for customer).

Secure Transactions Using Blockchain

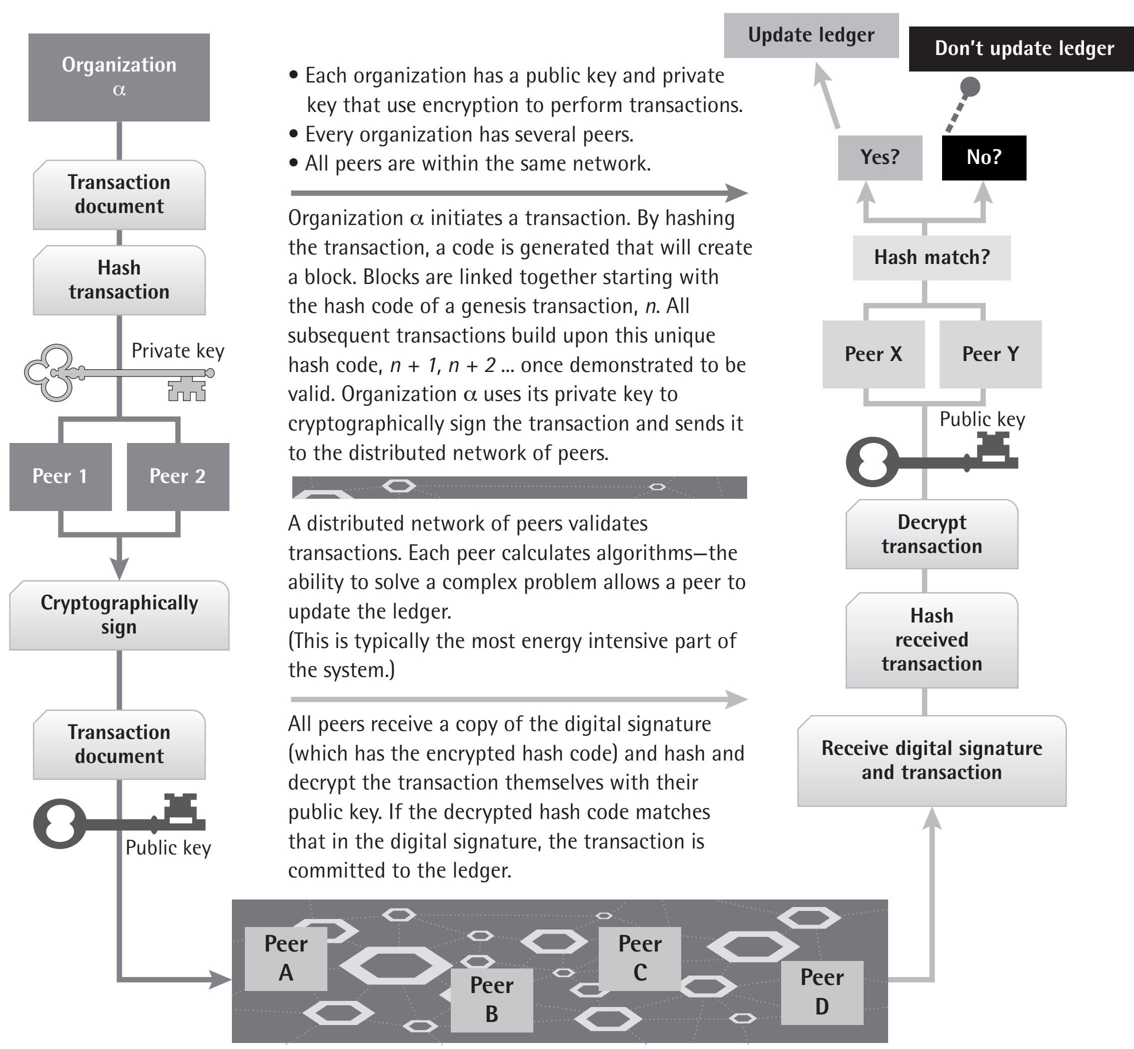
Transactions in a blockchain ecosystem are commonly and simply described as exchanging assets on a decentralized ledger database that stores immutable and auditable information using the most secure technology available on the market. The design of blockchain systems is such that stakeholders can access trusted and verified information in real time (Deloitte 2017; Fabiano 2017; Francisconi 2017; Kim and Laskowski 2016; Kshetri 2018). The mechanics of blockchain systems are discrete and must not be conflated: first, there are distinct blockchain platforms, applications, and services, offering clients a variety of options depending on needs, uses, and permission preferences; second, there are "four Ps" of blockchain technology—public, private, permissioned, and permissionless, which can be mixed and matched to create a system dictating the level of information accessible by stakeholders (who can read and who can write data) (Francisconi 2017). What makes blockchain transactions unique when compared to traditional ledger databases and IT systems is the secure transaction process and the decentralized network on which these transactions take place (Project Provenance Ltd. 2015). Cybersecurity is managed by the use of separate public and private keys for cryptographically signing and accepting transactions, and the use of algorithms for validating transactions, which are explained next (Jeppsson and Olsson 2017; Kshetri 2018).

