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Automated System for Transportation and Separation of Textile-Cutting Surpluses: A Case Study in a Portuguese Clothing Company

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Abstract: A significant proportion of waste generated by the fashion industry is either landfilled or incinerated, primarily due to the high cost and complexity of collecting and separating mixed textile materials. While research in textile recycling often emphasizes post-consumer waste, less attention is given to pre-consumer waste, particularly cutting surpluses generated during apparel manufacturing—a labour-intensive sector with low automation and operational inefficiencies. This study addresses this gap by presenting a case study on the implementation of an automated system for collecting, transporting, sorting, and storing textile surpluses in an apparel manufacturing environment. The research aims to identify the barriers, benefits, and sustainability impact of such automation. Using both qualitative and quantitative data, the system is evaluated through key performance indicators including time reduction, ergonomic improvement, and process reliability. Results suggest that automation enhances intralogistics, reduces non-value-added labour, and enables better utilization of human resources. This case study offers a practical framework for apparel manufacturers to assess the potential of automating textile-waste handling, helping to justify such investments based on labour use, process variability, and environmental benefits. The study contributes to the broader discourse on sustainable manufacturing and supports the apparel industry's shift toward digital transformation and circular economy practices.

Keywords: automation; intralogistics; recycling; sustainability; transportation

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1. Introduction

As companies advance in their digital transition, intralogistics is emerging as the key beneficiary of Logistics 4.0. However, this transition brings significant management challenges. Human-driven tasks such as internal transportation are evolving into more collaborative roles that maintain human involvement, although in a redefined manner [1]. Furthermore, the shift over the past decades from standard production to higher product customization has increased complexity in production and intralogistics systems, becoming key concerns for companies today [2]. These processes include material handling, storage and transportation, and strategic management decisions based on forecasting [3].

Automation, for example, is one of the key characteristics of Logistics 4.0 widely present in its processes. Since intralogistics manages materials and information flows, automation becomes preponderant for increasing companies' competitiveness by eliminating

activities that do not produce added value. It is mainly here, in the automation process, that companies in the Textile & Clothing Industry (TCI) have been focusing [4].

There are many challenges that TCI companies must overcome to maintain a certain level of competitiveness. Rising wages and a shortage of skilled labour, especially in Portugal, are driving companies to improve their process efficiency, requiring operators to perform more added-value tasks. TCI is also one of the most resource-intensive and globally polluting sectors. Throughout the several production processes, various waste is generated; however, most of it comes from discarded used clothes. Textile materials are difficult and costly to recycle post-use, primarily due to the high expense of collecting and sorting mixed fibres [5]. Research has focused on developing efficient and cost-effective methods for waste recovery, reuse, and recycling [6,7], often emphasizing post-consumer recycling and the principles of circular economy [7–9]. This waste is called textile waste, and it is estimated that, globally, approximately 74% of this waste is landfilled or incinerated, 25% is reused or recycled, and only 1% gives rise to new clothes [10].

To address this, scholars propose using sustainable raw materials, advanced processing technologies [7], and lean manufacturing to reduce waste [11,12]. However, the role of apparel manufacturers remains underexplored [8], despite their potential as a recycling source due to inefficient fabric utilization during cutting. This waste results from irregular part geometries that prevent optimal material usage. Proper separation of this recyclable material during manufacturing could offer an efficient, scalable recycling solution, yet the literature presents limited focus on in-process recycling within apparel production [7]. Based on this research gap, this paper proposes to show how to adopt an automated system for collecting textile-cutting surpluses, highlighting its barriers and expected benefits.

In this context, a consortium of 40 entities is working on the "Innovation Pact for the Digital Transition of the Textile and Clothing Sector" (TexP@CT) [13], focusing on developing and implementing solutions to facilitate the adoption of digital solutions and technologies in the TCI. TexP@CT aims to respond to the industry challenges and make this sector more resilient, sustainable, and attractive to the current and future workers of this industry. Therefore, the present work is carried out within the scope of TexP@CT, and it addresses the management of textile-cutting surpluses generated during garment manufacturing. It focuses on the implementation of an automated system for the transportation and separation of these surpluses, consisting in a continuous automatic conveyor system based on suction technology, capable of collecting different types of surpluses (textiles, paper, and plastics) and directing them to appropriate recycling areas. Currently, operators handle most of the transportation, separation, and identification tasks of this process, leading to errors and high waste of human resources. The aim is to improve recycling traceability, reduce process times, and promote sustainable waste management practices within the textile industry. It is fully aligned with the objectives of the European Green Deal and the Circular Economy Action Plan (CEAP), both promoted by the European Commission [14], and supports the foundation for future initiatives such as the Digital Product Passport (DPP), envisioned as a key enabler of circularity in European industry through providing better product information so that consumers can verify the green claims of the brands and the regulatory bodies can monitor sustainability compliance [14].

The remaining paper is organized into five sections: Section 2 presents a literature review on the topics of textile manufacturing wastes, and automation in textile surplus collection. Section 3 shows the research methodology used, including the detailed objective. Section 4 presents the case study, followed by a discussion in Section 5. The paper ends with conclusions, limitations, and future research directions.

2. Literature Review

This section addresses the topics of textile recycling, challenges in textile-waste management, automation in intralogistics, and textile collection and sorting.

