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ORIGINAL ARTICLE

Improving the economic and environmental sustainability of painting and glueing operations in a luxury leather goods industry using DMAIC methodology – a case study

J. Monteiro[1] · F. J. G. Silva[1,2] · C. R. Regattieri[1,3] · L. P. Ferreira[1,2] · R. R. Lucas[1,4] · R. C. M. Sales-Contini[1,5]

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Abstract
The luxury personal goods industry is facing increasing pressure to improve economic and environmental sustainability in its production processes. Thus, efforts need to be made to improve some of the traditional operations performed in this sector. In fact, a gap is found in studies intending to enhance the operational efficiency of this sector. Thus, this study seeks to improve painting and glueing operations in this sector using the DMAIC (Define, Measure, Analyze, Improve, Control) methodology. The research was focused on analyzing existing practices, identifying inefficiencies, and implementing targeted improvements. Key findings show that restructuring filter management enabled a reduction of 258.07 kg of waste sent to landfill after two weeks of implementation, resulting in weekly savings of €112.19 and 88.72% reduction in disposal costs. In addition, standardizing filter types across different equipment improved operational efficiency, reduced inventory discrepancies and became a large area in the warehouse. The results highlight the effectiveness of integrating Lean and Six Sigma methodologies in optimizing production in the sector. The study concludes that systematic improvements generate substantial economic benefits and reduce the environmental footprint. This case study serves as a reference for similar industries seeking sustainable practices without compromising production quality and competitiveness. The research reinforces the importance of continuous improvement to achieve sustainability goals in manufacturing.

Keywords DMAIC · Continuous improvement · Sustainability · Warehouse · Production improvement · Luxury products

Introduction

The luxury goods market is characterized by a unique production system, where know-how, exclusivity and differentiation are crucial for its growth. These characteristics unconsciously generate high expectations among end consumers, who demand impeccable, durable, and sustainable products. Therefore, it is essential to improve production processes and constantly seek increasingly sustainable solutions. The global luxury leather goods market size was USD 4,2743.74 million in 2021, and the market is projected to reach USD 60,633.19 million by 2031, exhibiting a CAGR (Compound Annual Growth Rate) of 3.56% during the forecast period [1, 2]. Regarding the large volume of money this industry is making, any effort to become more sustainable is very welcome and can positively contribute to the overall sustainable development goals. Because leather luxury products are made from natural and limited resources, sustainability is a particular concern. Economic impact is not the main concern as these products will be purchased by a society group that

✉ R. C. M. Sales-Contini
rcmsc@isep.ipp.pt

1 CIDEM, ISEP, Polytechnic of Porto, R. Dr. António Bernardino de Almeida, 431, Porto 4249-015, Portugal

2 LAETA, INEGI - Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial, R. Dr. Roberto Frias 400, Porto 4200-465, Portugal

3 Technological College of Taquaritinga, Centro Paula Souza, Av. Dr. Flávio Henrique Lemos 585, Portal Itamaracá, Taquaritinga, São Paulo 15900-000, Brazil

4 School of Engineering and Sciences, São Paulo State University (UNESP), Guaratinguetá, São Paulo 12516-410, Brazil

5 Technological College of São José Dos Campos, Centro Paula Souza, Av. Cesare Mansueto Giulio Lattes 1350, Distrito Eugênio de Melo, São José Dos Campos, São Paulo 12247-014, Brazil

usually does not present economic concerns, but the environmental impact needs all our attention and deserves particular consideration. The resources spent by the companies on logistics cannot be neglected. Lean management points out that it is a waste to have an excess of stock or manufactured products. Thus, luxury leather goods manufacturers need to care for their logistics systems, avoiding excessive stocks of raw materials and unnecessary transport of products into their facilities. These movements spend time and energy, generating pollution and creating waste that must be avoided.

These companies feel the need to optimize their processes and internal logistics. Thus, it is necessary to develop methodologies enabling to identify problems and mitigating them assertively. To improve the economic and environmental sustainability of processes in the high-value personal goods sector, it is needed to minimize material variation, reduce waste sent to landfill and improve the overall efficiency of the production process [3]. This study uses a descriptive, exploratory, qualitative and quantitative research approach based on Lean Six Sigma principles and the effective use of Lean tools such as the Ishikawa Diagram, 5W2H and 5S in conjunction with Six Sigma methodology. This combination has led to significant operational improvements and better management of resources, particularly in the use of filters in the glueing and painting processes. It was expected that by effectively redesigning the line supply method, the frequency of material deviations between workstations, the stock in the warehouse, the operators' movements, the way the filters are used and the amount of waste sent to landfill would be minimized, improving the economic and environmental sustainability of the process.

DMAIC together with Lean tools can help in identifying and quantifying the waste in this manufacturing sector, avoiding the waste of harmful products usually used in this sector, namely the glue. Moreover, other related products, as filters, are polymers that are difficult to recycle or reuse because they are contaminated by glue, resulting in damage to the environment. Thus, DMAIC and Lean tools, applied together, seem an excellent way to improve the overall sustainability of this specific industrial sector. The results indicate that the use of the DMAIC tool has resulted in increased process efficiency that can be replicated in other businesses within the group. This not only supports strategic objectives but also creates a competitive advantage in similar business environments.

The application of the DMAIC method in the context of the production of luxury leather goods proves to be an original contribution to the field of continuous improvement, especially by integrating principles of operational efficiency with sustainable practices in a sector traditionally focused on exclusivity and high aesthetic standards. This approach not only demonstrates the viability of applying quality tools in high-value-added segments but also offers methodological support for other industries that face the challenge of reconciling productive excellence and socio-environmental responsibility [4]. Thus, this case study can be understood as a replicable model, whose practices are capable of being adapted to different industrial contexts, contributing to the dissemination of an organizational culture focused on sustainability and continuous innovation.

Literature review

Regardless of the sector in which it operates, companies are forced to permanently reduce costs, continually increase the material's sustainability, reduce waste, and improve quality [5, 6]. Furthermore, they must fulfil orders promptly [7]. Therefore, companies must be concerned and committed to their continuous improvement systems [8]. Continuous improvement can be achieved through the introduction of automation [9], management tools [10], or a combination of both [11]. The luxury leather products industry is no exception [12], which also faces some ethical problems (animal skins) [13].

Production processes are extremely prone to accumulating waste in cycle time and material resources [14]. Although processes are increasingly designed with waste minimization in mind, in most cases, this is achieved during the life of the projects [15], mitigating any type of waste. Lean philosophy aims precisely to eliminate waste as much as possible [16], having essentially identified seven types of waste [17], to which an eighth waste was added when it was considered the waste of employee skills [18]. While the Lean philosophy was developed based on the so-called Toyota Production System that aimed to respond to the industry's problems in the post-World War II era [19], Bill Smith (Motorola company) developed a methodology for continuous improvement of production systems minimizing results variability in production, drastically reducing quality problems (also a source of waste) [20, 21]. Because both philosophies converge in the systematic resolution of problems and the minimization of waste, the Lean Six-Sigma concept upsurged [22], or LeanDMAIC [23], becoming a very popular strategy to mitigate waste. Thus, two main aspects of the Six-Sigma philosophy were raised: DMAIC (Define, Measure, Analyze, Improve and Control) and DMADV (Define, Measure, Analyse, Design and Verify). The first one is devoted to the improvement of processes already installed [24], and the second one is focused on the design of new manufacturing processes [25]. Lean Six Sigma has demonstrated extra abilities in solving complex problems, even in cutting-edge industries [26]. Below, some cases in which the Six Sigma methodology combined with Lean tools produced very positive results are presented, improving quality and reducing the initial waste.

Due to the significant variations observed in the dimensions of two components used in tire manufacturing for the automotive industry, namely the tread and the sidewall, Costa et al. [27] used the DMAIC tool to reduce the scrap generated during their production. After collecting the initial data, actions were planned, and procedures were developed to mitigate the problems. It was possible to reduce the scrap of extruded rubber products by 0.89%, which allowed an annual saving of €165,000 and a significant reduction in environmental burden (material hard to recycle). Pereira et al. [28] used the DMAVD tool to analyze customer satisfaction in the process of developing components for the automotive industry, trying to achieve 100% satisfaction. Parameters such as Quality Control and Time to Market were monitored, allowing for the identification of the factors contributing to the emergence of problems in the new product development, satisfying the criteria stipulated by customers. Based on the problems identified, it became much easier to replace or change processes so that the intended results were effectively achieved. The suggested and implemented improvements minimized delays and quality problems in the pre-series development phase. A similar study about customer satisfaction had been previously developed by Behara et al. [29] using a Six Sigma approach as well. Although the cases mentioned above can be of medium difficulty in solving, Nonthaleerak and Hendry [30] reported that the six-sigma methodologies are more easily adapted to complex cases. The combination of Lean + Six Sigma tools has also been used in the services sector, in some very complex cases, such as aircraft repair, improving problem identification, repair operations and quality improvement procedures, and decreasing customer complaints. Widiwati et al. [31] applied Lean Six-Sigma methodology in the food industry, enhancing the Process Cycle Efficiency from 66.19% to 70.98%. Consequently, the lost time decreased from 194 to 87 min, and the wasted products decreased from 25,146 units to 12,508 units. Also in industry, Daniyan et al. [32] also achieved very interesting results in improving the efficiency of a bogie assembly line in the railcar industry, cutting the process cycle efficiency by 46.8%, the lead-time by 27.9%, and increasing by 59.3% the value-added time, inducing a reduction by 71.9% of the wasted time. Gaikwad et al. [33] developed a novel framework putting together Lean, Green and Six-Sigma tools and methodologies to help in improving, in a generalized way, the manufacturing sector in India, but it can be extended to other countries. Surjit et al. [34] used mainly Six-Sigma methodology supported by some Lean Manufacturing tools to develop a novel framework to make the apparel industry more sustainable toward zero waste in the manufacturing process. Silva et al. [35] carried out a literature review focused on the automotive industry and how these tools can contribute to improving processes, eliminating waste, and increasing service quality. Unfortunately, no studies on the luxury products sector have been found, preventing a closer comparison of results between this work and previous works. However, other sectors are also intensively using Lean Six Sigma to overcome several issues found in the services sector.