The peer-to-peer transaction process is as follows: transactions are initiated by a user; a transaction is then authenticated by members within the network; a block (time-stamped data) is created; then blocks are validated using different algorithmic mining mechanisms (such as proof-of-work, proof-of-stake, hybrid models, and so on) to find the correct place to store this block; once validated, the block is "chained" (linked in chronological order) to previous blocks in the system. A user will have a public key and a private key. The former is shared with other users in the network; the latter is not shared externally and functions as a digital signature to authenticate ownership of goods and information. Both keys use encryption technology and the validation algorithms to keep transactions secure. When a user initiates a transaction, it is broadcast to the entire network and addressed to another user's public key using one's own public key. Typically, all peers in the network start solving algorithms to decrypt the transaction. Authenticity of a transaction is verified by the peer that properly solves the algorithm, and this peer then updates the ledger. To manipulate or change any information on a block after it is verified, the entire chain of blocks would need to be modified, which is exceedingly difficult because all blocks are time-stamped, and writing data requires consensus algorithms to be solved. Information could also be manipulated if any entity controls more than 50 percent of the network (Francisconi 2017; Jeppsson and Olsson 2017). See Figure 3 for simplified demonstration of transactions (Madhwal and Panfilov 2017).

Throughout the life cycle of a garment, transactions coupled with the appropriate metrics outlined in Table 1 would be added to blocks. Although the physical information network is decentralized, entities that are

FIGURE 3 Simplified blockchain transaction process—public permissionless ledger.

Source: (Francisconi 2017; Jeppsson and Olsson 2017; Nakasumi 2017). Distributed network image source: (Nair 2017)



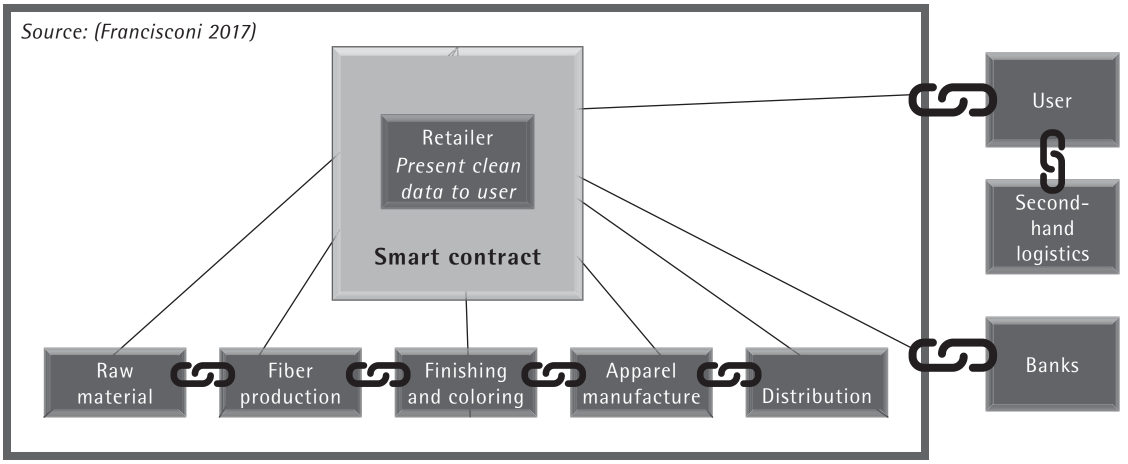
consumer-facing, namely retailers, could take on a facilitator role to harmonize the process and effectuate smart contracts (FranciscFrancisconi 2017) (see Figure 4). A critical precursor for a retailer to use blockchain is its ability to trace all upstream organizations in the supply chain and that all actors have the necessary IT infrastructure to support this new paradigm (Bonanni 2018). Assuming a retail initiative and the requisite infrastructure is in place, the transactions would flow as follows, with each separate stakeholder being a different user of the system. A genesis transaction creating a hash value for future blocks to be built upon (Wu et al. 2017) is initiated by the company harvesting and processing the raw materials and validated by the recipient of these raw materials; when raw materials are turned to fibers, transactions are initiated by the fiber producer and verified by the yarn producer once received; yarn producers initiate another transaction to be confirmed by finishing and coloring agents; then apparel manufacturers begin the unit-level authentication once they receive final fabrics. The apparel manufacturer incorporates a smart device into the garment, either into the physical fabric or the garment label, importing the legacy supply chain data. Distributors also document their activities on the blockchain network. Consumers can scan a smart device embedded in the garment to see provenance and impact data, which is curated by the retailer but verified using blockchain. Once users no longer want a garment, information on the blockchain can assist with responsible disposal, matching the garment with an interested second-hand party.

The implications of the blockchain transaction system are truly revolutionary because of the deviation from centralized networks that are prone to errors and fraud. Another game-changing feature is that blockchain flips the script of traditional linear transactions from data push to data pull (Francisconi 2017); rather than being sent a piece of data that could or could not be real, stakeholders can pull trusted, verified, real-time information from the network. Unlike traditional IT systems, blockchain systems can provide access to important stakeholders outside of the direct network, such as consumers and banks that rely on data being pushed out to them. In a blockchain system, banks would be included in the smart contract to expedite clearings and other important financial transactions (Francisconi 2017). Because banks are increasingly concerned with fraud, clearing times are delayed to provide extra time to validate transactions – an unnecessary constraint in a blockchain system where transactions are automatically verified (Korpela, Hallikas, and Dahlberg 2017).

Blockchain systems can provide immutable, secure, authentic, verified, agile, and real-time data to all stakeholders, which is a significant divergence from the status quo (Deloitte 2017; Francisconi 2017; Jeppsson and Olsson 2017; Project Provenance Ltd. 2015). Such a system can promote a circular supply chain, because with digitized components second-hand logistics providers can automate the distribution of garments to appropriate second-hand markets. Such a system can promote sustainable supply chain management because of the economic efficiencies, and because all actors involved

FIGURE 4 Textile retailer facilitating blockchain ecosystem

Actors traditionally outside the supply chain—users, second-hand collectors, banks—are engaged to promote closed-loop systems. Smart contracts increase overall efficiency.



in the supply chain—from raw material producers to consumers—can see the full environmental and social impacts of their choices and use this information as the basis for exploring alternative procurements.

