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Circularity and Technology in Textile Manufacturing: a Blockchain application

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Abstract

In recent years, sustainability has become a fundamental value factor for both companies and consumers. Circular Economy is the most adopted framework to foster sustainability, especially in the Textile and Clothing Industry. Textile manufacturing in specific, is one of the most impactful industries for the environment, generating huge quantities of scrap materials, waste, and hazardous chemicals during the production process. Moreover, the manufacturing industry in general is resilient to the adoption of technological solutions, especially in regards of digitalization and software solutions. Due to the structure of textile manufacturing companies, that often operate in districts, digital innovation that leverage collaboration between firms can easily have a positive impact on this matter.

After a brief overview of the current state-of-the-art digital technologies applied for the purpose of sustainability in the Textile and Clothing manufacturing industry, a model based on Blockchain technology is presented.

The model is based on collaboration between textile manufacturers, certifiers, and the municipality to create a transparent waste management strategy, allowing firms to exchange data regarding the impact of their products and the chemicals contained in their wastewater so that other actors can monitor and leverage this data when reusing it. This data is assumed to be collected using IoT devices and then shared over a private distributed ledger to reduce privacy concerns for the transparency of sensitive company information.

A software implementation of the model is provided and documented, demonstrating the potentialities of adopting this model and the low barrier to adopting it. The analysis of the practical application of the model is limited, as it has not been tested in a real-life scenario, but a critical review of the solution is provided, and its future improvements are then discussed.

Keywords: Textile and Apparel, Sustainability, Industry 4.0, Blockchain, DLT, Prato, Textile District, Circular Economy, Waste Management, Wastewater, Industrial Symbiosis.

Abstract in lingua italiana

Negli ultimi anni, la sostenibilità è diventata un valore di importanza fondamentale sia per le aziende che per i consumatori. L'Economia Circolare è il modello più adottato per promuovere la sostenibilità, in particolare nell'industria tessile e dell'abbigliamento. La produzione tessile, nello specifico, è una delle industrie più impattanti per l'ambiente in quanto genera enormi quantità di materiali di scarto, rifiuti e sostanze chimiche pericolose durante il processo produttivo. Inoltre, l'industria manifatturiera in generale è restia all'adozione di soluzioni tecnologiche, soprattutto per quanto riguarda la digitalizzazione e le soluzioni software. Data la struttura delle aziende manifatturiere tessili, che spesso operano in distretti, un innovazione digitale che fa leva sulla collaborazione tra le imprese può facilmente avere un impatto positivo su questo tema.
Dopo una breve panoramica sull'attuale stato dell'arte delle tecnologie digitali applicate ai fini della sostenibilità nell'industria manifatturiera del tessile e dell'abbigliamento, viene presentato un modello basato sulla tecnologia Blockchain.
Il modello si basa sulla collaborazione tra produttori tessili, enti certificatori e comuni per creare una strategia di gestione dei rifiuti trasparente, consentendo alle aziende di scambiare i dati relativi all'impatto della loro produzione e alle sostanze chimiche contenute nelle acque reflue, in modo che altri possano monitorare e sfruttare questi dati al momento del riutilizzo. Si ipotizza che questi dati siano raccolti tramite dispositivi IoT e poi condivisi su in maniera distribuita e privata, riducendo le preoccupazioni sulla privacy riguardanti informazioni aziendali sensibili.
Viene fornita e documentata un'implementazione software del modello, che dimostra le potenzialità dell'adozione di questa soluzione. L'analisi dell'applicazione pratica del modello è limitata, poiché non è stato testato in uno scenario reale, ma viene fornita una visione critica della soluzione e vengono discussi possibili futuri miglioramenti.

Parole chiave: Tessile e abbigliamento, Sostenibilità, Industria 4.0, Blockchain, DLT, Prato, Distretto tessile, Economia circolare, Gestione dei rifiuti, Acque reflue, Simbiosi industriale.

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Introduction

It is well known that the textile and clothing industry has a huge environmental impact and is very demanding in terms of resources. It is estimated that textile production uses more than 79 billion cubic meters of water, while the whole European Union economy needed 266 billion cubic meters. The sole process of dyeing and finishing textiles is responsible for about 20% of clean water pollution. Moreover, an enormous amount of microplastics and hazardous chemicals are released into the environment. [1]

For this reason, the European Commission adopted the Circular Economy Action Plan (CEAP) in March 2020. It is one of the main building blocks of the European Green Deal, Europe's new agenda for sustainable growth. The EU's transition to a circular economy will reduce pressure on natural resources and pushes individual countries to take action in this direction. [2]

The municipality of Prato (Italy) promoted this transition with the Prato Circular City Strategy. Alongside the many virtuous initiatives born at the micro level in the territory, the municipality aims to foster the development and affirmation of circular models with the goal to have a system that is increasingly integrated. The textile district that characterizes the Prato area has characteristics that are particularly suited to foster a transition toward a circular economy, innovation, and sustainability. In launching the strategy, the city administration has set itself the goal to establish a permanent environment for discussion among local stakeholders to promote shared, integrated, and participatory circular economy actions. [3]

To transition into a more sustainable production process, Industry 4.0 technologies can be leveraged so that the transition of a company's environmental impact also brings measurable value to the firm.

Distributed ledger technologies, such as Blockchain, fit the need for transparency and collaboration between firms in the same district perfectly, providing a secure way to share information, therefore, accelerating the adoption of Circular Economy practices in the companies. In addition to that, technological advancement in the processes of textile production can provide a scalable structure and standardization of data, that leads to an easier assessment of the sustainability metrics from certifiers and municipalities. From this perspective, this thesis aims at providing an overview of the use of Industry 4.0 technologies in the T&C industry with an analysis of how these technologies can reduce the environmental impact of textile production. A blockchain software implementation is then provided to implement a model that is applicable in a real-life scenario.

1 | Theoretical background

The preliminary research consisted in collecting background information on topics related to digitalization, production processes, and circularity in the textile manufacturing industry. This information not only sets a knowledge on this sector, supported by scientific evidence and industry standards but also allows to have an overview of the technological opportunities digitalization, especially with the use of blockchain, can bring to firms operating in the industry.

1.1. Digitalization in the Textile Industry

Despite the fourth industrial revolution brought innovation in many industries, the textile manufacturing industry is resilient to change. What is changing the most is the increasing demand for transparency and sustainability from policymakers and customers.
Trends toward sustainability will continue until the product becomes manufactured in an eco-friendly and cost-efficient manner. The key to enhancing sustainability in a traditional industry such as the one of Textile and Clothing (T&C) is **digitalization**.

In recent years, the T&C sector started to be more connected to the digital world. As manufacturing is a labor-intensive industry, digital technologies can provide significant improvements in terms of productivity, cost-savings, and process optimizations.
Studies on firms that make use of cutting-edge technologies indicate that these companies can access new market opportunities, acquire more marketing information from their customers and improve the product development process. [4]
Investments in digitalization enable a better strategic alignment between the technologies and tools utilized and the goals of the organization. [5]
New digital technologies give the possibility to monitor, measure, analyze, and improve working conditions and processes, reducing the environmental impact. Weaving and spinning automation are the more prominent application of digitalization in the sector, but industry leaders are now researching and implementing advanced software systems across the whole value chain, with a focus on the production itself.

Figure 1.1: STOLL technologically advanced weaving & knitting machine [9]

Developments related to the increasing digitalization of production planning and manufacturing systems include robotized production machines that fully automate processes allowing the manufacturers to perform all the production process steps in the same factory, moving the whole supply chain closer to the customer and improving the product quality. [6]

With this technological advent, on-demand manufacturing systems have become a good opportunity to create personalized products, optimize production, and reduce waste. This improves agility and reconfigurability in the textile manufacturing process. [7]

The key scope for strategic collaboration in the T&C industry is to support demand fulfillment. Industry 4.0 technologies allowed open digital integration between all the players working on the same clothing supply chain. Seamless information transfer supports new business models based on flexibility and collaboration. In this business model, customized garments are produced by a regional ecosystem of production units composed of small-medium enterprises ranging from design, production, and sales to the consumer. [8]

1.2. Textile recycling process

In order to apply the *Circular Economy* paradigm inside a company, strategies regarding circularity have to be adopted in terms of business model, design, production processes, and distribution.
The **3R model (Reduce, Reuse, Recycle)** is taken as a reference to implement changes along the whole value chain.
Reduce strategy focuses on using fewer resources in the production process, improving efficiency, and reducing consumption. Another goal is to reduce the waste produced in the process. In the T&C industry, this translates into dealing with the reduction of energy used and emissions relative to the production process. The textile creation processes require a great number of chemicals and substances that are considered harmful, optimizing the production would reduce waste produced and chemicals that in most cases end up disposed into the environment.
The reuse strategy aims at extending the product lifecycle. With textiles, this approach means that the product will be rented, traded, or inherited instead of being thrown away by the owner. Introducing this strategy into the company processes is highly appealing since there are no direct costs associated with energy demands or labor. Societal trends and marketing campaigns are pushing the reuse paradigm into more and more consumer minds, making it an easier strategy to implement.
Finally, recycle strategy implies that products at the end of their life cycle can be put into a new production process, providing them with a new life instead of being wasted. Using chemical and physical transformations the textile is dismantled and used partially (or totally in some cases) as raw material for the production of new yarn, reducing resource consumption and pollution. [10]

As Figure 1.2 shows, the circular economy paradigm can be applied to the T&C industrial production process. The highlighted steps in the process are the ones taken into account in the next section of the analysis as they represent a big part of the environmental impact of the T&C industry and are the scope of this thesis.

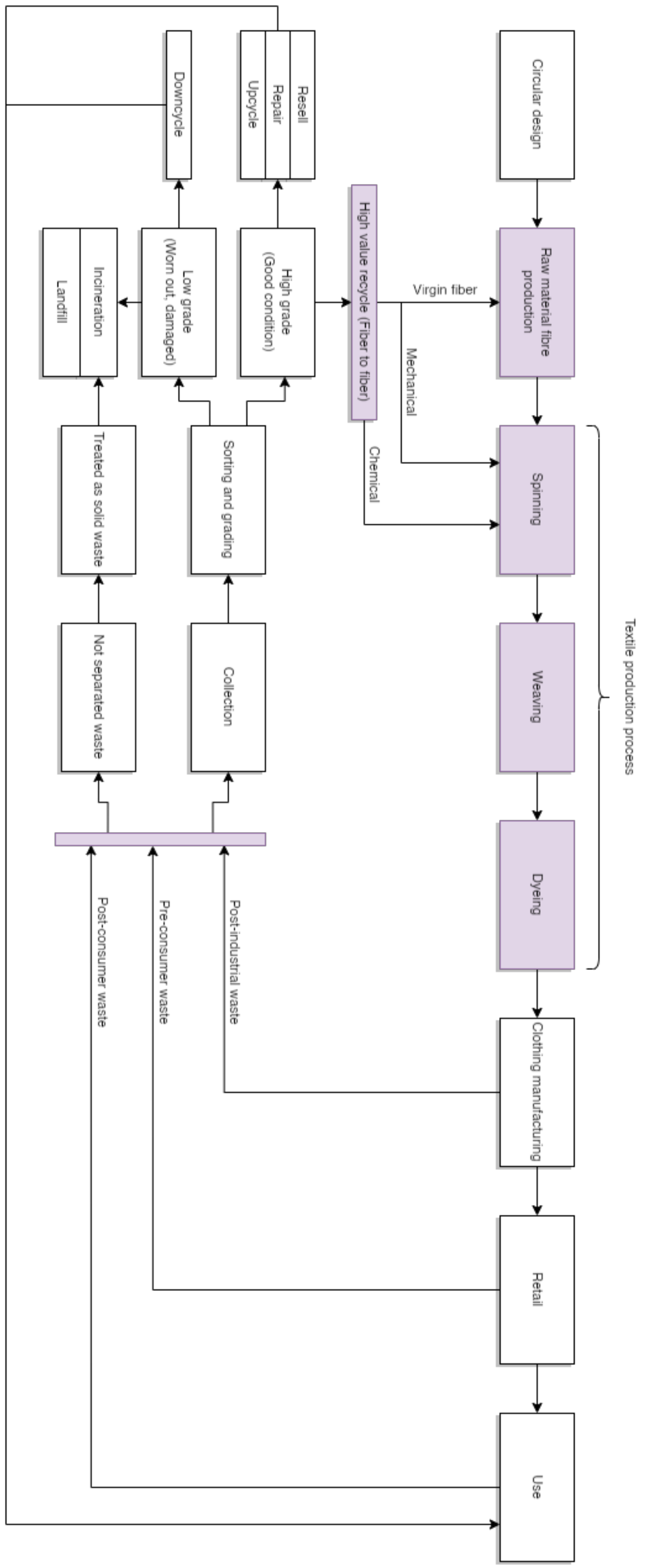

Figure 1.2: Circularity paradigm applied to textile production [11]

1.3. Critical steps in textile production: assessing environmental impacts

Even if in the whole textile lifecycle the circular economy paradigm is applied, the textile production process is quite linear and follows the same transformation process for all the kinds of fibers used (i.e. cotton, wool, synthetic), To obtain a garment the raw material is turned into a homogeneous fiber, the fiber into yarn with a spinning process and then waived to create the fabric. **Analyzing each step of the process and its environmental impacts allows us to measure the sustainability of the whole process, measure it and collect information about each step of the value chain.** This information is fundamental for various stakeholders: the company's management can use it to optimize their processes, institutions can verify sustainability standards and certifications and finally, the consumer is provided with extra transparency which translates into value. [12] [13]

1.3.1. From raw material to fiber

Before the fibers can be processed into textile products, the raw material has to be cleaned and prepared. This process in some cases is the most environmentally impactful of the entire production. A distinction can be made between natural and synthetic fibers as their preparation process is slightly different due to their nature.

Cotton and wool both contain impurities and specks of dust that have to be removed before spinning. The material is opened, dusted, and then washed in hot water in order to remove contaminants and excess fats. Moreover, cotton has a greasy out layer that is often dissolved in aqueous sodium hydroxide to facilitate future dyeing. Environmental issues associated with it are the emission into the water and solid waste generated. [14] Organic cotton and wools are more sustainable alternatives, in this case, the production process of the material follows organic and holistic principles and the amount of chemicals used is close to zero.
Lyocell, rayon, and bamboo are natural fibers made with wood pulp coming from mature forests. Lyocell and bamboo are generally more sustainable than rayon since the forests where the material is sourced are managed in an eco-sustainable way, replanting the three that are cut down. In the process of creating the filament that has to be spun, the wood pulp is softened using chemicals and then extruded mechanically, representing a focal sustainable impact in their production chain, in opposition to the

more sustainable growing and harvesting of their plants. [15]

Synthetic fibers instead are composed of a polymer in a process that uses various reagents and chemicals. Their technical characteristics, often associated with a low cost of production, have made them become the go-to material for cheap garments in fast fashion. Their environmental impact is related to the non-renewable fossil material used to produce them, the microplastics generated in the garment lifecycle, and their heavily industrialized production process.
In Table 1.1 a classification of the different fibers has been made, putting in evidence the environmental benchmarks of their production process.

Class A	Class B	Class C	Class D	Class E	Class F
Recycled cotton Mechanically recycled nylon Mechanically recycled polyester Recycled wool Organic hemp Organic linen	Tencel / Ryocell Organic cotton Chemically recycled polyester	Hemp Ramie PLA Linen	Virgin polyester Poly-acrylic Generic modal	Cotton Virgin nylon Cupra Bamboo viscose Wool Generic viscose	Silk Organic wool Leather Spandex Acetate Cashmere wool Alpaca wool Mohair wool Bamboo linen

Table 1.1: Environmental benchmarks of textile fibres [15]

1.3.2. Spinning process

Spinning is a process that involves various mechanical operations to comb, align, and spin fibers into yarns, which may then be twisted together to form a twine. To facilitate high-speed processing, chemical auxiliaries are used to provide lubrication.
In the past, mineral oils were widely used as lubricants, but they contain *polyaromatic hydrocarbons* (PAHs) that are toxic to humans and the environment. Nowadays, synthetic oils (such as silicone oils and polyglycols) and ester oils (such as esterified fatty acids) have largely replaced mineral oils due to their superior performance and uniform properties. These oils are applied in aqueous preparations that require non-ionic surfactants (such as alcohol ethoxylates and alkylphenol ethoxylates) as emulsifiers.
Synthetic oils are generally cleaner than mineral oils and may biodegrade, while ester oils are more biodegradable and easier to emulsify.
Other chemicals are used as preservatives to protect the preparations from getting attacked by bacteria and fungus during the storing. These chemicals are very dangerous for the ecosystem as they usually end up in wastewater discharged into the environment after the process.
Regarding waste generation, the spinning process has little or no emissions and doesn't produce water waste. The solid waste generated comes from packaging, discarded yarn fibers, and chemicals used during the process. [15]

1.3.3. Weaving

Weaving involves interlacing two or more perpendicular yarn systems, the longitudinal yarns, *warp*, are held in tension on a frame called *loom* while a transverse yarn, *weft*, is drawn through and inserted over and under the warp.
The warp yarns are placed under tension and are subject to significant stress during weaving, as the weft yarn is inserted between them at high speed. To reduce damage caused by the many abrasive contacts the warp endures, **a chemical preparation called size is applied** to the warp yarn prior to assembly on the loom. Size forms a film that makes the yarn stronger and slippery, bringing fundamental advantages such as: reducing friction, reducing the number of free fibers that may interfere with the weaving process, and the number of warp yarn breakages.
There are two kinds of size preparations: natural and synthetic. Starch is the most commonly used natural size. The source of starch varies geographically, for example, potatoes are the primary source in Europe, corn starch in the US, and various starches (rice, sago, maize, and tapioca) in Asia. Starch is increasingly chemically treated to

produce depolymerized derivatives such as *carboxymethyl cellulose* (CMC) to improve its performance and make it water-soluble for recycling. Synthetic sizing instead makes use of agents based on polyvinyl alcohol or they can be created using a mix of chemicals in order to perfectly fit the type of fiber and the specific process of the company that requests them.

Fabrics are usually made for the majority by warp yarn, making sizing agents a significant part of the weaving process. Cotton is the most heavily sized fiber, with loadings of up to 200 g/kg applied to the warp yarns. [15] Additional agents commonly used in cotton-size preparations include viscosity regulators, antistatic agents, wetting agents, defoaming agents, and preservatives. Sizes for fibers other than cotton generally contain only preservatives.

Chemicals used in spinning and weaving are typically left on the fabric by producers and must be removed by finishing houses before dyeing to prevent inconsistent results. These substances are generally not directly toxic to the environment, but the great quantity that it's used, especially in limited areas such as textile districts, still burdens the environment.
Finally, the waste resulting from the weaving process is mostly solid waste such as packaging, yarn, fabric scraps, and used oil, Sizing the yarn in preparation for this process on the other hand produces volatile organic compounds, releases biochemicals and chemicals in the wastewater and produces solid waste such as unused size.

1.3.4. Textile wet processing, dyeing, and printing

Textile wet processing involves various sub-processes that can have significant environmental impacts. These processes, which aim to improve the characteristics of the textile surface, are particularly resource-intensive. They require large quantities of water for washing, energy for heating the baths, and various chemical agents. [15]
The ennoblement process typically consists of four sub-phases: pretreatment, dyeing, printing, and finishing.