2.1. Recycling of Textile

A significant portion of the fashion industry's waste, comprising the production-related waste generated by apparel manufacturing, as well as post-production waste streams, including unsold, unused, and rejected garments, is disposed of in landfills or incinerated [7,15,16]. As a result of this process, many countries are facing economic and environmental challenges caused by the incorrect management of textile waste [8]. Data from the European Commission indicates that roughly 12.6 million tons of textile waste are generated each year in Europe. In light of new European regulations on textile-waste recycling, companies must implement more than mere adjustments to production processes; technological innovation should be pivotal. Advanced sorting technologies can enhance fibre separation and reduce contamination [17].

Textile recycling can be classified in four distinct ways [10]: up-cycling, down-cycling, and open/closed-loop recycling. Up-cycling and down-cycling are connected to the recycled product value, representing products that have higher or lower quality/value than the original. On the other hand, when a new recycled product has the same type as the original, it is called a closed-loop recycling process, while the other way around is considered open-loop. Textile recycling is a complex process that involves various stages, such as collection, sorting, processing, and manufacturing [8] to recover and reuse a particular fabric in new products. Fabrics can be disaggregated, preserving their original fibres, thus giving rise to a fibre recycling process [8,10]. Fibre regeneration involves turning fabrics into a compact mass of fibres, dissolving this compact mass through a solvent, and spinning these fibres. By recycling fibres (natural and synthetic), it is possible to reduce the production and consumption of virgin fibres, which in turn promotes sustainability by reducing environmental impacts [10].

Textile materials, after use, are very difficult/expensive to recycle, mainly due to the high cost of collecting and separating different textile materials as factors limiting its wider adoption [5]. The scholarly research in the domain of material waste within the textile and apparel industries focuses on the development of efficient and cost-effective methods for the recovery, reuse, and recycling of waste materials [6,7]. To overcome this problem, research has focused on recycling after use [7–9], highlighting the broader concept of circular economy [7,9,18]. However, less than 1% of material is recycled for new clothing [7,19]. To improve this situation, researchers propose the adoption of environmentally sustainable raw materials and innovative technologies as strategies to minimize material waste during textile processing [7], applying lean manufacturing principles for waste reduction [11,12], and they have identified several circuits for recycling and reusing textile materials. However, the focus on apparel manufacturers seems low [8,10].

The literature indicates that apparel solid waste is a matter of great concern, but the studies on waste generation and management in the upstream textiles and apparel production chain are limited [7]. Thus, apparel manufacturers can be a source of recycling because, in cutting processes, high waste is usually produced, generated by the non-use of the material in its entirety. This disadvantage is caused by the different geometries and characteristics of the parts to be cut, which make it impossible for them to fit perfectly into the cutting planes.

2.2. Challenges in Textile Waste Management

The environmental impact of textile waste is well-documented, with a significant portion ending up in landfills or being incinerated [10]. Despite legislative efforts and growing interest in sustainable textile recycling, current waste management systems face challenges in scaling up recycling efficiency, largely due to inefficient manual sorting processes [8,20,21]. Many challenges in sustainable textile recycling and barriers still need to be addressed. Textile recycling is a complex process that requires different equipment and expertise, which make it difficult to develop a streamlined and efficient process [8]. The Terra study [22] provides a comprehensive overview of sorting technologies, encompassing identification methods, advantages and disadvantages, supplementary technologies (such as colour sorting and artificial intelligence), machine manufacturers, and sorting systems.

Innovative textile waste management strategies integrate digitalization and automation. Smart contracts, blockchain, and Internet of Things (IoT)-based solutions have been proposed to enhance transparency and traceability in textile-waste collection [23]. Furthermore, Industry 5.0 is a concept that aims to develop more adaptable, efficient, and sustainable production systems, where humans and robots coexist peacefully by using the potential of cutting-edge technology like robotics, artificial intelligence, and the Internet of Things [24,25]. However, their practical implementation remains in early developmental stages, with scalability and cost efficiency being major barriers.

The apparel industry is a labour-intensive industry characterized by many different cloth-making processes, which require considerable human attention, a low level of technology, and little automation [11]. However, to achieve economic sustainability in the garment manufacturing industry, the implementation of automation is necessary [12]. Technology-organization environment studies and institutional theories for technology adoption in the garment industry are lacking in the literature, according to [26]. This represents a significant challenge in the sorting and categorization of often mixed textile waste, requiring immense human and time resources to effectively manage these processes on a large scale [8]. So, there seem to be no efficient solutions to show how to address these challenges, but due to technological evolution, automation seems promising.

2.3. Automation in Intralogistics

Intralogistics, the internal management of material flows within facilities, is being improved by the adoption of automated transportation systems. The shift towards greater efficiency, particularly under the Industry 4.0 paradigm, has driven rapid technological advancements in this sector. Automated Guided Vehicles (AGV) are among the earliest solutions, following fixed paths using magnetic tapes or laser navigation to reduce labour needs and improve safety, although their reliance on fixed infrastructure makes them less suited for dynamic environments [27,28].

Based on the literature research, the textile industry is still in the early stages of implementing Industry 4.0 globally. The primary elements of Industry 4.0 that were first recognized in the textile sector centre on the application of technology meant to computerise and automate procedures, with the primary goals of cutting expenses and raising outputs [4].