System Requirements and Technology

Finally, system requirements in terms of human capital, labeling, and consumer behavior were addressed to determine implications for technology implementation. The joint requirements of data security and legal compliance were also taken into account:

Human capital

The blockchain textile supply chain ecosystem is designed to educate and empower consumers to responsibly care for and discard their clothing, developing more robust second-hand circular markets. Any team of developers and coders can access open-source information to build the components of a blockchain ecosystem; alternatively, well-established and start-up private enterprises can be hired to build custom blockchain applications, platforms, or services (Vankov 2017a).

Labels

The link between tracing unit-level garments and the blockchain network can be the limiting factor of the system. IoT devices (devices collecting data that connect to the internet) embedded in garments will interface with users to tell the story of a product, its provenance and impact, and provide consumers with the necessary information for responsible care and disposal (Project Provenance Ltd. 2015). Utilizing QR codes on garment labels or other tech mediums embedded in garments, brands engage customers to stay ahead of the curve. EU regulation requires textiles to be labeled with their fiber composition. This regulation does not require any additional information to be included on the label (such as country of origin or care instructions) (European Commission 2011). A 2016 regulation requires that all products labeled as organic imported into the EU or traded among member states must be registered in the TRACES database and accompanied by certificates of inspection (European Commission 2016c). Despite the few direct labeling requirements, companies seeking a competitive advantage are increasingly disclosing voluntary environmental impacts of garments directly onto labels (GFA and BCG 2017). On the other hand, the few labeling requirements, as in the case with organic labels, would be streamlined in a blockchain system that could store certificates of inspection on the ledger. Many brands are already disclosing voluntary information via their garment labels, such as the relative carbon, water, and waste footprints compared to the industry standard, and responsible care instructions. Finally, companies use blockchain technology in different industries to trace product provenance and share information with customers in innovative ways. Customers can scan a QR code to "discover the unique journey behind this product" in a textile example displayed in Figure 5.

FIGURE 5 Garment label with QR code linked to blockchain displaying story map

Source: Project Provenance Ltd. 2018

Consumer behavior

Because of the heavy environmental impacts that occur during the use and disposal life-cycle phases of textile supply chains (GFA and BCG 2017; Muthu 2014), addressing these issues is of chief concern. While it is understood how consumer behavior changes can benefit sustainable supply chain management, it is unclear how to directly motivate behavior change or gauge what types of impact and care information they would want to see. Consumer care and disposal behavior can offer water, energy, and eco-toxicity savings. By washing clothing in cool water and line drying, up to 80 percent of a garment's greenhouse emissions can be avoided (Muthu 2015). Responsible care also includes implementing strategies to reduce microfiber pollution, which occurs from washing acrylic, nylon, and polyester fibers. These strategies include short, cold, full laundry loads that use liquid soap rather than powder soap, short revolution spin cycles, and, of course, reducing consumption of these fabrics in the first place (Italian National Research Council 2014). As consumers increasingly have access to data like these, it can reinforce demand on retailers to provide them. In Figure 6, a hypothetical textile label user interface using a QR code is drawn to expand the current model for information that can be harnessed using blockchain and IoT tracking devices.

FIGURE 6 Hypothetical textile label QR code —user display

Incorporating responsible care information on the garment label educates customers about the impacts of the choices they make. Furthermore, responsible disposal will help clothing avoid landfill and incineration. Certain textile materials are more favorable for recycling than others and all materials have a cascading recycling value; some garments are biodegradable and compostable (Pavarini 2017), and some clothing may retain a high consigning value. As individual garments become traceable in terms of their specific component materials and processing, second-hand markets can become more efficient—creating a win-win-win scenario for customers consigning garments after use, retailers that can gain increased customer loyalty and supply chain efficiencies, and governments eager for closed-loop solutions, data security, and legal compliance.

CASE STUDY OF EXEMPLAR GARMENT: LEGGINGS

This section applies the proposed framework to a case study garment. The selected garment is a pair of athletic leggings sold in the United Kingdom to a German customer that are traced throughout their life cycle using blockchain.

Fashion retailers that aim to enhance sustainability and ethical practices in their supply chains may provide customers with information about the provenance of individual garments (Know the Origin 2018b). The particular garment selected for this case study is a pair of black leggings. They are made from 100 percent Lenzing modal fabric (Know the Origin 2018a). The retail brand provides some explicit information that is used in this case study. The remaining information needed to implement the framework properly is assumed and denoted accordingly. The supply chain for this garment starts with raw material extraction in Austria, where wood is harvested from an integrated pulp mill that creates and processes cellulosic textile fibers into colored fabrics. A U.K. retailer designs the garment and contracts with an apparel manufacturer in India to assemble the garment using the aforementioned fabric. Then, the garments are distributed to the retailer and purchased by a consumer. To close the loop for this garment, various end-of-life strategies are outlined. See Figure 7 on the next page for the proposed closed-loop supply chain of this garment.