This methodology was also implemented in the healthcare sector, where Lean Six Sigma is also usually applied. Mitchell et al. [36] used Lean Six Sigma to identify and overcome failures in complying with the scheduled time for the first operations in the surgical center. Their study allowed for developing solid problem-solving methodologies, allowing for reducing the delays in the surgical workflow, improving its efficiency. Also in the medical sector, Gomez et al. [37] worked on urgent stroke endovascular intervention, where the workflow was not properly organized. Applying Lean Six-Sigma methodology, the authors improved the emergency performance based on the "door-to-puncture" time, achieving very interesting values compared to the baseline considered for that study. The need to quickly obtain and process data corresponding to patients in critical condition can be the difference between saving a life or losing it. Therefore, hospital processes for receiving critical patients must be prepared so that there is no loss of time in complementary diagnostic processes. This was the work developed by Mistry et al. [38], which resulted in significant savings in additional diagnostic time. Proudlove et al. [39] also devoted their attention to exploring how Lean tools and Six Sigma methodology could significantly contribute to increasing quality in the healthcare sector, particularly in the National Health Service (NHS) of the United Kingdom.

Although Lean Six Sigma (LSS) has established itself as an effective methodology for process improvement in traditional industrial environments, its application in high-value-added sectors, such as luxury goods, is still relatively incipient in academic literature. However, studies in niche industries, such as aerospace and healthcare, demonstrate the flexibility and adaptability of LSS to contexts that demand high levels of customization, accuracy, and regulatory compliance [40, 41]. In the aerospace industry, for example, LSS has been used to reduce critical defects and increase system reliability [42], while in the hospital sector, it has contributed to improving the quality of care and reducing waste in complex services [43]. Such evidence supports the relevance of exploring its applicability in other niche sectors, such as the luxury market, where process variability and the demand for high-quality standards become even more challenging. Thus, this work seeks to fill this gap by proposing a practical application of DMAIC in the production of luxury leather goods, aligning operational performance with values of sustainability and aesthetic excellence.

Given the multiplicity of cases in which the Six-Sigma methodology can be successfully applied in conjunction with the Lean philosophy, this work aimed to test its effectiveness applied to a different sector, where Quality assumes crucial importance. As quality can be affected by the degree of organization on the shop floor, the combination of methodologies can solve industrial problems in less usual environments, such as the luxury leather products industry. Because Six Sigma was not previously applied to luxury leather manufacturing, this was the route chosen to mitigate some problems in this industrial sector, constituting the main novelty of this work.

Methods

Regarding the specificity of this study, precise lean tools were selected to effectively implement the DMAIC (Define, Measure, Analyse, Improve, Control) methodology. This methodology was selected based on its ability to address the unique challenges faced in the luxury leather goods industry, particularly in the painting and glueing operations, as it is a problem-solving methodology capable of implementing Six Sigma into existing processes with the help of Lean tools. Other tools can also be considered, but the usefulness in solving problems of the Lean tools is more consensual and assertive, given the quantity and quality of data available and the focus of the work [38]. The Lean tools selected were those that, based on the literature consulted and the experience of previously developed case studies, offered greater guarantees of effective results in the short term. The diagram of Fig. 1 intends to describe the different steps of this methodology when applied to this specific problem, detailing the goals and actions to be performed regarding each step of the methodology.

Lean tools rationale

The selection and application of Lean tools in this research were guided by the need to adapt them to the specific challenges of luxury manufacturing, such as artisanal production, high process variability, extreme focus on quality and low production scale. The rationale behind the choice of each tool and how it was practically applied in the environment analyzed. The choice for Lean tools, such as Ishikawa's Diagram and the 5S methodology, was strategically oriented to address specific operational challenges in the production of luxury goods. The Ishikawa's Diagram is effective in identifying and categorizing the multiple potential causes of quality failures, allowing a detailed analysis of the factors that compromise the excellence of the final product [44, 45]. Moreover, in artisanal environments, variability and defects rarely arise from systematized causes. The Ishikawa Diagram was selected for its ability to facilitate the

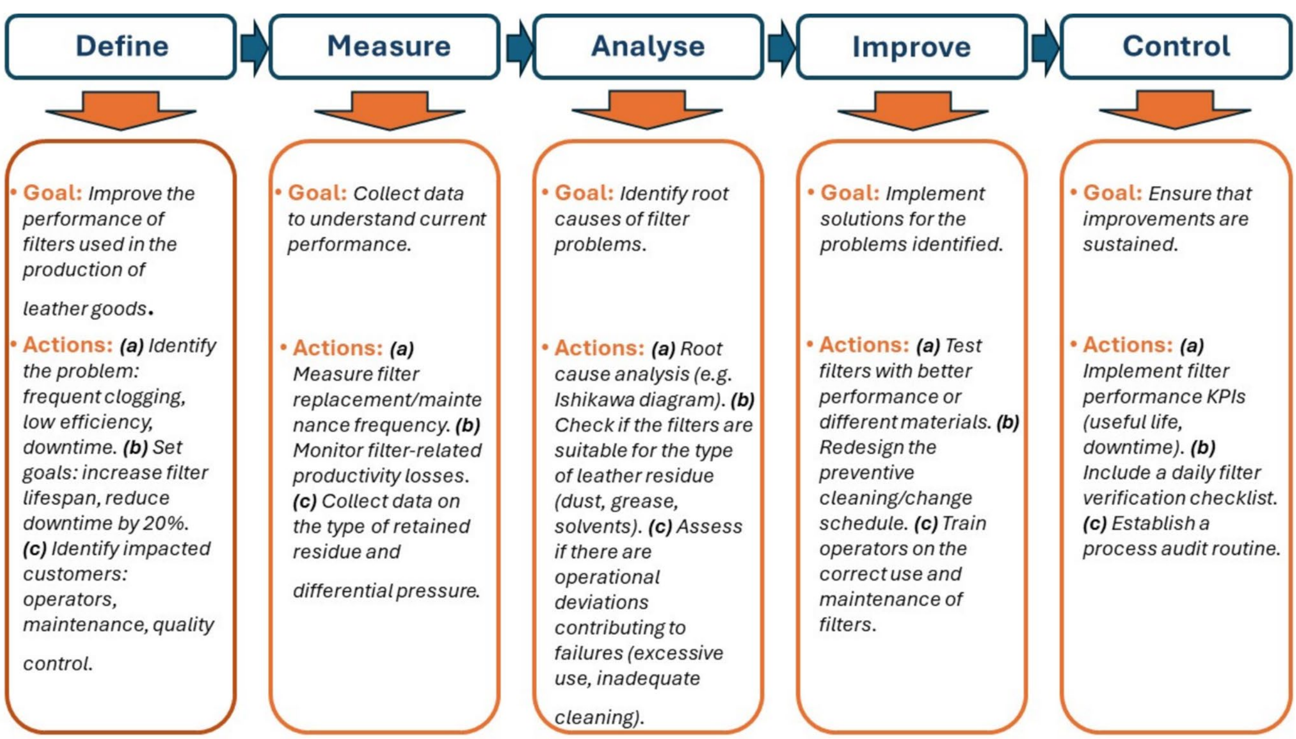


Fig. 1 Diagram on how the DMAIC methodology is applied in this specific case

structured identification of potential causes of quality problems, even when they originate from manual and subjective activities. 5S methodology, in turn, is essential to establish and maintain an organized and standardized work environment, crucial aspects to ensure consistency and quality in the manufacture of high-value-added products [46]. Moreover, 5S promotes organization and discipline, fundamental conditions for ensuring consistency in work environments that depend on human skill and where small failures can compromise the perception of luxury of the final product. Although tools such as Value Stream Mapping (VSM) and Kaizen events are widely used to improve continuous production flows and repetitive processes, their direct applicability in artisanal and made-to-order production environments, characteristic of the luxury industry, is more limited. In these contexts, where customisation and meticulous attention to detail are paramount, the emphasis is on accurately identifying specific causes of variability and creating a work environment that promotes craftsmanship [47]. Regarding the Poke-Yoke tool, the need to avoid human errors without resorting to excessive automation makes it ideal for the artisanal context. However, this cannot be directly applied to this case, as the filters are too flexible and difficult to allow a Poke-Yoke system. Otherwise, Pareto's tool is usually used to prioritize causes of problems based on their frequency or impact, especially in contexts of rework and quality failures, which is not the current case. Thus, the selected tools offer enough confidence to solve the proposed problem.

