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Empowering Eco-Friendly Choices: An Environmental Impact Assessment Decision Support System for Textiles and Clothing

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Abstract: The textile and clothing industry is one of the industries with the highest environmental impact, with a huge amount of waste during the product life cycle. However, there are few tools available for companies to assess the environmental impact of their production process. In this way, a decision support system was developed so that producers can calculate the environmental impact associated with the textile and clothing production process, with the main objective of helping producers and, consequently, consumers to make environmentally conscious decisions given the increasingly demanding market. The methodology of this study integrated the accounting of a set of indicators, allowing producers to calculate the environmental impact associated with the textile and clothing production process. The decision support system returns, depending on the results of the calculations of the indicators, different ecolabels that allow consumers to compare different products based on their environmental performance. In short, the study in question allows us to contribute to environmentally conscious decision making, both for the producer and the consumer, to promote sustainable practices in the textile and clothing industry. The decision support system is flexible and adaptable for different companies and industries in order to meet their needs and improve their environmental performance.

Keywords: textile waste; ecolabel; sustainability; recycling; performance indicators

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1. Introduction

The environment plays a crucial role for living beings, providing essential resources for life and raw materials for industry, maintaining biodiversity, and regulating the climate. However, it is heavily impacted by industrial activities, which contribute to increased pollution, resource depletion, and climate change. So, in contemporary society, sustainable development stands as one of the foremost challenges given the mounting concern for reconciling the needs of the present generation with those of future generations without compromising the latter [1].

Generated waste has a major negative impact on society in general and can lead to devastating consequences, such as health problems, loss of natural resources, and increased waste management costs, and it can even damage the economy itself [2].

Textile industry companies are highly developed and distributed around the world but far from sustainable, especially given the technical waste generated as a result of their various processes [3]. The situation is increasingly complex compared with previous years, so over the years, the pressure has been increasing, especially from customers, given the need for ecological production that reduces environmental impacts [2].

Textile consumption in the European Union (EU) ranks as the fourth most environmentally impactful sector, with notable repercussions regarding climate change. Furthermore, it ranks third in terms of water and soil resource utilization and fifth in primary raw material consumption and greenhouse gas emissions [4].

Considering these burgeoning industrial processes, the heightened generation of waste throughout the product life cycle can be observed. The viable recourse for such waste centers on recycling when reusability is unfeasible or on promoting reutilization. However, only a marginal fraction of textile material waste is reutilized or recycled, whether during the manufacturing process or via consumer utilization [5].

As the textile industry has limited tools to assess the environmental impact it generates, the objective of this study is to develop a decision support method utilizing the Excel software 2016 that enables producers to conduct an environmental impact analysis related to the production of their textile products. Furthermore, it facilitates consumers in decision making by creating an "ecolabel" with varying levels of environmental impact.

This manuscript is divided into several sections. Firstly, a brief theoretical framework of the environmental impacts caused by the textile industry is presented, followed by a presentation of the decision support system developed by the authors and its later practical application. The results obtained from three case studies are also shown, and finally, the conclusions are presented.

2. Theoretical Background

2.1. Characterization of the Textile and Apparel Sector

The textile and apparel industry (TAI) is one of the oldest and most traditional industries in Portugal, currently standing as one of the largest and most significant national business sectors. It encompasses a wide range of activities, ranging from the preparation and transformation of raw materials, both natural and synthetic fibers, to the manufacturing of finished products such as home textiles, technical textiles, carpets, and clothing [6].

Over the years, a decline in the number of companies in Portugal has been discernible. According to data provided by Pordata for 2021, the textile and apparel sector comprised 11,835 companies, of which 3527 were related to textile manufacturing, and the remaining were associated with the clothing industry, representing approximately 17.58% of the total national manufacturing industry [7].

This sector holds immense importance in the Portuguese economy given the numerous employment opportunities it provides. It is the third-largest employer and contributes significantly to the value-added obtained from the entire production process. According to the Portuguese Textile and Clothing Association (ATP), it constitutes 9% of production and turnover in the manufacturing industry, 20% of employment in the manufacturing industry, and 10% of total Portuguese exports [8].