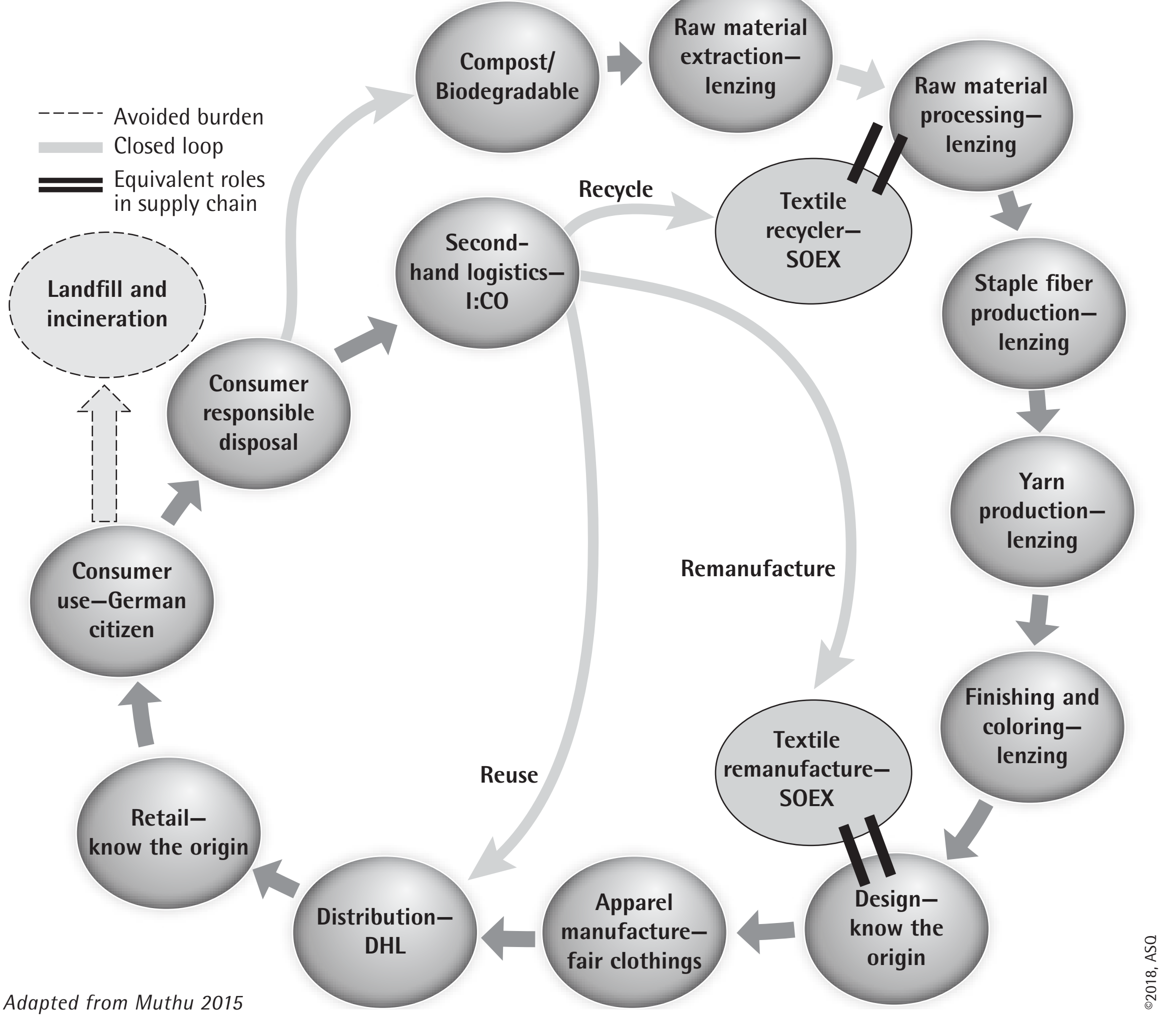
Managing Information and Physical Flows

There are numerous stakeholders in this garment's supply chain, and each has its own preferred metrics that it would record on the blockchain platform (detailed in Appendix 1). As metrics are captured on the permissioned ledger and become available to parties in the system, certain private information pertaining to prices and proprietary data does not need to be added to the ledger. Private chaincode channel connections demonstrate how segregated transactions can take place among subsets of private parties within a larger supply-chain network. Final garments have unique unit-level provenance, care, and disposal information available via a QR code. There are several ways to establish what exactly a customer will see when he or she scans the QR code. When a retailer sells a garment that makes verified blockchain data available, it is at this stage that *traceability becomes transparency.*

Secure Transactions on Blockchain Platform

The Hyperledger Fabric Framework is a Linux Foundation Project. Hyperledger Fabric (Fabric) is a permissioned blockchain platform that implements new approaches to executing permissioned peer-to-peer transactions in a distributed ledger where transacting parties are known. This framework manages members (peers, nodes, and