The successful implementation of these tools requires the commitment of senior management and the active involvement of employees. Recent studies highlight that leadership support and ongoing team training are critical factors for the success of Lean Six Sigma initiatives, especially in sectors that demand high-quality standards and customization, such as luxury goods [48]. In addition, the integration of sustainable practices into the production process has become a growing requirement in the luxury market. The adoption of strategies that combine Lean Six Sigma with sustainability principles has shown positive results in improving operational efficiency and reducing waste, aligning with the consumers' expectations and stakeholders for high-quality products produced responsibly [49]. Therefore, the selection and implementation of Lean tools must be carefully adapted to the particularities of the luxury goods industry, considering not only the objectives of efficiency and quality but also the demands for sustainability and corporate social responsibility.

DMAIC framework applied to this specific work

In the present work, the DMAIC methodology is strategically allied with selected Lean tools to facilitate a comprehensive approach to improving the economic and environmental sustainability of painting and bonding operations. Each stage of the DMAIC cycle is linked to a Lean tool. In the Define stage, a stock inventory was carried out, and the flow of stock movements was monitored using check sheets. In the Measure stage, consumption values were recorded and their variability calculated. In the Analyse stage, the Ishikawa diagram was used to summarise the main causes of discrepancies in stock control. In the Improve phase, the 5W2H analysis adapted to 3W1H, brainstorming and 5S were used to identify each action to be taken on the shop floor to increase productivity and reduce waste, and in the last phase, Control, new measurements were taken to assess the impact of the new adjustments made to the process. In this way, it is possible to monitor the effects and intervene to correct and improve the process. Figure 1 describes graphically the framework used throughout this work.

DMAIC implementation

Define

After observing the process, a strategy was followed using the DMAIC cycle. In the first stage, define the filters change processes were based on five points: Quality Control (1), Operational Efficiency (2), Cost Reduction (3), Waste Minimisation (4) and Training and Compliance (5). Filters are critical to maintaining the quality of the colouring and glueing processes in luxury leather goods manufacturing. Thus, the following problems and corresponding causes can occur:

- Incorrect or poorly maintained filters can adversely affect product quality. As a result, storage space needs to be increased to accommodate new raw materials and finished products.
- Current filter replacement practices are inefficient and time-consuming.
- Different filter sizes and a lack of predictive maintenance could reduce unnecessary expenditure on stock, filter consumption and associated labour costs.
- The existing process was generating excessive waste to landfills as contaminated filters were frequently discarded.
- Lack of focused training on technical specifications.

As a strategy to solve these problems, it will be necessary to measure the consumption, the consumption rate and possible standardization, reducing the number of references in use. The problems identified, after careful observation, make it possible to outline the desired routes and objectives for improving the process, as shown in Table 1.

Table 1 Identified problems on processes in luxury leather goods manufacturing and their proposed solutions

Item	Problem	Context	Main goal
Filters used as support for glueing and coloring operations	Large area occupied	Companies are constantly growing, which requires a larger area in the warehouse to receive new raw materials and finished products	Reduction of current space by 20%
	Measure the filter consumption	Identify the quantity and type of filter used in glueing/coloring	Identify the type that uses the most storage area, comparing the consumption of each filter model
	Problems root-causes identification	Lack of a routine for replacing side filters in the glueing process Poor purchasing process Lack of control over filter consumption in the glueing and coloring processes Failure to comply with filter change routines Incorrect filters use	Improve the production process through DMAIC methodology

Measure

The data collection period for the filter consumption analysis was set at three months for six reasons: (1) seasonal variation, (2) operational consistency, (3) statistical validity, (4) shift coverage, (5) baseline establishment and (6) comprehensive analysis. Next, some justifications are provided to support the previous ideas:

- A three-month period allows for the capture of operational variation in seasonal demand, where there are fluctuations in production volumes that may affect the frequency each type of filter is used and replaced.
- Collecting data over a longer period allows homogenize any anomalies or outliers (e.g. equipment downtime, maintenance or training periods) to be considered. This helps to ensure that the data reflects typical operations rather than isolated incidents.
- The longer data collection period increases the statistical reliability of the results. With more data points, it is easier to identify trends in filter usage and validate the effectiveness of the replacement and management processes being analyzed.
- The three-month period allows data to be collected across different shifts and work crews. This coverage is essential to ensure that variations in filter usage and operational compliance are captured, considering different user practices and equipment handling.
- This period serves as a baseline for future process improvements. By establishing a comprehensive understanding of current filter consumption and usage patterns, meaningful comparisons can be made after any changes have been implemented.
- The duration was long enough to accurately quantify the consumption rates of various filters and to assess the effectiveness and frequency of replacement, ensuring that the sampled data was typical of daily operations and not skewed by short-term adjustments. Table 2 presents the filter references that contributed the most to the unavailable warehouse area: C00278, C00275 and E14123.

Table 2 presents data on the consumption and average replacement frequency of side filters and carpet used in the production process. The material references are listed along with the quantity consumed and the estimated replacement period. The data show that Item E14125 has the highest consumption, with 21 units, but no specific replacement frequency is provided, which may indicate on-demand replacement or variable usage; Items E14126 and E14127 are replaced every 3 weeks, with 2 units consumed each; Item C00275 is replaced monthly, with 2 units consumed; Item C000279 is replaced every 3 months, with 16 units consumed. This information is useful for inventory planning and preventive maintenance of the equipment.

Table 2 Average replacement period for side filters and carpet used in the glueing and coloring process

Reference	Quantity consumed/month	Average exchange period
E14123	21 units	Every 3 weeks
E14126	2 units	
E14127	2 units	
C00275	2 units	Monthly
C00278	16 units	Each 3 months

For the coloring process, due to the difficulty in identifying the filter references used in these coloring booths, labels with specific references were developed. The amount consumed and the replacement periods for side filters are shown in Table 3.

In Table 3, it is observed that C000278 has high stock (20 pallets) with a consumption of 5 to 6 pallets, indicating potential overstock; E14123 holds 9 pallets for a weekly use of 1 to 2 pallets, also suggesting overstock; E13103, E13107, and E13105 have stock levels exceeding their respective weekly consumption (less than 1, less than 2, and less than 3 pallets) and C00275 shows a balanced scenario, with 2 pallets in stock and a matching weekly consumption of 2 pallets, suggesting efficient inventory management.

Analyse

The Ishikawa diagram, also known as the fishbone diagram, was used to identify the root causes associated with the large amount of space occupied by filters in the warehouse. The construction of this diagram involved categorizing potential causes into different categories, which makes it easier systematic exploration of the factors contributing to inefficiencies in filter management (Fig. 2). The information obtained from this analysis can help to identify the sources of variability and unsatisfactory performance, which can be very useful in improving processes.

Table 3 Change period for side filters and carpet considering the pallet stock and consumption

Reference	Pallets weekly stock	Pallets weekly consumption
C00278	200 units	Between 5 and 6
E14123	9 units	Between 1 and 2
E13103	6 units	Less than 1
E13107	7 units	Less than 2
E13105	2 units	Less than 3
C00275	2 units	2

This Ishikawa Diagram (also known as a fishbone diagram) identifies potential causes for the large area occupied by filters in the warehouse. The root causes are grouped into six categories:

- Machine: Issues with suction capacity and glue projection.
- Material: Use of incorrect filters for each painting booth.
- Method: Lack of periodic replacement routine, supply chain issues, and procurement process inefficiencies.
- Environment: Dirty and disorganized work areas.
- Manpower: Poor training, misuse of filters and equipment, failure to follow filter replacement routines.
- Measurement: Inaccurate estimation of required filter quantities.

