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Towards circular economy in the textiles and clothing value chain through blockchain technology and IoT: A review

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Abstract

The textile and clothing industry sector has today a big environmental impact, not only due to the consumption of water and the use of toxic chemicals but also due to the increasing levels of textile waste. One way to reduce the problem is to circularise the, currently linear, textile and clothing value chain, by using discarded clothes as raw material for the production of new clothes, transforming it into a model of circular economy. This way, while reducing the need to produce new raw materials (e.g. cotton), the problem of textile waste produced is also reduced, thus contributing to a more sustainable industry. In this article, we review the current approaches for traceability in the textile and clothing value chain, and study a set of technologies we deem essential for promoting the circular economy in this value chain – namely, the blockchain technology – for registering activities on traceable items through the value chain, and the Internet of Things (IoT) technology, for easily identifying the traceable items' digital twins.

Keywords

Circular economy, traceability, sustainability, BPMN, blockchain, IoT, textiles and clothing value chain

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Introduction

Today, humanity faces, and is the main responsible for, climate change. Its current status is mainly due to deforestation and the burning of fossil fuels as a result of intense industrial and agricultural activity and transports. The Textiles and Clothing (T&C) sector is currently among the largest industries in the world and growing at an exponential rate. This growth is partly due to the so-called 'fast fashion', whose name is explained by the fact that the products are manufactured, consumed and disposed of and at a very fast pace. Besides the huge consumption of resources, there is also the use of low-quality insoluble dyes, use of products based on heavy metals, use of synthetic fabrics derived from fossil fuels and so on. In addition, with the desire to keep up with fashion trends, the pieces produced by fast fashion end up becoming disposed of in the trash in a few months. With fast fashion, consumers wear the same clothes less often and for less time, and brands discard (usually burn) clothes that are not sold, the so called 'dead stock'.

The T&C industry sector is, today, one of the most polluting in the world (Niinimaki et al., 2020). The use of chemicals in the textile manufacturing process happens during the 'wet process' phases such as dyeing, washing, printing and fabric finishing, which potentially use around '200 tonnes of water for every metric tonne of textiles produced'. Besides that, the entire sector is responsible for being one of the largest GHG (greenhouse gas) producers, and its environmental impact is present from the raw material (fibres) harvest/production until the final consumer (Choudhury, 2014).

The T&C industry sector has a high environmental and social impact, being one of the most polluting and water-consuming sectors, and is often associated with workplace abuses (Fletcher, 2014).

The T&C value chain is extremely long and complex, spanning the whole world and having its various stages of production taking place in different countries, and also including the distribution of intermediate and final items and retail sale to final consumers (Jacometti, 2019).

Due to global warming, our society is increasingly vigilant to sustainability issues, especially environmental and social related. In what concerns to T&C products, consumers tend to look for products from brands considered to be more sustainable. This

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trend drives brands to announce the use of new more environmentally friendly and socially fairer fabrics or production processes, among other things. Nevertheless, for the consumer to trust brands, it is necessary to create transparency in the whole T&C supply chain. It is important to know the environmental impact of a product's value chain and find a way to measure it (Muñoz-Torres et al., 2021). To do that, it is necessary to store information, regarding sustainability impacts, in each step along the supply chain.

One way to mitigate the harms that the T&C industry is causing in the environment is to engage in circular economy (CE). CE is an economic system based on a business model that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in the production/distribution and consumption process (Limata, 2019). CE implies the transformation of the linear T&C value chain into a circular one.

For knowing the environmental impact of every activity in the value chain, it is crucial to trace every relevant item in the value chain, namely, each lot of raw material; each lot of intermediate products, such as yarn or fabric; and each lot or item of produced garments. For this, a traceability platform is essential. The blockchain technology (BCT) is already being used as a decentralised database for traceability among business partners. In a blockchain, transactions are stored in chronological order, creating a permanent and tamperproof record that offers transparency, durability and process integration in supply chains (da Cruz and Cruz, 2020).

With a traceability platform, every traceable item has its traceability information stored in that platform, as its digital twin. Every traceable item must be connectable to its digital twin (the information in the platform), and the Internet of Things (IoT) offers an easy way to do it.

In this article, we review the state-of-the-art of using BCT to support a circular T&C value chain, in order to store information about relevant indicators needed to measure the sustainability of items and participants in the value chain. We also study the state-of-the-art for using IoT to collect information about those indicators, and to enable a digital twin that stores sustainability information, for each traceable item in the value chain.

This article is structured as follows. The next section briefly addresses the method used for the selection of literature being reviewed. The following section presents the T&C value chain; highlights some important concepts, such as traceability, digital twin and CE; and discusses aspects and motives for products' traceability, along with providing some arguments towards traceability for promoting CE. In the same section, existing platforms for traceability in the T&C value chain are also identified. Then, follows a section that describes the T&C manufacturing process, at some abstraction level, identifying the main manufacturing activities. The section establishes a value chain-wide inter-organisational business process model and closes the loop, circularising the value chain. The 'Blockchain-based solutions for CE and traceability' section briefly explains BCT and presents existing blockchain-based solutions for products' traceability and to support CE. Then, the 'IoT solutions for CE and traceability' section addresses the use of edge sensors and actuators for traceability in the sector of T&C. Finally, in the last section, conclusions are drawn and ideas for future work, on the traceability of the CE in the T&C sector, are presented.

Method

For this review, we have searched Google Scholar for a combination of terms such as 'traceability system', 'IoT-based traceability', 'Blockchain-based traceability', 'Circular Economy', 'Fashion' or 'Textile and Clothing' and have downloaded articles from databases such as Scopus, Elsevier and Web of Science, from the last 15 years. We have selected recent papers and their citations of relevance for further analysis.

These papers have been individually analysed according to the following alternative criteria:

- The article should focus on techniques for registering and globally accessing traceability information, either centralised or distributed database-based techniques, or blockchain-based techniques.
- The article should focus on IoT-based techniques for identifying the traceable item or getting world information (e.g. temperature, global positioning) about the item.
- General-topic and non-relevant articles should be excluded.

At the end, a total of 96 research items have been retained including mostly research articles, but also one MSc thesis and five technical reports.

The selected publications report the use of blockchain and/or IoT techniques for products' traceability.

CE and traceability in the T&C value chain

Nowadays, the T&C industry is indispensable due to people's well-being fundamental need of clothing and its value chain economic and employment contribution to today's society. Nevertheless, this sector, including the fashion industry, has a significant environmental footprint across its value chain, especially regarding to water consumption, pollution by chemical products, CO_2 emissions and huge waste (Manshoven et al., 2019; Niinimaki et al., 2020).

With the globalisation of markets, and the breaking of territorial, commercial and cultural barriers, the T&C value chain has undergone profound transformations, which have been affecting the labour market and re-configuring industrial and commercial organisations in countries around the world.

The T&C value chain

The value chain of the T&C industry has gone global (Global Value Chain) and, nowadays, from the production stages to the final consumer, it involves a lot of different companies, from different countries. This value chain, or different value chains, may involve the participation of industries in the areas of fibres and filaments, clothing, home linen, technical textiles and other suppliers (e.g. chemical inputs, machinery and equipment). Each of these industries can operate in different countries and continents, so it also involves distribution, transportation and storage companies.

The T&C sector includes the manufacturing of shirts, underwear, dresses, suits and other fashion and clothing items; curtains, towels, bed linen and other home and furnishing items; and ropes and nettings, parachutes, medical textiles and other industrial and technical textiles. These manufacturing processes involve many companies in different locations, with some of them producing final products to the end consumer, but with most of these companies producing some kind of intermediate products, such as fibres, yarns, woven or knitted fabrics, and dyed or printed fabrics.

The T&C value chain typically involves sub-processes for (Wadje, 2009):

- Spinning natural or polymer-based fibres into yarn;
- Weaving or knitting yarn into fabric;
- Dyeing and further processing and finishing the fabric for delivering to a manufacturer of textile products;
- Producing (e.g. designing, sewing) the final product (e.g. apparel, home textile, technical textile).

The production of these products, and of the fibres (e.g. cotton, wool) that they are made of, consume great amounts of land, water, energy, chemicals and fossil fuels. The environmental impact of the industry appears throughout the life cycle of a textile product (Jacometti, 2019). This sector is a major contributor to climate change, given its energy use and waste production and management. A sustainable approach is necessary for a textile system that would minimise the environmental and social impacts brought upon the planet while respecting its carrying capacity.

It is important to know the environmental impact of the value chains and find a way to measure it (Muñoz-Torres et al., 2021). Therefore, it is necessary to know and store information about each one of the steps in the value chain, allowing traceability, enabling the final consumer to be informed and assessing whether or not to buy the garment.

T&C traceability

Traceability mechanisms allow insights upon product items or lots through connecting data that were previously siloed. When we allocate a digital identity to materials at a lot or item level, and follow it through a value chain, we are able to capture information from primary production all the way through to its ultimate use and to its disposal or reuse in the future. As described in Bailey et al. (2016), Cruz et al. (2019) and Kraisintu and Zhang (2011), this brings advantages in:

- *Sustainability* – by gathering sustainability credentials and allowing primary stakeholders the opportunity to assess and report on their appointed suppliers' approach to social and environmental sustainability factors.
- *Efficiency* – by having a decentralised trusted platform, such as a blockchain, that can use smart contracts to track and automate transactions without the need for a centralised authority.
- *Engagement* – environmental-social responsibility is a big factor nowadays, regarding consumer etiquette, and having a transparent product–consumer connection between the company and its clients allows the consumers to have a more favourable opinion towards the product and brand itself.
- *Safety* – in case there is a threat to public health (e.g. the use of toxic paint), it allows a quick and effective recall of all the products involved, because the products involved are easily located.