FIGURE 7 Proposed closed-loop supply chain for exemplar garment



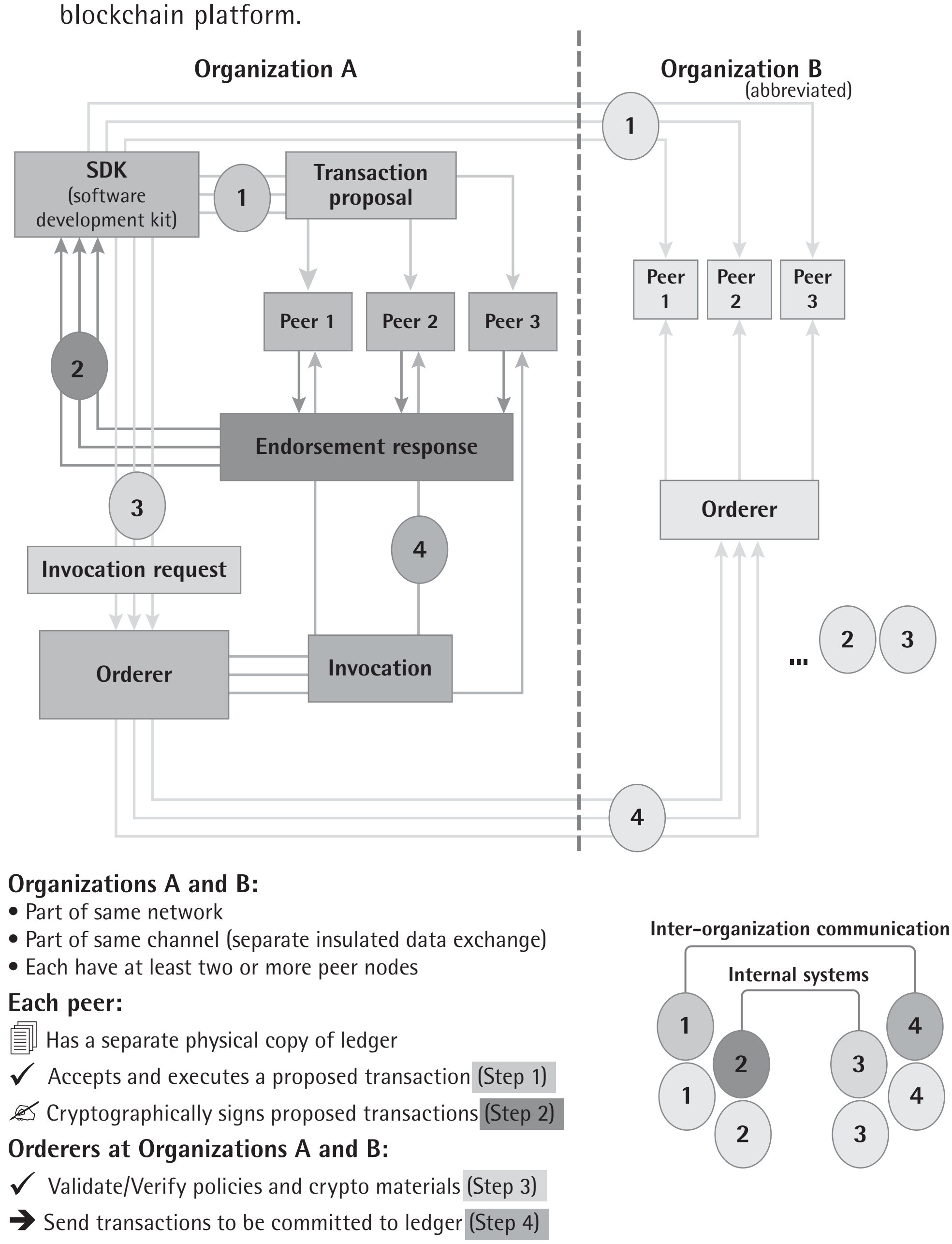
Adapted from Muthu 2015

ordering services) with membership service providers (MSP) and offers modularity—often described as a "plug-and-play" system—making it highly customizable and versatile. Fabric uses smart contracts, which it calls "chaincode," where members have access to specific, separated private channels to execute their contractual obligations confidentially while only broadcasting selected information to the entire blockchain network. Fabric's architecture separates transactions into three steps: execute, order, validate, diverging from most other blockchain smart contract-capable systems that follow dual order-execute structures, which rely on energy-intensive consensus mechanisms such as proof-of-work. The fabric three-tiered transaction mechanism allows transactions to be executed as long as the endorsing parties (parties to the specific chaincode channel who are known and permissioned in the system)—agree that a contractual provision has been met and is consistent with the endorsement policy that has been established ahead of time. This is opposed to proof-of-work systems, where transactions can be validated only after all nodes have participated in validating transactions to compensate for the fact that in public blockchains users are not known. The consensus protocols (how nodes in the system order information to be added to the chain) of Fabric are unique because users are *known* and *permissioned*, and different endorsement policies can be established depending on the circumstances (Androulaki et al. 2018; Hyperledger 2017).

There can be several or many MSPs in a network that issue keys (public and private) and enrollment certificates that allow parties to transact on the network.

The MSPs dictate who does what and when, signing off on transactions if they are within an endorsement policy. Each MSP will have at least two peers for redundancy purposes. When a member executes a transaction on the Fabric network, they are initiating a transaction simulation. The simulated transaction is then sent to the limited group of endorsers in the specific chaincode network who agree (or not) that a transaction is valid within the endorsement policy, then the validated transaction goes to the ordering service. The ordering service creates a new block with the chronologically time-stamped transaction data and publishes it to all the peers in the network, who receive an updated version of the ledger. Figure 8 demonstrates specifically how these transactions take place between organizations on the Fabric platform (Androulaki et al. 2018; Hyperledger 2017).

FIGURE 8 Simplified interorganization transaction on proposed private permissioned blockchain platform.



Source: creative commons adaptation from Hyperledger 2017; Vankov 2017b

This system prevents issues of double spending and eliminates race conditions. (Androulaki et al. 2018; Hyperledger 2017; Vankov 2017b) Most features in Fabric are customizable, and use cases exist where different levels of users outside of the transaction network can query the system. Such an application would be useful in this case study because this would allow customers and other stakeholders outside of the transaction network restricted access to the verified data recorded on the blockchain (Androulaki et al. 2018; Hyperledger 2017).