The main results of the analysis carried out by Ishikawa's diagram are (1) Causes of Variation, (2) Excess of Inventory and (c) Lack of training and procedures, which will be dissected below:

- Causes of variation: (i) Material inconsistencies: Differences in filter sizes and types led to a lack of standardisation in the filtration process. Some machines used different types of filters, leading to confusion and excess stock; (ii) Inadequate routines: Filter replacement schedules were not adhered to, resulting in delays and increased filter consumption due to operational inefficiencies; (iii) Purchasing practices: The purchasing process was not aligned with actual operational

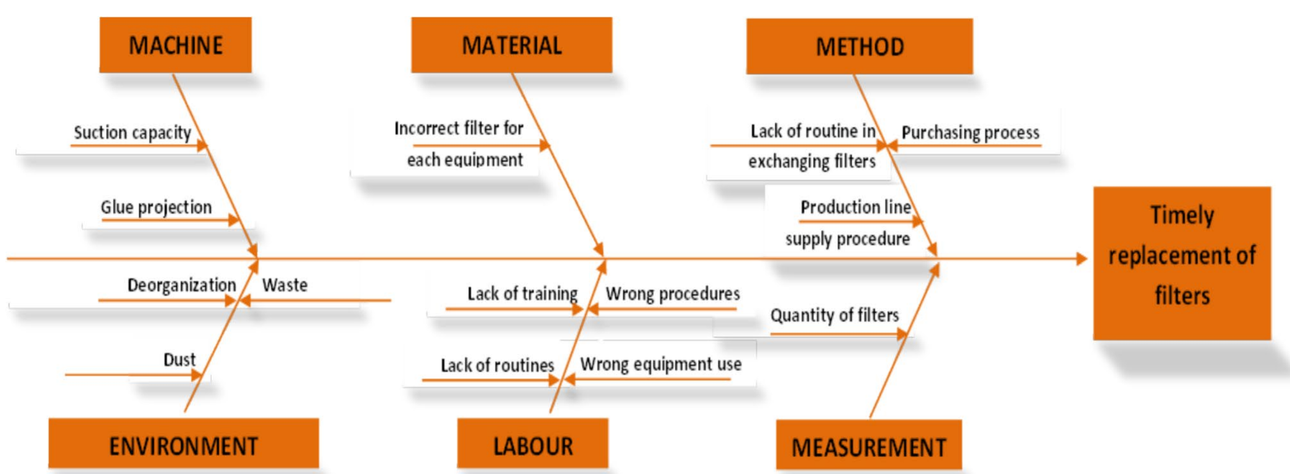


Fig. 2 Ishikawa's analysis regarding the problems around the filters exchange period

needs, resulting in overstocks of certain filters and shortages of others, disrupting operations.

- Excess of inventory: The chart showed discrepancies between actual production needs and stock levels, indicating unnecessary overstocking that limited warehouse space;
- Lack of training and procedures: It became apparent that there was a lack of knowledge among the workforce about the importance of filter efficiency and management. The lack of standard operating procedures led to inconsistent practices.

Then, a large discrepancy between the actual production consumption and the stock in the warehouse was observed, considering Ishikawa's analysis. Therefore, the filter purchasing process is not adjusted to the installed consumption, causing an excess of stock in the warehouse. A factor that contributes to stock instability is the lack of standardization in the use of filters in coloring booths, with the same equipment having different filter types, as it is depicted in Table 3. The filters standardization is considered a necessity and priority to ensure stable consumption of filter types on the shop floor. Although there is no excess stock concerning the side filters, inherent to the glueing process (E14125, E14126, and E14127), there is no periodicity for their replacement. On average, they are replaced every three weeks, depending on the request from the warehouse by the team manager. This factor can generate instability in stocks, so it needs to be corrected. Type A staining benches use two C000278 filters on top, which adapt to the size of the bench. However, this equipment has a roller filter holder, facilitating the replacement process. This filter must be inserted into the purchase process. Additionally, there is a C000278 filter inside the equipment, cut to fill the available space.

Silpar's model coloring booths also require filters to be adapted to the equipment by cutting them. Actions must be implemented to minimize replacement time and eliminate the cutting process, contributing to increased productivity and reduced waste. This also applies to the side filters of glue dispensing robots for certain by-products that need to be glued.

The duration of the filter replacement process, obtained by monitoring two shifts and getting the time spent in the process for four weeks, is described in Table 4. Table 4 compares the average time required to replace filters regarding different equipment and points out whether the process involves cutting. It is observed that the equipment requiring a cutting process tends to take longer for filter replacement, such as "Coloring bench A" (16 min) and "Carpet roll (side filters)" (12 min).

Filter replacement times can be considered actions that do not add value to the production process, promoting causes and effects, as shown in Table 5, and which will be addressed in the improvement phase.

Table 4 Time spent on changing filters per equipment

Equipment	Requires cutting process	Average time to exchange filters (min)
Coloring bench A	Yes	16
Coloring bench B	–	12
Coloring booth Silpar	Yes	7
Coloring booth A	–	4
Carpet roll (side filters)	Yes	12
Glueing robot 620 or 249 (side filters)	–	8

Improve

In the improvement phase (Improve), some Lean tools such as 5W2H analysis, adapted to 3W1H in this case, brainstorming and 5S, were adopted to make the process more effective. It will also be needed to ensure that necessary improvements and adjustments need to be made regarding actions that do not add value through the implementation of the proposed changes.

Brainstorming and critical analysis of improvement proposals To define the proposed improvements, the 5W2H tool was adapted to the 3W1H framework to focus on the essential elements needed to implement improvements to the filter management process, specifically to address the issues identified throughout the analysis, including those highlighted in Ishikawa's diagram. The adaptation of the 3W1H framework involved the following steps:

- The original 5W2H included "where" and "who", which are critical in many contexts. However, for this specific purpose, the team decided to narrow the focus to the key actions needed for improvement. The "where" and "who" were considered implicit in the implementation of the actions, leaving space to focus on the remaining elements.
- By simplifying the framework, the team sought to increase clarity and facilitate communication of the proposed actions. The simplified 3W1H provides a concise framework that can be more easily understood by the stakeholders at different levels within the organization.
- The adapted framework places greater emphasis on actionable strategies (what) and the rationale (why) behind those strategies, ensuring that each improvement made is supported by a clear understanding of its purpose and urgency. Thus, the 5W2H tool was adapted to 3W1H – What, Why, When, and How. As the Where and

Table 5 Actions without value-added, root causes and corresponding effects

Actions without value-added	Causes	Effects
Incorrect use of filters	The purchase process is unsuitable regarding consumption	Need for a larger warehouse stock area
Lack of information about the correct filter to be used in the equipment	Unnecessary employee travel to the intermediary shopfloor warehouse	Productivity loss
Failure to comply with filter replacements and failure to observe the technical specifications for programming glue robots	Lack of information on filters suitable for each piece of equipment and filter replacement routines Incorrect entry of glue robot programming coordinates Non-optimization of templates in glueing processes	Product quality issues Employee health issues (inadequate filtering) Equipment degradation Increased filter consumption

Who actions take place on the shop floor, the How Much action will be detailed separately. Table 6 demonstrates the proposed framework for 3W1H.

Regarding the implementation of the 3W1H framework, some solutions have been prioritized over others as shown in Table 6 and listed below:

- Direct impact on storage space: Priority was given to solutions that directly addressed the pressing issue of storage space, such as identifying suitable filters (item 1) and adjusting the purchasing process to better match actual consumption (item 5). These changes had the potential to provide immediate relief from space constraints, enabling the organization to operate more efficiently.
- Cost-effectiveness: Actions that could lead to significant cost savings, such as replacing the most expensive filters (item 3) and standardizing filter types (item 1), were prioritized. Financial savings were a key driver, especially in a competitive environment where effective cost management is critical.
- Feasibility and ease of implementation: Solutions that required minimal resources and could be quickly implemented were prioritized to ensure that improvements

Table 6 3W1H Frame adapted from 5W2H

Item	What	Why	When	How
1	Identification of suitable filters for each equipment	Lack of standard filters for each equipment/Quality problems	January 2024	Acquisition of filters with exact dimensions
2	Defining a filter replacement frequency	Coloring equipment has a defined periodicity, not respected. Periodicity of the side glue filters is not defined	January to February 2024	Coloring Filters: creating a defined routine / Glue Filters: Identifying lifespan
3	Replacing the most expensive filters	Decrease replacement costs	January to February 2024	
4	Replacing the filters with the highest consumption	Need to reduce the area occupied in the warehouse	February to April 2024	Creation of an easier and reusable filter-changing device
5	Adjusting the purchasing process to the shop floor needs	Reduce the warehouse stock area for new raw materials and products	March to April 2024	Kit systems creation for inventory management and material flow control
6	Improvements organization in the area related to the glueing process	Unnecessary movement and lack of ordering of the materials used	May 2024	5S tool use
7	Workers' training and awareness for the filter replacement process	Lack of respect for the filter exchange process by workers	May 2024	Training and awareness regarding filter changes and environmental impacts

could show results in the short term. For example, establishing a fixed frequency for filter changes (item 2) was a straightforward adjustment that would not require extensive resources or time.

- Potential for long-term sustainability: Solutions that promote long-term operational sustainability, such as training workers in the filter replacement process (item 7), were also prioritized. These actions not only address immediate operational needs but also ensure that the workforce is well-equipped to maintain these improvements over time.
- Data-driven decision-making: Prioritization was defined using the data collected during the analysis; solutions that had a clear, data-backed rationale for implementation were favored. This ensured that efforts were focused on changes that could produce positive results in the short term.