2.2. Impacts of Waste Generated by the Textile Industry

The textile industry is one of the industries that extensively utilizes natural resources and ranks among the most polluting sectors globally. Domestic textiles and clothing are considered to be among the most environmentally harmful products in the European Union (EU). The production of any textile product necessitates the substantial consumption of resources, including energy, water, nutrients, and chemicals, incurring significant environmental costs.

Furthermore, apart from the manufacturing process, the consumption of textiles and clothing results in substantial waste generation. In 2017, textile purchases in the EU led to approximately 654 kg of CO_2 emissions per person. According to statistics from the European Environment Agency, textile consumption in the EU exerted the third-highest pressure on water and soil usage in 2020 and ranked fifth in terms of raw material utilization and greenhouse gas emissions. Approximately 0.5 million tons of microfibers resulting from the washing of synthetic clothing are discharged into the ocean annually, accounting for 8% of European microplastics released into oceans. Globally, these figures range from 16% to 35% [5].

The stages of pre-processing (pre-treatment), processing (dyeing and printing), and post-processing (finishing) in the textile-processing process involve the extensive consumption of water, dyes, chemicals, and energy. These processes utilize substantial quantities of chemical loads and water; entail high energy consumption; and yield significant volumes of effluents, atmospheric emissions, and solid waste, comprising a range of substances that are detrimental to both the environment and human health. Thus, the environmental impacts are concentrated throughout a product's life cycle, from obtaining the raw materials to final disposal, also taking into account the emissions derived from the need to transport the product [9].

Given that textiles (and clothing) can endure for hundreds of years, undergo multiple uses, and be inherited by generations, it is imperative to assess the effects of textile waste resulting from the technical aspects of the process on environmental impacts. Conversely, improvements must be made in their collection, reuse, recycling, and disposal throughout their lifecycle. The lifecycle assessment (LCA) method allows for the evaluation of the environmental significance of a product, providing a specific framework for identifying various processes, alterations in favor of environmental impacts, and decision-making guidance.

2.3. Solutions for Minimizing Environmental Impacts

To minimize not only environmental impacts but also the number of raw materials, water, and energy needed during the manufacturing process of new products, one possible solution is the transition from a linear economy model to a circular economy in order to use the products and reintroduce them into various supply chains to recover value [10,11]. Various measures could, therefore, be implemented regarding the use and consumption of textiles to achieve a circular economy that is sustainable and free of toxic substances [5].

Recycling and reuse are, therefore, solutions whereby products that cannot be used for their original purpose can be transformed into new raw materials for manufacturing. However, after consumption, the majority is deposited in landfill sites without any kind of treatment. In Europe, every year, the population consumes around 26kg of textiles and wastes around 11kg. Worldwide, less than 1% of clothing is recycled as clothing, mainly because of a lack of suitable technologies for this purpose [5].

Before being recycled, waste goes through a sorting process in which the materials are identified and divided according to various characteristics such as color, type of fabric, or quality [10,11]. This stage is the most complicated given the complexity of these products, as they often contain other components, including buttons, zips, or other decorative elements [11]. Once this stage is completed, the waste goes on to recycling, which can be characterized based on the nature of the process—mechanical or chemical [11].

The mechanical recycling method is commonly applied to fabric scraps from cutting operations. In this process, the waste is organized by the type of material and defragmented to form new fibers, which become more fragile as they are defragmented and are then sold to other textile spinning companies (shoddy spinning) or reused in the manufacture of various products, such as cleaning materials, filling products, or insulation [11,12]. In turn, chemical recycling is a method of transforming waste previously destroyed by mechanical processes using chemical substances to break it down and obtain smaller polymers while maintaining a similar quality to the initial product [13].

2.4. Ecolabels

The ecolabels used in the textile and clothing industry allude to more ecologically sustainable textiles. In this type of industry, there are already some ecological labels, such as the GOTS (Global Organic Textile Standard) certification logo, which considers organic textile products from the harvest of the raw material to labeling and marketing, offering a credible guarantee to the final consumer. The GOTS is the world's leading standard for textiles made from organic fibers, with a mandatory minimum limit of 70% organic fibers [14].

GoBlue is the first organic label in the world applied to the certification of textile products. Labels can only integrate these logos if some requirements are met; for example, the base raw material needs to be organic and all additives used must be proven to be free of substances harmful to health [15].

OEKO-TEX® Standard 100 is an international certification system that evaluates, through tests, the raw materials and intermediate and end products of the textile sector at all stages of processing in order to award ecolabels to textiles free of harmful substances [16].