Giannakis and Papadopoulos (2016) analysed different supply chain risks, including the T&C value chain, and mentioned the importance of traceability to identify and eliminate potential sustainability-related risks. Product authentication emerged as the second most influential factor towards traceability, owing to the issue of counterfeit products that make brands suffer huge economic losses. The authors also mentioned that the current solutions of RFID (Radio Frequency IDentification) tags are difficult to apply in a production system for traceability purposes because they are very hard to produce in a large quantity due to high costs and advanced programming. On the contrary, we have barcode and two-dimensional (2D) codes that are easy to reproduce but are also very easy to counterfeit or copy. A summary of a traceability implementation solution for the T&C supply chain is presented in Agrawal et al. (2018).

Digital twin

The idea behind the digital twin is to create a virtual replica, completely faithful to a physical object, so that this digital model can provide all important data and in all perspectives on the use of the product.

While the physical product is going through the T&C supply chain in its life cycle, the different phases and processes on which it goes through should be recorded accordingly on a data system. Therefore, a digital twin profile of the physical product is created to efficiently track and trace the desired asset alongside with its basic information such as product identification and product name (Huang et al., 2020). This provides the general idea of a digital twin of an asset which is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product or system to mirror the life of its corresponding twin (Tao et al., 2018). However, how does one link the physical and digital realm?

According to Tao et al. (2018), IoT technology can help collect data at any product stage with devices that can ensure seamless tracking and reveal an asset's full story. When paired with BCT, this information becomes immutable, private and transparent, when it comes to data sharing as well as asset-token digitisation, by providing token ownership that would act as a digital watermark, correspondent to physical ownership (Jacobovitz, 2016; Kim et al., 2018). So, every time an event (transaction) happens to a specific product, its life cycle data can be captured by the use of IoT devices and properly managed with the use of BCT. The digital twin plays an important role in the implementation of the CE and in the traceability of a product.

Circular economy

CE (or circularity) is a business model that heavily contributes to the transformation of industry for a more climate-neutral and planet-sustainable approach, delivering substantial material savings throughout the value chains and production processes, generating extra value and unlocking economic opportunities (Kirchherr et al., 2017; Korhonen et al., 2018). It is a restorative and regenerative industrial system designed to minimise waste production and maximise resource efficiency and ecological sustainability where the value of products, materials and resources is maintained in the economy for as long as possible (Geissdoerfer et al., 2017).

The circular mind-set's focus is on decoupling economic growth from resource consumption operating at a micro- and macro level. To accomplish this, alternatives to the take–make–dispose model must be found to replace the different aforementioned levels: products, companies and consumers at a micro level; cities, regions, nations and beyond at a macro level (Kirchherr et al., 2017).

Unlike the linear economy model (model of production and consumption) that has been used during the 20th century, a CE represents its opposite. While industries in the linear model harvest and extract materials for manufacturing products for consumers to buy, use and discard, the circular approach switches the 'end-of-life' idea with restoration and recycling, together with the use of renewable energy and other actions to promote a self-sustainable functioning (Ellen MacArthur Foundation, 2013).

The T&C industry's current linear economy/take-make-dispose model is the root cause of the industry's environmental problems and economic value loss, making it one of the most polluting and resource-intensive production and consumption systems, especially in the production and use phase (Manshoven et al., 2019). It has substantial limits and does not appear to be able to attain the sustainable development goals that now dominate the agenda of policymakers at a global level. Increasing attention is therefore placed on the development of policies that allow a transition to a CE model (Jacometti, 2019). A more circular and sustainable textile system could contribute to the achievement of both European Union (EU) and global goals. In the EU, it would contribute to economic growth and job creation, as well as to meeting the aims of the CE and a number of climate, environmental and waste targets (Manshoven et al., 2019).

Solutions for traceability and CE in the T&C value chain

With the globalisation of supply chains, traceability, meaning the capability of tracking a product, is getting special attention, especially in food supply chains, because of public health reasons. In the T&C supply chain, it is also necessary to be able to track products, namely, knowing the origin and location of each product, to ensure the authenticity of a product's origin avoiding forgeries. Traceability is currently seen as synonymous of transparency in the value chains (da Cruz and Cruz, 2020).

Some platforms have been proposed for traceability in T&C value chain; some of them are presented next and summarised in Table 1.

Agrawal et al. proposed a blockchain-based traceability framework for the textile industry. Through a simulation-based demonstration of the used distributed ledger configuration and its operator's interaction, the authors provided a structural solution for its use case and applicability while maintaining data safety and trust among the value chain operators (Agrawal et al., 2021).

Agrawal et al. (2018) proposed a traceability solution for the T&C industry. The proposed system is based on Quick Response (QR) Code tags mapped with a secure code to provide an extra layer of authenticity and verification to fight the vulnerability of the sector to counterfeit products. These tags should be lasting enough until the user decides to recycle, making it optimal for a CE model.

Kumar et al. (2017) propose a system based on RDBMS (Relational DataBase Management Systems) and XML (eXtensible Markup Language) to capture data for the purpose of tracing a textile product's traceability within an operator of the supply chain or a full inter-actor traceability.

Fu et al. (2018) propose a blockchain-based emissions trading system, with the use of an emission link to evaluate carbon emission standards for a specific product in the fashion and apparel manufacturing industry. Although not built for traceability purposes, the system is a sustainability forward project integrated into the Industry 4.0 paradigm that measures how much of an environmental impact a certain clothing asset has had and suggests solutions to the operators for compensating carbon emissions of that same product.

Bullon Pérez et al. (2020) analyse how the use of BCT can help authenticate actors and products of the T&C supply chain and trace products back to their origin. Using a case study of a woman's shirt, they concluded that the use of a permissioned and open distributed ledger to store important data from the manufacturing processes' transactions would be beneficial for the end goal of textile traceability.

The T&C value chain: A generic circular business process model

In this section, we are proposing a new generic integrated business process model to represent the CE of the T&C industry. The

Table 1. Solutions for traceability and circular economy in the T&C value chain.

	Blockchain-based framework for supply chain traceability	A secured tag for implementation of traceability in textile and clothing supply chain	Developing a framework for traceability implementation in the textile supply chain	Blockchain enhanced emission trading framework in fashion apparel manufacturing industry	Traceability of ready-to-wear clothing through blockchain technology
Technology	Blockchain	QR Code & Data Server	RDBMS & XML	Blockchain	Permissioned Blockchain
Circular economy optimisation	X	√	X	√	√
Traceability	√	√	√	X	√
IoT integration	√	√	√	X	√
B2B/B2C apps	B2B	B2C	B2B + B2C	B2B2C	B2B2C
Features	N/A	QR Secure Counterfeit Code	N/A	Multi-operator carbon emission coverage & Industry 4.0 compliant	N/A
References	Agrawal et al. (2021)	Agrawal et al. (2018)	Kumar et al. (2017)	Fu et al. (2018)	Bullón Pérez et al. (2020)

T&C: textiles and clothing; QR: quick response; RDBMS: Relational DataBase Management Systems; XML: eXtensible Markup Language; IoT: Internet of Things; B2B: Business to Business; B2C: Business to Consumer; B2B2C: Business to Business to Consumer; N/A: not available.

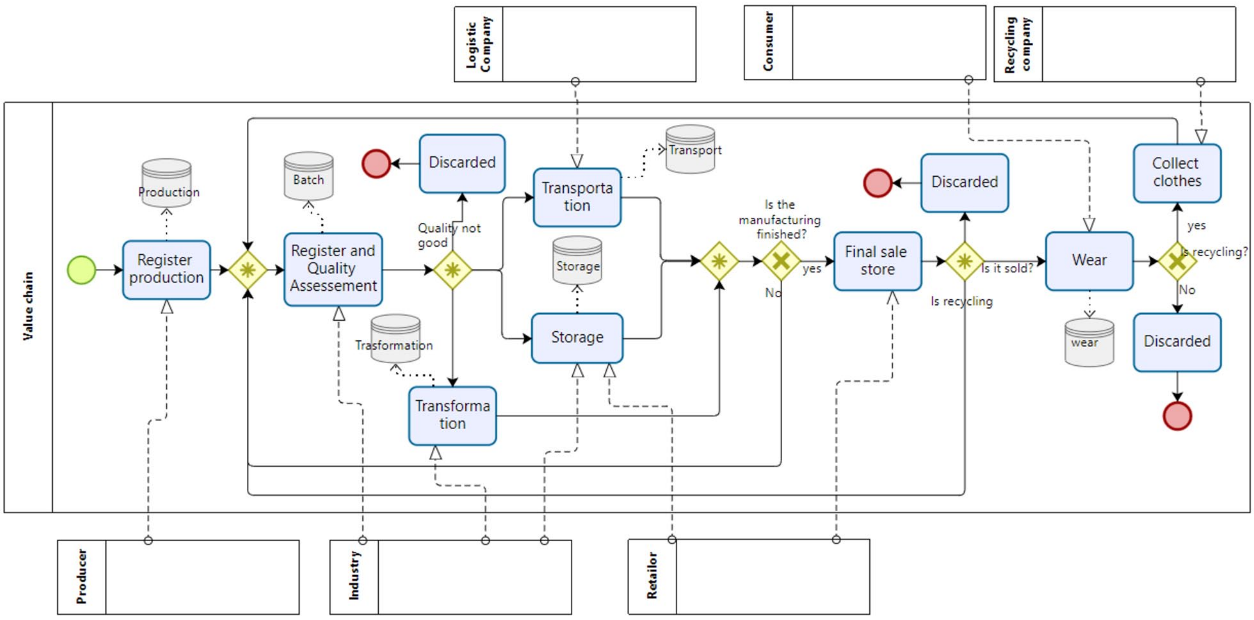

Figure 1. Generic integrated circular business process model for the T&C value chain.

business process model, represented in Figure 1, is using BPMN (Business Process Model and Notation) language mostly because it is a standard and a language easy to understand by everyone involved in the project. The presented business process model abstracts all activities and companies involved in the value chain.