Identification of suitable filters for each equipment The first action to be adopted was the standardization of the process.

Table 7 Filter replacement time with and without cutting process (per equipment)

Equipment	With cutting process (min)	Without cutting process (min)
Coloring bench A	16	9
Coloring booth Silpar	7	4
Glueing robot 620 or 249 (side filters)	12	8

All equipment must be equipped with the appropriate filters for its specific functions. This problem was particularly evident in staining equipment, especially in the corresponding booths. Furthermore, the lack of compliance with the replacement frequency resulted in an excessive accumulation of filters in the equipment. After consulting the coloring booth usage manuals, the filters were corrected. A common problem in these cabins was the need for the workers to cut and adapt the filters, resulting in long setup times. To solve this, filters of the appropriate size were purchased, making the change easier and faster. In type A stain banks, multiple C00278 filters were used, arranged to form a more extensive filter. However, these devices have support for a roll filter. After consulting the user manual, this type (E9003) was purchased, eliminating the use of C00278 filters. On carpet-glueing robots, workers had to cut and adapt filters before replacement. To solve this problem, filters with the correct dimensions were purchased, reducing the time required for replacement, as shown in Table 7.

Table 7 presents the impact of the cutting process on the time required for filter replacement. It is noticed that eliminating the cutting process significantly reduces the time needed to change filters, especially for "Coloring bench A", which drops from 16 to 9 min.

This action aimed at reducing the costs directly associated with filters, but rather to avoid selection and placement errors, standardizing procedures. Table 8 shows precisely the initial and final situation regarding the costs of the filters, where there is no cost reduction in the raw material, but there is a reduction in the time required for its replacement and a greater guarantee of suitability.

Table 8 Costs for purchasing new filters without the cutting process

	Initial situation		Final situation	
Equipment	References	Weekly cost	References	Weekly cost
Glueing robot	E13103	€11.92	E13103	€15.28
	E13107		E13101	
	E13105		E13105	
Colouring bench A	C00278	€15.30	E90003	€41.78
	–		E13106	
Colouring booth Silpar	C00278 (Variable)		E13298	
	E13107	€17.28	E13297	€25.24
	(Variable)	(Average)		(Average)
	–		E13108	
	–		E13109	
	C00278		C00278	
Colouring bench B	(Variable)			
	E13103	€18.20	E13103	€11.38
	(Variable)	(Average)		(Average)
	E13105		E13105	

Table 8 compares weekly filter costs before and after the implementation of a new system (without the cutting process). While some costs increased, such as for "Coloring bench A" (€15.30–€41.78), there is a rationalization in the number of filter references used, as seen with the "Glueing robot", which now uses fewer distinct filter codes. In the meantime, there was a reduction in costs resulting from the elimination of the cutting process. An MS Excel spreadsheet was implemented to document the existing filters, as well as the supplier, with the dimensions and relevant details to the process.

Definition of a filter replacement frequency for each equipment The coloring process equipment has a defined periodicity for changing the filters: twice a week. However, there are no specific days, and this periodicity was not respected. It was defined that the replacement would occur systematically on Wednesdays and Fridays, at the end of the last shift of the day, with awareness efforts carried out to ensure compliance. The side filters of glueing equipment do not have a defined periodicity, being replaced on average every three weeks. As this equipment has suction after the filter, the durability of the filters was studied using the airspeed that can be obtained in each measurement, determining that the filters should be replaced when the airspeed passing through them is less than 0.2 m/s, which represents saturation of the filter with glue or paint, according to the user manual. Daily measurements were taken on all glueing robots, except the conveyor robots, for eight weeks to control the equipment's suction speed. The values obtained converged and are presented in Table 9. In the case of tests carried out on robots in the P4 line, which are not yet in full operation, it was found that they showed great variation, which is why it was decided to postpone the implementation in this line, waiting for the process stabilization.

Table 9 shows the minimum filters' durability reported in different production lines. Durability ranges from 5 to 7 days, with P2 line showing the best performance (7 days) and P4 line the lowest (5 days), indicating a real variability in filter lifespan depending on the equipment. With this study, it was possible to conclude that the durability of the lateral filters is five days, these being the lowest values recorded, as shown in Table 9. Informative labels were designed and placed on all equipment.

Table 9 Durability of side filters

Production line	Equipment	Reported minimum durability
P1	CENC-00244	6 days
P2	CENC-00243	7 days
P3	CENC-00279	6 days
P4	CENC-00354	5 days

Replacing the most expensive filters A test was carried out to replace the side filters with a more economical solution. By measuring airspeed, it was identified that filters E13107 and E13103 have durability equal to or greater than current side filters (E14125, E14126, E14127), with the lowest durability recorded being six days. The tests were carried out under equivalent production conditions. Referring to the costs of these filters to the initial situation, it presents a possible weekly saving of more than €200. These values are shown in Table 10.

Table 10 compares the unit and weekly costs of side filters before and after replacing the models used. The new filter configuration results in significant savings, reducing weekly costs from €264.19 to €43.94 — a reduction of over 83%.

Changing the filters with the highest consumption Filters C00278 and E14123 are the ones that occupy the largest area in the warehouse and are the most consumed on the shop floor, especially in the glueing process, with weekly consumption of 600 and 120 units, respectively. Additionally, the C00278 filter is used in the coloring process, with an average of 24 units per week. In the glueing process, these filters are only used twice to support parts, which, in addition to taking up a lot of space in the warehouse, causes serious environmental consequences as they are discarded in large quantities. To overcome this problem, a plate, fixed or mobile, was developed that allowed the filter to be replaced and that could be reusable to reduce the consumption of these filters and promote the organization's sustainability. This board, developed in polymer, has the characteristics of having reduced weight (lighter), being resistant to glue and being easy to handle by workers. The tests carried out were based on thermoplastic materials, due to their recyclability. The chosen material was Alveolar Polypropylene, due to its low density, covered with PTFE film, with dimensions of $1500 \times 500 \times 8$ [mm], with holes, to optimize the fixation of the parts to the plate, using air circulation resulting from

Table 10 Costs with the new side filters

	Reference	Cost per unit	Weekly cost in the company
Initial status	E14125	€7.35	
	E14126	€12.29	€264.19
	E14127	€10.71	
	E13103	€1.84	
Final status	E13107	€2.28	€43.94
	E14128	€1.70	

the robot's aspiration. This improves the fixation of natural cowhide pieces with very thin thicknesses, avoiding rework to clean the glue. Each plate has a unit cost of €308.38. The elimination of drawer filters will allow a gain of 28 m^2 in the warehouse area and a saving of €82,056, also reducing the delivery of 258.07 kg of filter waste to landfill, resulting in savings of €112.19 per week, a reduction of 88.72%.

Adjusting the purchasing process to shop floor's needs – creation of kits After finding a solution for glueing robot drawer filters, it became necessary to improve the process of replacing coloring equipment filters and rethink the supply station in production, to ensure the correct replacement of filters, on the day and in the correct quantity. This will allow for adjusting the purchasing process and control inventory in the warehouse. The "supermarket" technique is a proposal for inventory management and material flow control, where a small warehouse supplies the pull system, allowing the customer to obtain what they need, when they need it, and in the desired quantity. The implemented solution is based on these concepts and consists of a kit system. A kit is a set of filters intended for a specific piece of equipment, stored on a roll and labelled with the corresponding equipment. This kit is distributed by the logistics supplier to the corresponding line on the correct replacement day. These kits are stored in a box with several dividers, organized by type of equipment and production line. The upper part is used for coloring benches and the lower part for coloring booths. Each column represents a specific production line. In addition, there are two spaces reserved for the two conveyor-based glue robots, which also use this type of filter every fortnight. Each area in the box contains two kits, one for each stipulated replacement day, making it easier to identify when a kit was not delivered to the corresponding line. This box is returnable. On Mondays, the supplier delivers the box with the necessary kits and collects the empty boxes from the warehouse installed on the shop floor. Then, the warehouse manager checks that there are two kits in each area of the box and places the box in the designated area. The kits are duly identified with labels placed by the supplier. This process is repeated on Fridays when the bin must be empty to be collected on Monday. A specific box was also developed for the side filters of the glueing robots, which previously used a more expensive solution, and were replaced by filters like those used in coloring equipment. With this solution, it is possible to increase the useful area of the warehouse and eliminate the filling station in production, resulting in a reduction in travel times.

Organization of improvements in the area related to the glueing process The 5S tool aims to reduce waste and create a culture of discipline to improve processes. It consists of five stages: ordering, organizing, cleaning, systematizing and disciplining. This tool was applied to all glueing robots that previously lacked organization. First, workers received training on 5S tool to implement it in their jobs. After the training, employees began to sort all the materials, classifying them as most used, intermediate, and least used. In the second step, they organized the materials according to this classification, removing unused items. Although a cleaning plan already existed, it was decided to increase its frequency due to the accumulation of glue residue in the area. Finally, areas were created at the bottom of the robots for weekly and monthly cleaning, as well as areas for placing utensils and maintaining components.