The EU Ecolabel is voluntary, being a differentiating factor for companies, and aims to reduce environmental impacts from the production and consumption of textiles, promoting products with a high level of environmental performance. The criteria for awarding this label are determined by taking into account the lifecycle of products [17].

So, the conversion of conventional products into products produced sustainably and safely, as well as, in turn, the use of ecolabels, ensures a supply of ecological products that are of low environmental impact, which also helps consumers to make environmentally conscious decisions and play an active role in the green transition. The ecolabels proposed in this research work through a decision support system (DSS) and are only related to the production process of clothing and textiles, helping not only the consumer but also the producer with knowledge of the different parameters that characterize each process.

3. Materials and Methods

This section presents a brief investigation of methods of evaluating decision support systems and then presents the developed system.

This research was carried out from a mixed perspective. Initially, a quantitative approach was taken to determine the value of the environmental impact produced by an organization since it is a reality expressed numerically and is independent of the beliefs and experiences of the researchers. However, the definition of environmental impact levels is determined from a qualitative perspective since the levels are defined according to the researchers' interpretations and are considered ordinal qualitative variables [18].

3.1. Mult-Criteria Decision Making

Multi-criteria decision making (MCDM) promotes evidence-based decision making by dealing with uncertainty and subjectivity in decision making, especially when it is related to probabilistic data, promoting the integration of the psychological preferences of those who make decisions and the analysis of multiple criteria. There are several MCDM methods, for example, the EDAS (evaluation based on distance from average solution) method and the TOPSIS (technique for order of preference by similarity to ideal solution) method. All of them are evaluation and decision-making methods and can be used to improve the efficiency of decision making in a selection scenario. The combination of the EDAS and TOPSIS methods can give rise to a useful tool for those who have the function of making decisions to select something; for this purpose, the method must consider certain criteria or parameters, such as quality, price, and delivery time [19].

There is another decision-making method called COPRAS (constrained ordinal preference-ranking method for enrichment evaluation) that has already been used in the selection of biodegradable dynamic plastics [20]. The COPRAS method is a multi-criteria decision-making method that helps to select the best option among several alternatives. It is based on an ordinal ranking approach, where alternatives are classified in order of preference based on specific criteria. The COPRAS method consists of three main stages: normalization of the criteria; calculation of the preference matrix; and calculation of the preference score. It is effective in selecting alternatives in situations where there are many criteria to be considered and where there is uncertainty and hesitation in the preferences of decision-makers [20].

It can be concluded that MCDM-based decision support systems are considered a valuable decision-making aid because they are able to deal with the complexity and uncertainty in decision making with multiple criteria [20].

Therefore, the evidence shows the importance of using MCDM and assessing the importance of the DSS developed in the present study case since it allows us to calculate the environmental impact of the textile and clothing sector [20].

3.2. Decision Support System

The DSS created helps producers to make decisions about the textile process by assessing its environmental impact. It allows the manufacturer (user), for example, to understand whether to keep the process as it is, to revise it to reduce the impact caused, or to check whether or not the production of a particular article is viable. In addition, it allows consumers to make a conscious choice between articles according to the level of environmental impact of each one.

The DSS, developed in the Excel software using Visual Basic for Applications (VBA), was designed for use by textile manufacturing producers, so it was intended to be as intuitive and simple as possible. Thus, the user can calculate the impact associated with their process and/or view their activity history.

3.2.1. Development of the Decision Support System

The user starts by accessing the DSS and is presented with a "Home Page", Figure 1, where they can get a brief idea of how the system works. Pressing the "Start" button opens a form, Figure 2, which asks the user what they want the program to do: calculate environmental impact or access their history. By selecting the "History" option, the user is directed to a page, shown in Figure 3, where the results obtained, as well as all the values entered in previous uses, are recorded.