As stated earlier, the fashion and textile supply chain from production to the final consumer can involve a lot of different companies and, in most cases, based in different countries. Each country has its own culture, traditions and laws. As a consequence, what is legally and socially well accepted in one country may not be in another. That is why the final consumer, and each participant in the value chain, must have access to all the information about what goes on at each stage of the process, in order to be able to evaluate according to their own standards.

In the T&C supply chain, there are, typically, four main types of participants involved, which are Producers, Industry, Logistic companies and Retailers. Each one of these participants is represented as external participant in the business process model in Figure 1.

- The ‘Producer’ external participant represents the producer/farmer of any type of fibre. There are several types of fibres from various sources: natural fibres of agricultural origin such as cotton, wool, silk and linen; fibres of mineral origin such as asbestos; and synthetic fibres of petrochemical origin such as polyester and nylon.
- The ‘Industry’ external participant represents any type of transformation industry, like industries for spinning, weaving, knitting, warping, sewing and dyeing.

- The 'Logistic company' external participant represents any type of storage and/or transportation company (it may involve boats, trains, trucks, aeroplanes or others).
- The 'Retailer' external participant represents any type of retailer, such as a seller of a final piece (e.g. a t-shirt) or it can represent the seller of an intermediate item such as fabric.

Each participant must provide information about their participation in the value chain and must provide all the detailed information of all necessary indicators about the performed activities (production, transformation, transportation, storage, etc.).

As mentioned before, for the T&C value chain to become more environmentally friendly, avoiding waste, reducing water consumption and so on, its business model needs to be circularised, by closing the loop of the currently linear model. For this to happen, the final consumer has a crucial role, by adhering to the CE. In order to portray the CE of T&C, it becomes necessary to represent, in the business model, the final consumer and also a new player that is the recycling company. Both are represented as external participants in Figure 1.

- The 'Consumer' external participant represents the final consumer, which becomes part of the value chain when recycling the clothes instead of discarding them.
- The 'Recycling company' external participant represents a company responsible for collecting textile and clothing items for recycling, making them re-enter in the value chain and closing the loop.

New types of industries may emerge in the value chain, for example, companies that actually recycle items, but they are already represented by the 'Industry' external participant.

The business process model in Figure 1 represents the main value chain activities at a high abstraction level. Each of these activities may represent a sub-process, meaning that the activity may be further decomposed in other activities (tasks) being executed internally to the company responsible for executing the sub-process activity.

Usually, the value chain starts with the production of fibre, represented in the first activity of the process (activity 'Register production' in Figure 1). The production information must be stored. These fibres will undergo various transformations (spinning, weaving, warping, sewing, etc.) and can be transported and stored several times throughout the value chain process, as represented in Figure 1. Each transformation can be done in a specific company, requiring transportation and probably storing between each activity. However, some companies can perform several transformations in the same facilities. As represented in Figure 1, usually, after executing one of these activities, the product quality is checked and if it is not acceptable, the product is discarded (or re-entering in the cycle contributing to the CE).

Some of these activities give rise to new products (e.g. yarn gives rise to fabric) and a new product lot is registered. After the internal manufacturing cycle is finished, the final piece will be sold to the final consumer to wear. According to Niinimaki et al. (2020), about 30% of the clothes are never sold. These clothes are usually burned, but instead, these clothes can be recycled, re-entering in the cycle, contributing this way to close the loop.

After wearing a garment, preferably many times, the end consumer is responsible for making the garment re-enter the cycle, by choosing to recycle (decision represented by the last gateway in Figure 1). The item to be recycled will then be collected and selected to be transformed to new raw material for new items of clothing. This way, among other advantages, waste is avoided and water consumption in the cultivation of new fibres is reduced, better preserving the environment.

Blockchain-based solutions for CE and traceability

When it comes to the implementation of traceability systems, especially in a CE model, blockchain is one of the best technologies that can tackle the various challenges that are posed in the T&C value chain in a Business to Business (B2B) domain (Agrawal et al., 2021). This distributed ledger technology (DLT) is getting increasing attention as a secure data management solution. Ever since the introduction of Bitcoin in 2008 (Nakamoto, 2008), the science behind blockchain has been applied to different commercial scenarios, including value and supply chain cases (Caro et al., 2018; Rejeb, 2018; Tian, 2017). However, there is almost no use of the BCT in the T&C value chain. The adoption of blockchain would be useful, as it provides compliance, transparency, tracking, tracing, error reduction, payment processing and many other advantages (Tapscott and Tapscott, 2017). A blockchain-based system is capable of safely recording important data about operations along the entire value chain inter-organisational process.

BCT provides transparency, traceability and security to transactions, real-time data and smart contracts to suit the needs of its users (Nandi et al., 2021) and may integrate with other areas, such as Big Data, artificial intelligence (AI), IoT, cloud computing and more.

After briefly presenting BCT and BCT-related concepts, this section focuses on the survey of BCT solutions for CE and Traceability, especially in the T&C value chain.

The BCT

BCT is a subset of DLT and thus, by definition, a blockchain is considered to be a distributed database that allows its participants (blockchain nodes) to store and share information in the form of blocks in real time and in a secure manner (Fu et al., 2018; Lam and LEI, 2019; Wang et al., 2019). Each of these blocks has a link to the previous block, hence the 'chain'. In other words, BCT is an open ledger that captures the transactions between two or more parties in a permanent and verifiable way (Lin and Liao, 2017).

The following subsections describe the four key concepts and components of the BCT, that is, DLT, types of permissions, smart contracts and consensus protocols (Agrawal et al., 2021; Gupta, 2020).

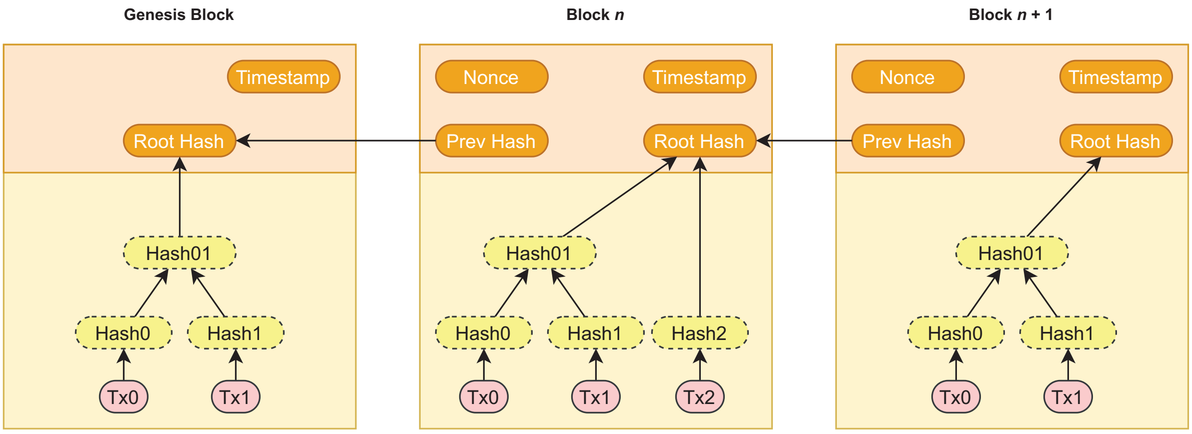

Figure 2. Block and blockchain structure.
Source: Adapted from Nakamoto (2008).

Distributed ledger technology. The same way a typical ledger records transactions in a double-entry book, in a blockchain ledger, which is shared between the authorised nodes, transactions between nodes are recorded. This ledger is permanently shared among the nodes, making it a distributed ledger (Grecuccio et al., 2020).

At the basis of a blockchain is a block, as shown in Figure 2. A block is composed of a block header and a block body. The header data consist of the following attributes (Huang et al., 2020; Wang et al., 2018):

1. Block version indicates the set of validation rules to follow for that specific block;
2. Root Hash represents the 256-bit hash value of the Merkle Tree root of transactions;
3. Prev Hash is the Root Hash of the previous block in the chain;
4. A Timestamp value corresponds to the date and time of the block creation;
5. The nBits field is a difficulty parameter/hashing target in a compact format;
6. Nonce stands for ‘number only used once’, which is a random number associated with the ‘Prev Hash’, ‘Timestamp’ and ‘Root Hash’, used to solve a mathematical puzzle for creating blocks.