- **The pretreatment phase**, similarly to the raw material processing, involves removing foreign materials from fibers improving characteristics such as uniformity and hydrophilicity and relaxing tensions in synthetic fibers. This phase requires the use of chemicals and water and has significant environmental impacts.
- **The dyeing process** is particularly intense in terms of water, energy, and chem-

icals used. To maintain dyeing characteristics while promoting environmental sustainability, research has focused on obtaining more stable and manageable dyes and solving problems related to their disposal. In conventional dye systems, reactive dyes, which are the most common dye for cellulosic fibers such as cotton have the lowest fixation rates: approximately 65%, with the remaining 35% of dye flushed away after the process. [16]

- **Printing** is a more complex process that involves using a wide range of chemical substances, such as different classes of dyes or pigments, auxiliaries, and other agents.
- **The finishing process** involves improving specific aspects or conferring new properties to textiles. As with all the others, even this process has environmental impacts related mainly to water consumption and the use of chemical products.

1.3.5. Recycling of high-grade waste

High-grade textile waste poses significant environmental and economic challenges as it's the most valuable part of the textile waste collected. The production of textile waste is a result of various factors such as production inefficiencies, product defects, and changes in fashion trends. It can be a valuable resource if properly managed. Recycling and reusing high-grade waste can significantly reduce the environmental impact of the textile industry and provide cost-effective alternatives to virgin materials.
Once the textile waste has been sorted, there are several options available for recycling it. In some cases, garments can be reused directly following sorting. This approach is generally considered more sustainable and resource-efficient than recycling. For instance, the energy and labor resources needed to set up dedicated recycling facilities and implement recycling processes can be significant. Recycling can also be less profitable compared to other waste management approaches such as the upcycling or downcycling of clothes, which allows using scrap garments in order to create other products of more or less value. [17]

As a result, recycling typically occupies a lower position in the waste management hierarchy. One approach to textile recycling is **mechanical recycling**, which involves shredding and carding the fabric to extract fibers, which can then be spun into yarn for woven or knitted fabric. This process is most effective for mono-fiber fabrics such as cotton and occasionally viscose. The waste fabric is shredded and then sent to a garnett machine for fiber extraction. The garnett machine performs rough carding actions, tearing the fabrics with opposite sets of sharp teeth to transform them into component fibers. The advantage of using mechanical recycling is that there is a minimum need for chemical processing, the yarn coming from a recycled garment keeps the dye and some of the properties from its previous production process. On the other hand, yarn produced this way has a worse fiber quality, which can be mitigated by combining them with virgin yarns. [18]

Chemical textile recycling instead is a process that uses a series of chemical procedures to depolymerize or dissolve the fiber from the fabric into a monomer or solvent form, which can then be used to create new fiber compounds or extract a single compound from a mixture. The resulting products from this process are usually of the same quality as their virgin counterparts, with no loss of physical properties during the recycling process. [19]

1.4. Industrial Symbiosis and its opportunities

To achieve sustainable and efficient resource use across local, regional, and global economies, industrial ecology requires careful monitoring of material and energy flows. One approach within this field is *industrial symbiosis* (IS), which fosters collaboration between previously isolated entities and encourages the physical exchange of materials, energy, water, and by-products. Industrial symbiosis not only helps to increase environmental sustainability but also yields economic and social benefits that are greater than the sum of individual benefits that could be achieved by working independently. The success of this approach hinges on collaboration and the potential for synergies that arise from geographic proximity.

Industrial symbiosis “requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle, from virgin materials to finished material, to components, to product, to obsolete product, and to ultimate disposal. Factors to be optimized include resources, energy, and capital”. [20]

Industrial ecology can be applied at different scales: as shown in Figure 1.3 a firm can adopt the 3R model and sustainable design practices, while at an inter-firm and global scale flows and collaboration between firms are necessary to reduce environmental impact.

There are different kinds of symbiosis between firms, the two most applied cases are:

- **Waste exchanges:** Some firms recycle, donate or sell recovered products acting as brokers to other organizations. Especially in the T&C industry, scrap dealers

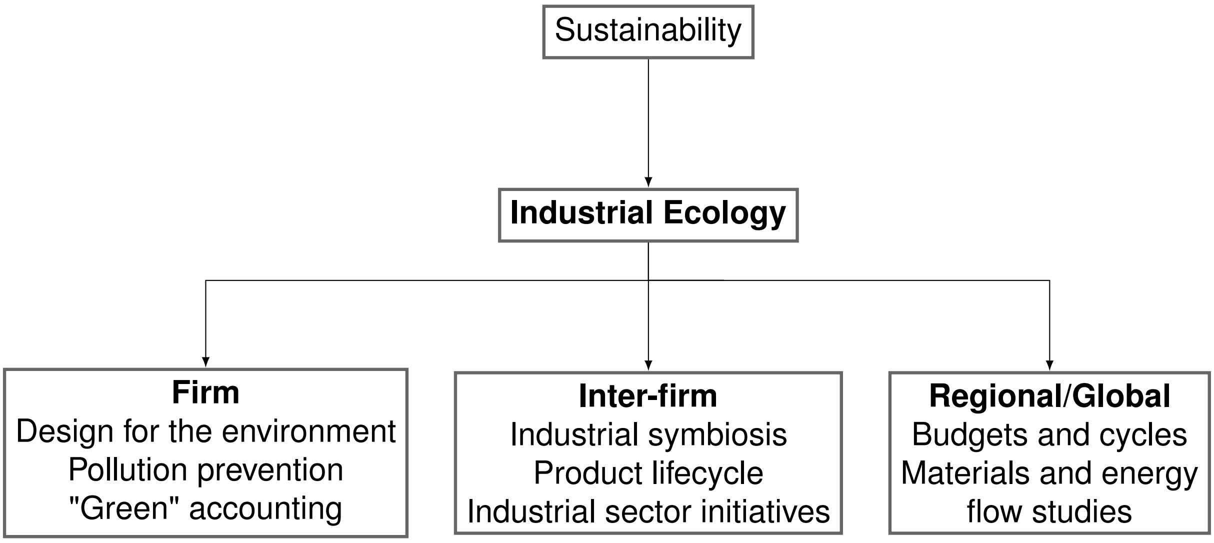

Figure 1.3: Industrial ecology operations at different levels [21]

play the role of facilitating the collection and sorting of garments that are re-sold to be recycled or donated to charity. This form of exchange is typically one-way and happens at the end of the lifecycle of a product. Waste exchange can be applied by creating a list of scrap materials every organization requires or can process and a list of companies that produce high-grade wastes of these categories. The scale of trade can be local, regional, or global and the exchanges get benefits on a trade basis. Usually, the trade regards materials rather than water or energy.

- **Industrial parks:** In this approach firms located in the same area or district can exchange water, energy, and products. Moreover, the companies can share information and services such as transportation, permits, and marketing. As in the waste exchange, there has to be transparency and optimization of the input and outputs of every firm in order to collaborate and optimize the need for resources. In this case, the benefits are along the duration of this collaboration and not on a trade basis.

In 2020 the European Commission adopted a *"Circular Economy Action Plan"* (CEAP) that includes legislative proposals on waste to push the transition to concepts of Circular Economy. The CEAP consists of a plan that establishes concrete actions to measure the production and consumption of companies, their waste management, and the reuse of recycled raw materials. [2]

To implement this plan and approach a circular waste management system, firms in the same district have firstly to adopt in depth the 3R paradigm (Reduce, Reuse, Recycle) as a waste strategy, and then investigate the use of waste in different production

chains, bringing together the private and public organizations that operate in the reuse sectors with the aim to produce innovation, aggregation, and networks.
Applications of industrial symbiosis in the textile industry can be found in the exchange of garment wastes that can be recycled and used to produce other textiles from firms in the same district. Synthetic fiber residues are the main concern in this application as the material is hardly recyclable and is usually disposed of through landfill (which represents a high economical and environmental cost) or incinerated. In contrast, natural fibers provide a lot of options for recycling if collected separately. Here technology plays a key role as with Industry 4.0 the tracking of textile materials and composition can be tracked in a transparent way during the garment life.
Finally, another application of IS is a wastewater treatment system. This solution consists of the creation of industrial (or civil) wastewater treatment plants that reduce sedimentation, dyes, and harmful chemicals from the water coming from the firms of the district. The sanitized water cannot be released back into the environment as the soil is still unable to degrade such quantities of polluted water, but more efficient reuse of water can be found by utilizing the water within the textile production process. In this case, technology allows reliable methods to test and track chemicals inside the wastewater and optimize its flow. [22]

1.5. Digitally-enabled textile circularity

In recent years the linear economy model (take-make-waste) that was the rule in the T&C industry is showing its problems. Several trends have brought the sector to this point: the increasing fast-fashion industry with its low-quality products and a throw-away attitude bringing a shortening of the garment lifecycle; the falling of clothing prices, which increases demands for inexpensive textiles with conventional fibers often produced without attention to sustainability and workers conditions as well as increasing the number of low-grade textile wastes. [11]
The transition to a circular model starts with waste prevention and improving the processes of fibers recycling: increasing virtualization, flexibility, and transparency brought by Industry 4.0 technologies have been highlighted to support the circular economy in both. [23]

One of the key applications in the circular supply chain where digital technologies brought a considerable contribution is **tracking materials and chemical processes** used in the production of textiles. By using tools such as Radio Frequency Identification

(RFID) and Blockchain technology increased traceability and provenance are obtained, which result in improved material reuse and optimized recycling industrial processes enhancing sustainability. In the supply chain, digital technologies also improve the scale of operations of sorting for the materials used in the textiles. Furthermore, additive manufacturing and other technologies have been implemented by small-scale designers such as Iris Van Herpen in order to create a circular design process. Garments produced in innovative ways can use waste materials and can incorporate designs that are easy to disassemble and recycle. [24]
Finally is worth mentioning the other two pillars of circular economy applied to this industry that can be enhanced through digital platforms and technologies:

- **Reuse and repurpose of clothing**: some countries have a collection rate of 75% of textiles, that are then exported to developing countries in order to extend their lifecycle. In these countries, this system stops working, since there isn't a structured way of collecting and dismantling clothing, so at the end of their cycle the garments end up in landfills. A solution to this is the complete repurposing of textiles products and a more solid system not only in rich countries but also in developing ones.
- **Resale and rental approach**: it's estimated that consumers who don't throw away clothes that they don't use save a total of $460 billion. [23] However, this goes against societal and personal needs. A solution to extend the life of used garments is renting clothes that are needed for special occasions and not often used, in order to distribute and reduce the environmental impact of their production. Moreover, vintage shopping and old clothes resale is a trend, especially among new generations of consumers.

1.6. Blockchain and Distributed Ledger Technologies

Blockchain technology is an approach to recording and sharing data across multiple distributed ledgers, making it a subset of the so-called *Distributed Ledger Technologies* (DLTs). This allows for storing data and transactions in a secure and transparent way. The name derives from the fact that the data structure is composed of a series of blocks, each one containing data, that are connected to each other forming a chain. Whenever a new block is created, its data has to be validated by other peers before adding it to the chain.
Each participant in the distributed ledger has their own copy of the whole ledger, while in traditional distributed databases the tables are shared for fault recovery purposes,

in DLTs the information is stored in order to maintain security: when a peer wants to modify a piece of information on its copy of the ledger, it has to ask consensus among other peers and then distribute the resulting updated information. In exchange for the verification provided, the peer performing the update pays a fee to the others. Users that are outside the network can still view the information inside the blockchain but only peers that participate in the distributed ledger can operate on it and perform transactions.

The technological innovation brought by blockchain is perceived as disruptive by entrepreneurs and businesses, not only for the technological changes from existing technologies but more for the cultural changes brought by it. This technology pushes even more in the direction of transparency of data and distribution, aligning it to the current trends in T&C industry.

There are three main paradigms in the distribution of ledgers and access to their data:

- **Public blockchain**: this DLT is permissionless and unrestricted, which means that anyone connected to the internet can join the network and become part of it. It maintains trust among participants by providing rewards to whoever validates transactions, so every peer is incentivized to act in an honest way and work for the improvement of the whole system.
- **Private blockchain**: Unlike the public, private DLTs require permission to join and operate in its closed network. It’s mostly used within organizations where only some members are allowed to access the blockchain, mostly in enterprises or companies where the chain is for internal use. A private blockchain is more centralized since a single authority maintains the network.
- **Consortium (Federated) blockchain**: It is a hybrid between the two, suited for organizations where there is a need for both types of DLTs. In this case, more than one organization is involved in providing the access to the network, there is more than one authority in charge of maintaining its decentralized nature.

In particular, Consortium-based DLTs represent the perfect fit for textile companies doing business in the same industrial district and multiple institutional stakeholders, giving them the opportunity to share data and leverage this technology without the danger of external actors exploiting private production information. Moreover, the collaboration of companies in the same district is expected to develop mutually beneficial relationships. [25]

Feature	Public	Private	Consortium
Accessibility	Anyone	Single person / Central in charge	More than one in charge
Who can join	Anyone	Permissioned and known identities	Permissioned and known identities
Consensum mechanism	PoS / PoW	Voting or multi-party consensum mechanism	Voting or multi-party consensum mechanism
Transaction speed	Slow	Lighter and fast	Lighter and fast
Decentralization	Completely decentralizzed	Centralized	Less decentralized
Merits	Trustable, no intermediaries	higher transaction speed, highly scalable	Suited for collaboration, scalable and secure, customizable
Demerits	Scalability, high energy consuption	More centralized, achieving trust is hard	Less anonymous compared to others

Table 1.2: Summary of the three DLT paradigms and their features [26]

2 | Research Objectives and Methodology

As discussed before, there's an upcoming need for sustainability in the textile manufacturing industry, which is derived both from societal trends, where customers are pushing all the companies in the fashion industry to improve their processes to reduce waste and energy consumption, and value diversification of the product. Textile companies compete on costs but with the advent of the fourth industrial revolution, more and more manufacturing companies implement digital services, technologically advanced textiles, and improved processes that increase the value perceived by the customer, making it possible to differentiate also on value.

This creates opportunities for technologies to intervene and make an impact on the sustainability of companies. The objective of this research is to propose **a model that facilitates the sharing of information** regarding textile waste and fosters industrial symbiosis, and to develop the relative **blockchain software implementation**.
To determine the best structure of the model and the environment in which textile firms operate a technical background is provided and **a literature view is performed** exploring and discussing the state of the art of Industry 4.0 technologies is explored, in particular, blockchain and all the technologies that have an impact on sustainability and energy consumption issues.
Moreover, this research will analyze the technical implementation of the ecosystem of technologies that this solution required and critically discusses the limitations of this technology.

2.1. Research process

The research put its foundations both on personal knowledge about the textile manufacturing industry and on the theoretical background researched and provided.
From this background, it is already clear that there are opportunities for technological

advancement in the industry, especially when it comes to leveraging collaborations between firms in the same district.
First of all, a systematic literature review is performed, to have both a complete view of how Industry 4.0 technologies are implemented in this industry and to seek specifically for other blockchain applications. During the literature review and related research, a focus is put on sustainability.
Performing the review, all the research papers were classified to measure the impact of innovation in this specific industry, especially giving more importance to the applications that regard the industrial production process. The objective of this part of the research is to narrow down all the solutions that are theorized or applied for now. Between them, some distributed ledger applications can be found and analyzed in dept to understand their strengths and weaknesses.
Starting from this classification, all the digital solutions found are presented, especially with their impact on sustainability and they are briefly discussed to have a complete vision of the industry. A focus is put on blockchain-based solutions as it's the scope of this research.
After analyzing the scientific literature collected with this systematic methodology, citations, and related papers were explored. This is often referred to as *"snowball effect"*: Starting from research that was classified as in scope for the thesis, all its sources were read and studied, then all the related papers from the sources are also analyzed until the starting research has been reached. This method is useful especially when exploring papers that lie at the intersection of different themes so that a more in-depth and accurate analysis can be performed on each of the themes.
With a clear view of the industrial applications of distributed ledgers, a model will be presented.
The model has to be based on the current state of the art as it needs to represent a practical and implementable solution that leverages the strengths of the blockchain technologies that are best practices in the industry. Moreover, the model needs to be designed so that it covers all the gaps in the literature review that will be found.
After the model proposition, the software implementing it is developed following a standard flow:

- **Production of the technical documentation** for the smart contract. The documentation tries to set requirements that follow the model designed, therefore it is deeply connected to the research performed in this thesis.
- **The implementation of a smart contract** with the use of the best blockchain technology for the use case. The development of this software is crucial because

it will be used to analyze and test the model.

- **Testing of the software project**. By testing the use of the smart contract we can analyze what are the limitations and benefits of the model and if it can be applied in a real-life scenario. A set of tests are also performed to provide a high-quality code.

- **Analysis and discussion** of the advantages and limitations of the solution provided and of the model.

After the implementation and testing of the software, the technical ecosystem needed to make the solution be effective in a real-life scenario is discussed referring to the state-of-the-art technologies that emerged.
A critical review of the issues of applying the software system for firms in the textile industry is performed also considering non-technological issues, expressing both its limitations and future improvements.

2.2. Research flow

The graph in Figure 2.1 represents the flow of the thesis research process along all the steps.
During the preliminary research in Chapter 1, the topics of sustainability, Circular Economy, and Industrial Symbiosis were explored to have an understanding of the environmental problems caused by the Textile and Clothing industry, refining the scope of this research and giving an understanding of which measures can be applied to reduce the impact of textile-related waste.
In Chapter 2.5 a literature review is then performed to have a general overview of the applications of technology in this specific industry, this resulted in a state-of-the-art analysis that pointed out the missing of specific digital applications that provide support firms operating in the industry to collaborate with each other in a horizontal way. This analysis also provided background knowledge on the state of all the Industry 4.0 solutions applied into the T&C industry.
This background knowledge is then translated into the model designed and explained in Chapter 5 that represents interactions between actors that would have an improvement on the current workflow of the companies in the same textile district.
In Chapter 4 series of requirements are stated and the model is adapted to be directly translated into a distributed ledger application using Blockchain.

Finally, in Chapter 6 and Chapter 7 an implementation of this model is produced so it can be tested, and an analysis of the model and possible adoption problems is performed, giving an overview of the opportunities and limitations of the solution provided.