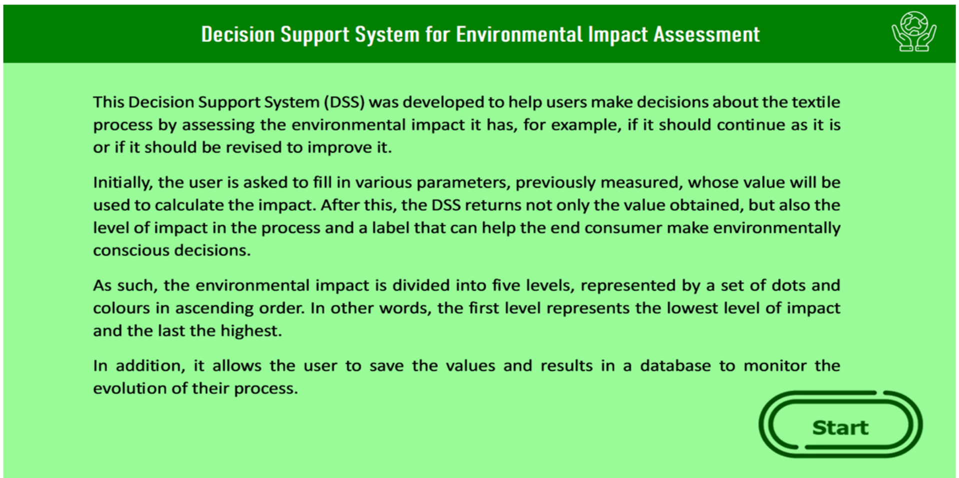


Figure 1. Home Page.

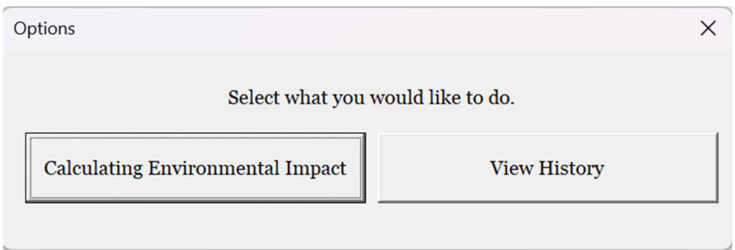


Figure 2. Options form.

Date	Impact Value	Level	Gaseous Emissions	Effluents					Resource Efficiency		
				Chemical Oxygen Demand	Pesticides	Total Kjeldahl Nitrogen	Heavy Metals	Absorbable Halogenated Organic Compounds	Consumption of Electrical Energy (kWh)	Water Consumption (m^3)	Amount of Fabric Manufactured (kg)
17/05/2023	57.51	3	145	12	0.0001	5	0.5	1	34	9	15
16/05/2023	125	5	1757.75	318.75	0.003125	21.25	6.25	0.725	24.8875	4.0625	10
16/05/2023	10	1	140.62	25.5	0.00025	1.7	0.5	0.058	1.991	0.325	10
16/05/2023	75	3	351.55	255	0.0025	17	5	0.58	19.91	3.25	10
16/05/2023	8.11	1	111	1	1	1	1	1	1	1	22
16/05/2023	0.4	2	897	146	0.06	2	1	0.2	10	10	450
16/05/2023	0.09	1	125	12	0.004	5	2	1	12	5	235

Figure 3. History page.

If the user selects "Calculate the Environmental Impact", they will be directed to the "Calculate Environmental Impact" page, shown in Figure 4, where information regarding several parameters must be entered, whose value will be used to calculate the environmental impact associated with the process. The parameters to be entered must be measured in advance using whatever method the user finds most appropriate. The only restriction defined by the DSS is relative to the units. These concern the quantity of gaseous emissions, expressed in mg·nm^{-3}; the quantity of effluents in mg·dm^{-3}; and resource efficiency.