By including the ‘Root Hash’ of the previous block in the header of a block, the blockchain is implemented in a linked list structure which provides the chain architecture formed between the blocks. The first block of a blockchain is called the ‘Genesis Block’, and it does not have the ‘Prev Hash’ attribute since there is no previous block to the first one.

The block body contains information regarding the transactions, specifically a transaction counter and the remaining Merkle Tree components. A Merkle Tree is usually a binary tree where each of its nodes is acyclically connected, directly or indirectly. The tree’s structure can be hierarchically classified into ‘Root’, ‘Internal Nodes’ and ‘Leaves’. Since the ‘Root’ hash is located in the block header, the rest of the nodes, which contain the hash pointer data to their children, are present in the block body (Bailey and Sankagiri, 2021; Bullón Pérez et al., 2020; Wang et al., 2018). The leaf nodes have data regarding the valid transactions within the network and do not have predecessor nodes, since their creation is inherently based on whether there are new transactions or not. The internal nodes, however, are the result of a hash function concatenating its two parent nodes and its single child node is used in the following hashing, iterating through the internal nodes successively until the root hash/node has two predecessors and no children (Bullón Pérez et al., 2020). This method allows for data storage efficiency because there is no need to store the entire block’s data to maintain data integrity and blockchain validation so, when the transactions are buried under enough blocks, the interior branches do not need to be stored (Nakamoto, 2008). The maximum number of transactions that a block can store is dependent on the block size and the transaction size as well (Wang et al., 2018).

A transaction is typically just the exchange of goods or services, whether monetary or not. In the case of the pioneer Bitcoin blockchain, it is a monetary transaction where a value is sent from one address to another by ‘digitally signing a hash of the previous transaction and the public key of the next owner and adding these to the end of the coin’, coin meaning transaction (Tx) data in this context (Nakamoto, 2008). But there are many cases of applicability where the transactions do not involve anything financial such as contract records, sensor data records and others (Lin and Liao, 2017). Within database systems, including most blockchains, a transaction corresponds to a persisted modification of data as the result of an operation. In a traceability system, a transaction may be seen as a standard template to record product life cycle data of digital twins. In a blockchain, these types of transaction are handled through smart contracts, as we will see below.

The data to be persisted in a transaction are encrypted with hashing functions, which are mathematical algorithms that transcribe variable data into a binary block with a fixed size, also called the ‘hash’ or ‘digest’ (Menezes et al., 1996; e.g. SHA256 – 256 bits SHA). Each of these algorithms work as a one-sided function that is not feasible to invert, as the slightest change to the function’s input is enough to change the resulting output through an avalanche effect on the output bits.

The digital signatures used in these transactions are a set of data that provides authenticity to a document's ownership, guaranteeing authorship based on the signer and the document being signed, unlike the casual handwritten signatures. Today, digital signatures are created through the RSA (Rivest–Shamir–Adleman) algorithm or by elliptic curve algorithms like ECDSA (Elliptic Curve Digital Signature Algorithm; Bullón Pérez et al., 2020).

Types of permissions. Blockchains can have different properties, depending on their three main types (Agrawal et al., 2021; Gupta, 2020):

- *Public blockchains* are open, where anyone can join and participate in it. These types of blockchains are truly decentralised, in the sense that no particular node controls the whole or part of a network (Bullón Pérez et al., 2020);
- *Consortium blockchains'* nodes have permissioned authority and are usually seen in partially decentralised B2B scenarios, where data can be public or restricted (Lin and Liao, 2017);
- *Private blockchains* put in place restrictions on participants' roles, and the nodes require adequate permission to join and perform transactions.

The more nodes a network has, the more decentralised it is, and the higher is its guarantee of immutability. However, a high number of nodes will decrease the network's efficiency for consensus (Wang et al., 2018). Blockchains are also categorised by their consensus process type which can be permissionless or permissioned. Public blockchains are open for anyone to join so they are permissionless. Any blockchain that has any node participation restriction falls under the permissioned type (Lam and LEI, 2019; Lin and Liao, 2017).

A different aspect of blockchain criteria is its availability for reading purposes, where blockchains can be categorised as open or closed. When combined with the consensus process type, a blockchain can have a more flexible access control – (public, consortium, private) and (open, closed) (Bullón Pérez et al., 2020).

Smart contracts. Assuming that the consensus protocol is secure, a blockchain can be thought of as a decentralised conceptual party that can be trusted for correctness and availability, but not for privacy (Kosba et al., 2016). Smart contracts, as first defined by Nick Szabo (1997), are computerised transaction protocols that execute the terms of a contract 'that control users' digital assets, formulating the participants' rights and obligations' (Lin and Liao, 2017). It can be seen as a complex if–then statement that is executed if and only if a set of conditions is met (Grecuccio et al., 2020). They are programmable logic and/or rules with strict implementation conditions that define a data structure and its operations, just like classes in an object-oriented context (Agrawal et al., 2021; Watanabe et al., 2016), and are stored in the blockchain, where they are automatically executed alongside transactions without human intervention, bringing convenience among participant corporations (Gupta, 2020; Kim et al., 2018; Wang et al., 2018). When a smart contract is deployed on a blockchain network, it cannot be changed, and it will always execute by the defined rules (Wang et al., 2019).

The pseudocode shown in Algorithm 1 represents a mock smart contract to output a product's data, including its traceability information (Bullón Pérez et al., 2020).

Algorithm 1: Product traceability smart contract pseudocode, adapted from Bullón Pérez et al. (2020)

```
Input: ProductID
Output: Product and traceability data
For each ith block in the blockchain do
    if ProductID ⊂ ith block then
        Retrieve block number;
        Retrieve block header;
        Hash from ith block ← Hash from
          (i − 1)th block|| Header block;
        Retrieve information from the block
          transaction;
    else
        Hash from ith block ← Hash from
          (i − 1)th block || Header block;
    end
end
```

Consensus protocols. In a blockchain distributed ledger, there is no central authority to effectively make sure that the nodes' ledgers are equal throughout the network. To tackle this issue, transactions can be verified and committed to the ledger through a consensus protocol, ensuring ledger consistency throughout all nodes in a blockchain (Gupta, 2020; Wang et al., 2018). These mechanisms guarantee that all blockchain nodes have to agree in the same transactions' block and can make sure that the latest block was correctly added to the chain, ensuring that the data stored by a node are the same for every node (Lin and Liao, 2017).

For public blockchains, like Bitcoin, the Proof-of-Work (PoW) consensus mechanism is used, and it makes the Bitcoin blockchain highly secured from attacks. PoW allows the miners (pool of processing nodes) to compete with each other to find the correct hash of the new block and earn a reward, in the form of Bitcoins, by calculating the 'Nonce'. As the difficulty of the block ('nBits') increases, the harder it is to solve the 'Nonce' problem (Agrawal et al., 2021).

There are several other consensus algorithms/mechanisms optimised for different blockchain types, for energy saving, and to tackle future concerns, like quantum computing. Some of the most popular ones used in several blockchain projects include the Proof-of-Stake (PoS), Proof-of-Elapsed Time (PoET), Proof-of-Authority (PoA) and practical Byzantine Fault Tolerance (pBFT) (Wang et al., 2018).

Blockchain-based solutions for traceability and CE

Nowadays, blockchain is being seen as one of the technologies that better fits the needs of traceability in the supply chains (da Cruz and Cruz, 2020). This technology is being used to implement traceability in many areas including agriculture and food

Table 2. Blockchain-based solutions for traceability.

		Blockchain and IoT: food-chain traceability	Blockchain-based traceability of carbon footprint	Blockchain Medledger	Electronic open-source traceability of wood	Harvest Network
Blockchain	Platform	Quadrans (Ethereum-based)	Ethereum	Hyperledger Fabric	Azure Blockchain Workbench (Ethereum)	Ethereum
	Consensus process	Permissioned	Permissionless	Permissioned	Permissionless	Permissionless
Circular economy optimisation		X	X	X	X	X
IoT integration		√	X	X	√	√
Application areas (use cases)		Food and cold chain	Food carbon footprint	Drug traceability system for counterfeit drugs in pharmaceutical industry	Wood supply chain	Food supply chain
B2B/B2C apps		B2B + B2C	B2B + B2C	B2B + B2C	B2B2C	B2B + B2C
Features		On-device signing, IoT RPC server	React DApp, NodeJS API and B2B2C Solidity smart contracts	Decentralised data storage (IPFS, Swarm and Filecoin)	Cloud deployment, REST API, Off-chain SQL server storage, Azure IoT Hub integration	ERC-721 NFT standard, asset tokenisation, GS1 integration, analytic dashboard
References		Grecuccio et al. (2020)	da Cruz et al. (2020)	Uddin (2021)	Figorilli et al. (2018)	Kim et al. (2018)

B2B: Business to Business; B2C: Business to Consumer; B2B2C: Business to Business to Consumer; IoT: Internet of Things; API: application programming interface; REST: representational state transfer RPC: Remote Procedure Call; NFT: Non-fungible Token; IPFS: Interplanetary File System.

supply chains, as is the case of Tian (2017), Biswas et al. (2017), Tan et al. (2018), Caro et al. (2018), Cruz and da Cruz (2020) and Alves et al. (2021); in wood supply chains as is the case of Figorilli et al. (2018); in textile supply chains as is the case of Agrawal et al. (2021); and many other areas.