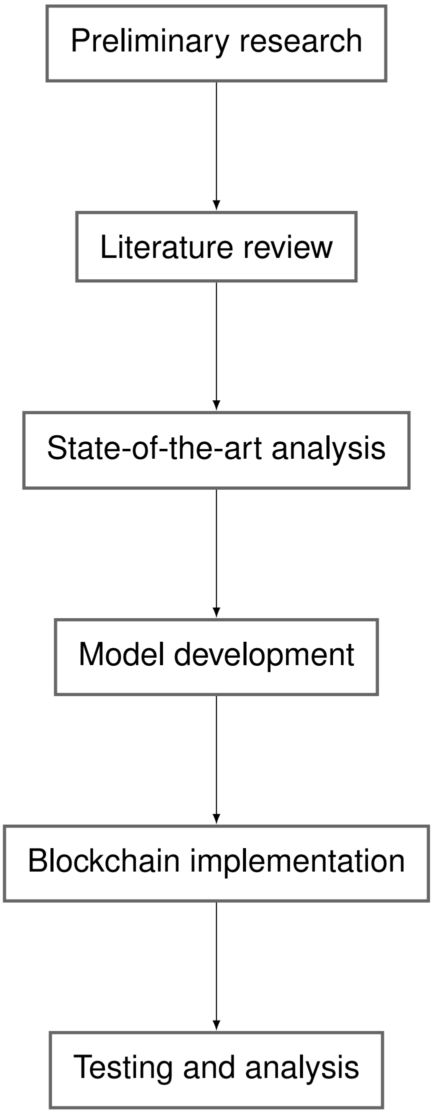

Figure 2.1: Research flow

2.3. Methodology adopted for theoretical background and literature review

To gather information from reliable sources during the process of the research, a methodology is followed while collecting information for the theoretical background and performing a literature review in a systematic way.
During the preliminary research, that resulted in the theoretical background and subsequently will be used to analyze and discuss the model, two types of information has been found:

- **Theoretical and technical information** about digitalization, Industry 4.0 technologies, and sustainability in the textile industry. This kind of information was collected mainly from research papers present on the Google Scholar database. Each paper was found singularly using keywords that best represent the topic of discussion.
- **Industrial standards and processes** were not only based on scientific publications but also books on the industry. Moreover, some information was collected aggregating different reliable websites and institutional sources.

This resulted in a background knowledge that was fundamental to understanding the status of the industry, and environmental issues caused by textile and clothing production, and already points out the opportunities that blockchain together with new technological trends can bring to the sector.
On the other hand, the literature review was performed with a systematic methodology. The literature review relied on the papers that are accessible on both Web Of Science (WoS) and Scopus since they contain a complete collection of academic research documents related to Industrial Engineering.
In the following Chapter 2.5, a more detailed analysis of how the literature review was performed gets addressed.
A query is composed using specific keywords regarding the topics of the research (Industry 4.0, Sustainability, and Textile industry) is performed in order to collect a set of scientific papers. These documents were then filtered using eligibility criteria, and after the first screening, they were categorized into clusters to identify the most relevant ones for the research.
The most pertinent papers were then analyzed and used as a base for the state-of-the-art analysis, together with complementary information found in reports from different media.

2.4. Background and motivations on the blockchain implementation

The purpose of facilitating the sharing of information between peers operating in the textile industry, as well as the structure in which firms of this sector are communicating, lead to the decision of adopting blockchain as the best technology for it.
Each of the characteristics of blockchain technology and the opportunities they bring, match the issues that this research is trying to solve.
Moreover, Industry 4.0 applications that rely on hardware, such as robotics and additive manufacturing, are more adopted in the manufacturing sector. There is an upcoming interest in software applications, like distributed ledger technologies, that are not widely adopted as their R&D cost is higher, and they require more effort to develop and integrate into established textile manufacturing businesses. By proposing a model and implementing it, this thesis is exploring the capabilities that a blockchain software solution has and how it adapts to the T&C industry.
The main characteristics of blockchain are:

- **Decentralization:** Blockchain allows the creation of a decentralized network where each of the actors participating in it doesn't have full control. This perfectly fits the scenario of textile districts, where firms operating in it create a business network but they are all at the same level.
- **Transparency and Immutability:** The data shared over the blockchain network is transparent and cannot be changed. This ensures a high level of integrity. Transparency can be regulated at various levels so that each participant can see only what he's allowed to do, allowing firms to share sensitive data.
- **Security and Trust:** Blockchain uses cryptography to secure data and transactions, making it highly resistant to fraud. Firms can therefore trust each other information, and regulatory bodies (such as certifiers and municipalities) can leverage that data to provide better services.
- **Smart Contracts:** Blockchain allows the self-execution of customized code called *smart contract* that can be personalized for each node and can regulate transactions. In textile districts, the information is shared between different actors and each of them has different needs that can be mapped using personalized smart contracts.

Finally, blockchain aims to remove intermediaries between transactions and facilitate

communication.
The goal of the model is to improve the sustainability of textile processes by collecting and sharing waste data between actors, therefore a distributed ledger that aims at the same purpose is the perfect solution to apply.

2.5. Literature Review

This literature review aims to assess the trends and technologies identified as “Industry 4.0” and the digital innovations applied in the Textile and Clothing industry, focusing on the applications that provide economic benefits, optimize their production, and improve sustainability.
Moreover, the literature review objective is to display how Industry 4.0 technologies are still not widely adopted in this industry, especially in the production process itself. A focus is put on **analyzing the role of distributed ledger technologies for the purpose of reducing environmental impacts in this sector**, as its the scope of this thesis.
By performing a literature review and integrating it with the theoretical background research, a model can be designed to cover the gaps that are eventually found in the current application of blockchain. Understanding what is the state of new digital technologies in textile processing and how this peculiar manufacturing industry works is crucial to reduce the adoption barriers of a theoretical model and will facilitate its implementation.

As summarized in Figure 2.2, the first step performed was the definition of the keywords: Industry 4.0 and synonyms, Textile and Clothing manufacturing, and Sustainability with a focus on Circular Economy, the documents are then filtered and clustered to facilitate the analysis and subsequently understanding the state-of-the-art.
The papers were collected on date 07th November 2022.

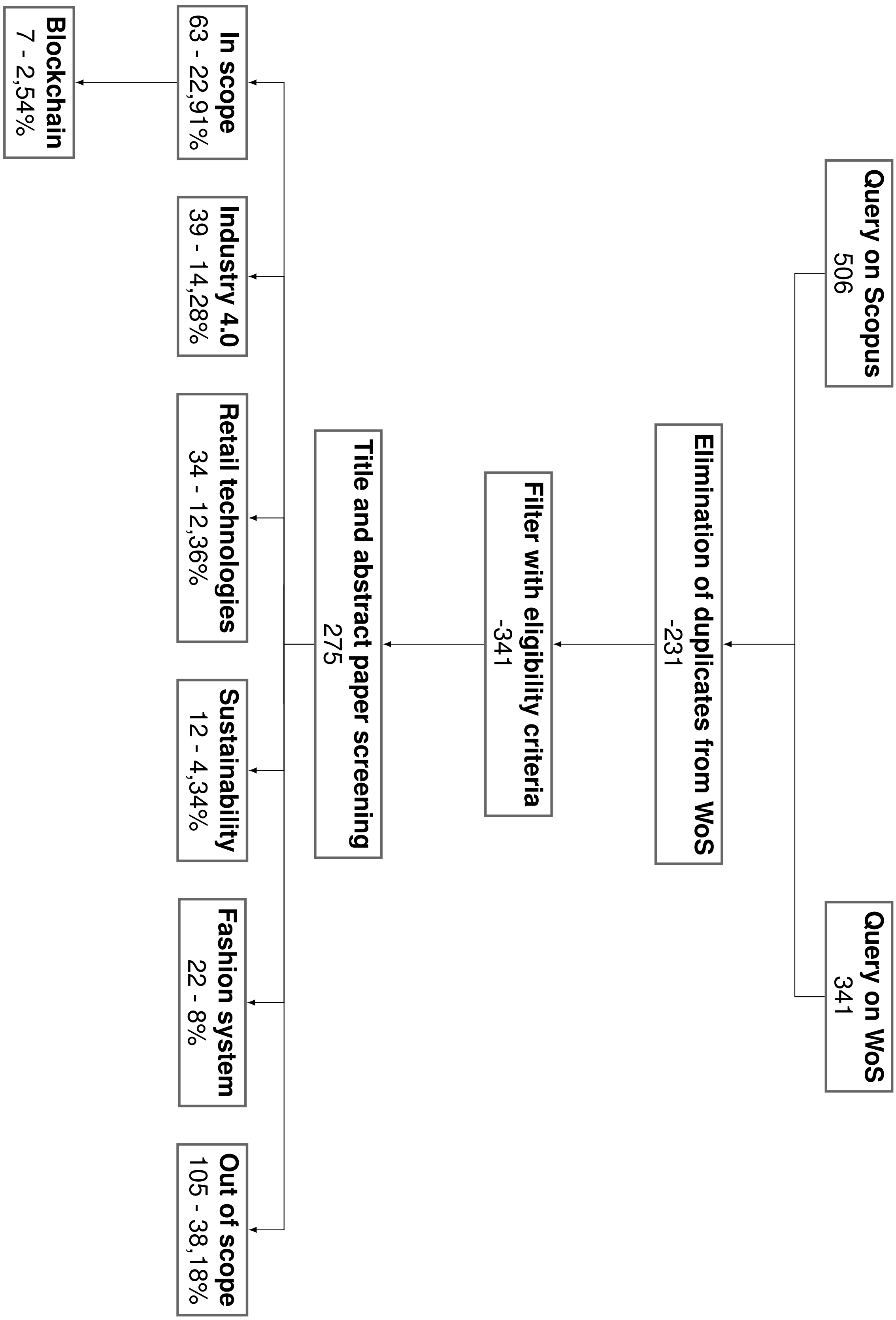

Figure 2.2: Paper screening process

2.6. Keyword and query definition

Venn diagram The definition of a specific area of research was done using the information provided by the theoretical background accordingly to the research topic of this thesis. Three main semantics area were identified:

- Industry 4.0 technologies and trends, in particular, Blockchain, Machine Learning, Internet of Things, and all the research regarding cutting-edge IT solutions. Even though this research focuses specifically on digital ledger technology the area of research was expanded to all the Industry 4.0 in order to have a global view of the digital environment, later the result will be refined through filters and clustering.
- Sustainability innovations, such as solutions regarding social and working conditions and the optimization of energy consumption in order to reduce environmental impact.
- Textile and Clothing Industry with all the research regarding both the retail and the manufacturing side of the industry.

Figure 2.3 shows the three areas of research using the Venn diagram and allows us to identify the topics that are lying in the areas between the different combinations of these three areas.
In particular, topics laying at the intersections between different areas helps to identify the clusters that will be then used to group the papers extracted during the literature review.
It can be noticed that the goal of this research lies at the intersection of all three literature areas. This subset will be the object of the state-of-the-art analysis as it includes the "applications of blockchain technologies to foster sustainability in the T&C industry".

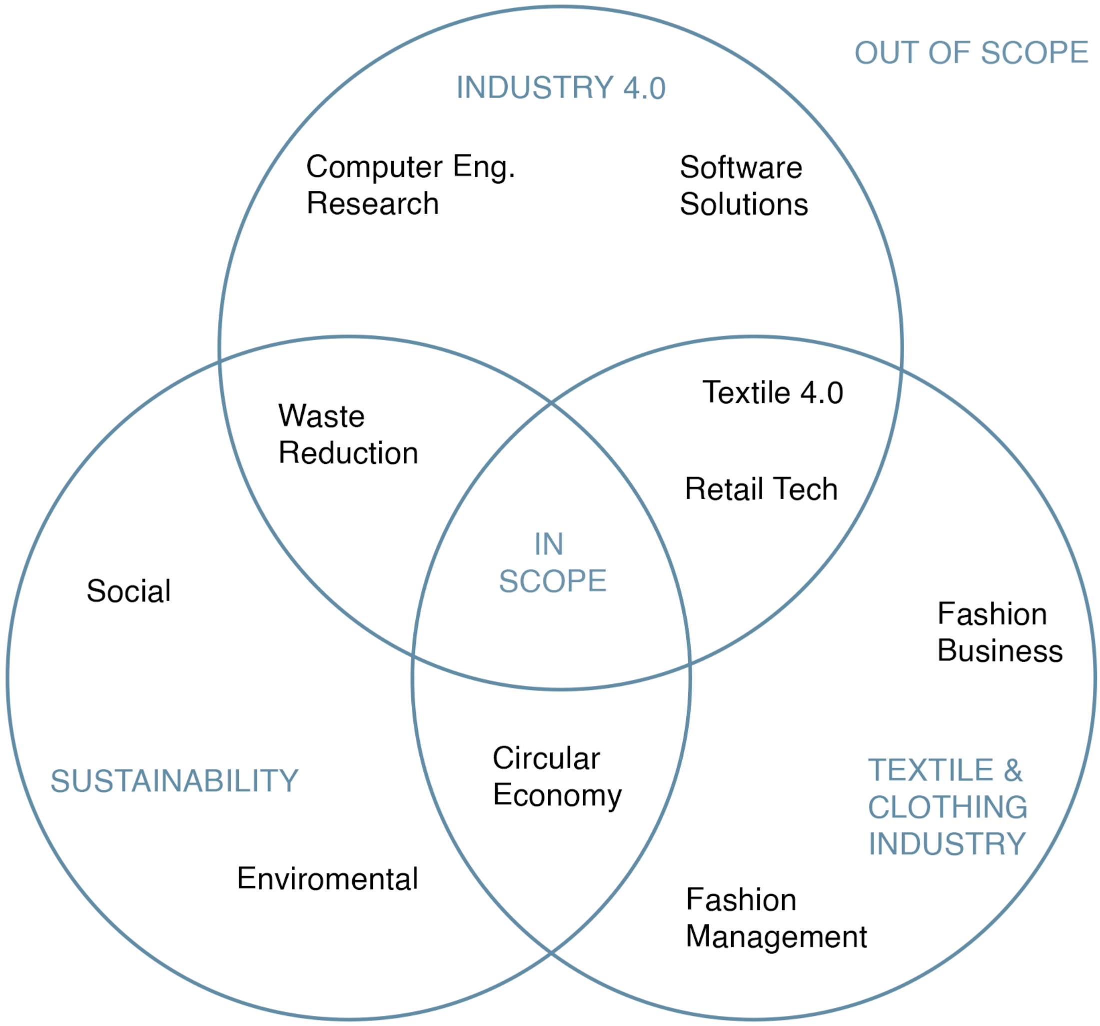

Figure 2.3: Venn diagram of the semantics area

Keywords are used to search documents in scientific databases, looking into the title and the abstract of the paper.
Starting from a previous literature review performed by Dal Forno et. al. [27] that investigates the intersection between “Textile” and “Industry 4.0”, other synonyms were added to have a complete view of the scientific publications.
To do so, the keywords related to Sustainability and Circular Economy were removed from the query, and the subgroup of documents regarding these topics will be asses during the screening process.
Moreover, by using the keyword "Industry 4.0" we expand the collection of papers for

this literature review to a wider range of technological solutions, inside which we can find distributed ledger and blockchain applications. This allows us to retrieve information on the general processes of digitalization in this industry while also being able to later filter out these papers and analyze just the documents regarding the scope of this thesis with more attention. Therefore, the resulting query is:

```
( ( "Industr* 4.0"  OR  "Smart Manufactur*"  OR  "Digital Transformation" )
AND
( "Textile*"  OR  "Clothing*"  OR  "Apparel*"  OR  "Fashion" ) )
```

2.7. Eligibility criteria and filtering

As a result of the use of two distinct databases a total of 847 documents were collected, several of which were duplicated.
The first step of filtering was eliminating the duplicates, as they don't represent additional value for the literature review.
Subsequently, the methodology adopted for filtering out the unique papers was to adopt some eligibility criteria.
The first criterion is to filter out records where the writing language of the publications wasn't English. The translation of foreign documents would have brought complexity to the process, moreover, the literature review was performed also to better understand worldwide industry standards, which are often written in English.
The second criterion was to only consider documents published in Books and Journals. Conferences and Surveys were excluded because they would not provide in-depth technical analysis of the Industry 4.0 technologies since they usually refer to a broader audience, and the keywords used to query could lead us to general conferences that are out of scope.
Filtering out duplicates and applying the eligibility criteria removed a total of 572 documents.

2.8. Screening and Clustering

The screening was performed by reading titles, abstracts, and keywords for all 275 eligible papers.
Part of the document would be read in the documents where the abstract does not state clearly the topics discussed.
The papers are classified into six clusters to allow easier navigation of the information

they provide and exclude some general categories:

- **In scope:** This cluster contains the publications that discuss digital innovations and technologies applied to Textile manufacturing and related industrial processes, primarily to improve their sustainability. This document cluster represents the foundation for the state-of-the-art analysis. A subgroup of these provides information specifically about applications of blockchain and distributed ledger technologies.
- **Industry 4.0:** This cluster contains publications that explore a wide range of Industry 4.0 technologies and their application to various other industries, either providing a general view of them or being too technical and implementing a technology that is unrelated to the textile industry. These documents are helpful since they provide a comparison metric between industries and ideas on the innovations that different technologies could bring.
- **Retail technologies:** This category includes all the applications of Industry 4.0 technologies and trends in the textile industry but with a focus on the whole supply chain or only regarding the retail customer experience. These applications, while improving sustainability, are a bit out of the scope of this research since the focus is on manufacturing processes.
- **Sustainability:** This cluster includes papers that are too focused on sustainability and circular economy, taking a management and business point of view, so they were excluded from the analysis.
- **Fashion system:** This category contains research publications regarding Fashion management and Fashion business and uses the researched keywords to introduce general topics, so this cluster is excluded from the analysis.
- **Out of scope:** This cluster contains a wide range of excluded research publications regarding Strategy, Business, and Societal trends.

2.9. Considerations on the Literature Review

From the analysis of the scientific literature, it can be recognized that the applications of Industry 4.0 technologies to foster sustainability are a trending topic in recent years, but there's a lack of these applications in the textile manufacturing industry.
Only the 22% of eligible documents were in the scope of the research (laying in the intersection of the diagram of semantic areas), and fewer of them were focused on the

blockchain.
The majority of papers that are considered that fully respect the selection criteria to be considered in a topic just propose a sustainability model or innovation, lacking its implementation or critical analysis on its application in the real world.

The adoption of the Industry 4.0 paradigm is expected to improve product quality, process sustainability, and competitiveness of the textile value chain.
Some benefits expected are optimized material flows and logistics, efficiency and cost reduction for production lines, savings on material inputs, reducing overall energy consumption. However, only a few firms actually implemented some innovative solutions [28].
Most textile firms are reluctant to innovate their production systems for two major factors:

- Digitalization and **adoption of new technologies require concentration and resources** that can't be assigned due to the demands of high-quality products demands and present customers. Competitiveness on cost pressure textile companies, which means innovative firms can't gain larger market shares offering advanced products which leads to fewer investments in R&D.
- The implementation of new **technologies depends on exchange and transparency** regarding data and sensitive information. Textile firms usually distrust each other and in some environments are very competitive, so they obstruct constructive collaborations. Secure data transmission and anonymization play a key role in the solution for this.

The use of blockchain technologies is found to not be very popular, most of the technologies widely applied in the industry are more related to electronic IoT devices and ways to directly improve production performances, while software solutions represent only a little subset of the papers clustered in scope.
There is a clear gap in the application of distributed ledger technologies. Across the pool of papers and documents selected and clustered, only 12 of them contain the keyword *"blockchain"*.
After performing the literature review we can state that the T&C industry lacks implementation of blockchain solutions.
Moreover, most of the digital ledger solutions are used to foster the traceability of products along the supply chain to either authenticate luxury items or improve its logistic, they are considered *"vertical"* solutions along the value chain. The scope of this research instead is to provide an *"horizontal"* blockchain solution that has its core in the

production system of each company and allows firms to communicate between peers at the same level, therefore it aims to fill the gap found in the literature review.

3 | Analysis of the literature

In this chapter, a review of the state of the art of blockchain technologies applied to the textile sector is performed. A focus is put on the applications that have an impact on reducing the environmental impact of the production processes or are related to sustainability practices.
As already stated before, most of the blockchain solutions found in the scientific literature clustered in the "In Scope" category of the literature review are applications of distributed ledgers in a vertical way along the whole supply chain.
The review that will be performed in this chapter is therefore useful to understand the potential impact of a horizontal solution and allows us to assess what are the current opportunities and improvements that applying this technology brings.
This chapter is also included scientific literature that has been collected by following citations and papers related to the ones contained in the systematic literature review.