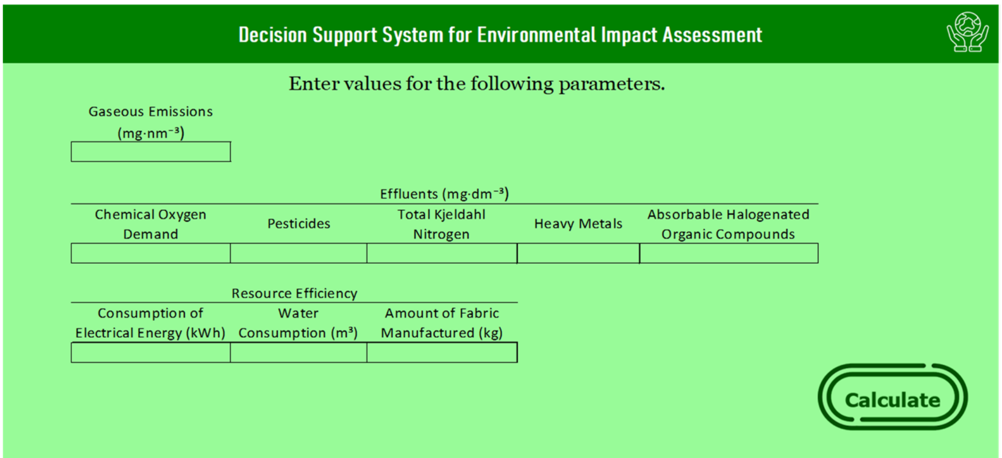


Figure 4. Calculate the Environmental Impact page.

As far as effluents are concerned, five factors are considered: chemical oxygen demand, which provides an estimate of water pollution—i.e., it measures the amount of oxygen needed to de-pollute water [21]; total Kjeldahl nitrogen, which measures the amount of nitrogen present in water [22]; pesticides; heavy metals; and absorbable halogenated organic compounds. The latter can be derived from the chemicals used in manufacturing processes. In turn, to calculate resource efficiency, the consumption of electrical energy in kwh, water consumption in m^3, and the amount of fabric manufactured in kg are considered.

Once filled in, by pressing "Calculate", the DSS returns the value obtained, the level of impact the process is at, and an example of a label that can help the end consumer make environmentally conscious decisions using an environmental scale. The results page is shown in Figure 5.

The environmental impact is, therefore, divided into five levels, represented by a set of dots and colors in ascending order (Figure 6). In other words, the first level represents the lowest level of impact, and the last represents the highest.

On this results page, the user has three buttons: "Save", "History", and "Finish".

By clicking on "Save", the program copies the results and values entered into the "History" sheet; in "History", it shows the database for previously saved calculations, allowing the user to follow the progress of their process; and in "Finish", the DSS clears the data entered and returns to the Home Page.

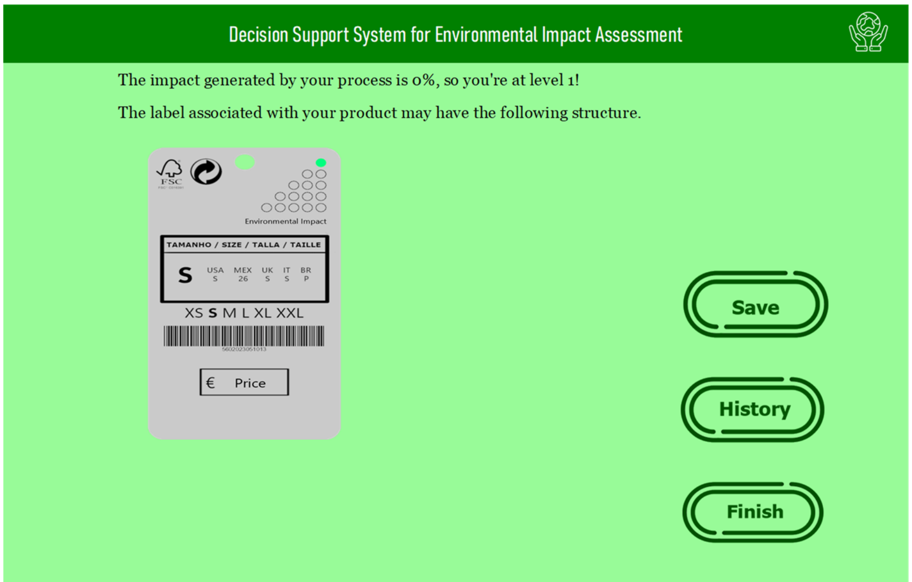


Figure 5. Results page.

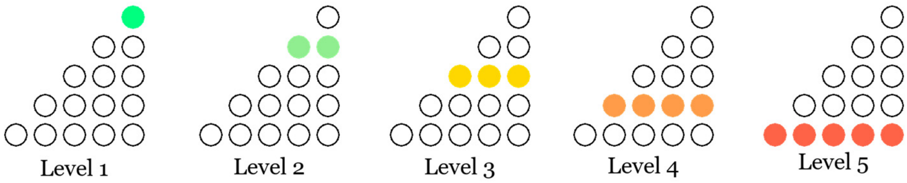


Figure 6. Representing environmental impact levels.