The proof-of-concept system proposed in Grecuccio et al. (2020) promotes interactivity between edge IoT devices and an Ethereum blockchain in a food-chain traceability scenario. The specific use case of a fish products' cold supply chain is suitable for IoT integration by capturing temperature sensor data for quality assessment needs.

da Cruz et al. (2020) present a distributed Ethereum-based solution for a carbon footprint traceability decentralised application.

As mentioned before, Mueen Uddin proposes a track and trace blockchain-based solution – Medledger – for transactions' registration for traceability in the pharmaceutical drugs supply chain (Uddin, 2021). Enabled by the Hyperledger Fabric blockchain platform, the Medledger minimises the need of a central entity/authority and also integrates other decentralised systems like distributed data storage (IPFS: Interplanetary File System, Swarm & Filecoin).

Figorilli et al. (2018) are using BCT to implement traceability in wood supply chain. The system is based on RFID sensors and open-source technology. The system is able to trace wood from the forest (marking and cutting trees) until the final consumer, passing through activities such as stacking, transport, sawmill processing, production and selling.

With the food supply chain in mind, Kim et al. (2018) present the Harvest Network which is a blueprint for a food traceability application, providing a distributed ledger accessible to every operator within the value chain. The Harvest Network includes the use of an ERC-721 non-fungible token standard for asset digitisation as well as GS1 product standards integration.

Alves et al. (2021) propose a blockchain-based platform to implement traceability in PDO (Protected Designation of Origin)/PGI (Protected Geographical Indication)/TSG (Traditional Specialty Guaranteed) products. The platform has two main goals: the first one is to avoid forgeries and the second one is to provide information to the consumer about when, by who and where the product (and raw materials) are produced or manufactured. Table 2 summarises these approaches.

With the growth of blockchain usage for traceability purposes, several platforms emerged from different companies to provide the solutions needed by supply chain entities to apply this technology for their benefits. Table 3 gathers several platforms that use blockchain for the traceability and CE and compares them in aspects such as blockchain platform used, IoT, use cases, among others.

Everledger stands out as one of the main providers of these types of services when it comes to blockchain-based traceability. The Everledger Platform uses enterprise-grade blockchain services for Hyperledger Fabric powered by IBM. There are multiple and useful features for supply chain participants included in the Everledger Platform v1.3 (Everledger, 2020) such as:

- IoT integration through real time with sensors, intelligent labelling and tamper detection. This intelligent labelling is achieved by RFID, near-field communication (NFC), synthetic DNA markers, QR codes and other identifiers within an

Table 3. Blockchain-based solutions for circular economy.

		Everledger	Circularise	VeChain	Waltonchain	Ambrosus
Blockchain	Platform	Hyperledger Fabric	Ethereum	VeChainThor	Go Ethereum	Ambrosus
	Consensus process	Permissioned	Permissionless	Permissionless	Permissionless	Permissioned
Circular economy optimisation		√	√	N/A	N/A	N/A
IoT integration		√	N/A	√	√	√
Application areas (use cases)		Diamonds, electric vehicle batteries	Plastics	Anti-counterfeit, supply chain management, food safety, intellectual property	Food traceability, clothing traceability	Pharmaceutical industry
B2B/B2C apps		B2B + B2C	N/A	N/A	N/A	B2C (programming interface)
Features		Analytics, Brand and mobile support	ZKP Smart Questioning, CIRcoin cryptocurrency	Improved proof-of-authority consensus, Two token system (VET + VTHO), VTHO smart contracts	Fabric and solidity smart contracts, custom WPoC (PoW + PoS + PoL)	IPFS distribution, sensor network optimisation, proof-of-authority consensus
References		Lu and Xu (2017), Everledger (2020), Clincy and Shahriar (2019)	Licht et al. (2016), Bolier (2018)	VeChain Foundation (2019)	Waltonchain (2018)	Ambrosus (2018), ambrosus.io

N/A: not available; IoT: Internet of Things; B2B: Business to Business; B2C: Business to Consumer; ZKP: zero-knowledge proof; WPoC: Waltonchain proof of contribution; PoW: Proof-of-Work; PoS: Proof-of-Stake PoL: Proof-of-Lucky-Id; VET: VeChain's Token; VTHO: VeChain Thor Energy - Token for paying transactions in the VeChain network; IPFS: Interplanetary File System..

object's label or packaging to authenticate objects with interaction with a variety of devices;

- User access control via Access Control Layer (ACL) to specify which users or system processes are granted access to objects, as well as what operations are allowed with ISO27001-compliant standards-based mechanisms for authentication services;
- Analytics and reporting by displaying interactive graphs and visualisations of different types of metrics and data;
- Brand and mobile support for white-labelled progressive web applications (PWAs) with the NFC/QR service from Everledger, and integrated WordPress sites, using React with a suite of third-party plug-ins and integration partners;
- A service infrastructure through RESTful API DLs (Representational State Transfer Application Programming Interface Description Languages) to allow uploading data to the Everledger platform;
- AI capabilities, mainly with advanced optical character recognition (OCR);
- On-demand traceability records by showcasing an asset's provenance record, event and transaction history, related certifications, warranty information and more, alongside industry compliance that can be evidenced by organisations;
- Digital twin features of supply chain asset(s). This involves unique identity (UID) association with the physical product.

Circularise is a CE-focused company capable of providing transparency to global supply chains and help them move towards a CE. With its main focus on the plastics value chain, it works with Ethereum BCT and has Solidity smart contracts at the core of its protocol (Licht et al., 2016). The system that they call CIRbase focuses on accelerating the transition of companies into a CE, by helping with the exchange of information between parties while maintaining the competitive nature that these may have. By validating the supply chain operator's encrypted material information and applying a smart questioning system powered by zero-knowledge proof (ZKP) technology and ring signatures for anonymity, it is possible to have a fully trusted platform where its members provide the needed data. However, it is also important that these members are willing to accept the norm of this type of information sharing protocols (Bolier, 2018).

Some frameworks are solutions under which a developer can create their own traceability solution. These frameworks are also summarised in Table 3 and are briefly described next.

VeChain is a Singapore-based company that defines its existence to disrupt the conventional supply chain model. Highly integrable with IoT devices like RFID, NFC and/or QR Code, the VeChainThor blockchain provides its users with two native cryptocurrencies to handle the network. VET is used for economic purposes, and VTHO is used for smart contracts execution (VeChain Foundation, 2019).

The Waltonchain uses RFID chips to track and trace products in the supply chain, just like VeChain. Their focus is on combining BCT with IoT and RFID, specifically a device that can generate its own hash and upload it to the ledger through an RFID reader. The applicability of this ecosystem in a supply chain use case is beneficial, allowing tracking and traceability throughout the entire value chain (Waltonchain, 2018).

Finally, the Ambrosus protocol is specialised in specific supply chain projects, such as pharmaceutical industries. With its proprietary blockchain with the same name, the company uses a PoA consensus mechanism to validate its transactions and the ledger is optimised for interconnection with several other devices like sensors and/or Enterprise Resource Planning (ERP) systems (Ambrosus, 2018; ambrosus.io).

Benefits of BCT implementation on a T&C value chain

The aforementioned BCT components provide the following key features and characteristics (Gupta, 2020; Lin and Liao, 2017; Wang et al., 2018):

- *Decentralisation* is achieved by running the network in a distributed peer-to-peer (P2P) topology. Any transaction in the blockchain network can be conducted between any two peers without the need of authentication by a central agency. This also reduces central server costs and performance bottlenecks.
- *Immutability* is an intrinsic trait of BCT due to the near impossibility of changing previously registered data, other than a 51% attack or the uncertain future capabilities of quantum computing.
- *Pseudonymity*, although some authors agree on anonymity instead, is an advantage for avoiding identity exposure in the network through encrypted addresses.
- *Auditability* for traceability purposes is a key factor in BCT due to its timestamp server recording the transactions in chronological order, providing greater provenance capabilities.
- *Autonomy* is another blockchain benefit. Every node in the system can safely manage data, so the idea is to trust a system instead of a single person with no one to intervene in it.
- *Transparency* is present in these distributed ledger systems because any node can consult the data records. More so, several blockchains are open source, allowing for transparency within the platform itself.

In a value chain context, the blockchain operates as a decentralised transaction environment, with participating members that share product lots' traceability data and concurrently agree to authenticate the true state of shared data. In a blockchain environment, data are stored as transactions in blocks, which are chained in a shared immutable ledger as they continue to grow. At all times, the data are transparently accessible to the value chain participants. Such a collaborated effort for information sharing improves traceability in both global and local supply chain scenarios (Nandi et al., 2021).