A collection of instruments or automated machinery used to help or carry out operations typically performed by people is known as industrial robotics [29]. Autonomous Mobile Robots (AMR) have emerged, capable of navigating flexibly within a factory or warehouse [28,30]. AMR are currently being introduced in many intralogistics operations [28]. The integration of Internet of Things technologies and cloud platforms further improves transportation systems. For example, centralized fleet management through cloud services

increases resilience and enables real-time monitoring, allowing faster reactions to logistical demands [31]. Both systems also have inherent disadvantages. AGV are inflexible and costly to reconfigure when production layouts change, while AMR, although adaptable, may struggle with navigation reliability in complex environments [28]. Maintenance of robotic components, as well as battery management, increases the total cost of ownership over time. Cybersecurity risks, particularly in cloud-connected systems, present another major challenge [32].

Alternative transportation systems are also common in intralogistics. Conveyor belts, for instance, offer high throughput and efficiency in structured environments. Conveyors are cost-effective for continuous transport with minimal power requirements and human involvement, but suffer from poor flexibility and high maintenance cost, and layout modifications are costly [33,34].

Pneumatic tube systems, using suction and air pressure, are efficient for rapid point-to-point transport of small loads [35,36]. These systems provide speed and integration benefits for small-item delivery; however, they are constrained by limited payload capacity, high installation costs, and difficulty in expanding after setup [36].

It can be concluded that AGV and AMR are better for flexibility and dynamic tasks, while conveyors and pneumatic tubes excel in repetitive, structured, or very rapid transport of lightweight goods.

Robotics can be employed in logistics processes in the TCI through autonomous vehicles, which offer flexibility and efficiency when moving goods and materials internally in factories, or externally to clients and suppliers [37–39]. Two instances are drone deliveries of clothing [40], and stock monitoring and control, utilizing an autonomous vehicle model equipped with tracking technology [41].

In a shared work environment, collaborative robots (cobots) with internal sensors for movement and obstacle perception can work alongside people to complete tasks like folding parts, gathering packages, making batches, and packaging goods [42–44].

According to [4], the textile and apparel industries have mostly invested in the adoption of technologies that are intended to improve business management, lower operating costs, and increase production-process efficiency as they move to Industry 4.0. The implementation of projects that incorporate information technologies; IoT (RFID, QR codes, sensors, actuators); software for production process planning, programming, control, and management; and robotics into production processes are examples seen in their review.

2.4. Textile Collection and Sorting

Automated collection systems, powered by smart tags and sensor networks, are starting to be adopted in textile-waste management. Despite improving efficiency in tracking and sorting, they require refinement to reduce costs and ensure widespread adoption [45]. AI-powered robotic sorting systems have demonstrated success in waste separation, particularly in related fields such as beverage container recycling [21]. By employing AI-driven image recognition and high-speed grippers, automated systems can efficiently sort materials based on composition and quality. Similar techniques could be adapted for textile separation, addressing the limitations of manual sorting.

Near-infrared spectroscopy and optical sorting are among the most advanced techniques currently used in textile-waste separation [23]. These technologies enable the classification of textiles based on fibre composition, facilitating downstream recycling processes. However, challenges remain in detecting clear or mixed-material textiles, necessitating further advancements in AI and sensor technologies [45].

The sorting process is easier to manage during manufacturing, which occurs in a controlled and predictable environment, compared to after the product has been used by the customer. The automation of the textile-waste sorting should improve manufacturing efficiency, contributing to company sustainability. Intelligent robot technology for waste sorting has advanced significantly in recent years. Numerous investigations have looked into the detection and sorting of various waste types, using robots equipped with sensors and computer vision [46].

Despite the relevance of the problem and the existence of alternative solutions, there is a lack of research presenting the best practices or methods to support managers of apparel manufacturers on how to select efficient solutions tailored to their context.

3. Research Objectives and Methodology

This section presents the main objectives of the case study, its selection, and the methodology implemented to obtain the analysed data.

3.1. Research Objectives

Building upon the existing literature and technological advancements, this study's aims are the following:

1. Describe the implementation of automated systems: Investigate the implications of adopting automated technologies for collecting textile-cutting surpluses, and assess their potential economic benefits.
2. Promote adoption: Given the limited documentation and adoption of automated systems for collecting textile-cutting surpluses, developing an effective and efficient pilot can promote adoption by other garment manufacturers, enhancing textile recycling and sustainability.
3. Identify barriers to adoption and propose solutions: Explore the challenges hindering the widespread adoption of automated textile sorting technologies, such as technical limitations, and propose strategies to overcome these obstacles.

By addressing these objectives, this study seeks to contribute to the advancement of sustainable textile-waste management practices through the implementation of an automated system for transportation and separation of textile-cutting surpluses.

3.2. Case Selection

The selection of the case followed a purposive sampling strategy, ensuring its relevance to the research objectives [47]. The case was chosen from a company belonging to the TexP@CT consortium, which had decided to automate the collection of its textile waste generated during textile cutting. In this particular case, part of this textile waste is converted into new recycled fibres (fibre regeneration) for the production of new garments. Fibre regeneration involves turning fabrics into a compact mass of fibres, dissolving this compact mass through a solvent, and spinning these fibres. By recycling fibres, it is possible to reduce the production and consumption of virgin fibres, as well as the burning and landfilling of textile materials, which in turn promotes sustainability by reducing environmental impacts [10]. In Figure 1, it is possible to observe the several circuits for recycling and reusing of textile materials.

By focusing on this particular case, the study aims to provide detailed and contextually grounded findings that contribute to the broader understanding of the challenges hindering the widespread adoption of automated technologies for textile recycling.