Training and awareness of workers for the filter replacement process Finally, awareness training was developed for the correct use of filters. The training covered several topics, including the importance of frequency in changing filters, the functioning of the kit system, in addition to the environmental impact of new solutions. A contextualization of the glueing process was also made, highlighting the importance of limiting robots to reduce glue consumption. To achieve the Effectiveness Analysis of Training Programs, both qualitative and quantitative indicators were collected through employee satisfaction surveys, direct feedback, and performance comparisons before and after training. After data collection and analysis, the results indicated that 94% of employees rated the training content as "relevant" or "highly relevant" to their roles (Training satisfaction), and 89% reported being able to immediately apply the knowledge gained to their daily tasks (Practical applicability). Moreover, a 28% decrease in non-conformities related to filter replacement was observed within three months post-training (Reduction in operational errors). Furthermore, the average replacement time dropped from 12.3 min to 8.7 min, indicating efficiency gains directly linked to the training (Reduction in average filter replacement time), and, finally, Supervisors reported a 40% increase in operator autonomy during the replacement process, reducing the need for rework and technical support (Improvement in operator autonomy). These indicators show that the training programs contributed directly to operational improvements within the manufacturing sector. This highlights the importance of maintaining continuous training cycles and measuring their impact as a strategic practice for operational excellence. Graphically, these results can be summarized as depicted in Fig. 3.

The workers' awareness of five important aspects related to filter replacement management was also assessed using a seven-point Likert's scale, trying to assess their sensitivity to each issue before and after the training provided. The improvement was notable, as can be seen in the graph of Fig. 4, where the green line represents the initial state of

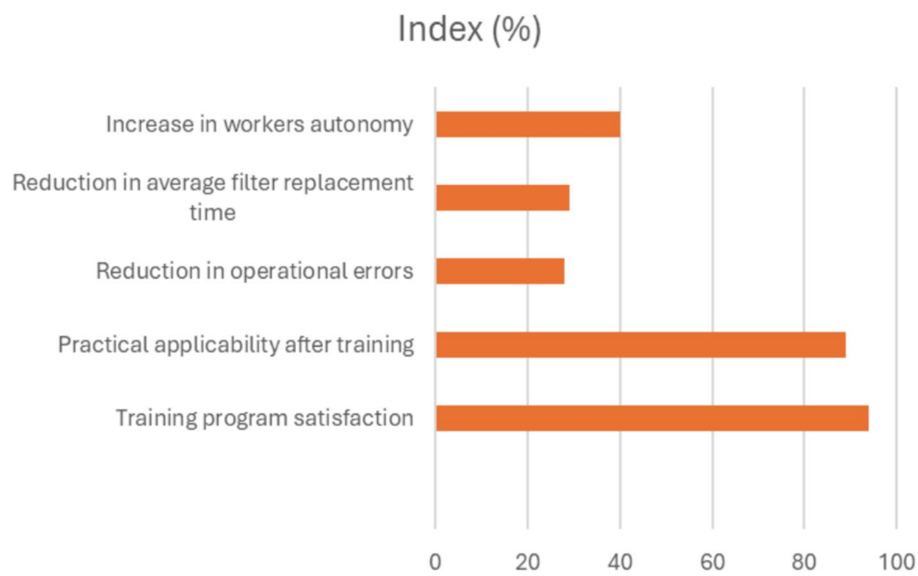
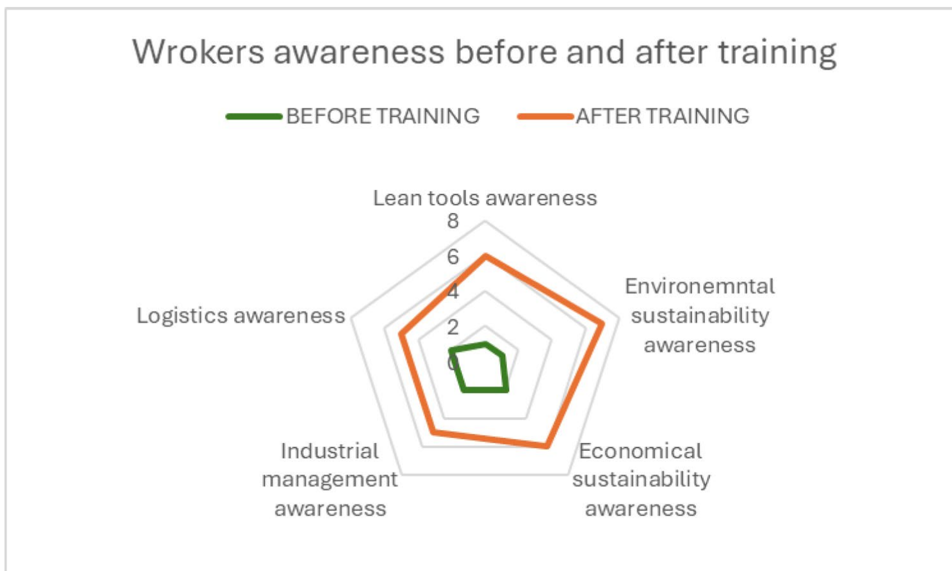


Fig. 3 Achievements brough by the training program



(*) Sevel levels considered, from 0 corresponding to "Not aware at all" to 7 "Excellent expertise".

Fig. 4 Workers awareness about the entire filters management system before and after training. (*) Sevel levels considered, from 0 corresponding to "Not aware at all" to 7 "Excellent expertise"

understanding of each aspect involved, while the orange line represents the state after training.

Control

In the control phase, the aim is to ensure that the proposed improvements are sustained to increase reliability and to plan for possible corrections or setbacks. New measures were taken to validate the impact of the improvements implemented. After implementing a suitable replacement routine and standardizing the filters in each piece of equipment, it was possible to create a simpler and more controlled process, facilitating stock management in the warehouse. To ensure the sustainability of the improvements implemented through the DMAIC methodology and adapted 3W1H framework, a robust monitoring and control plan was developed. This plan included several components designed to track performance, assess compliance with new processes and facilitate ongoing adjustments to optimize efficiency, as described below:

- Establishing Key Performance Indicators (KPIs): KPIs were established to quantify improvements in filter management and overall operations. Relevant metrics may include monitoring the reduction in filter procurement costs and overall expenditure related to filter management, measuring the square footage used for filter storage before and after implementation, aiming to maintain or improve the increased usable area achieved by the changes, and tracking adherence to defined filter replacement schedules to ensure that filters are replaced promptly to prevent the build-up of inefficiencies.

- Performing regular audits and inspections to assess compliance with new procedures, such as filter replacement routines and purchasing processes. These reviews could be performed on a monthly or quarterly basis. Periodic spot checks will also be used to ensure that standards are consistently met across different teams and locations.
- Establishing channels for workers to provide feedback on the new processes will help in identifying any challenges or areas for further improvement, and regular meetings between team members and management can facilitate open discussions about the effectiveness of the changes implemented and any adjustments that may be needed.
- Using digital tools for monitoring, such as a digital tracking system (like ERP or specialized software), which can allow for automatizing the filling out of dashboards and reports.
- Performing continuous improvement cycles and iterative changes, using the DMAIC framework again if necessary.
- Implementing training and retraining programs to ensure that all workers remain aware of the procedures for filter management and other changes implemented. Onboard training for new employees should be implemented to maintain the sustainability culture.
- Performing regular assessment of waste reduction: monitoring the amount of waste sent to landfills will ensure that the changes implemented continue to reduce environmental impact.
- Regarding the side filters of the glue robots, E14125, E14126, and E14127, the replacement with a more economical solution allowed significant weekly savings. The fortnightly filters, used by the supply station in production, were adapted to the kit system, as well as the side filters of the glueing robots, which were more expensive. With the implementation of this system, it was possible to reduce the occupied space from 17.5 m^2 to 2.75 m^2, representing a decrease of 26.81% in the area occupied in the warehouse.

The kit system also ensures compliance with the replacement frequency, which was previously not respected in coloring equipment and the side filters of conveyor glue robots. Furthermore, it guarantees the correct installation of filters on equipment, preventing worker errors. With the implementation of the kit system, the filling station previously installed in production was eliminated. Thus, all unnecessary trips related to replacing filters on coloring equipment and conveyor glueing robots were eliminated. This results in a not very significant increase in productivity, but which, accumulated with the remaining savings, increases the economic sustainability of the process.

With the implementation of the plate system on two shop floor robots, it was possible to obtain significant savings in resources, in addition to eliminating unnecessary trips by workers to the gas station. Consequently, as the filters are sent to landfills, this solution contributes to reducing the organization’s environmental impact. There was an average weekly reduction of 76.32 kg in sending filters to landfills, resulting in weekly savings of 29.57%.