Through the analysis of DLT potential, Lam and LEI (2019) mention several blockchain applications, and their benefits, in the textile and apparel industry. Cases like the prevention of fake product purchase, where the digital asset transactions are immutable from manufacturer to costumer, maintaining the product's This is the case, for instance, of preventing the purchase of fake products, where the digital asset transactions are immutable from manufacturer to costumer, enabling the product's authenticity verification. Track and trace capabilities, through unchangeable transactional data, are also obtained. The incorporation of Health, Safety and Environmental (HSE) compliance information could be updated by certified auditors, subjecting compliance conditions into the value chain's contracts. Increased trust between operators would be attained based on the fact that no specific organisation provides trust, instead the technology itself creates the trust by default.

Challenges of BCT implementation on a T&C value chain

Although providing several benefits, as seen before, the BCT also raises some challenges. The main issues being (Agbo and Mahmoud, 2019; Zhang and Lee, 2020):

- *Power consumption*: Some BCTs, as seen earlier, have compute-intensive consensus mechanisms. These mechanisms, such as the PoW, carry an enormous carbon footprint, because of the energy spent by the miners on calculating the 'Nonce'. Blockchains such as Bitcoin or Ethereum have this drawback. Despite this, there are consensus mechanisms that do not depend on power consumption nor on cryptocurrencies, such as the ones available for Hyperledger Fabric.
- *Transaction cost*: Public blockchains are typically based on rewarding the miners for their work in achieving consensus. These kinds of blockchains are associated to cryptocurrencies, which are created in committing transactions. This has, consequently, a high transaction cost.
- *Security*: Public blockchains do not support users with disparate permissions nor private transactions. Nevertheless, they offer a great resistance to data tampering. Blockchains based on the PoW or PoS consensus mechanisms may only be attacked if half plus one of their nodes coordinate their efforts for an attack operation. Private or consortium blockchains typically support users with different permissions and private channels. This enables better security mechanisms and private transactions, even if the associated consensus mechanisms may have less tolerance to attacks, such as pBFT.
- *Scalability*: A great number of blockchain miners increases security but, together with a growing number of transactions, increases each transaction time, reducing the transaction throughput (transactions per second (TPS)).

For T&C value chain implementation purposes, there are some specifications on which properties are best suited for that domain. Since all the value chain operators within a textile or clothing product's life cycle can create a consortium, the most optimal blockchain type is a consortium blockchain (Huang et al., 2020), and thus, the consensus protocol should be optimised for a consortium type such as the pBFT (Wang et al., 2018). When the tangible product is going through its life cycle processes, any of these changes can be represented in a transaction with or without the need of ownership transfer (Huang et al., 2020).

IoT solutions for CE and traceability

Nowadays, IoT technologies represent not only objects that can communicate, but rather a complete ecosystem that is far beyond connectivity, embracing distinct technologies that run in a higher abstraction layer and can be used to share resources and intelligence, such as IoT platforms available in IBM Cloud, Microsoft Azure and others. Currently, the use of AI within the IoT ecosystem is also gaining a lot of attention, due to the advent of edge computing, which presents a huge potential to apply, not only machine learning techniques at the edge but also computer vision, fuzzy logic and natural language interfacing. This edge computing convergence has been used in IoT ecosystems to efficiently integrate heterogeneous data sources with distributed computing to reduce data dimension and thus help to face the exponential data growth that characterises the overall IoT ecosystem.

As seen in the previous sections, products' traceability is crucial in many production chains such as food (Pérez et al., 2020; Tsang et al., 2019; Wang and Li, 2019), manufacturing (Cao et al., 2020; Massaro et al., 2019; Prato et al., 2019), farming (Banerjee et al., 2020; Chun-Ting et al., 2020) and pharmaceutical industries (Botcha et al., 2019). In addition, the integration of IoT and DLT (cf. Cao et al., 2020; Chun-Ting et al., 2020; Gong et al., 2020) increases supply chains' productivity and accountability, due to DLT's known security features mentioned before.

The use of low-cost sensors for monitoring has had a recurring presence in several IoT applications, and product traceability is no exception (Prato et al., 2019). For example, both food (Alfian et al., 2020; Pérez et al., 2020; Tsang et al., 2019; Wang and Li, 2019) and pharmaceutical (Botcha et al., 2019) value chains need extra attention regarding production traceability, which may include additional sensor data, such as the variations in temperature and humidity that products or goods face during the production, preparation or distribution stages (Alfian et al., 2020), to avoid damage or contamination at any point of the value chain. In this case, traceability systems provide extra sensor-based information that is collected along the value chain to guarantee the quality and safety of food or drugs, respectively.

This section focuses on the survey of IoT Solutions for CE and Traceability in the T&C value chain. First, an IoT traceability model is put forward and then several potential IoT traceability technologies are introduced and compared. Then some real-world implementations are discussed, and finally main challenges and future directions are pointed out.

IoT traceability model

Figure 3 presents a general IoT Traceability Model that includes not only the production and supply chains but also the business side (operations and strategy). The proposed model will be followed in this document and includes six main stages that have been identified, having in mind the T&C value chain:

1. *Create*: includes the production of the production textile/clothing goods and the integration of Sensors/Tags that will enable IoT traceability along the value chain;

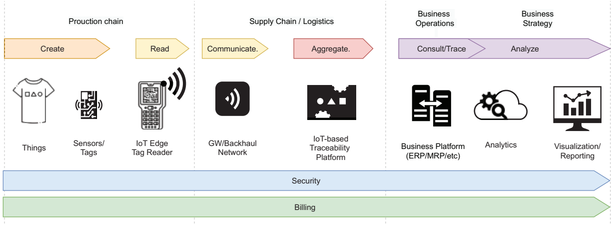

Figure 3. Generic IoT traceability model for the textile and clothing value chain.

2. *Read*: read sensor/tag information within a specific time-space, that is, geographical context of the tracer must be also provided. Note that a sensor/tag can be used to store information or sense environmental information using distinct types of implementations;
3. *Communicate*: data communication of the traced information that can be supported with several technologies that must communicate the collected data (at its geographical context) and guarantee high interoperability (through transparent translation between protocols), which is a critical factor at this stage, because several communication protocols can be used. Therefore, the usage of reference models and standards that create a service-oriented and transparent integration of a multitude of technologies must be considered, for example, oneM2M IoT Standardized Architecture (https://onem2m.org), which particularly addresses the need for a common services Layer that can be easily embedded within hardware and software development;
4. *Aggregate*: reconciles multiple data formats and ensures consistent semantics in data that come from distinct sources. Moreover, this stage confirms that the dataset is complete and consolidates data into one place or multiple places (Time Series Database (TSDB), data warehouses, etc.);
5. *Consult/Trace*: business operations management that integrates traceability operations, supply chain, reporting, manufacturing and related human resources activities with a focus on the business operations management (ERP/MRP: Enterprise Resource Planning/ Manufacturing Resource Planning);
6. *Analyse*: consumes and interprets data using analytics blocks to compute high-level information metrics and indicators that can be used with enriched visual analytics approaches and used to analyse and evaluate the business processes and create value in the business model with a focus on the business strategy.

IoT traceability technologies. In the model proposed in Figure 3, a sensor, tag or smart tag (which combines a tag with sensing capabilities) can be seen as a technology artefact that enables parameter reading (sensor) and unique identification, and data transmission.

Legacy traceability technologies include Barcodes or QR codes that use manual IR (Infra-red) or camera-based scanners. The one-dimensional (1D) barcodes store up to 30 digits of data horizontally on an identifiable tag using the width and the spacing of the parallel black and white lines (Goel and Singh, 2015; Mishra and Mathuria, 2017). Over the years, various types of 1D barcodes emerged with different characteristics than the previous one such as the UPC (Universal Product Code), EAN (European Article Numbering), Code 39, Code 128 and more (García et al., 2012). Even though it is not a relatively new technology, barcodes are still being heavily used nowadays by society and in study cases as in Fan et al. (2019) where the authors combine barcode tags with RFID technology for the development of a traceable labels identification system. The introduction of a second dimension to these barcodes brought along the QR Code is an evolution of its predecessor, the 1D barcode. Its history traces back to the Japanese automotive parts industry in the late 1990s, but nowadays it has mass adoption making it way more popular. It is also an ISO international standard approved technology (ISO/IEC18004; Singhal and Pavithr, 2015; Soon, 2008). With uses in proposed traceability systems (Qian et al., 2012; Tarjan et al., 2014), the 2D code provides a significant opportunity for supply chains.

On the contrary, IoT traceability technologies typically include RFID, NFC and Bluetooth low energy (BLE), which are now widely available technologies, integrated by several smartphones' manufacturers as built-in technologies. For example, several smartphones have built-in RFID readers, and the adoption of NFC and BLE technologies is now common among smartphones/tablets' manufacturers.

RFID systems follow a set of standards (ISO, IEC: International Electrotechnical Commission, ASTM International, the DASH7 Alliance and EPC: Electronic Product Code-global) and consist of a reading device called reader and a small radio frequency transponder called RF tag (Al-Sarawi et al., 2017). Passive tags use lower frequencies and do not have an internal power source. When in context with traceability platforms, RFID technology has been a subject of study in Catarinucci et al. (2011), where the devices work together with a different set of sensors to provide the wine sector full traceability from vineyard to consumer glass. The same concept is applied in the work (Alfian et al., 2017), also involving sensors with a slight change in the domain into environment-sensitive agricultural food products. Active RFID Tag Systems, however, have an active radio frequency transmitter and their tags use batteries to power the board and to communicate with the reader (Ward et al., 2006). It has found uses in suggested platforms like iLocate (Zhang et al., 2014), a highly accurate object location solution using active RFID technology.