3.1. Blockchain technology

As discussed before, **blockchain technology** can be the perfect tool to improve sustainability and add value to textile manufacturing. Decentralized ledger technologies allow secure and transparent sharing of data that can help to promote sustainability in areas such as reducing environmental degradation, social injustice, and labor rights violations alongside the whole supply chain.
Some applications of this technology in the textile industry are:

- The *Emission Trading Scheme* is a system in which companies are allowed to produce a certain amount of CO_2 emissions related to the quantity of ETS quotes they have. The number of these quotes is fixed across the European Union leading to a cap on the total emissions produced. In the system proposed in "Blockchain Enhanced Emission Trading Framework in Fashion Apparel Manufacturing Industry" the sustainability and emissions of each company are tracked and stored in a blockchain, that automatically trades ETS quotas between them in order to incentivize economically companies to reduce emissions. [29]

- Distribute ledger technologies can also be used to facilitate circular economy practices. The transparent tracking of the whole supply chain allows the verification of recycled yarn. Textile fibers processes and raw yarns can be tracked in order to assure high quality and the source of the textile produced. This not only reduces waste but also promotes a more circular textile industry.

3.2. Blockchain enhanced emission trading framework

This study provides a blockchain solution that aims at helping companies operating in the T&C industry at improving their sustainability. [29] Each node of the blockchain runs a smart contract with different regulations that need to be met in order to communicate and transact with other peers. This assures the integrity of the information shared while keeping customized business rules for each firm.
The research proposed in the paper is prompted by the same need for digitalization and reduction of the environmental impact of the industry as this thesis.
The Emission Trading Scheme cited in Section 3.1 wasn't designed for the T&C sector, therefore it lacks specificity. Blockchain technology allows the incorporation of all the details of textile production processes in the scheme, and exposing to the public this information motivates to reduce emissions throughout all the production steps.
Such service allows, on the one hand, the authorities to supervise and improve the operations regarding ETS, on the other hand, incentivizes firms to be more sustainable by facilitating the information exchange and the related quotes.
The framework tracks the company emissions that are shared in the distributed ledger and evaluates them in a systematic way by using a set of algorithms. The emissions are evaluated both from a company perspective and at a product level. Uncertainties are also taken into account.
After assessing the environmental performances of a firm, the system redistributes the ETS quotas and facilitates the sharing of quotas of companies with better performance, providing them with an economic incentive.
The paper provides the architecture of the model and a detailed case study for a prototype product. The comparison between a traditional mechanism of sharing ETS quotas and the blockchain-integrated one proves that the latter has significant improvements in terms of environmental performance and political acceptability.

3.3. Opportunities for blockchain in textile supply chain

In the paper by Shaik V.A. et al. [30] an analysis of the state-of-the-art digital technologies applied to the T&C industry is performed.
The research doesn't provide new frameworks or models but allows us to grasp some key ideas on the opportunities that distributed ledger technologies can bring.
Blockchain allows sharing of all transactional data between the participants of the supply chain providing customized access to it and still allowing this information to be verifiable.
The framework cited focuses, in a vertical manner, to engage the supply chain at all organizational levels.
The blockchain applications proposed include methods for personalized access to the data, configuration of private infrastructures, and networking. Therefore, the main operations that benefit from it are ordering services and membership services.
This brings great opportunities in the field of traceability, planning, and organizing, but little to no improvements on the matter of sustainability.
Segments of this research still bring key ideas, one of them being a differentiation between the data that can be shared publicly and data that needs to be kept private.
Consortium blockchain allows the differentiation of the privacy of information shared: public data can be shared with third-party operators in the supply chain, customers, and authorities; private data containing critical pieces of information can instead be shared only between restricted groups of entities. In both cases to validate the transaction the information needs to be checked against the global state of the shared ledger.

3.4. Digital transformation of circular fashion

As stated in the theoretical background, adopting a circular model in the fashion industry is the key to reducing environmental impacts, improving the overall sustainability of the industry, and providing value to the customers. Circular models often focus on reducing or reusing waste and extending the lifecycle of a product.
An article by Heim and Hopper [31] presents pilot studies of the application of blockchain for this purpose.
The opportunities that blockchain brings are its fundamental characteristics: transparency, trust, and traceability. This powerful tool perfectly applies to supply chains of any kind so it is natural to think it could also bring innovation to the T&C industry.
The cited study cases regard FibreCoin [32], VeChain [33], and Zalando [34]. All three

applications allow companies to track all the steps in their supply chain, from fiber manufacturing to finished goods. The information collected is stored in the distributed ledger and can be accessed by the final customer using the ID found on the garment. The customer can therefore have visibility of all the production steps and their environmental impact, this pushes manufacturers to optimize their production processes and improve their sustainability.

The authors of the article also conducted interviews among textile producers to identify the challenges in adopting blockchain technologies that revealed three main categories of issues: technical, social, and entrepreneurial.
The findings regarding social and entrepreneurial categories are common to the adoption of Industry 4.0 technologies, transparent communication, and cooperation between firms are fundamental to making these solutions work. Managers also expect to have a good return on investment and they perceive that the value that this application brings is not clear both to them and to the customers.

As for the technical issues, the biggest problem is common data ontology. Each firm and actor in the textile supply chain adopts a different standard for collecting and storing data. There are only a few global standards that are not widely adopted. This is the key requirement for the adoption of a solution, such as a blockchain, that is based on data sharing.
Finally, the article suggests that once these barriers are overcome, there is no doubt that distributed ledger technologies will facilitate a circular economy in fashion, especially when paired with other technologies such as IoT and RFID.

3.5. Other applications of Industry 4.0 technologies

By reviewing the scientific literature clustered in the "In Scope" and "Industry 4.0" categories of the literature review performed, a collection of technological and software solutions applied to the industry is composed. This analysis allows us to have an idea of the opportunities that all the other technologies bring, as most of them *(especially the Internet of Things)* could be enhanced by integrating blockchain technology.
This is also useful to provide a clear and global view of the digitalization process of the industry, even if it goes outside the scope of this research.
Technologies such as IoT, RFID, and Artificial Intelligence can also have an impact on the sustainability of companies' production processes and they can be seamlessly in-

tegrated with distributed ledger solutions to unlock their full potential.
The industry 4.0 technologies presented in this section can all be used to collect data at different points of production. This data can then be elaborated and stored on a blockchain system to provide transparency and security to the information.

3.5.1. Internet of Things (IoT)

Internet of Things (IoT) refers to the interconnection via the internet of all the embedded devices and sensors that are present in modern manufacturing robots. Sensors and devices can collect data alongside the value chain, this data is then transformed into information that is used to optimize processes and resource usage.
The use of this technology in textile manufacturing is increasing and leads to opportunities to enhance sustainability by reducing waste, optimizing raw material usage, and lowering the environmental impact of production.
The application of IoT devices enables the use of all the other technologies discussed in the state-of-the-art.
With such sensors, the energy and water used in textile production can be monitored and reduced. Moreover, IoT devices can track and trace the whole supply chain allowing for more transparent and sustainable production processes.
IoT solutions are implemented in almost any manufacturer of spinning and knitting robots on the market, allowing the machine to understand and analyze the environment where it is working. Moreover, these solutions are supported by software services that allow companies to leverage the data obtained. [35]

3.5.2. Radio-Frequency Identification (RFID)

Radio Frequency Identification (RFID) is a technology that allows the identification of products in a hand-free way using electromagnetic waves.
The key advantage of this technology in the manufacturing industry is that identification can happen at a distance.
Using RFID a company can store data regarding the production process of each individual item that can be then leveraged to improve operations.
There are three elements that compose an infrastructure using RFID: [36]

- **RFID tags**: tags can be either passive or active, a passive tag turns on when scanned while an active tag is always on. Tags are composed of an antenna, a small battery, a memory to store data, and eventually some sensors to communicate with the environment.

- **RFID reader**: the reader, or scanner, is how the information is read from tags and stored in the system. When a tag is activated its unique identification code and the data saved in the memory are communicated to the reader.
- **RFID system**: the system is composed of a database where the information is stored and analyzed and all the types of machinery that save data into the tags.

The most common application of this technology in the textile and apparel manufacturing industry is supply chain tracking. Each product has an RFID attached to it, from production to the consumer. At each step of the supply chain, the tag is read and the information is stored in the database allowing transparency along the chain in order to provide the user with more value and at the same time give the company data to optimize the chain. [37]
Another application of RFID tags is the configuration of sizing, cutting, and yarning machines. Along the production process materials and textiles are associated with RFID tags that when being processed communicate the product characteristics and allow the machine to configure the process parameters, [38]
As for the recycling and dismantling of clothes in order to collect the fibers which are composed, each garment can be associated with an RFID on its label, which not only can allow customers to have information about the composition but can also inform recycling companies on how to dismantle and process the item with the right parameters and chemicals to have a more sustainable process.

3.5.3. Artificial Intelligence and Machine Learning

Artificial intelligence (AI) is the ability of a system to mock the human brain functions like learning and problem-solving. AI uses mathematical models to replicate these functions. The manufacturing industry is becoming a fundamental tool to enhance quality, lower operating costs and control production systems in real-time.
Machine learning is the way in which an AI trains using a set of data, without getting explicit instructions from a human. This automatic way of learning allows the system to improve using its previous results and experience.
The most common way of machine learning is called *neural network*, a group of algorithms and models that tries to replicate the connections between neurons in the human brain.
In the state-of-art, there can be found many applications of AI and Machine Learning applied to the textile industry:

- Quality control: machine learning algorithms can be used to identify faults in textiles and garments during the production process. One way to reduce faults is preventive maintenance and fault detection, by simulating the environment and parameters of the production, an AI can try to predict which garments and textiles are most likely to come out below quality standards. An application of this algorithm can be found in Seçkin et al. regarding glove manufacturing. [39]
  By using a set of pictures containing common faults in the textile such as missing yarns, print defects, and needle lines it is possible to recognize automatically when a textile is faulted. The system after being trained on faulted textiles inspects the output with cameras and is able to recognize efficiently which parts have a mistake and improves real-time production schedules and decision-making. [40]
- Inventory management: by using artificial intelligence is possible to predict the demand for textiles, helping manufacturers to optimize stocks and reduce waste.
- Design and development of the product: machine learning can be used to forecasts trends based on data coming from the internet and buyers, analyzing consumer preferences. This lead to an improvement in production and designers' efficiency and drives sales. The system is also capable to work with constraints on material availability.
- Energy consumption: machine learning is also useful to improve energy consumption and sustainability. Analyzing data coming from sensors along the whole supply chain, an intelligent system can identify ways to optimize production schedules and supply chain routes in order to not only generate profit but also improve sustainability and meet green standards.

3.5.4. Cloud Computing

Cloud computing is a service that allows access to shared computer resources, such as storage and computation, over the internet. One of the main advantages of this technology, especially for the manufacturing industry, is the ability to access and store large amounts of data from anywhere just with access to a fast internet connection. This can enable the sharing and elaboration of all the information from machines, sensors, and IoT devices that can then be analyzed to identify patterns and optimize operations.
Another advantage of cloud computing is the ability to improve agility, scaling IT resources up or down as the demands for production change. The time and costs associated with the purchase and maintenance of the infrastructure are externalized to the

provider of the service. This also reduces entry barriers to the adoption of new technology, which is usually a key pain point for companies operating in traditional industries such as manufacturing.
For manufacturers with multiple factories in different locations, cloud computing can improve collaboration among departments and partners. The information stored in the cloud can be accessed by all the employees facilitating a more efficient collaboration.
In the literature review performed, we find applications of cloud computing in textile manufacturing such as:

- Cloud-based systems can enhance the collaboration among different actors along the supply chain such as manufacturers, suppliers, and retailers. Providing a centralized platform to share data can facilitate handling unpredictable demands, cross-border trades, and communication between all trading partners. [41]
- *Advanced Planning and Scheduling systems* are fundamental systems used to optimize the process scheduling of a manufacturing company. This system can be deployed in a cloud or hybrid way in order to improve the modeling efficiency and have data coherence between the other ERP systems in the company. [42] Other parts of the ERP system can leverage cloud computing for example providing a global real-time machine availability and production capacity across multiple locations.
- Textiles and garments companies usually work in divisions, each of them responsible for a specific part of the project, such as the design, operations, accounting, and management. A cloud-based information-sharing system can help to collaborate not only between external actors but internally in the company, allowing seamless product development. [43]

3.6. Prato Circular City: an Industrial Symbiosis application

Prato Circular City (PCC) represents the integrated strategy promoted by the City of Prato to promote the city's transition to a circular economy following the European Union regulations presented in 2020. [3]
This program aims to foster the development and affirmation of circular models aimed at sustainability that are increasingly systemic and integrated, flanking the many virtuous initiatives born at the level of individual enterprises.
The homogeneous production district that characterizes the Prato area focused on the

textile manufacturing industry, has characteristics that are particularly well suited to fostering a transition to the circular economy, innovation, and sustainability, as it lends itself well to the application of the principles of Industrial Symbiosis.
In launching the Prato Circular City strategy, the city government set the following goals:

- Promote the city's transition to a circular economy.
- Strengthen the image of Prato as a "circular city".
- Establish a permanent environment for discussion among local stakeholders to promote shared, integrated, and participatory circular economy actions.
- Create circular city governance.

All the actions developed are included in a strategic plan for digitization and Industry 4.0 designed to provide companies, municipalities, and citizens with the tools needed to implement projects for this transition.
The model that the City of Prato has been proposing for some years at the European level is that of a "circular city" based on three fundamental axes:

- The innovation of production processes.
- Urban regeneration
- The strengthening of social cohesion

Building on the experience gained within the European partnership, Prato Circular City proposes a similar working methodology, adapted to the city and district levels.
The actions developed in Prato Circular City aim to contribute to the following Agenda 2030 sustainable development goals in Figure 3.1.

Within the PCC strategic plan, the municipality of Prato is discussing wastewater reuse. Prato was the first textile district to arrange a water reuse cycle so firms in the district are able to reuse wastewater more than one time within the textile production process. In 1981 the *Gestione Impianti Depurazione Acque S.p.A.* (GIDA) constructed a treatment plant in Baciacavallo, this was the first plant of the current centralized system of civil and industrial wastewater treatment, which aims at providing safety to the population of the municipality for biological and chemical hazards and also provide to the water-intensive needs of the firms operating in the T&C industry. The structure that GIDA put in place is synergetic to the PCC strategy established in more recent years.
On weekdays the plant can treat up to 130,000 m^3/d, breaking down up to 100,000 kg of COD per day and 4,500 kg of surfactants per day. It essentially consists of stages for equalization, primary sedimentation, biological oxidation, sedimentation, flocculation,

Figure 3.1: Sustainability development goals of PCC [3]

and a final refinement with ozone to remove color and surface residues. The sludge line consists of gravity thickening, mechanical dewatering by centrifugation, and sludge incineration. [22]

Wastewater treatment plants play a fundamental role in the water supply chain as they enable water sanitation and reuse, even though this water cannot be released directly into the environment, as the environment is not able to degrade quantities of polluting substances higher than their own disposal capacity, they can be reused for future textile manufacturing processes. Development plans for the Prato textile district also consider construction plans focussed on fostering sustainability. Based on a collaborative model supported by distributed ledger technologies, instead of a single wastewater treatment plant, smaller treatment facilities can be built in proximity to each textile manufacturer. The information distributed between the producers of wastewater and the receiver of it can be leveraged to increase the specialization of each individual treatment process, allowing companies to operate more locally and in a collaborative way, optimizing the exchange of waste and resources and the sustainability of the whole process.

3.7. Standards and certificates as sustainable practices

Textile manufacturing sustainability certifications are third-party certifications offered by private or public companies that aim at evaluating the production processes and their environmental impact. These certifications also provide standards to follow that help

manufacturers to assure that their production follows local regulations and laws. Certifications allow consumers to be sure that the textiles and clothing they are purchasing have been produced in a sustainable and ethical manner. Therefore, consumers can make a more informed purchasing decision and manufacturers are encouraged to promote transparency and disclosure of their production practices.
Manufacturers are evaluated along different aspects of the production process such as water and energy usage, labor conditions, and chemical management. [44]
The role of certifying bodies is not only to measure standards but also to provide a way to monitor and reduce the environmental impact of the firms. For this purpose, proposing innovative solutions to track and collect information about sustainability, and more specifically waste produced, is crucial.
Standards and certifications bring both advantages and disadvantages to firms requesting them:

- Standards aid in minimizing waste, as monitoring some parameters and providing a way to do so, facilitates the firms to lead towards sustainable development and measure the impact of their decisions in terms of environmental impact and waste produced. Moreover, standards and working towards complying with them helps firms to cutting down costs and increase their productivity.
- Standardization of procedures and collection of data helps innovation and fast-changing technologies adoption easier. Setting collection and communication standards for data and procedures is fundamental especially when working on technologies that require information sharing. Standards also often help to ensure safety, as procedures are tested and it can be measured if a firm is working correctly.
- Especially in the textile industry there are many standards and certifying bodies with similar objectives but different requirements. This makes it difficult for organizations to choose a suitable standard to follow. Moreover, implementing the standard may take extra time and money, resulting in a loss of productivity for the initial period. Proposing a global standard that is easy to implement is therefore important.

3.8. Textile dye wastewater

Based on the research discussed in Chapter 1, the process of fiber and textile production in factories is incredibly heavy for the environment.

The production process is divided into two parts: dry and wet processes. The wet process uses a considerable quantity of potable water and releases highly contaminated wastewater. This process consists of sizing, de-sizing, sourcing, bleaching, mercerizing, dyeing, printing, and finishing techniques. Each of the steps discharges wastewater with different pollution. [45]

For the scope of this thesis, it is important to understand which are the typical characteristics of textile effluents in order to be able to design a model that can standardize and track this information.

Effluents usually contain mixtures of dyes, chemicals, and solids (such as metals). In order to have a more efficient treatment process all these parameters needs to be evaluated, as different concentrations and values of chemicals require different treatment processes and techniques.

In Table 3.1 and Table 3.2 the typical characteristics of effluents are summarized. Each source provides data that is similar for some parameters but very different for others. This is because wastewater has different standards and regulations for each industry and geographical area.