DISCUSSION AND CONCLUSIONS

There is a pressing need for sustainable solutions in many industries, but particularly in the textile industry. The first step toward implementing sustainable solutions is to increase traceability and transparency, something blockchain technology can address. The proposed framework can help policy makers, businesses, and consumers avoid risks by proactively designing traceability and sustainability solutions into the system. The case study demonstrates that blockchain can enhance sustainability, traceability, and transparency, enabling all supply chain stakeholders to evaluate total life-cycle impacts and make better and more strategic procurement decisions—proactive rather than reactive. The introduction of blockchain simultaneously can empower consumers to adopt better consumption, care, and disposal behaviors, and reduces barriers for second-hand markets.

The proposed framework in this study supports long-term management in several ways. First, it allows the industry to comply with existing and future regulations in more streamlined and efficient ways. Analyzing the public policies listed in the Appendix 2 holistically, it seems that the textile industry needs a way to proactively manage current and future compliance requirements. Textile retailers that facilitate blockchain solutions early on will be more resilient to industry disruptions because they will be able to trace their entire supply chain and ensure compliance on the various levels required of them. Organizations will face mounting pressures from policy makers to address traceability and data security issues, and the ones that do not implement solutions quickly will face compliance risks or be pushed out of the market. Additionally, with the increasing information transparency and credibility afforded by blockchain, consumers will demand assurance that their clothing is made in more environmentally and socially friendly ways, and may not be willing to pay for items that do not meet higher standards in the future. Therefore, looking forward, all stakeholders are behooved to adopt traceability solutions sooner than later. To date, blockchain is the best available technology to securely manage and trace all of the variables in this complex supply chain (Deloitte 2017).

As cybersecurity and data security become more prevalent and serious issues, this framework details how assets can be exchanged securely using the best available cryptography and algorithmic validation technology. Data are stored in a decentralized fashion as opposed to traditional systems where data are vulnerable due to centralized storage. These state-of-the-art security features offer technical solutions to comply with EU GDPR regulations. As IoT devices continue to proliferate, the framework of this study details how companies can proactively plan to incorporate tech with textiles in accordance with the guiding principles of privacy-by-design (Fabiano 2017). Without this long-term management strategy, industries will be vulnerable to technological and security perturbations later on (Deloitte 2017).

Governments can actively manage environmental risks that arise from practices abroad that conflict with domestic policies. Chemicals that are banned in Europe (such as NPE) are used in textile processing in foreign countries and ultimately imported into Europe, causing the same environmental and human health problems the domestic policy sought to avoid (European Commission 2016a).

There is a critical need to embrace systems and life-cycle thinking. The current paradigm and mindset of "take-make-waste" is the root cause of the sustainability issues discussed in this study. If progress and risk avoidance are desirable outcomes, then systems and life-cycle thinking, as well as interaction design, should be emphasized as tools for understanding how to begin to address sustainability challenges (Ellen MacArthur Foundation 2016; Ramkumar et al. 2018). Future research is needed on quantitative and local implementations, as well as consumer behavior motivations. This study was conducted from a global perspective; however, waste is managed on a local level and, therefore, a local pilot project to test the implementation and quantify the proposed intervention is necessary.

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APPENDIX 1 Stakeholder information and material flows for case study

Stakeholder role	Identity	Location	Interests	Metrics written on blocks	Private chaincode connections	Source
Raw material extractor and processor *Lenzing integrated pulp and fiber plant**	Lenzing AG* **"B"**	Austria, Europe	Streamlined integration; reduced EI	Smart contract; location of resource; virgin vs. recycled material use; chemicals used for material processing; safe chemical use certifications; environmental and social certifications. **Specifically recorded per kg** • Virgin Austrian beech wood • Pulp processing chemical disclosure • Environmental: FSC license code C041246 (certified audited responsible forestry practices); PEFC Chain of Custody Certificate number NC-PEFC/COC-028625 (sustainable forest management).	B ⟺ C B ⟺ A	[1], [7], [8], [12], [13]
Fiber, yarn, and spun-dyed fabric producer *Lenzing Modal COLOR+*	Lenzing AG*+ **"B"**	Austria, Europe	Streamlined integration; reduced EI; profit	Smart contract; chemicals used during processing; safe chemical use environmental certifications; environmental certifications; social certifications; Higg MSI score. **Specifically recorded per kg/m** • Functional: biodegradable, color retention, enhanced breathability, moisture management and thermal regulation, long-lasting softness. • Environmental: ISO 14001 (effective environmental management system), renewable energy used for processing, EU-Eco Label AT/016/001 (third-party certified Type I ISO 14024 for environmental excellence), USDA BioPreferred® product. • Social: OHSA 18001 (reduce workplace hazards and boost employee morale), OEKO-TEX® STANDARD 100 (consumer product chemical safety) • Higg MSI score: 23.		[1], [2], [7], [9], [10], [11], [14], [17], [18]
Apparel manufacture *Cut and Sew "Lotus" leggings*	Mila Fair Clothings Pvt Ltd.* **"C"**	Tamil Nadu, India	Social sustainability; economic opportunity	Label QR code activation; tracing; smart contract; social certifications **Specifically recorded per garment unit** • Social: certified Fairtade (Fairtrade Labelling Organizations International) • Functional: add QR label	C ⟺ B C ⟺ D	[1], [3], [7]

* *indicates information was explicitly provided by retail brand*
\+ *indicates information was assumed for the purposes of this case study*

APPENDIX 1 Stakeholder information and material flows for case study *(Continued)*