There are also two buttons in the "History" section, one that allows you to return to the results page and another like "Finish".

All the buttons were created using Excel's Macros option as follows:

- Insert the desired icon;
- In "Programmer", select "Save Macro";
- Name the Macro;
- Recreate the steps that you want the button to perform (for example, on the "Start" button, click on the "Evaluate process impact" sheet);
- Select "Finish Recording";
- Select the icon;
- Press "Assign Macro", and select the Macro you want.

3.2.2. Calculating the Environmental Impact Value

As mentioned above, three categories of parameters were used to calculate the environmental impact. These were determined using mathematical expressions, except for gaseous emissions, which is a directly measured value. Thus, Equation (1) was used to calculate the effluent [23], Equation (2) was used to obtain the electricity efficiency value [24], and Equation (3) was used for water efficiency [24].

$$\text{Effluent} = 5 \times (\text{COD} + \text{P} + \text{TKN} + \text{HM}) + 100 \times \text{AOX} \quad (1)$$

where

- COD: Chemical oxygen demand;
- P: Pesticides;
- TKN: Total Kjeldahl nitrogen;
- HM: Heavy metals;
- AOX: Adsorbable halogenated organic compounds.

$$\text{Electrical energy efficiency} = (\text{electrical energy consumption})/(\text{quantity of fabric manufactured}) \quad (2)$$

$$\text{Water efficiency} = (\text{water consumption})/(\text{quantity of fabric manufactured}) \quad (3)$$

As the categories reflect different quantities, they cannot be added together; thus, they are calculated as proportions using Equation (4).

$$(\text{measured value})/(\text{reference value}) \times 100 \quad (4)$$

The maximum value allowed by law for each parameter was taken as the reference value, except for electricity and water consumption, where the average value for the sector was taken. They are all organized in Table 1.

Table 1. Reference values.

Parameter	Maximum Value/Average Value
Gaseous Emissions ($mg \cdot nm^{-3}$)	1406.2
Effluents ($mg \cdot dm^{-3}$)	1443.01
Chemical Oxygen Demand	255
Pesticides	0.0025
Total Kjeldahl Nitrogen (TKN)	17
Heavy Metals	5
Adsorbable Halogenated Organic Compounds	0.58
Resource Efficiency	1.158
Electrical Energy Consumption ($kWh \cdot kg^{-1}$)	1.991
Water Consumption ($m^3 \cdot kg^{-1}$)	0.325

The maximum value for effluents was obtained by substituting the maximum values for each parameter into the formula for calculating effluents, Equation (1). In contrast, the value for resource efficiency was obtained from the average consumption of electricity and water. This means that

$$\text{Environmental impact } (\%) = (\text{gaseous emissions} + \text{effluents} + \text{resource efficiency})/3 \quad (5)$$

Based on the percentage of environmental impact, five levels were created, the limits of which are shown in Table 2. It was noted that the last level exceeded the values permitted by law, which is why it exceeded 100%.

Table 2. Environmental impact level limits.

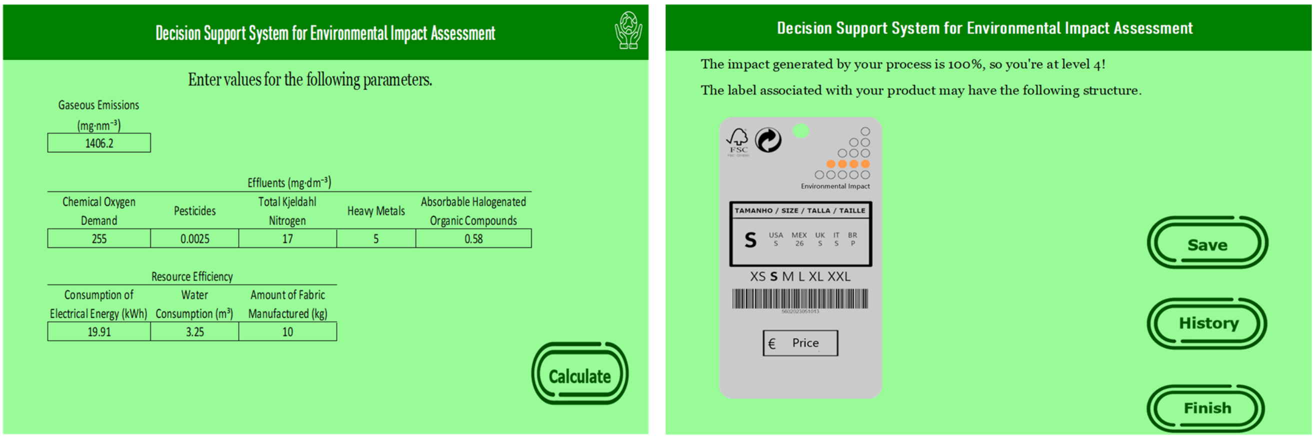
Level	Limit (%)
1	0–25
2	25–50
3	50–75
4	75–100
5	>100