NFC is a proximity communication subset of RFID technology based on electromagnetic fields (Dragomir et al., 2016). It operates within the radio frequency of 13.56 MHz, has bandwidth speeds up to 424 kbits/s, and is heavily customer-oriented with a variety of mobile devices already supporting it (Lopez et al., 2013; Shah and Yaqoob, 2016). Vasquez et al. (2015) used NFC technology for a system to correctly identify and monitor the health patients in hospitals and health-related centres for better tracking and control. Another example of NFC being useful is in Halevi et al. (2012) where the proximity was explored to provide secure validation on transactions by using NFC featured mobile phones alongside its ambient sensors (audio and light).

BLE is a short-range, low bandwidth and low latency protocol for IoT applications. Its power consumption can be 10 times less than the classic Bluetooth while its latency can be 15 times less. It can also support an unlimited number of nodes with its star network topology (Al-Sarawi et al., 2017; Salman and Jain, 2017). BLE has been used in several studies that include domains from smart manufacturing on industrial devices (Tei et al., 2015) to agri-food product track and trace systems (Visconti et al., 2020).

The concept of Low Power Wide Area Network (LPWAN) is relatively recent when considering the spectrum of long-range connectivity and communications (Sinha et al., 2017). Many of these technologies have gained traction licensed/unlicensed realm of frequency bandwidth. Most notably, Sigfox, LoRa and NB-IoT (narrow-band IoT) are the present leading emergent technologies that are categorised as LPWAN (Mekki et al., 2019). Sigfox was a pioneer in the LPWAN market, being founded in 2009 with significant growth since then. By employing ultra-narrow-band modulation on its physical layer and keeping the network protocols secret (Centenaro et al., 2016), Sigfox provides a solid solution for implementing LPWAN technology in the suggested agriculture context in Mekki et al. (2019) where the inherent need for long-lasting battery sensors is required. Long-Range Wide-Area Network (LoRaWAN) is a type of LPWAN standardised by the LoRa Alliance, an open non-profit association that develops LoRaWAN (LoRa Alliance, 2017). It is optimised for a larger capacity and range while bringing low power consumption and cost (Dragomir et al., 2016). Regarding traceability purposes, this low power WAN has been used in previous work like in Zinas et al. (2017) where the authors implemented a LoRaWAN architecture for long-range communication and cattle tracking, including the design and development of the application and protocol. It has also been suggested in Kim et al. (2017) that LoRaWAN is an effective way of capturing an object's traceability when the paper applied it to develop a bicycle location tracking and management system. NB-IoT is a 'narrow-band LPWAN technology which can coexist in LTE or GSM under licensed frequency bands' (Mekki et al., 2018). This new cellular technology was introduced in 3GPP Release 13 for wide-area coverage in IoT domains (Wang et al., 2017).Narrow-band technologies enable deployment flexibility, better autonomy, and effective cost and signal coverage. Petrenko et al. (2018) propose an Industrial Internet of Things (IIoT)/IoT Control Center model with basis on the Russian NB-FI ('Narrow Band Fidelity') standard for wireless communications, which is NB-IoT based. The technology can also be used in a smart city context as demonstrated in (Shi et al., 2017) where a smart parking system was built based on NB-IoT with successful deployment in two cities in the Zhejiang province of China. Global Navigation Satellite Systems (GNSS) consist of four satellite technologies (Sholarin and Awange, 2015):

- GPS: United States' Global Positioning System;
- GLONASS: Russia's GNSS;
- BDS: China's BeiDou Navigation Satellite System;
- Galileo: European Union's Civilian GNSS.

These consist of three segments that provide point precise positioning and timing that other connectivity-based technologies lack (European Global Navigation Satellite Systems Agency, 2020). The utility of these systems is present in services and activities like sailing, aviating, car driving, hiking and emergency rescue (Maine et al., 2003). Research in Hadwen et al. (2017) shows that Global Positioning System (GPS) trackers used in combination with LoRa technology can be effectively used for a dementia patient traceability and tracking system with a 1-minute location update cycle. Through the work in He et al. (2009), the authors proposed a solution architecture for an integrated supply chain track and trace platform with the use of a synergistic hybrid of RFID and GPS technologies.

The wide availability of these technologies, notably RFID, NFC and BLE, has been pushing the increase of smart tags along with sensory data, like ambient temperature/humidity, vehicle speed, geolocation, that can be processed and aggregated to effectively enhance the supply chain traceability. Moreover, the usage of conventional smartphones/tablets as readers increases the cost–benefit of this approach, since most of the effort will be on the business side, that is, in the development of a software application that directly interacts with the IoT platform using SoA (Service-oriented Architecture) or microservices software architectures. Table 4 compares some relevant IoT traceability technologies that have higher potential for the T&C value chain.

Comparing the IoT traceability technologies in Table 4, it is worth noticing that these devices can be applied to different phases and processes in the textile CE model proposed in the fourth section of this article. The aspects of IoT adoption in the garment industry as presented in Mishra (2018) are the following:

1. *E-garments*: clothing with embedded purposeful sensors for business model compliance;
2. *Automated monitoring of factory operations*: monitoring and controlling the major parameters of the physical environment of a factory;
3. *Equipment maintenance*: important machine operating data can be accumulated and synced in real time and then analysed;
4. *Weaving and embroidery machines efficiency and exiting loading of products*: the machinery used in garment manufacturing can preserve data related to output per hour, thread counts, maximum hours worked and so on for later analysis;
5. *Product development*: ‘Virtual Sampling Tools’ are used to convert designs as digital samples for future applications;
6. *Digital printing*: IoT has lowered the cost of production and increased operational efficiency in digital textile printing;
7. *Guided sales process/E-commerce/virtual reality*: virtual product samples and product images have been replacing the traditional mode of displaying products or physical display;
8. *Streamline operations*: sensors attached to the machines and related software can provide real-time data regarding the performance of the machines;
9. *Increase uptime*: ensure equipment uptime through automated conditional monitoring systems.

With that said, Table 5 lists related work implementations as well as author suggestions for each aforementioned area of IoT adoption with its own assigned IoT technology used/suggested in the implementations.

Benefits of IoT traceability in the value chain

The value chain of any product is intrinsically dependent on a series of links or connections. If those links and connections experience difficulties, such as operational faults, antiquated production machinery or transport delays, these supply chain problems directly result in increased costs which compromise profit margins. Therefore, IoT technologies are crucial to improve the value chain management through real-time and end-to-end traceability mechanisms that arise from the IoT deployment in the supply chain. These IoT devices can provide improvements in the supply chain links or connections, which rely on the interaction of physical and cyber parts, to generate data and consequently information. The collected data can then be transmitted, aggregated and analysed to improve decision making and optimise the supply chain operational inefficiencies. Next, the four main benefits of IoT traceability in the value chain are identified:

1. *Transparency*: Customers are becoming more conscious in terms of choosing products that are produced more sustainably. Using IoT devices for traceability in the value chain, information flows smoothly, and problems can be identified in real time, which delivers exceptional value chain transparency.
2. *Delivery optimisation*: Optimising the delivery process is crucial because the delivery experience has profound impacts on the chances of customers’ repeat orders. The information acquired by IoT devices in a value chain can help to optimise delivery by detecting likely problems and changing delivery routes in real time.
3. *Operational efficiency*: IoT devices can perform inventories much more efficiently than humans, being not only more efficient than human inventory management but also resulting in fewer errors.
4. *Improved tracking/tracing*: Product value chains are particularly complex to manage. For example, optimal shipping conditions are crucial. With regard to the temperature of transport, for example, some degrees too hot or too cold can damage a product. IoT devices with equipped sensors can help to track and trace the conditions within shipping containers in real time, which can help to prevent product damage during shipping.

Challenges in the adoption of IoT traceability

IoT and distributed ledger technologies for traceability present some challenges in their adoption in the supply chain, which can be seen as non-technical and technical challenges. Technology

Table 4. IoT technologies for traceability and circular economy.