References	Ghaly et al. (2014)	Kehinde and Aziz (2014)	Hussein (2013)
Temp. (℃)	35–45	21–62	33–45
pH (–)	6–10	6.95–11.8	5.5–10.5
Colour (Pt-Co)	50–2500	50–2500	
COD (mg/l)	150–12,000	150–30,000	150–10,000
BOD (mg/l)	80–6000	80–6000	100–4000
EC (µS/cm)			
TS (mg/l)		6000–7000	
TSS (mg/l)	15–8000	15–8000	100–5000
TDS (mg/l)	2900–3100	2900–3100	1500–6000
Chlorine (mg/l)	1000–6000		
Chlorides (mg/l)			200–6000
Free chlorine (mg/l)	<10		
TA (mg/l) as CaCo3		17–22	500–800
TH (mg/l) as CaCo3			
TKN (mg/l)	70–80	70–80	70–80
TNK(mg/l)	10–30		
NO3-N (mg/l)	<5		
Free ammonia (mg/l)	<10		
Na2CO3 (mg/l)			
NaOH (mg/l)			
NaCl (mg/l)			
Phosphate (mg/l)	<10		
Sulphates (mg/l)	600–1000		500–700
Sulphides (mg/l)			5–20
Sulphur trioxide (mg/l)			
Oil and grease (mg/l)	10–30	5–5.5	10–50
Dye (mg/l)			
Zink (mg/l)	<10		3–6
Nickel (mg/l)	<10		
Manganese (mg/l)	<10		
Iron (mg/l)	<10		
Copper (mg/l)	<10		2–6
Boron (mg/l)	<10		
Arsenic (mg/l)	<10		
Silica (mg/l)	<15		
Mercury (mg/l)	<10		
Fluorine (mg/l)	<10		
Chromium (mg/l)			2–5
Potassium (mg/l)			30–50
Sodium (mg/l)	7000		400–2175

Table 3.1: Typical characteristics of textile effluents [45]

References	Upadhye and Joshi (2012)	Kalra et al. (2011)	Al-Kdasi et al. (2005) and Turhan and Turgut (2009)
Temp. (℃)	35–45	35–45	35–45
pH (–)	6–10	6–10	7–9
Colour (Pt–Co)	50–2500	50–2500	
COD (mg/l)	150–10,000	150–10,000	150–12,000
BOD (mg/l)	100–4000	100–4000	80–6000
EC (µS/cm)			
TS (mg/l)			
TSS (mg/l)	100–5000	100–5000	15–8000
TDS (mg/l)	1800–6000	1800–6000	2900–3100
Chlorine (mg/l)			
Chlorides (mg/l)	3000–6000		
Free chlorine (mg/l)			
TA (mg/l) as CaCo3	500–800		
TH (mg/l) as CaCo3			
TKN (mg/l)	70–80	70–80	70–80
TNK(mg/l)			
NO3–N (mg/l)			
Free ammonia (mg/l)			
Na2CO3 (mg/l)			
NaOH (mg/l)			
NaCl (mg/l)			
Phosphate (mg/l)			
Sulphates (mg/l)			
Sulphides (mg/l)			
Sulphur trioxide (mg/l)			
Oil and grease (mg/l)	10–30		
Dye (mg/l)			
Zink (mg/l)			
Nickel (mg/l)			
Manganese (mg/l)			
Iron (mg/l)			
Copper (mg/l)			
Boron (mg/l)			
Arsenic (mg/l)			
Silica (mg/l)			
Mercury (mg/l)			
Fluorine (mg/l)			
Chromium (mg/l)			
Potassium (mg/l)			
Sodium (mg/l)	610–2175	7000	

Table 3.2: Typical characteristics of textile effluents [45]

4 | Requirements for the model and application

From the analysis of the literature review performed in Chapter 2.5 and the subsequent state-of-the-art discussed in Chapter 3 it's clear that the adoption of blockchain solutions in the textile industry is not yet widely spread.
The cases cited in the literature mostly consider the whole supply chain and its transactions. Instead, this research, the model, and the application proposed need to fulfill the gap of DLT applications that focus on sustainability at a production level *horizontally*, between firms at the same level.
The model that is designed aims to cover a set of requirements that are both technical and practical because it needs to operate in an industry where the adoption of new digital technologies is low.
Moreover, it needs to be designed with the software requirements in mind, as one of the objectives of this research is to provide a concrete implementation of the solution.
The first two requirements are:

- **R0.** The software allows different kinds of actors to interact and share data between them in a secure and transparent way, as collaboration in textile districts is known to bring improvements both in terms of sustainability and economic terms. [25]

- **R1.** The software allows firms to store data regarding textile processing and the sustainability of the practices they adopt in a standardized way as standardization is a key requirement to facilitate the certification process and the adoption of best practices. [44]

These requirements come directly from the analysis of how the textile industry would benefit from adopting a blockchain solution as discussed in Section 3.4.
Transparency and privacy are requirements that can be fulfilled by using a consortium model, where different actors can access different data, while still being at the same level in the supply chain.

Standardization is therefore natural to be able to share data between firms.

The second set of requirements is set to bring value to the firms adopting the model and to facilitate the flow of information between the numerous actors. The mapping of the interactions between firms operating in textile districts can be inferred by analyzing the structure of the Prato Circular City program [3] and the evidence found in the literature on the matter of industrial symbiosis. [21]

- **R2.** The software allows firms to exchange the data stored between multiple actors operating in the same district.
- **R3.** The software allows certifying bodies to automatically check if a firm respect the sustainability standards set.
- **R4.** The software allows certifying bodies to issue sustainability-related certifications to textile firms that share data with them.
- **R5.** The software provides a system that allows municipalities to retrieve data regarding the sustainability of firms operating in their district.
- **R6.** The software allows municipalities to coordinate waste management services and exchanges between firms operating in their district.

Setting up requirements for the model to be designed assures that the model has its foundations in the theoretical notions found in the literature. Moreover, it is a best practice in the software implementation of complex projects because it allows us to evaluate the results and test the solution implemented.

5 | Proposed model

The proposed model is useful for exchanging, storing, and standardizing data regarding the sustainability of textile manufacturing processes, in particular wastewater effluents. The model also simplifies information transactions between firms operating in the same district fostering circularity and industrial symbiosis. This chapter describes the key concepts behind this model and the motivations that lead to system design choices. In the following chapter instead an implementation of the model using blockchain is provided.

5.1. Model explanation and information sharing flows

The model proposed is represented in Figure 5.1 where the flow of information and the interactions between each actor in the system are shown.
As displayed, the model follows the application of industrial symbiosis that the Municipality of Prato implemented, discussed in Section 3.6. The peers that are represented in the model design are textile firms, certifying bodies, and municipalities, supported by some actors that act as facilitators.
The system, therefore, takes inspiration from the way firms operate in districts such as the Prato one, explained in the paper by Borsacchi et al. (2018) [22] and previously analyzed, and proposes a new way in which actors can share information related to their waste.

Actors interact with the distributed ledger via a blockchain node that allows them to send and receive information that is validated by the blockchain itself using cryptography, this operation is called *transaction*. The information shared using transactions is transparent, reliable, and immutable.
There are three main actors in the system:

- **Textile manufacturers:** Textile manufacturers are firms working in the T&C industry, in the model proposed each of these firms needs to apply circularity principles to their production processes. Each firm produces wastewater as a result of the dyeing and processing of textile fibers, the hazardous chemicals and the sustainability metrics of the wastewater are tracked using IoT devices and shared on the distributed ledger. Between them, some firms can also process wastewater locally so that can be reused for future production processes.

- **Certifiers:** Certifying bodies are institutions that aim to assess the environmental impact of firms in the T&C industry and provide them a certification if they respect some standards. By sharing on the distributed ledger the standard requirements that a firm has to respect, the procedure to obtain certification can be automatized.

- **Municipalities:** Municipalities are public institutions governing a certain area or textile district. Public institutions play a key role in the management of circularity and industrial symbiosis in the area they govern. As Prato Circular City shows, municipalities not only have the duty to create laws and regulations that push the transition to a more sustainable system, but they also have a central role in management and coordination between firms that want to exchange their waste resources or require waste to be recycled and reused from other companies.

In order to manage the blockchain network, the model requires two supporting roles: a Notary and a Network Operator. Their duties are explained in detail in Chapter 6 as they are specific to the blockchain solution chosen to implement the model.

- **Notary:** The notary's role is to supervise and validate transactions between two actors. Notaries are important because in distributed systems malevolent agents could use a technique called *double spending* to try to add on the ledger transactions that are not approved.
  Notaries can represent third-party firms that verify that the data inserted in the blockchain by manufacturers represent reality.

- **Network Operator:** The network operator's role is to manage the distributed network and the permissions of each actor interacting on it. While in a public blockchain, each node has the same permissions and rights to share transactions, in a private or consortium blockchain each node has a different role and access to the distributed network is limited, therefore an admin of the network is necessary.

The model proposed facilitates the sharing of information between the main actors of the distributed ledger network, creating therefore circularity of data (and the related wastewater) in the same textile district. The principal interactions that a Textile Manufacturer does are the request for a sustainability certification from a Certifier and the exchange of wastewater between other firms in its district. These interactions were translated into multiple information flows between actors, in particular:

- **A Textile Firm shares data regarding its wastewater pollution to a Certifier.** Data about hazardous substances and chemical components contained in effluents are communicated to a certifying body in order to receive the certification. This communication can be scheduled each time a batch of wastewater is produced after textile processing.
- A **Certifier, upon receiving pollution data, issues a certification in response.** After receiving information from a textile firm, a certifying body compare the data with its own standard, in case all the requirements are met a certification is issued to such textile company. Else, the rejection is transmitted to the firm with a brief explanation of the parameters that weren't acceptable.
- **A Textile Firm requests wastewater from the Municipality or informs the Municipality that they produced an excess of wastewater.** To promote the circularity of waste, a firm can communicate with the municipality every time it produces excess wastewater, providing also information about the environmental impact of that waste and its composition. Municipalities can also receive communications about a request for waste from companies that have the capability to recycle that material. Such companies will have an economic incentive to request and reuse waste instead of utilizing new resources for their production.
- **The Municipality, upon receiving a request, shares information with the Textile Firm about other firms that have an excess of wastewater.** Municipalities play an important managing role. Once inquired about the wastewater availability in their textile district they can provide to the textile firm a list of available other companies that have an excess of waste and the information about the hazardous chemicals of it. Firms receiving that list can then check which of the waste they can recycle and therefore which other firm in the district could provide it.

This structure provides a model that allows a transparent exchange of information between firms fostering their collaboration in industrial symbiosis. This collaboration reduces the environmental impact of company processes and the effort required for such companies to apply sustainability practices. An advanced environment regarding industrial processes, digitization, and regulations is required to make the model work efficiently, therefore municipalities play an important role in it.

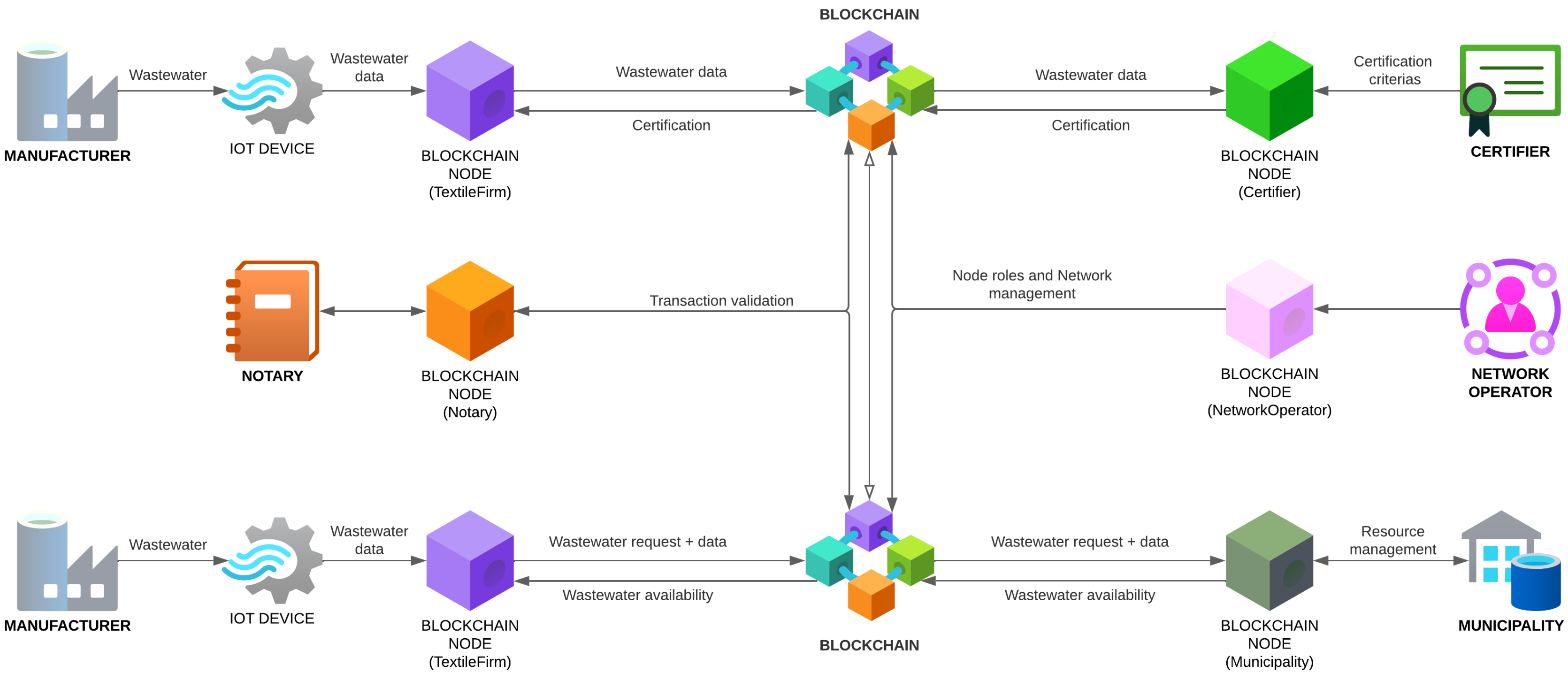

Figure 5.1: Sharing of information between the involved actors in the proposed model

5.2. Modelling the waste information shared

As discussed in Chapter 1, the T&C industry is responsible for many environmental pollution problems. One of the most impacting is wastewater, which is water that has been used during dyeing and finishing processes and so contains a mix of various contaminants at a variety of ranges.

The legislation allows firms to treat these effluents and reuse them for other textile processing instead of discharging them into the watercourse.

Therefore during the treatment process, it's fundamental to monitor and compare parameters such as *pH*, *Suspended Solids* (SS), *Chemical Oxygen Demand* (COD), and more.

As discussed in Section 3.8, collecting and monitoring these parameter values allows companies to choose which water treatment method to use and the number of chemicals to use for each treatment, allowing the firm not only to optimize the treatment process but also to reduce its impact of it.

The exchange of this data between firms in the same districts also allows them to choose the most suitable wastewater provider based on the receiving firm's treatment plant and procedures.

Table 3.1 and Table 3.2 display the typical characteristics of textile wastewater. Starting from this data from various references, a subgroup of the most relevant and tracked parameters have been chosen. In particular, the choice was to track the parameters that were more commonly collected between firms and previous research:

- Temperature
- pH
- Chemical Oxygen Demand (COD)
- Biological Oxygen Demand (BOD)
- Total Dissolved Solids (TDS)
- Chlorides
- Total Kjeldahl Nitrogen (TKN)
- Sulphates
- Oil and grease
- Zink

- Copper
- Arsenic
- Sodium

These parameters and the related data will be shared between firms in a standardized format. The format follows the JSON standard as it allows future changes and additions. As each individual firm operating in the district can track or may want to share, a different number and type of parameters, the standard needs to allow it. Moreover, legislations are different in each country or territory, particular regions may want to keep track of specific parameters for their environmental safety.

5.3. Textile manufacturing sustainability certification

As previously reported in Section 3.7, the T&C environmental impact can be measured, and when a firm meets the standard requirements that third parties company and legislators set, they are eligible to receive a certification that often adds value to their production.
The worldwide leading textile processing standard for organic fibers is the T&C industry is the **Global Organic Textile Standard** (GOTS), which covers the whole textile supply chain. [46]
Consulting a wide range of standards, such as GOTS and the European Union Ecolabel [47], and benchmarks across different certifications discussed in Section 3.7, limits for the chemicals and hazardous materials inside textile wastewater were extrapolated. The provided limits allow us to create a mock requirement standard to use during the model implementation that focuses on the specific characteristics of effluents that are tracked. Each certification body can then provide its own standard values.

- Temperature $\leq$ 35 ℃ unless the temperature of the receiving water is above this value.
- pH between 6 and 9 unless the pH of the receiving water is outside this range.
- Chemical Oxygen Demand (COD) shall not exceed 20 g COD/kg of processed textile output.
- Biological Oxygen Demand (BOD): Most standards don't provide a limit value but effluents are considered rapidly degradable when the ratio of BOD5/COD is $\geq$ 0,5, so with the limit of COD $\leq$ 20 g/kg of processed textile we obtain that the

BOD shall not exceed 10000 g/kg of processed textile output.

- Total Dissolved Solids (TDS) $\leq$ 2100 mg/l in most industries.
- Chlorides $\leq$ 600mg/l In most industries across the world, Italian legislation puts a limit of up to 1200mg/l. [48]
- Total Kjeldahl Nitrogen (TKN) typically between 35 and 60 mg/l. [49]
- Sulphates $\leq$ 2000 mg/l for most industrial wastewater discharges across the world, $\leq$ 1000 according to Italian legislation for effluents to sewers. [50] [48]
- Oil and grease $\leq$ 200 mg/l for industrial wastewater discharges across the world, the Italian regulatory system for sewers discharge limit is $\leq$ 40 mg/l but it may be inaccurate in our use case. [50] [48]
- Zinc $\leq$ 1,0 mg/l. [48]
- Copper is permitted up to 5% per weight for specific dyes and pigments in goods, while a limit value < 4 mg/l is set for sewer wastewater from industries. [48]
- Arsenic < 0.2 mg/kg.
- Sodium limit values have not been found in the literature but an estimation based on data collected can be used to set a limit value up to 2100 mg/l.

The parameters on this list are stored on the certifiers entity following the same format as the data shared by textile firms allowing easy comparison and a model that allows future changes and additions as some standards may differ on the kind of parameters and data used to provide the certification.
An example of the JSON standard format to set the certification parameters, which is the same standard used to share the wastewater data, can be found in Figure 5.2.

```
{
  "SMC1_cod": {
    "naturalFiberManufacturingValue": 20.0,
    "syntheticFiberManufacturingValue": 20.0,
    "spinningValue": 20.0,
    "weavingValue": 0.0,
    "dyeingValue": 20.0,
    "cuttingSewingValue": 0.0
  },
  "SMC1_bod": {
    "naturalFiberManufacturingValue": 10000.0,
    "syntheticFiberManufacturingValue": 10000.0,
    "spinningValue": 10000.0,
    "weavingValue": 0.0,
    "dyeingValue": 10000.0,
    "cuttingSewingValue": 0.0
  },
  "SMC1_chlorides": {
    "naturalFiberManufacturingValue": 1200.0,
    "syntheticFiberManufacturingValue": 1200.0,
    "spinningValue": 0.0,
    "weavingValue": 0.0,
    "dyeingValue": 1200.0,
    "cuttingSewingValue": 0.0
  },
  [...for all the parameters set]
```

Figure 5.2: JSON standard for certification parameters

5.4. Categorization of waste parameters and standardization

The model in which data is shared and compared to the standard has to be both standardized and flexible. The scope of the project implemented wastewater sharing but companies may want to exchange and reuse all kinds of waste.
In order to obtain a complete view of the sustainability of a company the data has to be

collected throughout the production process. Following the steps illustrated in Section 1.3 the data for each parameter needs to be collected during:

- Natural fiber manufacturing
- Syntethic fiber manufacturing
- Spinning
- Weaving
- Dyeing
- Cutting and sewing

In the model presented wastewater data is mostly collected during fiber manufacturing and the dyeing process.
Each of the parameters is also grouped into a Sustainability Macro Category. Each category helps firms to clearly understand which parameters they need to improve and aligns the model to the standardization already provided by United Nations Economic Commission for Europe in their documents.
The SMC in the model are:

- SMC 1: Hazardous chemicals
- SMC 2: Water pollution
- SMC 3: Air pollution
- SMC 4: Energy efficiency
- SMC 5: Solid waste

Regarding textile effluents, the main categories of the parameters collected are hazardous chemicals, which are a crucial component of all certifications and represent a risk for workers involved in the production process, and water pollution, since responsible use of water is a priority for ensuring an adequate, safe, and clean production.