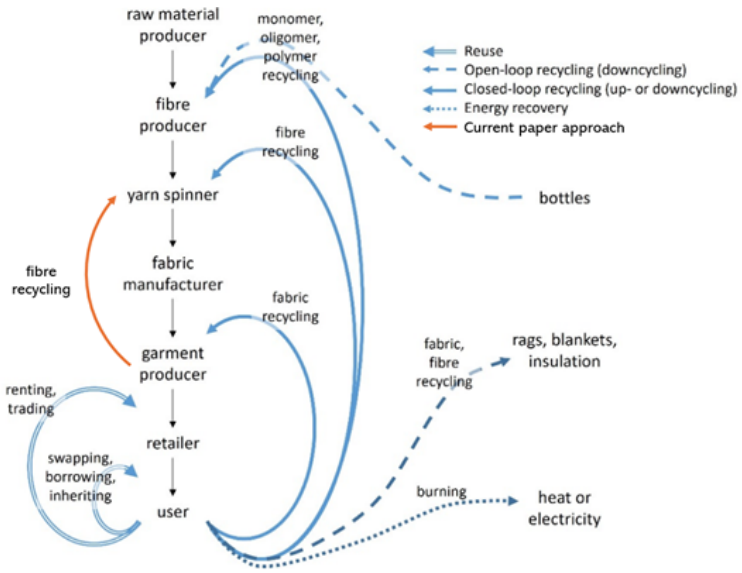


Figure 1. Classification and different circuits of recycling and reuse of textile materials. Adapted from [10].

3.3. Case Study Approach

This research employs a case study approach to investigate the automation of textile-cutting surplus collection in a garment manufacturer, as it allows for an in-depth exploration of complex real-world phenomena within their natural contexts [48]. A case study is particularly suitable when the objective is to understand contemporary events where the researcher has little control over behavioural events [48]. This methodology is widely used in qualitative research, providing rich insights through multiple sources of evidence [49]. The methodology steps used in this case study are identified in Figure 2:

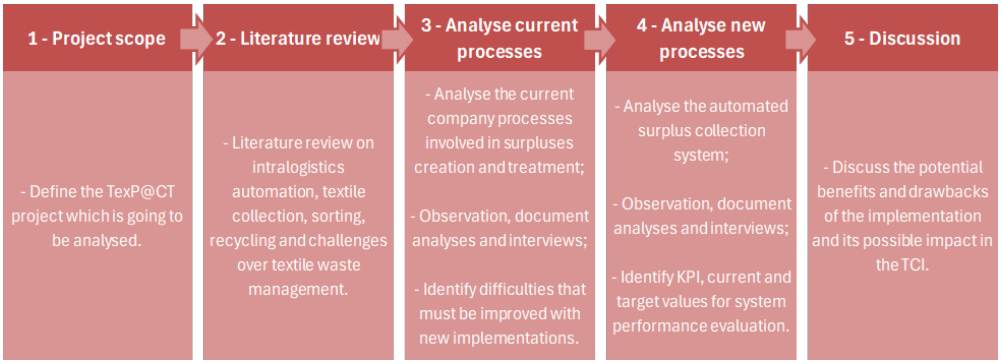


Figure 2. Case study methodology steps.

Data were collected through multiple sources to ensure triangulation and increase the validity of the findings [50].

Direct observations were carried out in manufacturing plant during several visits, allowing the researcher to capture contextual elements that might not be evident through other data collection methods [48]. These on-site assessments enabled us to understand and observe how the processes flow, before and after the new automated system implementation, namely how the surpluses are created, collected, transported, separated between the different areas and the same cutting order, which technologies are involved, and especially how the traceability is assured throughout the processes. Additionally, these visits were also an opportunity to perform unstructured interviews, understand some technical sheets used in the processes, and identify relevant KPI for process performance evaluation.

Five interviews for stage three and six for stage four were conducted. The interviewees for both stages were the same (two cutting operators and one supervisor, one warehouse operator and one project manager); however, for stage four, the supplier was also interviewed. At least four of the interviewees had more than 20 years of experience in the field, and two of them contributed directly with suggestions to the newly implemented system. These interviews aimed to capture in-depth perspectives on how the manual separation of textile-cutting surpluses takes place and the inefficiencies it entails, as well as to provide a clearer understanding of the system implemented and how it improves the process. All of these topics will be addressed over the next section, as well as the textile-cutting process, since this process has a major impact in the collection of surpluses.

A review and analysis of relevant documents, such as reports, policies, and archival records, was also conducted to supplement the primary data [50].

The collected data were analysed. To enhance the reliability and validity of the findings, member-checking was employed, allowing participants to review and confirm the accuracy of the interpreted data [51].

4. Case Study

This section, firstly, provides a brief description of the company and key aspects of the processes related to the production of cutting surpluses prior to the intervention and, secondly, describes the automated system implemented for the transportation and separation of the textile-cutting surpluses.

4.1. General Presentation of the Company

This project was carried out at Pedrosa & Rodrigues, S.A., within the scope of the TexP@CT. Its integration into the TexP@CT arises not only from its commitment to sustainability, but also from the focus on increasing the company's competitiveness.

Pedrosa & Rodrigues, S.A. is a family-owned textile company specialized in the development and production of high-quality garments. The company has its own plant in the north of Portugal and offers the capacity to develop clothing products such as tailor-made clothing, high-end urban loungewear, sportswear, and others. It is classified as a small and medium-sized enterprise.

Besides goals such as becoming carbon neutral and reusing all the water consumed in their plant, the production of raw materials generated by their cutting surpluses—which after being reprocessed into yarn give life to recycled fabrics—highlights, once again, their concern for the environment.