Results and discussion

The Lean Six Sigma methodology, with the DMAIC tool – Define, Measure, Analyse, Improve and Control, usually results in process improvements, greater employee engagement and more defined action plans for teams, as pointed out by Proudlove et al. [39] in their work. Lean methodology is increasingly being implemented to manage such challenges because it improves a company's responsiveness to changing customer demands while at the same time optimizing underlying operational processes, as confirmed by Chandrasekaran et al. [50] in their corresponding work regarding a metalworking company. This research is based on a single case study within the luxury leather goods sector. This specificity may limit the generalizability of the findings to other industries or sectors, as operational challenges and contexts may vary significantly. However, this case study can serve as a roadmap, as its unique nature may not be directly applicable to different environments.

To better understand the real cost savings in the glueing and coloring process of a luxury leather goods company after implementing the DMAIC methodology and the correct use of Lean tools, Table 11 has been developed. This table explicitly shows the company's savings before and after implementation.

The economic impact and cost savings associated with the implementation of the DMAIC methodology and Lean tools in the high-value personal goods sector can be listed as follows:

- The implementation of new filtering systems and changing procedures resulted in an 88.72% reduction in waste sent to landfills. This not only contributes to environmental objectives but also reduces the costs associated with waste disposal. Indeed, landfills collect waste from different activities, such as domestic activities to industrial activities, and there is a deep concern in reducing the volume of waste being dumped in landfills, as the landfilled material also contributes to greenhouse gas emissions [51–53]. Although some waste can be converted into energy [54], a strong effort must be made to reduce the landfilled materials.

- The redesign of the filter management system reduced the area used for storage from 17.5 m^2 to 2.75 m^2. This was expected to increase the usable storage area by 77.73%, allowing more efficient use of space and potentially reducing storage and handling costs.

In other words, approximately 0.645 tons of CO_2 were avoided by simply optimizing waste disposal, which reinforces the positive impact of the Lean Six Sigma approach on the environmental sustainability of luxury goods manufacturing operations. Furthermore, the initiative provided weekly financial savings of €112.19, which extrapolated over a year (assuming 52 weeks of operation), results in annual savings of:

$$€112.19/\text{week} \times 52 = €5,833.88/\text{year}112.19/\text{week} \times 52 = €5,833.88/\text{year}$$

- Streamlining operational processes and reducing unnecessary operator movements minimised labour costs and time, resulting in an estimated savings of €42,193.84 from improved operational practices.
- By optimizing the supply of materials to the production lines, the methodology aimed to reduce inventory levels and associated costs. The improvements are expected to generate additional savings of €105,207 through system gains of efficiency.
- Once all the suggested improvements have been implemented, the expected total annual savings are expected to be around €150,000 (€105,207 + €42,193.84), considering all these process efficiencies, waste reduction and improved storage solutions.

Another result was to quantify the environmental benefits of improvements in filter management and overall operational processes, particularly in the context of the luxury leather goods industry, potential reductions in CO_2 emissions and other environmental impacts. The reduction values are as follows:

Reduction in waste to landfill

To quantify the environmental impact of reducing solid waste in the production of luxury leather goods, carbon dioxide (CO_2) emissions savings were estimated based on recognized emission factors. In this case, it was considered that each kilogram of leather waste sent to a landfill represents approximately 2.5 kg of CO_2 equivalent, according to parameters published by the Environmental Protection Agency [55] and adjusted for waste of animal origin. The restructuring of filter management resulted in a total reduction of 258.07 kg of solid waste to be landfilled, which represents a significant advance in the company's sustainability practices. Considering the average emission factor of 2.5 kg of CO_2 equivalent per kg of treated leather waste [55], the emissions savings can be estimated as follows:

$$CO_2\ reduction\ (kg) = Waste\ reduction\ (kg) \times Emission\ factor\ (kg\ CO_{2e}/kg)\ CO_2\ reduction\ (kg) = 258.07 \times 2.5 = 645.18\ kg\ CO_{2e}$$

These savings not only demonstrate the financial return of the intervention but also highlight the alignment of the strategy with Environmentally Sustainable Goals principles, increasingly valued by stakeholders in the luxury sector [46, 47]. The improvement by 88.72% in waste management demonstrates the effectiveness of the DMAIC methodology applied in this study and it is a strong indication of the potential for replicability of the approach in other artisanal manufacturing segments with high-quality requirements.

Improved material and resource efficiency

Regarding the filter consumption reduction, improvements have led to better filter management, reducing the need for additional filters and thus reducing the resources required for production. Assuming that reduced filter production results in reduced CO_2 emissions, it can be estimate that it takes about 1.5 kg of CO_2 emissions to produce 1 kg of filters (this varies depending on materials and manufacturing processes), and the reduction in emissions due to filter savings can be estimated. If the improvements lead to a reduction in filter usage of around 30% from a previous usage of 10,000 kg/year, then the reduction in emissions can be estimated as follows:

Reduction in filters: 10,000 kg × 30% = 3000 kg of filters saved per year.

CO_2 savings from reduced filter production:

Annual CO_2 emission reduction = 3000 kg of filters × 1.5 kg of CO_2/kg of filters = 4500 kg of CO_{2eq} (or 4.5 tons).

Estimated total reduction of CO_2 emissions

Combining the two main sources of emission reduction, considering reduced landfill waste, 3.97 tons CO_{2eq}, and reduced

Table 11 Summary results of pre- and post-implementation of DMAIC Cycle and the lean tool application in the coloring and glueing process

Item		Before	After
Filter replacement time—cutting process	Coloring bench	16 min	9 min
	Coloring booths	1 min	4 min
	Side filters	12 min	8 min
Acquisition of filters without cuts	Despite the increase in cost, it resulted in an improvement in the standardization of the Process, avoiding errors in filter replacement, which resulted in an improvement in Productivity	62,70 €	93,68 €
Replacing the most expensive filters	E14125 by E13103	7,35 €	1,84 €
	E14126 by E13	12,29 €	2,28 €
	E14127 by E14128	10,71 €	1,70 €
		Total 264,19 €	Total 43,97 €
Implementation of the kit system, eliminating the supply stage	15% cost savings	585,12 €	508,80 €
Occupied area reduction		17.5 m^2	2,75 m^2

filter production, 32.25 tons CO_{2eq}, the following value can be obtained:

Total annual CO_2 emission reduction: 3.97 tons + 32.25 tons ≈ 36.22 tons CO_{2eq}, per year.

Table 12 presents a summary of the improvements achieved in this specific case through the implementation of Lean Six-Sigma methodologies.

Other environmental benefits

Improvements not only reduce waste and emissions but also lead to reducing resource use, contributing to economic and environmental sustainability.

Better filter management can also reduce the use of chemicals that contribute to pollution during manufacturing. Reduced emissions can contribute to improved air quality in the vicinity of manufacturing facilities. Through the combination of waste reduction and improved material efficiency, the organization is expected to achieve significant environmental benefits, quantified as a reduction of approximately 36.22 tons of CO_{2eq} emissions per year. These improvements not only help to reduce the organization's carbon footprint but also support wider sustainability goals within the high-value personal goods industry [56].

The Lean Six Sigma and Green Manufacturing approach helps manufacturing organizations compete in global markets by implementing sustainability strategies. Waste reduction is recognized as another important practice in Manufacturing Management that involves great synergy with lean manufacturing. Manufacturers are believed to be one of the largest producers of waste [57]. In the current competitive business scenario, all sectors strive for continuous performance improvement, involving the relentless elimination of waste to consistently add value [58]. Despite the evidence of cost reduction, quality improvement, waste reduction and better use of available space, the study does not consider other process variables that can directly influence the production process. The successful application of the chosen methods may be hampered, and the sustainability of the improvements made affected if the human factor variable is not considered.

Figure 5 shows a roadmap on how the different phases of the DMAIC methodology have been applied in this specific case, as follows:

Figure 5 describes a logical sequence of DMAIC implementation, from the initial survey to the failure analysis, which facilitates the understanding of the applied methodology as a whole. Each step contains important information, such as filter types, frequency of replacement (based on history, manual and operating conditions), and safety procedures during replacement. The inclusion of a preventive maintenance plan and the continuous monitoring step (saturation indicators) are good practices that help to avoid unexpected shutdowns. The recording and traceability step is

Table 12 Summary of the improvements achieved in this specific case through the implementation of Lean Six-Sigma methodologies

	Before	After	Reduction (Value)	Reduction (%)
Waste sent to landfill (kg)	13,421,17	9452,53	3,97,000	29,57
CO_2 emissions (kg CO_2e)	107,500	71,280	36,220	33,69
Costs (€/year)	131,938,21	89,744,37	42,193,84	31,98
Filters consumption (kg/year)	10,000	7000	3000	30,00
Occupied area (m^2)	17,5	2,75	14,75	84,29