5.5. From IoT to distributed transactions

As remarked in Chapter 3, IoT technologies are essential to collect data across the production processes in an efficient and continuous way. At the same time, IoT devices can lead to difficulties and problems as the amount of data they produce is huge and they're very prone to malfunctions. A distributed system of IoT devices paired with

a distributed ledger technology, such as Blockchain, seems the perfect way to cope with these problems.
Since IoT devices miss a consensus mechanism to validate the data stored they don't represent a solution to the need for transparency and immutability that blockchain provides, but they are the best way to collect that data to store it in a scalable way.
The main challenge related to the integration between IoT and blockchain is the huge amount of transactions per second that the big number of IoT devices generates. In the model proposed this problem is mitigated by the fact that the data is stored on-chain only when this information is transmitted to either a municipality or a certifier. Moreover, each transaction on the most popular blockchain technologies can take a long amount of time with a high monetary cost. This is mitigated by the fact that in the model the transactions are not required in real-time and applying to get a certification have an impact on the firm finances even with the current process.
Moreover, the blockchain chosen for the model implementation, **R3 Corda**, is highly compatible with most IoT devices and allows 10000 free transactions and a low service fee for network maintenance. This together with the benefits that will be explained in Chapter 6 makes it the perfect candidate to serve this purpose.

6 | Development of a Blockchain solution

This chapter provides technical documentation and an explanation of the implementation of the model provided. The distributed ledger solution chosen is explained in detail and an overview of the architecture of the software implemented is displayed. The model's architecture is directly translated into the implementation of the blockchain solution, so it can be easily adopted in a production environment to understand its perks. Finally, a discussion on how the model was implemented and tested is provided so that an analysis of the opportunities and limitations can be performed.

6.1. R3 Corda

The different needs for trust, security, transparency, and traceability of the data inside the network requested from the T&C industry align with the characteristic of permissioned blockchain. **R3 Corda is a distributed ledger technology that allows sharing of information between nodes in an efficient way and with different levels of privacy**, this solution perfectly fits the needs of the industry. [51] [52]
The Corda network is composed of nodes that communicate with each other with point-to-point transactions, without the need for a global broadcast of information. That allows firms operating in the same district to share information only between parties that they fully trust, allowing them to keep some secret information that can represent a competitive edge.
The network is permissioned and the access is regulated through an entity called Network Operator that manages the access to it, the identity of each node participating, and their roles, allowing categorization between different kinds of nodes that can access different sets of transactions. This aligns with the need of having different entities that collaborate inside the same textile district.
Each peer of the network has a well-known identity that links it to a real-world institution and it's used to represent the node in transactions. A network map service is used

to share the identities of nodes across the distributed system granting scalability and making it easier to add a new node to the network.
Each node maintains its own database of data and the facts it's aware of. The distributed ledger is therefore a composition of all the subsets of data contained in single nodes. Once a transaction happens the nodes involved that share facts and both nodes will have an exactly identical version of the data, so the immutability and correctness of the information are still assured.

6.2. Corda key concepts

Facts are represented on the blockchain as **states**, which are immutable objects stored in each node's database. A state contains the information between the two parties sharing it, an input, eventually an output, a timestamp, and a unique identifier. States cannot be modified so the sequence of updates of a state is managed by creating a new version of it, allowing users to have historical data on how the state changed.
Each node's database is called **vault**. As represented in Figure 6.1 the vault service maintains the states inside it by consuming the old versions and just keeping valid the most recent ones. The distributed ledger is so composed of all the unconsumed states across the vaults.

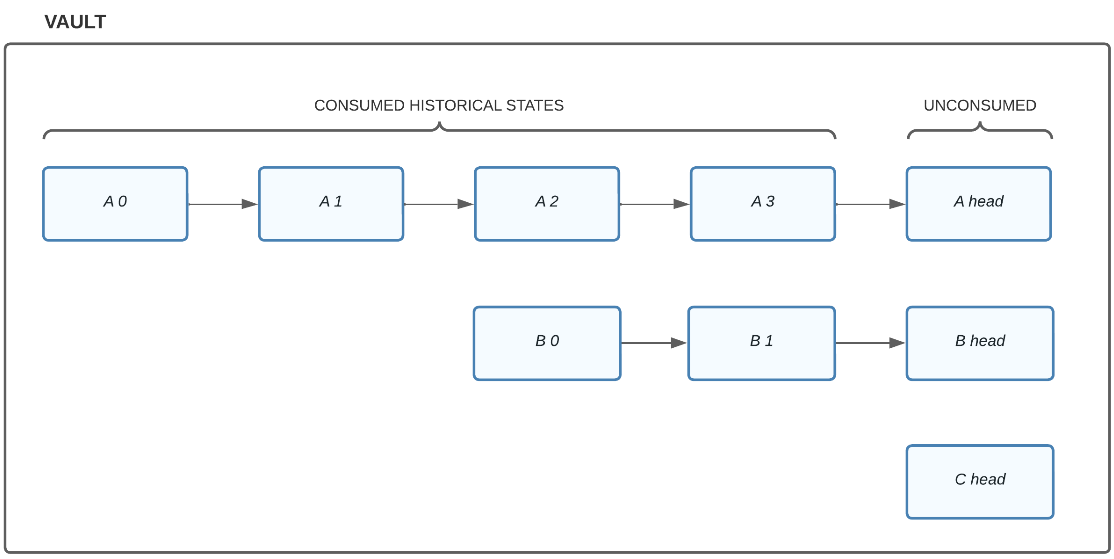

Figure 6.1: Corda's vault system represented

The ledger evolves over time via **transactions**. A transaction is marking zero or more states as historic (the input), consuming them, and providing a more recent state (the output). The transactions, therefore, create a chain of states. This chain always contains the hash of the input transactions and the output state that has to be created inside the participant nodes' vaults.
Initially, the transactions are just proposals, to become reality the transaction must receive the signatures of all the parties involved and a notary.
Notaries are authorities that not only prevent double-spending but also validate the transaction. Each notary can have a different consensus algorithm and can be located in a different part of the world, granting load balancing. Notaries can be of two types:

- Validating notaries: In this case, the notary can see the full content of the transaction and its dependencies, this leaks potentially private data but assure that all the states consumed are correct.
- Non-validating notaries: In this case, the notary just checks for the uniqueness of the transaction but can't prevent attacks such as the "denial of states" where malevolent agents re-use a consumed state.

To validate a transaction the nodes make use of **contracts**. Contracts check validity by ruling the possible input and outputs of a specific transaction and the type of transaction (creation of state, update, deletion, etc). Contracts are written in Java or Kotlin so they allow complex operations over the data contained in the transaction states, making them a powerful tool for validation.
Finally, the automatic communication of transactions between nodes is called **flow**. Each node can access different flows based on the role and permission given by the network operator. As shown in Figure 6.2 the flow process creates states, interacts with them, creates and validates transactions, signs them, and shares them over the network point-to-point.

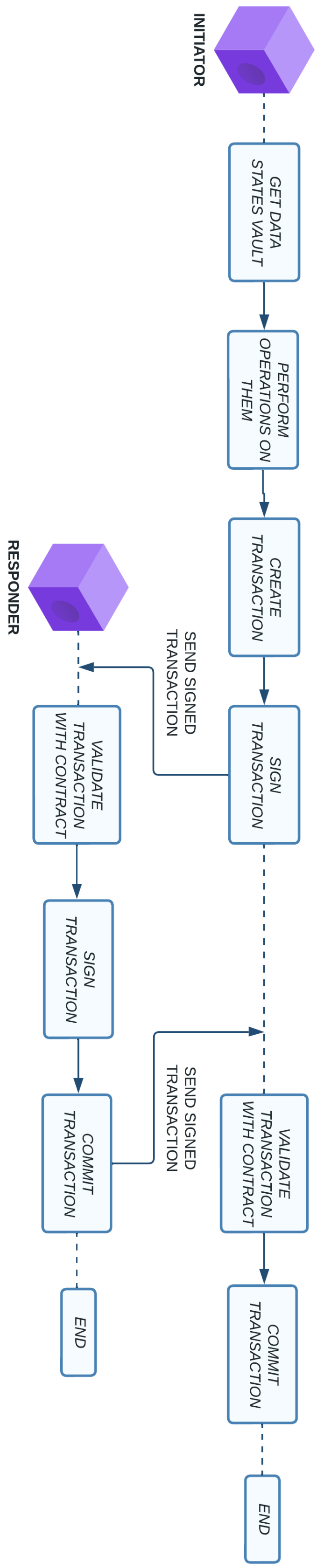

Figure 6.2: Corda's flow sequence

6.3. Architecture of the solution

The architecture of the solution presented is divided into two categories, following R3 Corda's best practices in the development of software on the platform: Contracts and Workflows.
Between these two categories, the functionalities related to the network management and the four interactions described in Chapter 2 as requirements and in Chapter 5 as a model are implemented.
Contracts are designed to standardize and validate the data that is shared between nodes using transactions, therefore they contain the *model* of information exchanged, the *states* that are consumed and stored in each node's vault, and the *contract* itself, with all the principles that allow checking the correctness of states exchanged and the validity of the transaction.
In Figure 6.4 the UML class diagram of the contracts part of the code base is shown. The model contains:

- **SMC**: *Sustainability Macro Category* is the representation of a standard used to measure the values of a certain hazardous chemical or parameter over a set of production processes (fiber manufacturing, spinning, weaving, dyeing, and sewing).
- **WasteWaterData**: An object that aims to standardize the wastewater data collected by IoT devices that needs to be shared. The object model is strictly related to the JSON representation of the data. Corda transactions allow only to share of textual information therefore the JSON representation is used inside transactions while the Java object converted from it can be used to perform other operations on the values such as comparisons. The wastewater data is composed of a group of SMCs, one for each parameter measured.

The states contained in the vault are of two kinds: the ones representing the identity of the actors in the network (**TextileFirmIdentity**, **CertifierIdentity**, **MunicipalityIdentity**) that simply contains a unique code for identification purposes and eventually some permission sets (i.e. only textile firms can share wastewater data over the network); the ones representing the transaction information related to the model functionalities implemented (sharing of wastewater data, issuing of a certification, communication of a surplus/need, communication of wastewater providers and their related data).
States that represent functionalities have mandatory parameters such as sender and receiver identities and the network in which the transaction was performed, allowing each node to operate on different networks eventually as each firm could possibly op-

erate in different consortium or textile districts.
The four contracts instead are used to validate the four transactions that represent the four interactions that the model allows. Each interaction has different requirements but follows the same pattern:

- Verify the command of the transaction: This model allows nodes to only issue new states, transactions that try to update a state or delete one are invalid as we need to preserve a historical collection of data.
- Extract the memberships of the two nodes: Both nodes performing the transaction needs to have a membership for the network, to prevent leakage of data.
- Exam the identities of the two nodes: each specific transaction has different requirements. In the issue of certification, for example, the sender must be a node with the Certifier identity while the receiver must be a node with the Textile Firm identity.

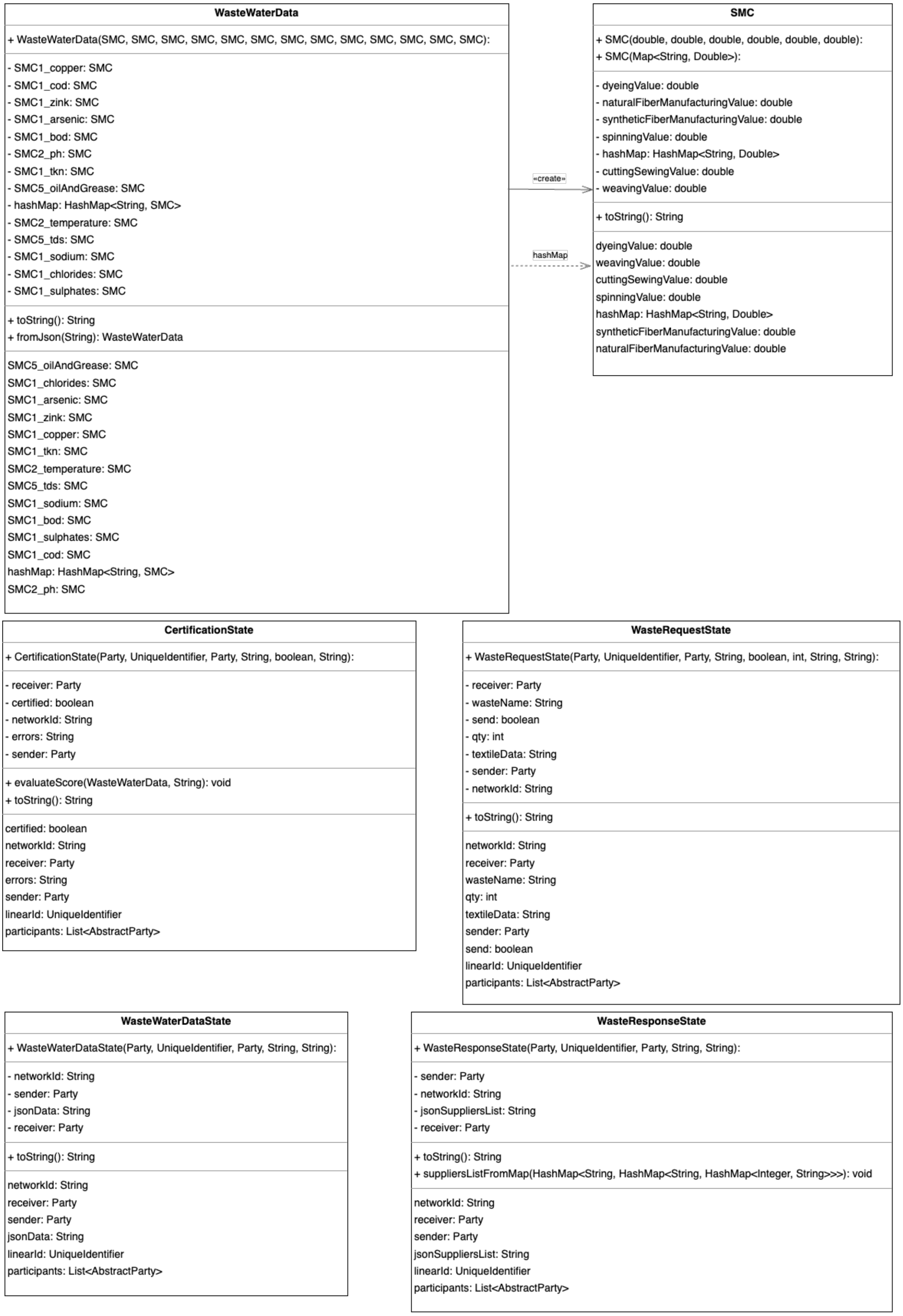

Figure 6.3: Contracts UML class diagram

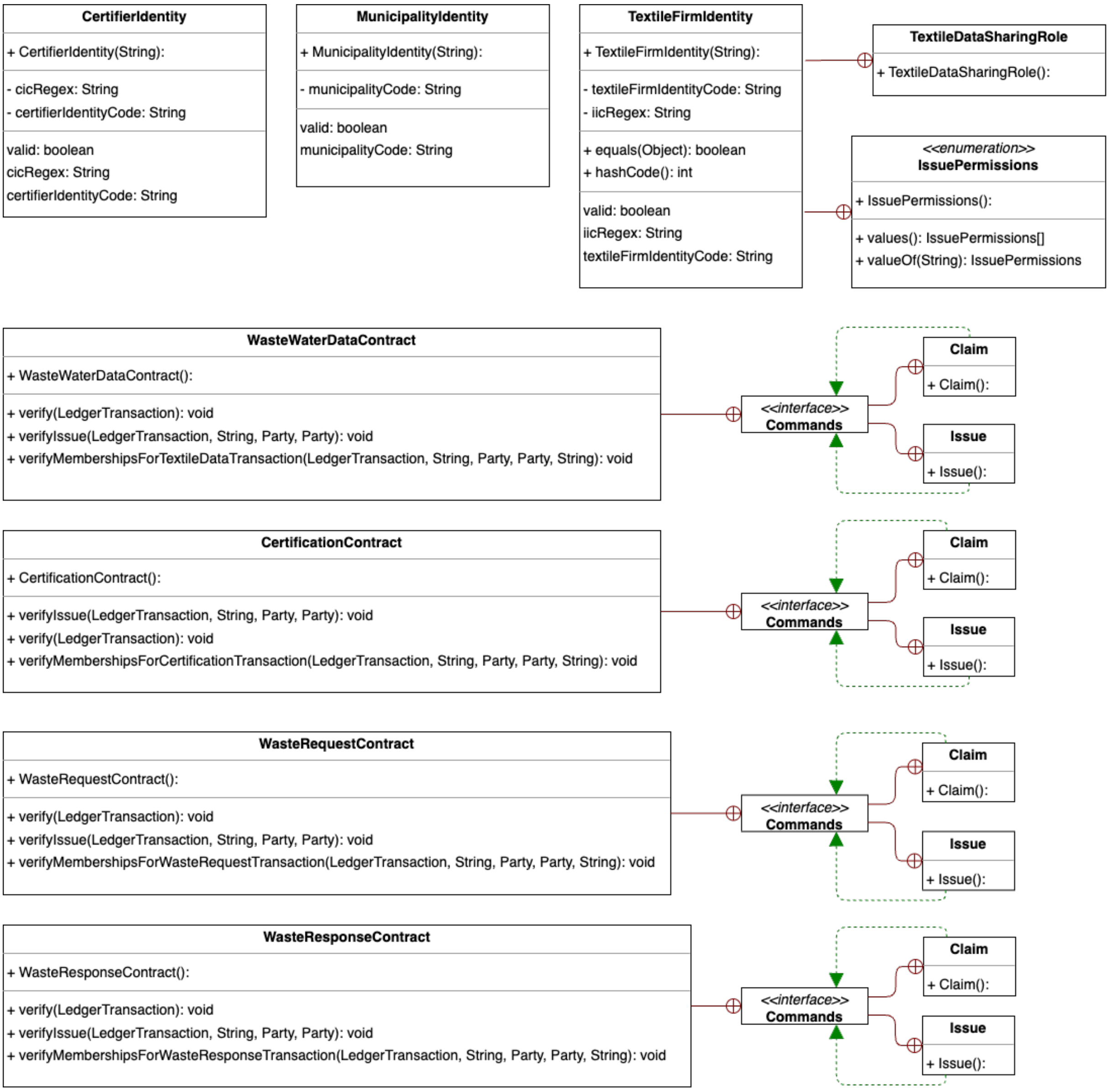

Figure 6.4: Contracts UML class diagram

Workflows instead are the classes that allow the communication of transactions from point to point, the signing of them, and their validation using their specific contracts. The UML class diagrams are shown in Figure 6.6 grouped by category. The first category of workflows is the one related to network management, and therefore used mainly from the Network Operator's node:

- **CreateNetwork**: Create the business network that represents the textile district in which all the actors are operating.
- **RequestMembership**: Each node uses this flow to request to the Network Op-

erator to join a specific business network.