4.1.1. Textile Cutting

Within the organization, the textile-cutting process is the production process that most impacts the quantities of textile material sent for recycling. This phenomenon occurs due to the high complexity of fitting the geometries to be cut in a cutting plane, which ends up generating inevitable waste of raw materials. From now on, "cutting plane" will be refer as a "cutting order". The cutting order varies according to the type and total of pieces to be cut, and it can be composed of a single layer or multiple layers. This number of layers is also usually called "number of sheets".

The cutting process begins at the "spreading" stage of the textile material. This material can arrive in the form of a roll or already unrolled (in the case of having elastane); however, the machine has two different supply systems to support both cases. Usually, the spreading stage begins with the placement of a layer of perforated paper on the cutting table. Then, the textile material is spread over this layer of perforated paper, up to a certain length (being cut there) and to a certain number of layers, according to the cutting order quantities. In this

process, it is natural that to complete a certain cutting order, several rolls of different dyeing batches are necessary. In addition, several colours of the same material can sometimes be cut simultaneously to optimize cutting times, leading these two situations to the need for a clear distinction between dyeing batches or materials. Their separation becomes essential due to the possibility of different shades of colour between batches, caused by the amount of chemicals used to carry out the dyeing process, machine conditions, and environmental conditions, among other causes. When incorrectly separated, it is possible that after the manufacture of clothing products, parts of the garment with different shades may occur within the same garment, which causes a non-conforming product.

For the above-mentioned distinctions, a layer of a different material (e.g., paper or obsolete textile material) is usually applied, allowing a clear distinction between the different dyeing batches and materials used. Once all the necessary material to execute the cut order has been extended, a layer of plastic is also spread, creating a vacuum effect during the cutting process. Although the described process is the standard, the use of perforated paper or plastic may not be necessary depending on the technology employed, particularly in the case of single-layer cutting. However, cutting multiple materials simultaneously creates challenges in separating surpluses, requiring a meticulous decontamination process before the textile surpluses go for recycling.

Once the spreading phase is over, the effective textile-cutting process can be started, and surpluses are then generated.

4.1.2. Collection and Separation of Surpluses

The collection and separation of surpluses are the process that follows the textile-cutting process, consisting of the collection and separation of cut material that has not been used to form parts of a product (e.g., t-shirt sleeves), thus resulting in surpluses. Different surpluses result from this cutting process: paper, plastic, and textile materials. In this context, textile materials are classified as either recyclable (materials converted into fibres for the production of new garments) or non-recyclable (materials transformed into filling materials for other types of products). These recycling processes are conducted off-site using mechanical methods. Figure 3 illustrates the several steps of the surplus-collection and separation process, with the arrows present in the figure representing manual transportations.

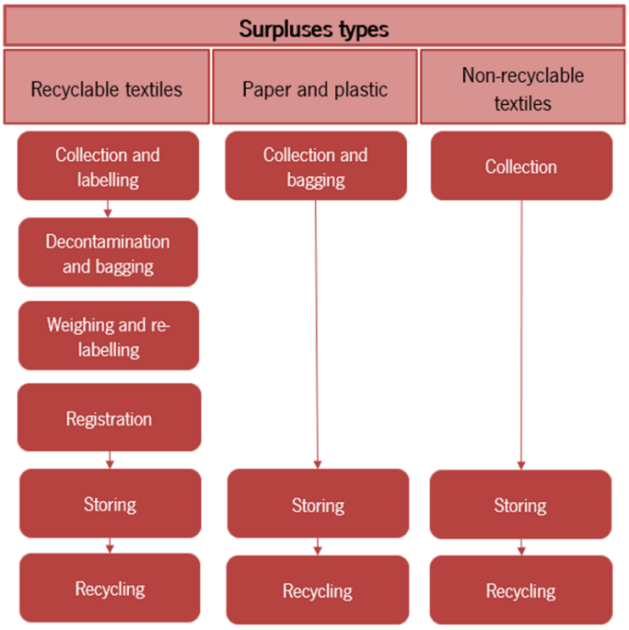


Figure 3. Company processes for each type of surplus treatment.

Transportations are carried out with the use of some non-automated manual equipment, such as trolleys. Figure 4 presents two examples used in the company at the textile-cutting area (other types of trolleys can be found) for moving cut fabric parts required for manufacturing (Figure 4a), and textile surpluses (Figure 4b).



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

Figure 4. Trolleys used to transport (**a**) cut textile parts for manufacturing and (**b**) surpluses for decontamination.

4.1.3. Processes Overview Before Implementation

Currently, the process of collecting and separating surpluses is very rudimentary, having manual transportations covering distances around 100 m every time a cut order is finished. The process is also not ergonomic, implying efforts such as rising and dropping bags manually (e.g., decontamination). Labelling is also manual and registered on paper, which implies registering the data after the process in an Excel database for stock management. This process has several disadvantages, which highlight the following:

- Lack of robustness in labelling and registration processes, leading to mistakes or missing information;
- High time spent by operators with no added value tasks, such as long transportation distances in manual transportations;
- High efforts in non-ergonomic tasks, which hinder the sector's attractiveness;
- High need of available human resources to immediately collect and identify the surpluses generated, guaranteeing traceability losses do not occur, which is essential for the downstream recycling process.