	1D barcode	QR code	RFID		NFC	BLE	LPWAN			GNSS
			Passive	Active			SigFox	LoRaWAN	NB-IoT	
Passive/active	Passive	Passive	Passive	Active	Both	Active	Active	Active	Active	Active
Cost-effective	√	√	√	X	Tag type dependent	√	√ (LPWAN-wise)	√	X	X
Real-time tracking	X	X	X	√	X	√	√	√	√	√
Power consumption	N/A	N/A	N/A	9 mW (low)	60 mA (low)	25 µA (low)	Ultra-low	32 mA (low)	125 mA (low)	22 mA (low)
Storage capacity	30 digits	3 Kbytes	2 Kbytes	128 Kbytes	Tag type dependent (up to 8 Kbytes)	N/A	12 bytes	243 bytes	1600 bytes	36 Kbytes
Scanning range	Code size dependent (usually contact/ short range)	Code size dependent (usually contact/ short range)	1 m (short)	Frequency dependent (100 m at 433 MHz)	<10 cm (contact)	<30 m (medium)	Up to 10/50 km (city/rural)	<20 km	<10 km	Global
Continuous scanning	√	√	√	√	√	X	√	√	√	√
Communication flow	Unidirectional	Unidirectional	Unidirectional	Bidirectional	Bidirectional	Bidirectional (mesh)	Bidirectional	Bidirectional	Bidirectional	Unidirectional
Sensor compatibility	N/A	N/A	√	√	√	√	√	√	√	N/A
Battery autonomy	N/A	N/A	N/A	1 year	N/A	Connection interval dependent	1.5–2.5 years (2400 mAh)	>10 years	<20 years	3 days (real time: 10 hours)
References	Cucu et al. (2008), Sivakami (2018), García-Betances and Huerta (2012), Iqbal et al. (2014), Pereira et al. (2020)	Soon (2008), Li et al. (2017), Singhal and Pavithr (2015), ISO/ IEC 18004:2015 (2015), Mishra and Mathuria (2017), Sivakami (2018)	Frenzel (2012), Costin et al. (2012), Al-Sarawi et al. (2017), Pais and Symonds (2011), Shobha et al. (2016), Catarinucci et al. (2011)	Pais and Symonds (2011), Maharjan (2010), Chae and Yoshida (2010), Ward et al. (2006), Dressen (2004), Yamada et al. (2005)	Lopez et al. (2013), Shobha et al. (2016), Dragomir et al. (2016), Lazaro et al. (2018), Halevi et al. (2012)	Boric et al. (2017), Wu et al. (2017), Yusheng et al. (2020), Tei et al. (2015), Lopez et al. (2013), Radhakrishnan et al. (2015), Garrido et al. (2016)	Mekki et al. (2019), Mekki et al. (2018), Centenaro et al. (2016), Raza et al. (2017), Gomez et al. (2019)	Peng et al. (2018), Sinha et al. (2017), Mekki et al. (2019), Mekki et al. (2018), LoRa Alliance (2017)	Mekki et al. (2018), Sinha et al. (2017), Soussi et al. (2017), Raza et al. (2017), Mekki et al. (2019)	European GSA Agency (2020), Dow et al. (2009), Sholarin and Awange (2015), Maine et al. (2004), Hadwen et al. (2017)

IoT: Internet of Things; QR: quick response; RFID: Radio Frequency IDentification; NFC: near-field communication; BLE: Bluetooth low energy; LPWAN: Low Power Wide Area Network; GNSS: Global Navigation Satellite Systems; N/A: not available.

Table 5. IoT implementations in textile manufacturing processes.

Phase/area	IoT technology	Implementation(s)
E-garments	1D Barcode, QR Code, RFID (passive)	A secured tag for implementation of traceability in textile and clothing supply chain (Agrawal et al., 2018) QR Code Fabric Tag System for textile companies in Turkey (ÖZYAZGAN et al., 2016) Passive UHF RFID textile tags as wearable moisture sensors (Shuaib et al., 2017)
Automated monitoring of factory operations	LoRaWAN	Integrating IoT into operational workflows for real time and automated decision making (Louis and Dunston, 2018)
Equipment maintenance	RFID (passive), RFID (active)	Framework of an IoT-based industrial data management for smart manufacturing (Saqlain et al., 2019)
Weaving and embroidery machines efficiency and exiting loading of products	RFID (active)	Big Data Analytics for Processing Time Analysis in an IoT-enabled manufacturing Shop Floor (Kho et al., 2018)
Product development	NFC	Contact range identification in manufacturing process
Digital printing	QR Code	A survey on interactive clothing based on IoT using QR code and mobile application (Mutkule and Ankoshe, 2018)
Guided sales process/E-commerce/ virtual reality	GNSS	Display in-store stock
Streamline operations	BLE	Machinery proximity optimal for BLE mesh topology
Increase uptime	RFID (active)	Continuous monitoring for machine performance

IoT: Internet of Things; QR: quick response; RFID: Radio Frequency IDentification; NFC: near-field communication; GNSS: Global Navigation Satellite Systems; BLE: Bluetooth low energy; UHF: Ultra-High Frequency.

availability does not guarantee by itself a successful deployment and direct benefits for the business operations and strategy. For example, although the RFID technology has reached a high maturity level, many points and stages of the value chain are still operated with legacy methods, that is, relying on paper.

Non-technical challenges include factors that impact the adoption of these technologies , including the lack of understanding of technologies among business administrators, which remain reluctant in investing in new technologies and suffer the consequences of first comers, due to the lack of industry-wide standards and practices, being market acceptance a key challenge to address (Jabbar et al., 2021). Furthermore, common and legacy ERP tools do not support these new technologies impacting its acceptance, since the high cost of licensing these tools has a longer return of investment, which may not yet be achieved. Finally, existing staff needs to be trained, which may be difficult, since the integration of new technologies requires new technical skills, as well as an understanding of the business-related activities that depend on the supply chain optimisation.

On the contrary, major technical challenges rely on the scalability and interoperability of such technologies. In the former, to operate in a continuously changing environment – such as a product value chain, which needs to stay competitive through continuous improvement – scalability stands as one of the major challenges in the use of IoT with distributed ledger technologies for traceability. The exponential growth of IoT devices and the demand for distributed ledger technologies, such as the blockchain, represents a huge challenge that may be addressed with new distributed and federated computing paradigms, by moving computation to intermediate and lower layers, such as fog and edge computing layers, respectively. On the contrary, interoperability among heterogeneous devices, not only for networking but also for federated computing environments, becomes a major challenge in future IoT traceability architectures. In this case, the need for standardisation practices, which are also related to policy making, must be considered to promote a straightforward integration among such heterogeneous IoT ecosystems, which will enable not only the development of cognitive-communication strategies but also the use of more efficient federated computing paradigms.

Analysis and conclusions

The T&C industry sector is currently of great importance not only due to the need of clothing for the well-being of people but also due to the weight of the sector in the economy, both in terms of the large number of jobs created and in terms of the sector's turnover. However, the T&C sector has a significant environmental impact, and this impact is felt throughout its entire value chain, especially with regard to water consumption, chemical pollution, CO_2 emissions and enormous waste production (Manshoven et al., 2019; Niinimaki et al., 2020).

The CE is one of the most promising business models for sustainable development. This model is based on the continuous reuse of materials and resources, allowing the reduction of waste and the preservation of natural resources. To adopt a CE business model, this has to be supported by applications that allow data collection to measure circularity. As seen in this article, the blockchain is a very promising technology that fits the needs of traceability and CE.

BCT has been used in several approaches for products' traceability in several value chains, including T&C. The BCT together with IoT are ideal technologies for implementing the CE.

Nevertheless, some challenges arise, when integrating IoT and BCT. One challenge relates with the use of IoT edge devices to gather and communicate readings (e.g. temperature, geographic coordinates) about a traceable item (e.g. product item, product lot). Typically, these readings generate a large volume of data that increases at a fixed time interval pace. For example, in a food cold value chain, the temperature readings for each traceable item typically come at a high pace. At this pace, these readings must be registered in a high-performance database technology, such as a time-series database. However, in the T&C value chain, this may not be as critical, as any eventual sensor reading must be associated with a business partner activity such as the production, transport and selling of a product lot (e.g. yarn, fabric) or raw material's lot.

Another challenge is related with the use of digital twins, that is, the information about a traceable item (typically a product lot). Through IoT identification labels (e.g. RFID, QR Code), the information about a traceable item is registered in the traceability system. A traceable item may be a garment piece or, more probably, a product lot. When it is a product lot, a value chain activity may not involve the entire lot, as when only part of a yarn's lot is sold, transported and used as input for producing a fabric's lot. Also, when the final consumer delivers a shirt for recycling, there is no way of identifying one shirt. The shirt has the code of the lot produced years earlier. So, each value chain activity on a product lot must also identify the quantity (e.g. number of shirts, weight of cotton, length of yarn) that the activity affects.

The use of BCT technology for traceability and enforcement of a CE in the T&C value chain has, as main advantages over other solutions, the fact of being decentralised, as it runs on a P2P network where each transaction can be confirmed without the need of authentication by a central agency. The data recorded in the blockchain ledger are immutable, as it is nearly impossible to change previously registered data, because the majority of the consensus nodes would need to agree. And, the transparency of transactions is another advantage of BCT, as anyone is able to consult the recorded data. This transparency also enables easy auditability for traceability purposes as each data record has a timestamp reinforcing its chronological order. The BCT also poses its own challenges, such as energy consumption or transaction cost, but an informed selection and configuration of technologies allows the use of a blockchain for supporting the CE in the T&C value chain that respects the environment it is trying to help protecting, at a reasonable cost. For example, Hyperledger Fabric offers a comprehensive toolset for implementing diverse privacy and security policies with support for granular access control and private channels, and it does not require a compute-intensive consensus protocol nor cryptocurrency incentives to mining operations (Agbo and Mahmoud, 2019).

When integrating BCT with IoT in a T&C value chain CE, one may also benefit from increased operational efficiency, as IoT devices are not only more efficient than humans but also make fewer errors in inventory management and in providing track and trace conditions within transport containers, warehouses or other environments, in real time, which can help to prevent product damage during transportation.

In a CE business process, the loop in the process is closed by the final consumer, as this is responsible for delivering the end-of-life T&C items for recycling. The use of gamification techniques may come in handy for engaging the final consumer in participating in the process.

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