- **QueryAllMembers**: The Network Operator can use this flow to visualize the list of nodes that made the request to join his business network.
- **ActivateMember**: This flow allows the network operator to accept the node's request to join, activating its membership in the business network.
- **CreateNetworkSubgroup**: This flow allows the operator to create subgroups inside the business network, this could be useful for managing members and allows further customization on roles and permissions.
- **AssignBNIdentity**: This flow allows the operator to assign to a member of the business network a Business Network Identity, which allows differentiation on the kind of memberships a node has. The identity is composed of a unique identifier and a firm type (TextileFirm, Certifier, Municipality).
- **AssignWasteWaterDataSharingRole**: Members with the TextileFirm identity can receive permission to share their wastewater data on the network by the operator using this flow.

The second and last category of workflows is the one that allows the four kinds of information sharing:

- **SendWasteWaterData**: Members with the TextileFirm identity and with the sharing permissions can share their wastewater data with another member of the network with the Certifier identity.
- **SendCertification**: Members with the Certifier identity issue a certification for a specific TextileFirm actor identified with its membership ID. The certification contains a flag (pass/not pass) and eventually a list of parameters that exceed the certification limit.
- **SendWasteRequest**: Members with the TextileFirm identity and with the sharing permissions can share their effluents request quantity or surplus to another member of the network with the Municipality Identity. Together with the surplus quantity, the textile firm has to share the related wastewater data.
- **SendWasteResponse**: Municipality members can send to a member with the TextileFirm identity a collection of other textile firms that provide excess wastewater with the related data for each source.

Each of these flows follows a standard pattern of interactions.

The flow is initiated by the sender, either by command line or using a remote procedure call, requesting the Initiator subclass. When the flow is triggered and initiated, the output state is composed inside of it and the transaction is signed by the sender, that also requests a Notary from the network to validate the transaction.
The standard flow **CollectSignatureFlow** is called within the initiator: as the name resembles, this flow manages the connection between two nodes and asks the receiver to sign the transaction.
Once prompted to collect the signature, the receiver node check and sign the transaction using the Acceptor subclass.
Finally, when the transaction is signed by both parties it is registered in the distributed ledger and the states are stored in the node's vault.
Before signing the transaction each party checks that both the sender and receiver are part of the same business network by using the function *businessNetworkFullVerification* and the support subclass Memberships.

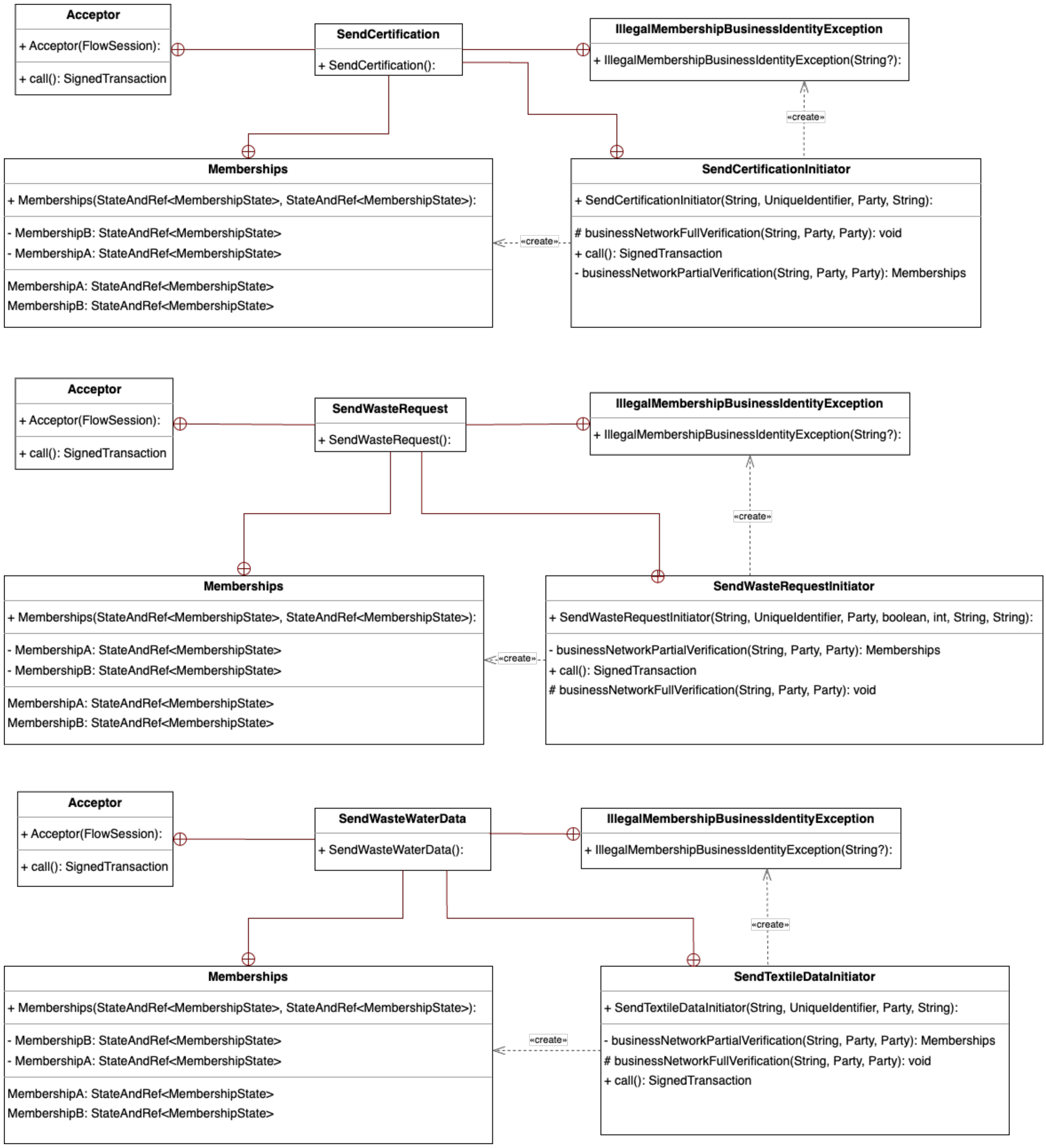

Figure 6.5: Workflows UML class diagram

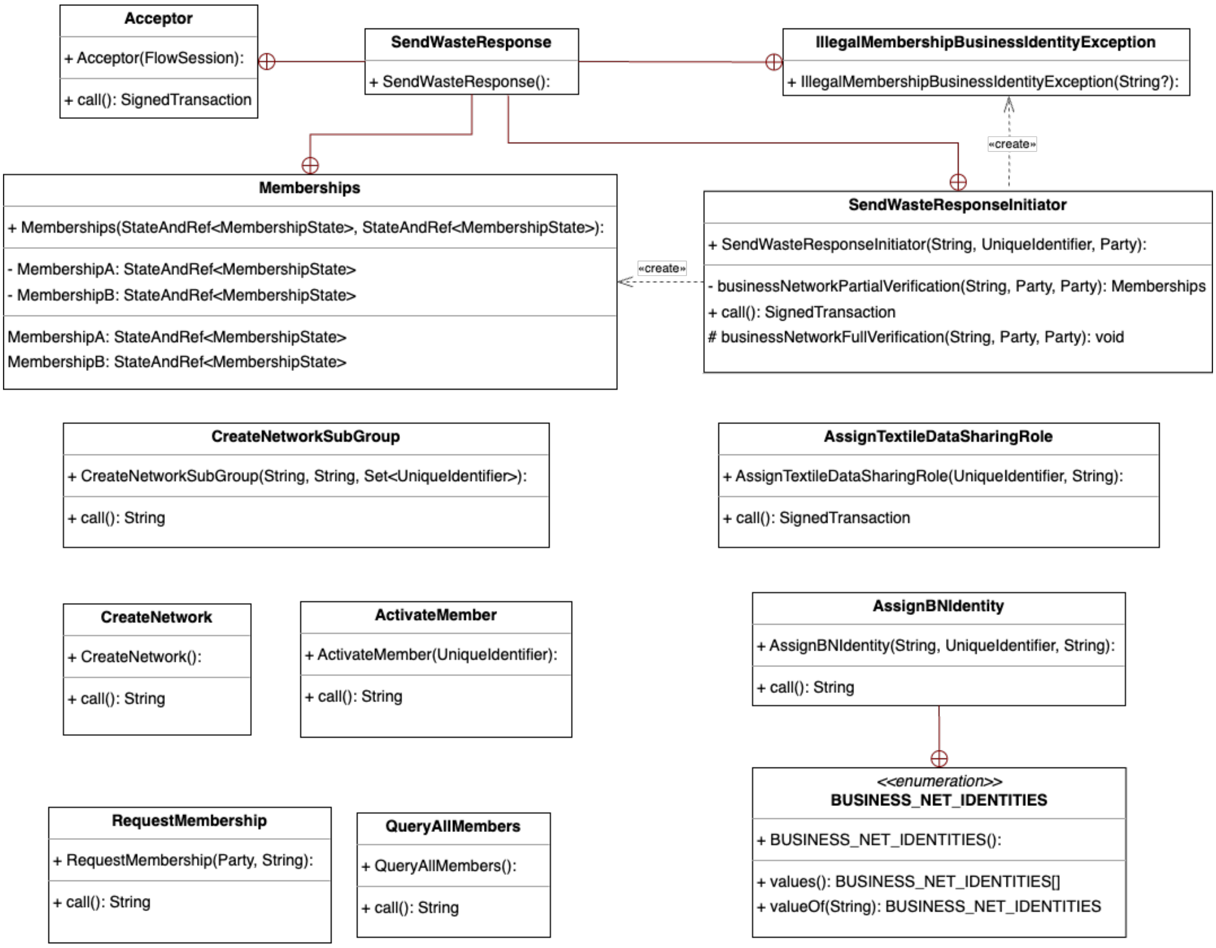

Figure 6.6: Workflows UML class diagram

6.4. Software implementation

The project was implemented using Java following the sample material provided in the R3 Corda technical documentation. The project is using Gradle as a build automation and therefore, while R3 Corda runs also on Kotlin, the choice of the language was Java to achieve faster builds. [53]
To develop the application a version control system was used in order to maintain a history of the changes. Following the principles of transparency that blockchain offers, also the repository is public and accessible at:

`https://github.com/tgolfetto/textile-sym-dlt/`

In order to develop and run Corda applications locally a static network map has been produced. For each node in the map, an instance of Corda running on a locally hosted Corda node is built. In order to have meaningful interactions and testing between the nodes, the network map instantiates:

- One notary's node

```
node {
    name "O=Notary,L=Rome,C=IT"
    notary = [validating : false]
    p2pPort 10002
    rpcSettings {
        address("localhost:10003")
        adminAddress("localhost:10043")
    }
}
```

- One network operator's node

```
node {
    name "O=NetworkOperator,L=Milan,C=IT"
    p2pPort 10005
    rpcSettings {
        address("localhost:10006")
        adminAddress("localhost:10046")
    }
    rpcUsers = [[ user: "user1",
                "password": "test",
                "permissions": ["ALL"]]]
}
```

- Two textile manufacturer's nodes

```
node {
    name "O=TextileManufacturer1,L=Prato,C=IT"
    p2pPort 10008
    rpcSettings {
        address("localhost:10009")
        adminAddress("localhost:10049")
    }
    rpcUsers = [[ user: "user1",
```

```
                "password": "test",
                "permissions": ["ALL"]]]
}
node {
    name "O=TextileManufacturer2,L=Scandicci,C=IT"
    p2pPort 10013
    rpcSettings {
        address("localhost:10014")
        adminAddress("localhost:10055")
    }
    rpcUsers = [[ user: "user1",
                "password": "test",
                "permissions": ["ALL"]]]
}
```

- One municipality's node

```
node {
    name "O=Municipality,L=Prato,C=IT"
    p2pPort 10011
    rpcSettings {
        address("localhost:10012")
        adminAddress("localhost:10052")
    }
    rpcUsers = [[ user: "user1",
                "password": "test",
                "permissions": ["ALL"]]]
}
```

- One certifying body's node

```
node {
    name "O=Certifier,L=Zurich,C=CH"
    p2pPort 10016
    rpcSettings {
        address("localhost:10017")
        adminAddress("localhost:10058")
```

```
        }
        rpcUsers = [[ user: "user1",
                    "password": "test",
                    "permissions": ["ALL"]]]
    }
```

In enterprise scenarios, the network map is built dynamically by each node.
Each of the nodes can be reached using *Remote Procedure Call* (RPC) by devices on the same local network. Using this protocol both IoT devices and third-party applications (such as front-end web applications) can communicate with the network, allowing easy access to the distributed ledger and its flows.

6.5. Testing

The testing of the application was performed locally on the static network shown in Section 6.4.
To run and test the application locally users can download the source code provided and build the project using Java 8 SDK and Gradle. To facilitate building, interactions, and operations over the network an IDE is suggested, the recommended choice is IntelliJ IDEA as it also provides an R3 Corda plugin to monitor the network nodes.
The project can be built using a bootstrapper by using the command:

```
./gradlew clean build deployNodes
```

By building the project the nodes that were described in the static network map are created and the CordaApp smart contract is deployed into each of them.
Subsequently, all the nodes can be run by using the command:

```
./build/nodes/runnodes
```

Now that the network is up and running the user can interact with each node by typing in each of the terminals prompt.
By following the set of commands expressed in the Algorithm 6.1 all the interactions of the model can be tested.

Algorithm 6.1 Interactions and flows of the Corda network

Step 1: Create the network in NetworkOperator's terminal.

```
flow start CreateNetwork
```

Sample output:

```
Wed Apr 12 10:35:47 EDT 2023>>> flow start CreateNetwork
[...]
Flow completed with result:
A network was created with NetworkID: <xxxx-xxxx-NETWORK-ID-xxxxx>
```

Step 2: non-member makes the request to join the network. Fill in the networkId with what was returned from Step 1.

```
flow start RequestMembership
authorisedParty: NetworkOperator,
networkId: <xxxx-xxxx-NETWORK-ID-xxxxx>
```

Step 3: From the admin node query all the membership requests.

```
flow start QueryAllMembers
```

Step 4: In this step, Network Operator will activate the pending memberships Textile manufacturing firm: fill in the node MembershipId that is displayed in the previous query for each firm.

```
flow start ActivateMember
membershipId: <xxxx-xxxx-FIRM-ID-xxxxx>
```

Step 5: The Network Operator creates a subgroup representing a textile district and adds group members.

```
flow start CreateNetworkSubGroup
networkId: <xxxx-FROM-STEP-ONE-xxxxx>,
groupName: Prato_Textile_District,
groupParticipants: [<xxxx-NETWORKOPERATOR-ID-xxxxx>,
    <xxxx-xxxx-TEXTILEFIRM-ID-xxxxx>,
    <xxxx-xxxx-CERTIFIER-ID-xxxxx>,
    <xxxx-xxxx-MUNICIPALITY-ID-xxxxx>]
```

Step 6: The Network Operator assigns a business identity to all the members.

```
flow start AssignBNIdentity
firmType: TextileFirm,
membershipId: <xxxx-xxxx-TEXTILEFIRM-ID-xxxxx>,
bnIdentity: PRATOT76CZX

flow start AssignBNIdentity
firmType: Certifier,
membershipId: <xxxx-xxxx-CERTIFIER-ID-xxxxx>,
bnIdentity: PRATOC44OJS

flow start AssignBNIdentity
firmType: Municipality,
membershipId: <xxxx-xxxx-MUNICIPALITY-ID-xxxxx>,
bnIdentity: PRATOM35OJS
```

And then assigns business identity-related ROLE to the textile firm to allow it to share the wastewater data.

```
flow start AssignWasteWaterDataSharingRole
membershipId: <xxxx-xxxx-TEXTILEFIRM-ID-xxxxx>,
networkId: <xxxx-xxxx-NETWORK-ID-xxxxx>
```

Now to see our membership states, we can run these vault queries.

```
run vaultQuery contractStateType: net.corda.core.contracts.ContractState
run vaultQuery contractStateType: net.corda.bn.states.MembershipState
```

Step 7: Now each of the nodes can use the flows to communicate and share data.

```
flow start SendWasteWaterDataInitiator
networkId: <xxxx-xxxx-NETWORK-ID-xxxxx>,
senderId: <xxxx-xxxx-TEXTILEFIRM-ID-xxxxx>,
receiver: <xxxx-xxxx-CERTIFIER-ID-xxxxx>,
jsonData: <JSON-WASTEWATER-DATA>
```

```
flow start SendCertificationInitiator
networkId: <xxxx-xxxx-NETWORK-ID-xxxxx>,
senderId: <xxxx-xxxx-CERTIFIER-ID-xxxxx>,
receiver: <xxxx-xxxx-TEXTILEFIRM-ID-xxxxx>,
criteria: <JSON-CERT-CRITERIA>

flow start SendWasteRequestInitiator
networkId: <xxxx-xxxx-NETWORK-ID-xxxxx>,
senderId: <xxxx-xxxx-TEXTILEFIRM-ID-xxxxx>,
receiver: <xxxx-xxxx-MUNICIPALITY-ID-xxxxx>,
send: true,
qty: 100,
wasteName: water,
wasteWaterData: <JSON-WASTEWATER-DATA>

flow start SendWasteResponseInitiator
networkId: <xxxx-xxxx-NETWORK-ID-xxxxx>,
```

And the data stored in the distributed ledger's vaults can be accessed by performing queries on the following states:

```
CertificationState
WasteWaterDataState
WasteRequestState
WasteResponseState
```

Moreover, **unit and integration testing** were performed. Unit testing aims to test and cover individual units or single components of the software system isolating them from the rest of the architecture, in order to check if the single part works as intended. Unit tests in this case were performed over the model representing the standard for exchanging wastewater data, the different States saved in each node's vault and the Contracts regulating transactions, providing a mock input and output state. The unit tests cover 80% of lines of code and 64% of the methods involved, providing confirmation that every single transaction can be validated without bugs.

Integration testing, on the other hand, is a type of testing where multiple modules of the software system are tested together. They are used to ensure that the operations that the user performs on the system work correctly. Flows are tested with this methodology, and all the functions from joining the network to sharing data and receiving certifications are tested all together assuring that errors won't arise during the user's operations. The coverage provided with integration testing is 88% of the code lines and 93,85% of the methods.

Both unit testing and integration testing are important because they help ensure the quality and reliability of the software solution provided to implement the model. They helped to detect and establish any errors that occurred during the development cycle, reducing both the software defects and the errors of the model proposed.

Table 6.1 shows a complete view of the testing coverage across the project classes.