In summary, a very rudimentary surplus-collection process prone to errors was found in this company. It requires available human resources every time a cut order is finished to handle tasks such as transportation and labelling, leading to variable execution times, mistakes, and costs that do not add value to the product and to the company. Therefore, its automation is relevant to make this process more robust and efficient. In this context, an automated pneumatic system for the separation of surpluses was defined for implementation.

4.2. Implementation of the Automated Surplus Transportation and Separation System

The improvement proposal defined for this process was a continuous automatic conveyor and consists of an automated piping system that works on the basis of suction. This system should be able to collect the several types of surpluses (paper, plastic, and textiles) and transport them to a specific recycling area, according to the type of surplus, fully guaranteeing the traceability of textile materials defined for recycling.

4.2.1. System Introduction and Key Performance Indicators (KPI)

The surpluses are generated in the textile-cutting operation, at the end of the textile-cutting machine (A area, Figure 5).



Figure 5. Textile-cutting surplus-collection area (A area).

Then, they are transported to another area through pipes—using suction—for decontamination, segregation, and registration (B area, Figure 6).



Figure 6. Decontamination, segregation, and registration area (B area).

After the processes performed in B area, the textile surpluses are stored in C area (Figure 7), which is right next to B area.



Figure 7. Storage area for recycling textile surpluses (C area).

B and C areas are in the same plant as A area; however, there are around 100 m separating them, which implies long transportation distances. The other surpluses are transported into large containers, which are placed within the same plant, waiting until they become full to be collected and taken for recycling. This process is exposed in Figure 8 and is more detailed in the next section, as well as the technologies involved. The arrows in Figure 8 represent manual transportations performed by operators. Recycling is performed by suppliers in an external area of the plant.

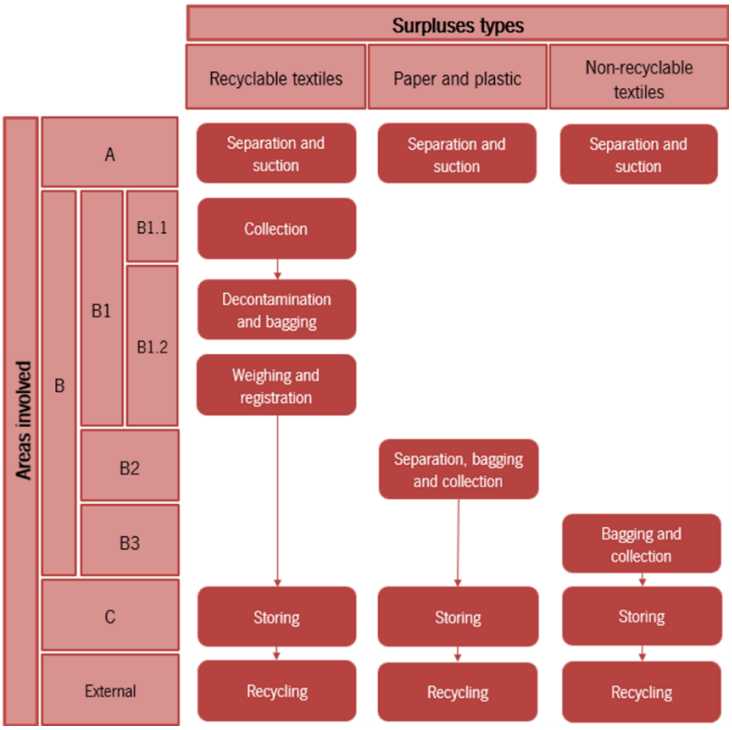


Figure 8. Areas and operations involved in the surplus separation process.

To evaluate the performance and gains of the new system, a set of performance indicators was defined and evaluated. The goal was to establish a baseline for future comparison (Table 1), so the KPI selected were some of the main tasks that will undergo major changes, such as collection, transportation, and tracking. Aside from the improvements in the decontamination phase, this task was not evaluated for KPI, since improvements were considered for operator working conditions (e.g., ergonomics), but are not relevant to processing times because it will still be a manual task. Additionally, targets were defined for the approval of such an automation project, since the expected gains in terms of time and performance are relevant to identify cost reductions that should be obtained by the project deployment.

Table 1. KPI identified to assess the impact of the automated surplus transportation and separation system.

#	KPI	KPI Extended Description	Unit	Pre-Project Value	Target Value
1	Collection time per Purchase Order (PO)	Total time consumed per average PO	Minute	16	10
2	Traceability management time at the cut exit	Time consumed in identifying surplus batches	Minute	4	2
3	Transport time to the decontamination area	Time consumed in transporting the surplus to the decontamination area	Minute	18	0
4	Post-decontamination traceability management time	Time consumed in quantifying the batches of surplus produced after decontamination	Minute	6	5
5	Searching for big bags to send for recycling	Time consumed searching for bags of a given reference	Minute	5	2

4.2.2. Purpose of Different Areas and Technologies Involved

A few procedures have been changed and new technologies have been added to the process in order to carry out the various procedures that were presented in the preceding section:

A area: Three compartments with different colours have been installed for the separation of surpluses (Figure 5), right after the cutting operation: blue (paper), yellow (plastic), and grey (textile materials). In this area, an operator is needed to separate the surpluses into different containers. Every time material is detected in these containers, the surpluses are vacuumed, from one container at a time, through several pipes that connect the containers to the respective B areas, as mentioned in Figure 8. This detection occurs through infrared sensors. The cutting orders are associated with the vacuumed surpluses through a Human-Machine Interface (HMI), also present in this area.