4. Results

To analyze the results, we decided to conduct a sensitivity analysis to determine the variation intervals of the parameters. Three hypothetical case studies were conducted to analyze how the parameters change.

4.1. Case Study 1: Use of Legal Maximums

Assuming that the user's process is at the threshold of what is allowed by law (shown in Table 1), their process will have an impact of 100%, which corresponds to level 4 on the scale. Figure 7 shows the data used for this case, as well as the results obtained.



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

Figure 7. Case Study 1: (**a**) data; (**b**) results.

4.2. Case Study 2: 90% Reduction

Considering that the user decides to improve his process and that a 90% reduction concerning the maximum legal values is achieved, the impact he will generate is 10%, which corresponds to level 1 and is, therefore, closer to the ideal scenario. Figure 8 shows the data used for this case, as well as the results obtained.

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

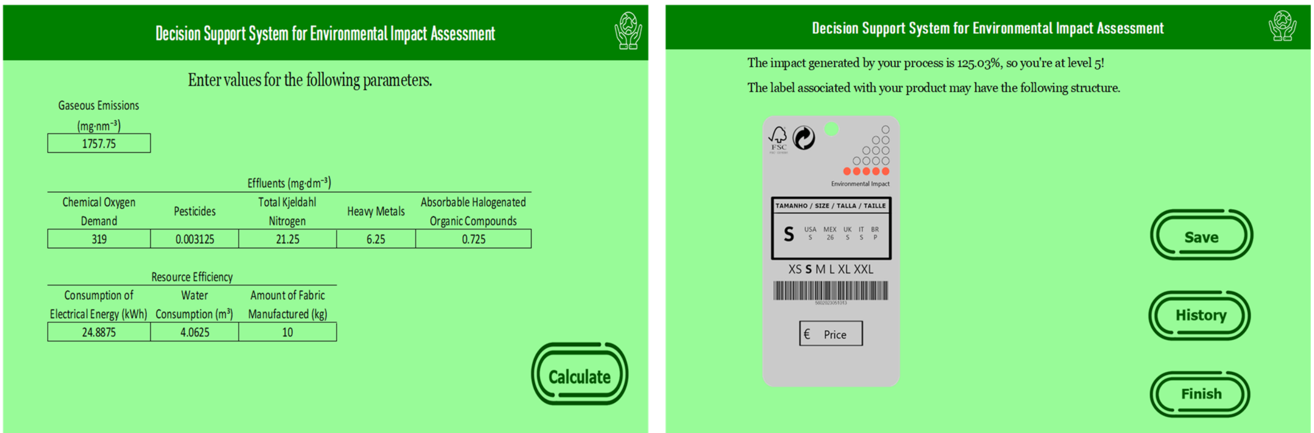
Figure 8. Case Study 2: (**a**) data; (**b**) results.

4.3. Case Study 3: 25% Increase

If there is a 25% increase, the impact generated is 125% and is, therefore, at level 5.

Whenever a process is at level 5, the user can see that it has exceeded the legal limit in some parameter. It is, therefore, advisable to analyze the production process to see where improvements can be made to reduce the environmental impact. Figure 9 shows the data used for this case, as well as the results obtained.

The study's findings consider the practical implications for organizations seeking to implement decision support systems, aiming to restrain adverse environmental impacts within the textile and clothing industry. A comprehensive strategy that encompasses raw material analysis, facility and equipment updates, cost considerations, human resources training, marketing and market approach changes, and digitalization is recommended to guide organizations toward sustainable and environmentally responsible practices.



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

Figure 9. Case Study 3: (**a**) data; (**b**) results.