Package	Class, %	Method, %	Line, %
it.polimi.tgolfetto.states	**100% (9/9)**	**88,7% (47/53)**	**94,2% (97/103)**
WasteWaterDataState	100% (1/1)	87,5% (7/8)	92,3% (12/13)
WasteResponseState	100% (1/1)	88,9% (8/9)	94,1% (16/17)
WasteRequestState	100% (1/1)	90,9% (10/11)	94,7% (18/19)
TextileFirmIdentity	100% (3/3)	100% (8/8)	100% (14/14)
MunicipalityIdentity	100% (1/1)	66,7% (2/3)	75% (3/4)
CertifierIdentity	100% (1/1)	75% (3/4)	83,3% (5/6)
CertificationState	100% (1/1)	90% (9/10)	96,7% (29/30)
it.polimi.tgolfetto.model	**100% (2/2)**	**18,5% (5/27)**	**52,9% (45/85)**
WasteWaterData	100% (1/1)	17,6% (3/17)	68,6% (35/51)
SMC	100% (1/1)	20% (2/10)	29,4% (10/34)
it.polimi.tgolfetto.flows .membershipFlows	**100% (8/8)**	**100% (15/15)**	**97,3% (71/73)**
RequestMembership	100% (1/1)	100% (2/2)	100% (5/5)
QueryAllMembers	100% (1/1)	100% (2/2)	100% (10/10)
CreateNetworkSubGroup	100% (1/1)	100% (2/2)	100% (12/12)
CreateNetwork	100% (1/1)	100% (2/2)	100% (4/4)
AssignTextileDataSharingRole	100% (1/1)	100% (2/2)	83,3% (10/12)
AssignBNIdentity	100% (2/2)	100% (3/3)	100% (25/25)
ActivateMember	100% (1/1)	100% (2/2)	100% (5/5)
it.polimi.tgolfetto.flows	**70,8% (17/24)**	**87,7% (50/57)**	**84% (267/318)**
SendWasteWaterData	83,3% (5/6)	92,9% (13/14)	88,3% (68/77)
SendWasteResponse	66,7% (4/6)	85,7% (12/14)	78,5% (62/79)
SendWasteRequest	66,7% (4/6)	85,7% (12/14)	86,2% (69/80)
SendCertification	66,7% (4/6)	86,7% (13/15)	82,9% (68/82)
it.polimi.tgolfetto.contracts	**66,7% (8/12)**	**85,7% (24/28)**	**93,5% (116/124)**
WasteWaterDataContract	66,7% (2/3)	85,7% (6/7)	93,5% (29/31)
WasteResponseContract	66,7% (2/3)	85,7% (6/7)	93,5% (29/31)
WasteRequestContract	66,7% (2/3)	85,7% (6/7)	93,5% (29/31)
CertificationContract	66,7% (2/3)	85,7% (6/7)	93,5% (29/31)
Total	**80% (44/55)**	**78,3% (141/180)**	**84,8% (596/703)**

Table 6.1: Coverage

7 | Discussion, opportunities, and limitations

Blockchain and more in general Industry 4.0 technologies are revolutionizing the Textile and Clothing industry providing solutions that allow production processes to be optimized and less impactful on the environment. The model implemented follows this trend and tries to fill the gap recognized in the application of distributed ledger technologies for this purpose. This certainly doesn't come without challenges and limitations. This final chapter discusses the benefits provided by the model and the related blockchain application implemented. It also aims at identifying both societal challenges that become adoption barriers to the spread of this solution in professional environments and also analyze possible technical limitations, providing solutions and critical reasoning on them. Reviewing the model and discussing possible limitations and how to overcome them is important so that future researchers can exploit the features and opportunities this software provides.

7.1. Discussion and relation to the state of the art

The model and implementation proposed in this research need to be evaluated by comparing it to the requirements proposed in Chapter 4 alongside the current applications found in the literature.

The requirements stating the architecture of the model to be designed were fulfilled: the model was based on the current procedures and interactions that happen between actors operating in the same textile district. The main actors operating (namely Textile firms, Certifying bodies, and Municipality) each have their own node in the distributed ledger network.

By developing the project with a permissioned blockchain like R3 Corda each actor in the network can access and share information with a different level of privacy, lowering one of the main adoption barriers that was the concern for sharing sensitive data outside of the company. 3.3

The second main technical adoption barrier that was found in numerous papers in the state-of-the-art analysis was the need for a standardized model of data. While it is true that the model designed focuses only on textile districts, a standard representation for waste and sustainability information is proposed. This representation can be applied alongside the whole supply chain to collect other types of data and can be expanded while maintaining its structure.

The requirements regarding the flow of information shared were also satisfied. The model maps all the possible interactions between actors in this scope and allows them to be independent of each other, improving the scalability of the solution. For example, each certifying body can have different criteria for issuing their certification, each firm can decide which data to share and to who, and each municipality can administrate the exchanges with the system they prefer.
The research and articles discussed in the literature review and its analysis only proposed theoretical models that lack implementation. The only implementations found in the literature were study cases where blockchain was applied to the supply chain for traceability purposes, often lacking a focus on sustainability.
It is hard to compare the model proposed with any other found in the literature as even if the objective of improving sustainability is the same, they operate on different scales and with a different model.
Therefore, research of this thesis not only fills the gap of a horizontal solution that allows firms at the same level to communicate and helps them reduce their environmental impact but also provides a software implementation that can be applied in real-life scenarios.
Study cases where a solution is provided and implemented resulting from private businesses so it's important to have produced an open source solution and research on the matter.
As stated in various documents in the state-of-the-art, there is no doubt that distributed ledger technologies, when applied, will bring improvements compared to the traditional way of operating. 3.2

7.2. Opportunities and future improvements

By analyzing the state-of-the-art of digitalization in the T&C manufacturing industry it was clear that this sector is very behind in the implementation of these new technological trends compared to others. Especially when it's regarding sustainability matters.

The papers and research that have been made are for most theoretical work, without further implementation in real-life scenarios. Moreover, technological solutions of this kind have little to no impact on sustainability and the environment.
This research on the other hand, after identifying the status of this industry, provides both a model and an implementation of the software solution.

Future studies can aim at testing the solution provided on firms operating in the market further to understand the feasibility of this distributed ledger solution and eventually provide a different implementation of the model that better suits those firms.
The model proposed only maps some interactions between different actors that collaborate inside the same district but in order to promote industrial symbiosis principles it may be necessary to introduce more information-sharing flows.
The solution provided started by giving a general view of textile wastes but only modeled textile effluents. The model is therefore capable of managing different types of waste and is structured in a way that allows future research to expand and cover all the different waste and recycling processes that happen between firms in the same district.

Finally, the software implementation of this research project is shared on GitHub allowing public access to it. By applying the open-source software paradigm it is expected that the project can be optimized and improved by any researcher that is interested in it. The implementation provided represent just a layer of the whole architecture of the system, the communication between IoT devices and the blockchain needs to be explored and a graphical user interface can be useful for users that are not expert, even though in real-life scenarios, only professional users interact with blockchain solutions and they often use RPC or command lines interfaces, Figure 7.1.

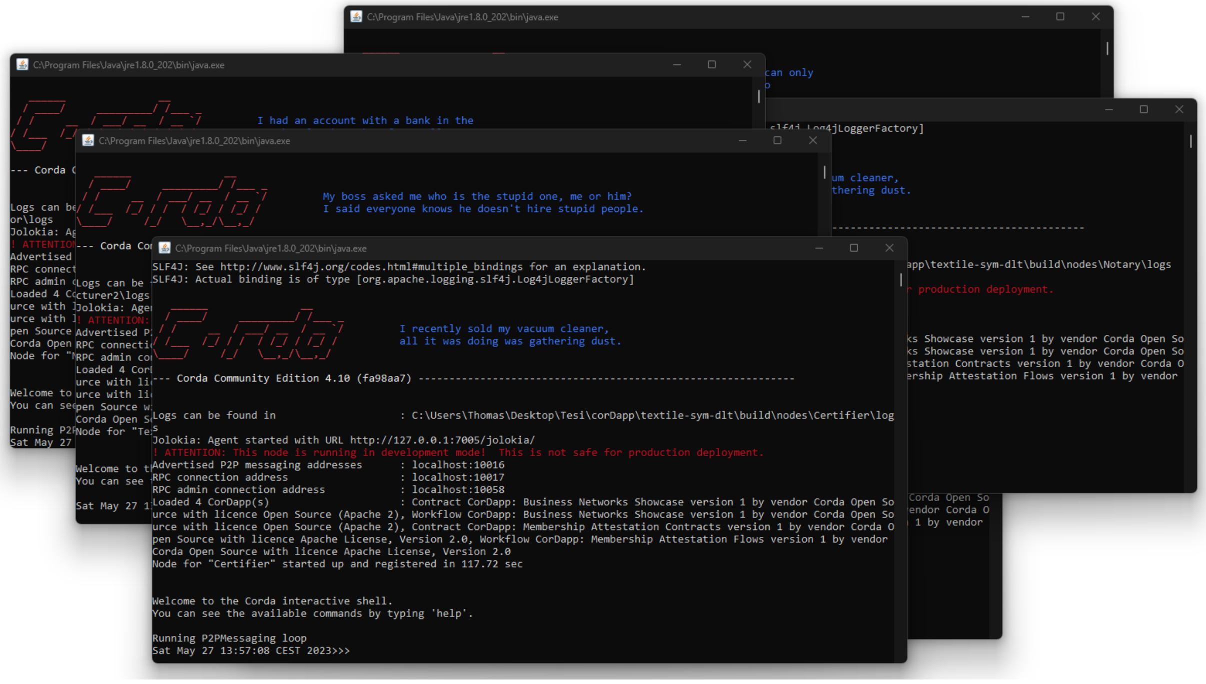

Figure 7.1: Terminals used to interact with the software solution implemented

7.3. Adoption barrier

Implementation of technologies and automation in the T&C industry represents a possibility that would reduce labor costs and optimize production in a sector that is still mainly human-operated. There are some areas of production where Industry 4.0 is already in practice, such as in the supply chain, spinning, and weaving. However, most of the textile industries are small to medium enterprises which have problems related to financial resources and they can't afford to invest in R&D.
The lack of skills required from employees to implement and use digital technologies, together with the lack of understanding and vision from upper management, really puts brakes on the advancement of digital technologies in this sector.

The main issues in implementing the model proposed are three:

- **Lack of standardization**: T&C firms are operating on a worldwide scale.Each manufacturer needs to comply with different regulations based on their geographical presence and the local market they operate in. In most cases, a production process standard can be found in local districts, but can't work properly on wider scales. Therefore, a limitation of the solution provided is that was structured following the model of the Prato industrial district and the industrial symbiosis cases

found in the scientific literature.
On the other hand, the model design allows customization and further improvements to better fit other industrial districts. New actors and blockchain nodes can be created and customized to better fit the industry's needs while still maintaining standardized information sharing. Its application in professional scenarios may be limited by the current state of the project but further advancements can be made and a solution can be tailored with little R&D effort for companies that want to adopt it.

- **Privacy**: Privacy concerns in the manufacturing industry represent one of the biggest adoption barriers. Industry 4.0 is shifting the competitive edge of companies more towards value offering to the client respecting the classic paradigm of price competition, but the industry as a whole is still sticking to close competition. [28] Adopting a model that is based on data sharing between peers in a transparent way is clearly scary for firms that want to keep industrial secrets as the base for their competitive advantage. As explained in the research from De Man A.P. [54] the advantage of collaborative efforts against an economy based on competition in business networks is still a topic that is been explored in recent years and there is not a clear winner, but emerges that collaboration in small networks would be beneficial for firms. The solution provided tries to patch this problem by adopting a private blockchain network, where companies share data only between the ones participating in their local business network. Firms outside of the network have no visibility on the wastewater data shared. Moreover, the different accesses to data and type of transactions that can be performed is regulated using different roles in the distributed ledger network. The model will still face some adoption barriers from the management of companies that don't have a clear view of the benefits, both economical and in terms of sustainability, brought by industrial symbiosis but scientific evidence assure that the adoption of it and a system based on collaboration will improve companies profitability and reduce their environmental impact.

- **Environment, legislation, and crowd effect**: In order for the model to bring clear benefits to the firms adopting it, all the firms operating in the district needs to adopt the distributed ledger technology. Certifying bodies require far less effort to set up their nodes and the optimization regarding issuing certification is clear, while textile firms and manufacturers need to adopt a technological infrastructure that allows them to communicate with each other and the value provided by the model only shows when multiple companies adopt it, as waste exchanges on smaller scale exist already and are regulated by one-to-one deals. Moreover, municipalities play a key role in pushing this change, they not only have to act as an intermediary for managing exchanges, but they also need to introduce optimized services based on this model. More efficient waste collection and effluent treatments have to be implemented levering the data shared on the DLT. Moreover, municipalities have to legislate in order to create an environment where is easy to adopt the model. Both the Prato Circular City program and the Europen Commission are important institutional figures that are acting like trailblazers in matters of sustainability, economic incentives, and digitalization. In the near future more institutions and regulatory bodies will have to face the growing sustainability issue of the T&C industry and with their support solutions can be put in place to reduce friction on the company's adoption.

7.4. Technical challenges for IoT-based blockchain solutions

As discussed previously, Internet of Things devices and blockchain solutions are a powerful combination. The most critical problem of distributed IoT devices is the lack of security and privacy, which meets the success factors in adopting blockchain-based distributed ledgers. There are still some common risks in combining these two technologies, for some of them solutions are inherited in the model while for others a solution is provided but wasn't implemented in the software, therefore is suggested as a future improvement:

- **Scalability:** IoT devices collect an extensive amount of data over the whole network of sensors. Blockchain transactions on the other hand require time to be validated as the process requires multiple interactions between the parties. Therefore scaling the model to share different types of waste information across the network could be difficult. In the model proposed the data have to be collected during the production process but only pushed on the chain when the firm shares the wastewater to the network, or when asking for a certification. That allows the IoT devices to operate and collect the full amount of data without limitations and then when sharing the data an average can be made, reducing the stress on the distributed ledger.
- **Security:** Blockchain smart contracts and nodes are prone to be attacked by malicious actors. In public DLTs this is mitigated as every party can review the

data shared on the chain while in private networks is harder to mitigate attacks. The integration tests performed aim at reducing the vulnerabilities in the smart contracts, but it remains difficult to assure security and have control over the transmission of data collected in the real world to the digital ledger. Actors could tamper their sensors in order to collect more sustainable data and then share it on the blockchain. Software solutions to recognize suspicious data exist, but physical control by third-party institutions is still mandatory. Moreover, as the system is distributed, there are multiple points of attack that need to be kept secure. While this concern is legitimate, it is also true that in the current state of the industry, physical controls are regularly performed by institutions and third parties, collecting and sharing additional information using the solution proposed will facilitate this task improving the overall integrity of the system.

- **Data reliability:** It is essential for a model based on data exchange and sustainability regarding hazardous chemicals that the data measured by sensors is reliable. Also in this case, as the system is distributed so the maintenance of the infrastructure becomes difficult. Preventive maintenance and the adoption of all the best practices that innovative solutions require are mandatory and can mitigate this issue.
- **Computing power and time required:** As blockchain transaction needs to be verified using *"Proof of Work"*, a very computing intensive algorithm, usually the power and time required for nodes to execute a transaction is very high and can not only limit the IoT data throughput but also represent a cost in terms of infrastructure. In the model presented instead, a private blockchain is proposed. R3 Corda, since it's a private blockchain, is faster than public ones and verifies transaction with the support of a third-party node (the Notary) that needs to check the validity of the data shared and don't need to perform heavy computation. Therefore, this challenge is not present in our specific case.

7.5. Limitations of the solution provided

It is crucial to understand the limitations of the model provided in order to guide future improvements and have a critical, but complete, analysis of the solution proposed. Even though the model might present a comprehensive architecture, it is essential to keep in mind that it is not without faults.

First of all, during the literature review and the modeling of the solution, general tex-

tile waste exchange was considered in order to provide a solution that would allow firms to adopt circularity in all of its forms. During the refinements of the model, it was discovered that a general model like such would be difficult to implement and would exceed the scope of a thesis. Moreover, the literature review and state-of-the-art analysis only pointed out that Industry 4.0 technologies, in particular blockchain, weren't widely adopted in the textile industry for sustainability purposes, a general solution to cope with the wide industrial gap identified was therefore designed. During the refinement of the model regulations and further research pointed in the direction of wastewater exchanges in industrial districts and **the model was adapted to focus on the specific waste category**. Adapting the model allows future improvements to be easily implemented but on the other hand, narrows the use cases of it.
Each industrial symbiosis framework found in the literature is tailored specifically for a district operating at a local level: this architecture follows Italian regulations. A local architecture of this kind is **hard to scale and replicate around different textile districts** as each of them will have different interactions between the firms operating in it and local regulations on the use of refined wastewaters change drastically. The solution is highly customizable without losing its perks, so it is possible to overcome this challenge with future improvements by adapting the smart contacts and validation rules of each node and by expanding the flexible standard that is proposed.

Another limitation of the model and the software solution implemented is the **lack of testing and empirical results**. The solution isn't yet tested or adopted by companies and operators in this sector. The model provided is only theoretical and based on evidence found in the scientific literature, which is not sufficient to validate it. The implementation of the distributed ledger using R3 Corda blockchain confirmed that the model can be implemented in real life and allows companies and future researchers to easily validate or identify other issues in the model.

Finally, **adoption barriers may be challenging to overcome**, especially in the Italian industrial environment. The concern about the company's data and the competition between firms operating in the same district is prevalent. It is proven that firms will benefit by adopting the model but it is still unclear how much and therefore is hard to overcome the aversion of management towards collaboration. Also, technical challenges may represent a problem for the software solution implementation on productions. Solutions to each of the technical challenges were presented but they need to be tested to prove their effectiveness.

8 | Conclusions

Sustainability is a key value factor for consumers in recent years. Firms operating in the Textile and Clothing industry need to address their huge environmental impact in order to keep their competitiveness in the market, comply with the current legislation and improve their production processes.
The literature review performed, together with the subsequent analysis, shows that this industry in particular it’s reluctant to adopt technologies commonly refer to as "Industry 4.0" that can impact on improving the sustainability of textile manufacturing.

The analysis performed showed a gap in the use of blockchain solutions for this purpose, since they are often used to solve problems related to the supply chain. This is set in a broader productive environment where firms operating in the same district don’t collaborate with each other and generally resist the adoption of new software-based technologies.

The objective of this research was to design **a model to foster circularity and sustainability by exchanging information** about wastewater generated during the textile production process, following principles of circularity and industrial symbiosis.
The model that is proposed allows companies operating in the textile districts to not only be more sustainable but also bring them an advantage by optimizing their processes.
Firms adopting this model can share in a standard form hazardous chemicals present in their effluents, and they can communicate with certifying bodies to get certifications in an automated way and, following the example of Prato Circular City, they can share waste with each other, as it can be treated and reused for further productions.
In order to design the model, a systematic process was followed: information has been gathered from multiple reliable sources that created a theoretical background, and using this information a literature review was planned and performed in order to collect and analyze the current state-of-the-art of blockchain and its adoption in the T&C industry. The model is therefore based on all the information analyzed since it has to be

both theoretically useful and applicable in real-life scenarios.

The model proposed was also implemented using an R3 Corda blockchain, allowing companies to easily adopt it. The distributed ledger solution provided is powerful and can be adapted or generalized to better fit the characteristics of each textile district, also setting a standard for communications of this kind.
Adoption barriers for a solution of this kind are related to societal issues, such as managerial decisions, economic reasons such as lack of resources in R&D, and technical obstacles. All of these barriers were examined and solutions to each were provided.
With the implementation of this distributed ledger model, firms operating in the T&C industry can easily adopt Industry 4.0 technologies and increase their digitalization, not only reducing the environmental impact of the industry but also gaining competitive advantages by optimizing the operations related to waste disposal and recycling.

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