B area: As indicated earlier in Figure 8, in this area (Figure 6) there are three different main separation areas: recyclable textiles (B1 area), paper and plastics (B2 area), and non-recyclable textiles (B3 area). In the B area, there is a limit switch installed in the pipes that is controlled by a programmable logic controller and defines the appropriate path of the textile surpluses (recyclable or non-recyclable), depending on if there was a cutting order selected in the A area or not. If no cutting order was selected, the textile surpluses go to the B3 area, since those textile surpluses are not for recycling.

B1 area: Consists of a collection area (B1.1) and a decontamination, bagging, weighing, and registration area (B1.2) for recyclable textiles. The aim of the B1 area is to ensure that the recyclable textile surpluses are properly separated and do not contain any other type of surpluses; otherwise, it could damage the fibre-recycling process.

B1.1 area: The vacuumed surpluses are autonomously dropped into containers with Radio-Frequency IDentification (RFID) tags, used for keeping surpluses traceable. Every time a cutting order is selected in A area, that information is associated to the RFID tag of the container in the dropping area. This means that each container corresponds to a single cutting order, which may include several textile materials with different compositions (requiring later separation for proper recycling); however, a single cutting order could be in several containers, due to their limited capacity. All containers are on top of a rotative platform which autonomously rotates, always leaving an empty container, or a container with the same cutting order that will be vacuumed in the A area, in the dropping area, at least till the container becomes full. This container capacity is checked by the infrared sensors allocated in the surplus outlet pipe, measuring the distance between the height of the surplus placed in the container and the sensor itself. In the B1.1 area, there is also a mechanical system to close and open the outlet pipe whenever it is needed. When there are no free containers, this information is displayed on an HMI on-site, and an operator removes the full containers from the rotative platform, supplying them with empty ones. Additionally, when a container is removed, it passes through an RFID reader in the exit area, and its location is updated. In turn, when empty containers enter the rotative system, their RFID tags are also cleared, and the location is redefined. All human intervention in this B1.1 area is limited by metal barriers and photocells to avoid interactions with the suction system while it is in operation. The HMI also has the function of stopping or restarting the suction system, so that containers can be removed, or safely supplied by an operator, as well as displaying the capacity status of each container.

B1.2 area: Here is the decontamination, bagging, weighing, and registration area. In this area, the operator places a single container at a time on a lifting platform, equipped with an RFID reader to identify the cutting order and the materials which are going to be handled. The surpluses are then dropped on top of a "table" with vacuum and a grid, facilitating the process of separation, and also preventing textile particles from being inhaled by the operator. The operator then manually separates the surpluses for large bags, according to the type of material and composition, and then the separated surpluses are weighed in the balance. The quantities separated for recycling are then manually registered

in the company Manufacturing Execution System. Every large bag also has its own ID to help track the material.

B2 area: This area contains a single entrance for paper and plastic, which are separated at the exit of the equipment into two separate large bags. Here, there is a mechanical system that opens the desired exit and closes the opposite one, according to the surpluses vacuumed in Area A. When a large bag is full, it is collected and transported into a large container located outside the warehouse for future recycling.

B3 area: The collection of surpluses here is also carried out in containers, but without RFID tags. The container capacity status is also detected using infrared sensors in the same way, such as in area B1.1. Here, the flow of containers is unidirectional, with a buffer of empty containers placed at the back of the outlet pipe. Whenever a container reaches its maximum capacity, the surplus outlet pipe closes, and a sound alert signals that material is ready for collection. The full container is then automatically transported forward, and another empty container goes to the dropping area. To collect containers, it is necessary to stop the system from operating in the HMI near the access area, at that time unlocking the metal barrier door. Resuming the process requires returning to the same HMI. In the same way as in the B2 area, when a container is full, the collected material is transported to a big container located outside the warehouse for future recycling.

C area: This area is used to store the textile surpluses for fibre recycling. This storage is made inside large bags, allocated to modular structures that can be easily stacked, tracked, assembled, and disassembled (Figure 7). Every time one of these structures is assembled and stored, its location is registered in the database. These structures are stacked using forklifts.

5. Discussion

The focus of this paper is not on the technological solution per se (as other technologies could have been selected to collect and transport the textile-cutting surpluses), but rather this study aims to highlight the initial challenges associated with performing this task manually, illustrating one potential pathway towards automation. This case study starts by examining how the surplus collection was performed manually, with trolleys, as this sector is dominated by low-level technology levels as referred to by [11]. It highlights problems such as requiring operators to carry out non-value-added tasks, lack of robustness in labelling and registration processes, and high efforts in non-ergonomic tasks, confirming similar problems also reported by other researchers [20,21].

Then, it shows how the automated surplus separation system was developed, expecting to create a more ergonomic, safer, faster, and reliable process, as suggested by [12]. The system is still in the implementation phase, but it is expected to reduce variability and time required to carry out several operations (identified in Table 2). The new standard times for the collection process can be evaluated after full system implementation. At that stage, statistical tests can determine whether they differ significantly from historical or target values.

Prior to the implementation of the project, the recorded KPI were all obtained through human intervention. Therefore, they presented variability in their values, despite its average or nominal value (pre-project value per event) being recorded in Table 2.

These transportations were performed by different operators (for example, if one operator is absent, their functions should be performed by another operator), and the transportation is not the only task the operator does. It is also a non-priority task, compared to other tasks that add value to the product. This means that transportations can be carried out before the container is full, while in some cases the containers could be overfilled. The

time variability of the transportation could cause a delay in a planned value-added task an operator would do, potentially causing delays in order execution.