In terms of raw material analysis, organizations should adopt a rigorous, scientifically grounded approach. Decision support systems can play a crucial role in identifying environmentally friendly alternatives through methodologies like lifecycle assessments. These assessments, incorporating parameters such as energy consumption, emissions, and resource use, provide a holistic understanding of the ecological footprint associated with each material. Raw material assessment is required to apply ecolabels. This will require tighter quality analysis.

Facility and equipment updates require a systematic approach guided by decision support systems. Scientifically validated assessments of existing infrastructure, including energy efficiency, waste generation, and pollutant emissions, should inform strategic modifications. Employing advanced technologies for facility monitoring, including IoT sensors and digitalization, ensures real-time data acquisition and performance optimization. Updating facilities and equipment to comply with eco-friendly production is costly and long, as it is an action point that can take some time to implement.

Human resources training is a critical component that should be conducted through scientifically curated programs embedded within decision support systems. These programs should focus on ecological literacy, educating employees on understanding and implementing sustainable practices. The emphasis is on fostering a culture of environmental responsibility through continuous education and scientific awareness.

Market strategies should be scientifically informed and implemented. Analyzing market trends and consumer preferences with digital tools allows organizations to strategically position and communicate their environmentally conscious practices. Scientifically validated marketing campaigns, emphasizing the transparent communication of eco-friendly attributes, can positively influence consumer behavior.

The integration of digitalization into companies and, consequently, into decision-support systems requires a strategic approach. Organizations should invest in cutting-edge technologies such as IoT, big data analytics, and blockchains. Scientifically driven digital solutions can provide real-time insights into environmental performance metrics, ensuring data accuracy and reliability. Incorporating machine learning algorithms can optimize processes, further reducing environmental impacts.

In summary, adopting decision support systems in the textile and clothing industry requires a multidimensional and scientifically guided approach. Organizations should follow and structure the order of procedures for raw material analysis, facility and equipment changes, human resources training, and marketing and market approach changes—each one considered with cost and human resources impacts in a strategic and scientifically informed manner—to achieve meaningful reductions in adverse environmental impacts while maintaining economic viability.

In essence, the convergence of decision support systems, environmental impact assessment, and digitalization in the textile and clothing industry represents a transformative approach. Digital tools and technologies enhance the capabilities of decision support systems, making them more adaptive, data-driven, and effective in promoting sustainable practices within the industry. A versatile approach to assessing and minimizing environmental impacts while positioning organizations as environmentally responsible entities aligns with the rising demand for sustainable products and contributes to broader environmental conservation goals.

5. Conclusions

Concern about the awareness of textile waste and its negative effects on ecosystems has increased significantly in recent decades. The textile and clothing industry is one of the largest polluters and has the greatest environmental impact, and textile recycling is an important and necessary process for reducing the environmental impact caused by textile waste.

The decision support system developed here helps both the user and the consumer, in that it allows different parameters such as gas emissions, effluents, and resource efficiency to be recorded and accounted for to calculate the environmental impact associated with the production process. Each percentage, from the lowest to highest environmental impact, is assigned a level from 1 to 5, thus making it possible to check whether the process is viable and to implement alternatives that minimize its impact. These generated levels are defined based on an ecolabel to help consumers make environmentally conscious purchases, which is an advantage. However, it still has not been applied to real cases, which is part of recommended future work, which can be interpreted as a disadvantage.

However, three hypothetical cases were analyzed in order to understand the variation in the levels of impact between them. Thus, for the first case, the maximum values allowed by law were taken into account, and the fourth level of environmental impact was obtained. The second case simulated what would happen if the values used in Case 1 were reduced by 90 percent, resulting in the first level of environmental impact. Finally, in the third case, a 25 percent increase in the legally admissible values was considered, which resulted in an increase in the impact level to the fifth and worst level.

The development of this system presented some difficulties, namely, a lack of quantitative data required for most of the parameters accounted for in the calculation of environmental impact and the difficulty in defining an equation for calculating effluents, so we had to use one that already exists in the literature with defined parameters. In addition, it was not possible to find a referenced formula for calculating environmental impact, so we opted instead for an arithmetic average of the different categories analyzed.

Finally, it would have been pertinent to carry out a sensitivity analysis of the decision support system created. However, this was not possible, as the variables all have the same weight when calculating environmental impact.

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