Stakeholder role	Identity	Location	Interests	Metrics written on blocks	Private chaincode connections	Source
Distribution *Distribute to Know the Origin retail in U.K.*	DHL **"D"**	Tamil Nadu, India	Profit; efficiency	Smart contract; record downstream distribution locations **Specifically recorded per garment unit** • Environmental: DHL GoGreen Solutions Carbon Calculator in accordance with EN 16258:2012 (EU common methodology for calculation and declaration of GHG emissions of transport services)	D ⇔ C D ⇔ A D ⇔ F	[3], [15], [16]
Retail *Consumer-facing*	Know the Origin* **"A"**	London, U.K.; brick and mortar retail location	Ethical fashion; product differentiation.	**Specifically recorded per garment unit** On label: • Athletic leggings made of 100% Lenzing Modal, a bio-based fabric made from Austrian virgin beech wood, assembled in India at Fairtrade certified manufacturer. Higg Material Sustainability Index score: 23 • Responsible care: Hand or machine-wash on delicate setting in cool water. Line dry. Generated from scanned QR code: • Responsible disposal: Scan QR code to find the nearest drop-off location. This product is also biodegradable and compostable. • Environmental: FSC licensed raw materials (code C041246), PEFC Chain of Custody Certificate (number NC-PEFC/COC-028625), ISO 14001 fiber production, renewable energy used for fiber processing, X tons of GHG eq. in shipping from India. • Functional: biodegradable, compostable, color retention, enhanced breathability, moisture management and thermal regulation, long-lasting softness. • Social: OHSA 18001 (Reduce workplace hazards and boost employee morale) • Higg MSI score breakdown by impact categories: 23.4 Global warming: 2.8 points Eutrophication: 2.3 points Water scarcity: 2.9 Abiotic resource depletion (use of fossil fuels): 2.7 Chemistry: 12.7	A ⇔ E A ⇔ B A ⇔ C A ⇔ F	[1], [9], [14], [19]

* *indicates information was explicitly provided by retail brand*
\+ *indicates information was assumed for the purposes of this case study*

APPENDIX 1 Stakeholder information and material flows for case study *(Continued)*

Stakeholder role	Identity	Location	Interests	Metrics written on blocks	Private chaincode connections	Source
Consumer	German citizen+ **"E"**	Düsseldorf, Germany	Ethical fashion	**Specifically recorded per garment unit** Optional product registration; optional responsible disposal registration; incentives from retailers and market researchers. Scan QR code for full product details and responsible disposal information.	E → F D ⟺ E	+
Second-hand textile logistics	I:Collect GmbH+ **"F"**	Ahrensburg, Germany	Closed-loop textile SC	Collect garments. Pull data from garment units. **Specifically record downstream distribution.**	F ⟺ A F ← E F ⟺ G F ⟺ H F ⟺ I	[4]
Textile remanufacturer *Apparel manufacturing for global modern fashion; Design*	Hofmann-Maschenstoffe GmbH+ **"G"**	Donzdorf, Germany	Profit; quality; apparel composition.	*Pull data from garment unit.* **Specifically record downstream distribution and maintain legacy garment information in remanufactured garments.**	G ⟺ F	[5]
Textile recycler	SOEX Recycling Germany GmbH+ **"H"**	Bitterfeld-Wolfen, Germany	Profit; quality; apparel composition.	*Pull data from garment unit.* **No metrics written unless recycling garments into new yarn – then follow process for yarn/fiber producers.**	H ⟺ F	[6]
Banks	Generic **"I"**	Global	Profit; anti-fraud assurance.	*Only specified chaincode access*	All (save J)	
Government	European Union **"J"**	Brussels, Belgium	Waste management; GhG reduction; legal compliance (chemicals, water, labels)	*Request compliance reports from A, B, F, G, H, I* **No metrics written**	None	

Table sources:

[1] (Know the Origin 2018a)
[2] (Terinte et al. 2014)
[3] (Mila Fair Clothings Pvt Ltd. 2018)
[4] (I:Collect GmbH 2018)
[5] (Textile Infomedia 2015)
[6] (SOEX Recycling Germany GmbH 2018)
[7] (Lenzing AG 2013, 28)
[8] (Shen and Patel 2010)
[9] (Lenzing AG 2018)
[10] (ISO 2015)
[11] (BSI 2018)
[12] (FSC and Rainforest Alliance 2017)
[13] (PEFC 2018)
[14] (Sustainable Apparel Coalition 2018a)
[15] (DHL 2018)
[16] (European Committee for Standardization 2012)
[17] (European Commission 2017b)
[18] (OEKO-TEX 2018)
[19] (The Laundress 2018)

* *indicates information was explicitly provided by retail brand*
\+ *indicates information was assumed for the purposes of this case study*