Table 2. Time needed to carry out several operations.

#	KPI	Pre-Project Value Per Event	Target Value Per Event	Events Per Shift	Expected Savings Per Shift
1	Collection time per PO	16 min	10 min	a	(16−10)∗a min
2	Traceability management time at the cut exit	4 min	2 min	b	(4−2)∗b min
3	Transport time to the decontamination area	18 min	0 min	c	(18−0)∗c min
4	Post-decontamination traceability management time	6 min	5 min	d	(6−5)∗d min
5	Searching for big bags to send for recycling	5 min	2 min	e	(5−2)∗e min
	Total	49 min	19 min	a + b + c + d + e	6a + 2b + 18c + d + 3e min

By automating the surplus recycling processes, this variability should be reduced, increasing the reliability of operating times. Thus, depending on the events monitored by the proposed KPI, it a daily reduction is expected in those operating times of 6a + 18b + 2c + d + 3e min, where a, b, c, d, and e represent the number of events per day. For example, "Collection time per Purchase Order" had a nominal time value of 16 min. After automation, it will have a time of 10 min. If the number of purchase orders are "a" in a day, the reduced time will be (16−10)∗a. This daily reduction in man-workhours can be translated into a financial benefit. Other benefits more difficult to estimate are related to the reduced variation of this activity that will not cause delays or variability in tasks carried out after this transportation. Thus, production planning will be more reliable, and order execution less risky, in terms of delays.

The automation problem that is centred on consumption and circularity [19] is given more attention in the literature than the surplus of raw materials. We describe basic and straightforward estimations of productivity improvements derived from the use of automation, and give a case study with issues that are typical of various apparel industries. These benefits differ depending on the particulars of the businesses, including the variety of tasks as well as the average time to complete them. Since the systems will have varying savings depending on different layouts, there is merely a computation approach and no in-depth quantitative study.

The system also offers advantages such as improved working conditions for operators, considering ergonomics and occupational safety. Material handling is now mostly automated, eliminating the need for manual efforts such as lifting or dropping bags. Also, the equipment should now contain small particles generated during the decontamination process, making the process less harmful to the operators' health. All these benefits have influenced the decision to automate this collection system.

In addition, RFID tags will ensure the full traceability of the several surpluses, which is essential for their proper recycling and consequent production of recycled fibres. Additionally, it provides reliable information for sustainability compliance about the surpluses collected, supporting the foundation of future initiatives such as the Digital Product Passport (DPP).

The modular structures used in the C area (Figure 6) allow a clear identification of the position of any stored material, and a better use of the available space, since now the structures only take up space if required and are quickly disassembled.

During the planning and implementation of the automation system, other potential improvements were identified as candidates for future improvement projects, such as the development of internal software to manage surplus stocks, replacing the Excel file currently used. This type of improvement will help to increase the company's productivity, since they streamline processes, increase their robustness, and make information easily accessible almost immediately. In addition, they also promote sustainability.

This implementation allowed us to create an illustrative image of the clear advantages of process automation, which remains a significant challenge to apparel manufacturers [8]. Addressing the challenges of [21,23], this case study shows that the integration of automation and advanced sorting technologies presents a viable solution for addressing textile-waste challenges within manufacturing intralogistics. Although the system is not fully operational and it is not currently possible to compare their performance with the processes previously used, it is expected that the acquired solutions will serve as an example of the importance of intralogistics automation, not only for Pedrosa & Rodrigues, S.A., but also for other companies from the TCI sector.

6. Conclusions

This paper describes the implementation of an automated surplus transportation and separation system in a textile company, specialized in the development and production of high-quality garments. It describes the initial situation where the surplus collection was made, using trolleys and requiring operators to undertake such non-value-added activity. It investigates the drawbacks of the initial situation, and assesses potential benefits of automating such processes.

Most of the literature focuses on recycling end-of-life textiles, with few papers on the initial separation of surplus raw materials and its challenges. This case study aims to overcome this gap with empirical research, forming a conceptual solution and considering a long-term perspective. Furthermore, with a predictable system, the variability of operations is reduced, and consequently, there are gains for the company.

Given the limited documentation and adoption of automated systems for collecting textile-cutting surpluses, this case study describes in detail the automated system developed, which can influence other garment manufacturers to adopt such types of automated systems, enhancing textile recycling and sustainability.

The development of the automated solution was accompanied by a set of KPI that assess the implementation and can quantitatively show improvements over the initial situation. With the project, it is possible to see that the proposals for improvement presented include clear advances in the automation of the company's intralogistics. These advances, at least, allow a reduction in the variability of activities as a consequence of activities involving human intervention that would be carried out by automatic equipment, and with employee training in the use of automation, efficiency increases, resulting in a reduction in the time required to collect and process textile waste, making collaborators available to perform other tasks, which may be value-added tasks. This case study shows that the integration of automation and advanced sorting technologies presents a viable solution to address the challenges of textile waste within manufacturing intralogistics.

One limitation of a single case study is its inability to generalize findings. Therefore, we propose as a direction for future research the examination of multiple case studies that have implemented automation within the described context, with the aim of evaluating the return on investment associated with the adopted automation technologies.

The project described in the case study is only a small step towards process improvement, and there were other improvement proposals, identified to progress the automation of the company's intralogistics. Future research should focus on improving the efficiency

and scalability of automated sorting technologies to maximize the environmental and economic benefits of textile-waste recycling.

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Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

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