APPENDIX 2 EU policies that impact the textile industry

EU Policy Category	Description	Reference
Trade	Quotas removed on imported textiles within WTO countries. Liberalized markets. *Opportunity: Free trade allows businesses to capitalize on global markets.* *Challenge: Relinquishment of direct control over supply chain.* Consigned plants imported into the EU and within EU member countries—including textile fibers and cotton—must be registered with accompanying documentation in a centralized database called TRACES. *Opportunity: Requirement for certificate registration is an opportunity for smart contracts and blockchain.* *Challenge: Reporting requirements can be costly and obtaining upstream information from supply chain can be difficult.*	(European Commission 2004; 2016b)
GHG reduction	Cap and trade emissions trading system first implemented in 2003 as part of EU's energy policy framework. Calls for a 43 percent reduction in CO_2 eq. emissions from certain industries. The textile industry is indirectly impacted by this policy through its connection to oil refining, pulp, and bulk organic chemicals industries that are directly regulated in this directive. *Challenge or opportunity: Compliance requires capital investment and could impact raw material prices.*	(European Commission 2003; 2005)
Waste	Textiles are classified as municipal waste in the EU. Waste policy in the EU follows what is known as the waste management hierarchy—prioritizing reduction of waste, followed by preparing waste for reuse, recycling (including composting), recovery (for energy), and finally disposal. The Waste Framework Directive (WFD) complies with the "Polluter pays principle" and "Extended producer responsibility." A comprehensive Circular Economy Package (CEP) amending the WFD was officially adopted on April 18, 2018, by European Parliament. The CEP aims to manage waste so as to reduce its concomitant risks. With this plan, increased resource efficiency is expected to bring economic benefits. The following measures will be implemented and impact the textile industry: • "Member States shall make use of adequate economic instruments to provide incentives for the application of the waste hierarchy." • Waste Prevention: "encourage the setting up of systems promoting reuse activities, including in particular for … textiles. …" • By 2025, the "preparing for re-use and the recycling of municipal waste shall be increased to a minimum of 60% by weight; By 2030, increase of the preparing for re-use and recycling target for municipal waste to 65%; Gradual limitation of the landfilling of municipal waste to 10% by 2030." *Opportunity: Funding and resources available to develop closed-loop systems; industry leadership can be a competitive advantage. Blockchain for closed-loop supply chain management.* *Challenge: Changing consumer behavior for disposing textiles.*	(European Commission 2015; 2016e)
Chemicals	Registration, evaluation, authorization, and restriction of chemicals (REACH) is the EU's regulation pertaining to chemical use. Users and importers of chemicals must adhere to requirements and register all chemical products. Applies to industrial processes within textile supply chains. In the early 2000s, the EU banned the *use* of a chemical, NPE, in textile manufacture *within its borders*. In 2015, an amendment to REACH *expanded the ban to imported textiles* containing NPE because it poses an "unacceptable risk" as an endocrine disruptor when it runs off into waterways. Effective January 2036, imported textiles cannot contain more than 1 ppm of NPE. *Challenge: Tracing upstream textile processing is not always possible in today's paradigm; penalties for noncompliance.* *Opportunity: Blockchain for supply chain management can store upstream processing information.*	(European Commission 2018b) (European Commission 2016a; Flynn, 2015).

APPENDIX 2 EU policies that impact the textile industry *(Continued)*

EU Policy Category	Description	Reference
Water	In 2000, the Water Framework Directive (WFD) was adopted to protect freshwater resources within the EU. Member states are responsible for monitoring and creating management plans for water basins to achieve "good status" by 2027. Substances on a "watchlist" have strict restrictions on their concentration limits due to the risks they pose. Certain persistent organic pollutants such as perfluorinated compounds and polybrominated flame retardants on this watchlist are used as coatings and flame retardants in textiles. Through the monitoring and management schemes established in the WFD, human pressures on the environment will be identified to recover costs in line with the polluter pays principle. *Challenge: Tracing upstream textile processing is not always possible in today's paradigm; penalties for noncompliance.* *Opportunity: Proactive water stewardship can be a competitive advantage.*	(European Commission 2016d; European Parliament 2017)
CSR Corporate social responsibility (CSR)	In 2014, a directive on non-financial reporting was passed, obligating companies with more than 500 employees to produce reports "containing information relating to at least environmental matters, social and employee-related matters, respect for human rights, anti-corruption and bribery matters … use of renewable and/or non-renewable energy, greenhouse gas emissions, water use and air pollution." In 2017, a Flagship Initiative was introduced to enforce mandatory due diligence in the garment industry in accord with OECD guidelines (not yet a law, but on policy radar). *Challenge: Reporting requirements can be costly, obtaining upstream information from supply chain can be difficult.* *Opportunity: Proactive industry leadership can be a competitive advantage. Blockchain for supply chain management can store aggregated supply chain CSR efforts.*	Binder
Labels	A 2011 regulation requires textiles to be labeled with their fiber composition. Does not require any additional information to be included on the label (such as country of origin or care instructions). A 2016 regulation states that all products labeled as organic (including organic cotton) imported into the EU or traded among member states must be registered in the TRACES database and accompanied by certificates of inspection. *Opportunity: Digital fiber composition labeling can be a competitive advantage and assist with closed-loop efforts. Requirement for certificates, registration, and provenance tracing are opportunities for smart contracts and blockchain.* *Challenge: Mechanisms for certifying product provenance are nascent.*	(European Commission 2011;2016c)
Data privacy/ cyber security EU GDPR	Effective May 25, 2018, new consumer data privacy laws went into effect, EU GDPR, obligating companies to proactively protect and obtain consent from individuals to collect and use their data. Asserts the notion that digital data is personal property. EU Cybersecurity Strategy adopted in 2013. In addition to security from malicious cyber-attacks and fraud prevention, the EU prioritizes leadership in industrial technology innovation e.g., cryptography and privacy by design (PbD). Security must be integrated as a functional requirement in IoT devices throughout the life cycle. *Challenge: Dynamic and serious security threats.* *Opportunity: Customers can be empowered by owning their own data and develop long-lasting relationships with retailers. Funding and resources available for blockchain solutions to security issues. Decentralized information management with blockchain.*	(European Commission 2017a; 2018a; Fabiano 2017)