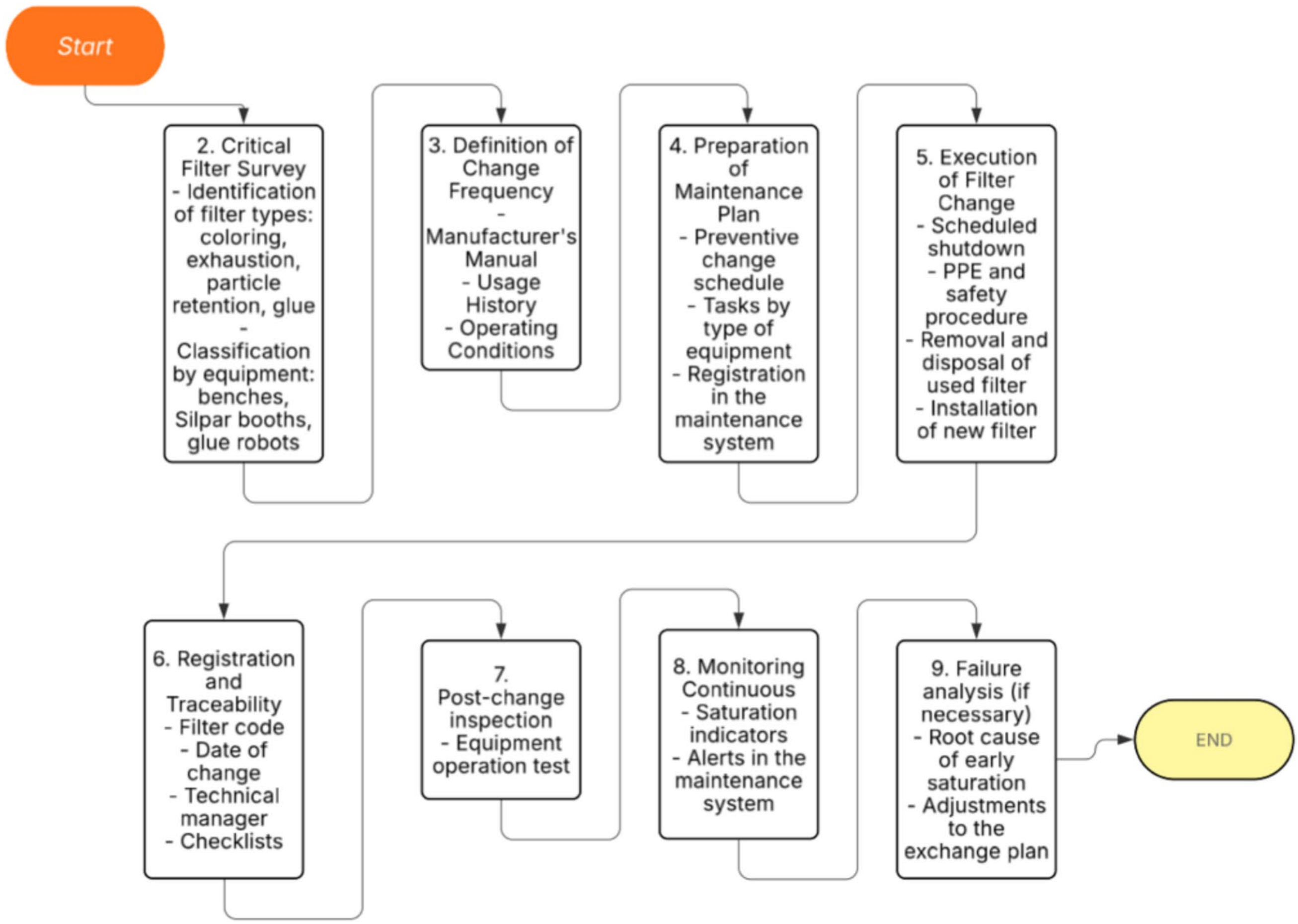


Fig. 5 Filters changing process flowchart after improvements

essential for audits and maintenance history, demonstrating maturity in the process. Step 9 provides for failure analysis and adjustments to the replacement plan, demonstrating a continuous improvement approach, filter process management map. This roadmap intends to make easier the generalization of the use of this methodology in other handcraft sectors, helping to translate each specific step of this implementation, in a helpful step in other specific problem needing to be solved.

The advantages achieved through this work are evident and can be replicated in other intensive handcraft industries with the corresponding adjustments.

As limitations of this work, the lack of a more in-depth critical analysis of possible biases or limitations in generalizing the results can be pointed out. It is essential to consider how the findings may vary significantly depending on differences between sectors, particularly in terms of specific workforce dynamics and supply chain structures. For example, sectors with high worker turnover or outsourced operations may face different challenges in implementing Lean Six Sigma (LSS) methodologies when compared to sectors with more stable and integrated operations. Moreover, the level of expertise available in each region can vary a lot, influencing the training needs and the perception of the workforce of the problems and possible solutions. The current framework is designed for the low level of training usually found in this kind of sector. Furthermore, the luxury leather goods industry sometimes values more the ability of workers to manually perform some intricate operations than a wide expertise in industrial management and vision of the industrial problems as a whole. In addition, the discussion could be enriched by highlighting areas where more research is needed, such as: (a) Integration of additional lean tools: the application of methods such as Value Stream Mapping (VSM), Kaizen and Total Productive Maintenance (TPM) in conjunction with LSS may reveal synergies that have not yet been explored; (b) Intersectoral comparisons: comparative investigations between industrial and service sectors can identify critical factors for success or failure in the application of LSS, considering different operational contexts; (c) Longitudinal studies on sustainability: There is a lack of long-term analyses on the sustainable impacts of implementations, including the use of tools such as Life Cycle Assessment (LCA); (d) Automation and compatibility with Lean: How the introduction of automated technologies affects lean principles is still an open question that deserves attention; (e) Culture of continuous improvement and employee engagement: Understanding how to develop an organizational culture that supports LSS and aligns with employee engagement can be decisive for the success of initiatives; (f) Standardizing metrics and quantitative evaluation: The lack of widely accepted indicators makes it difficult to compare studies, because there is a need to develop and apply robust metrics that assess performance gains and explore correlations between different LSS practices.

Although the results presented provide relevant contributions to the application of Lean thinking in the luxury leather goods industry, some methodological and structural limitations should be considered in the critical analysis of the findings. The adoption of a single case study limits the ability to generalize the results obtained, since the organizational, cultural and productive specificities of the company analyzed — especially its emphasis on artisanal production — may not reflect other organizations in the sector [59, 60]. Future research with a comparative approach, involving multiple companies, could increase the external validity and robustness of the conclusions. Data collection through observations and interviews during Lean training and interventions is subject to observer bias, because the presence of researchers may have an influence on the behavior of participants, a phenomenon known as the Hawthorne effect [61]. Thus, the current work used anonymized surveys to overcome this problem. However, employees may have provided socially desirable responses, which compromise the authenticity of the reports and perceptions about the improvements. Although the gains obtained with Lean tools have been significant in the short term, the lack of automation or digitalization of processes raises concerns about their future sustainability. Maintaining improvements depends heavily on the continuous engagement of the workforce, operational standardization and demanding control through constant audits. In contexts of high variability and turnover, as observed, the lack of technological support can compromise the persistence of the results obtained [62].

Incorporating these points would substantially strengthen the limitations section, expanding its academic relevance and practical usefulness.

These results, based on the LSS methodology and the use of the DMAIC tool, demonstrated an increase in the efficiency of the process, which can be transferred to other businesses within the group, promoting strategic and tactical objectives, creating competitive advantages in similar business conditions.

Conclusions

The combined use of Lean tools such as the Ishikawa Diagram, 5W2H and 5S, in line with the Six Sigma methodology, enabled the use and management of filters to support the leather glueing and painting operations traditionally used in the production of luxury leather goods to be significantly improved, resulting in significant operational improvements.

Once all the improvements have been implemented, annual savings of more than €150,000 and a 77.73% increase in usable warehouse space are expected. The environmental impact of the organization has also been reduced, with an 88.72% reduction in the amount of waste sent to landfills.

There have been no changes in labor costs, as employees are compensated based on the function performed rather than time-based productivity. After the training, the data analyses demonstrated that 94% were increasingly satisfied with their roles, 89% reported to be confident to develop their daily tasks (Practical applicability), 28% non-conformities decreased after three months post-training, process time decreased in 3.6 min, and, finally, Supervisors reported a 40% of improvement in operator autonomy.

The material optimization induced important saving in operational costs, as follows: savings of €220.25 per week (~83% reduction) regarding filter replacement cost (weekly), gain of 7 min per replacement in coloring process, gain efficiency of 4 min per replacement in cutting process, filter acquisition cost per set was 31,15 €, while unit costs increased. However, total costs decreased due to better standardization and reduced waste.

A significant reduction in the volume of waste sent to landfill was achieved due to improved filter usage. This reduction represents 76.32 kg per week and 3967.84 kg annually. Reduction of CO_2 emissions by 0.654 tons weekly, contributing to corporate carbon footprint targets and SDG 13 (Climate Action).

In addition to the reduction of CO_2 emissions, the improvements implemented also led to broader environmental benefits. The elimination of the filter-cutting process reduced chemical exposure and cutting tool use and contributed to a safer working environment and less hazardous waste. These changes align with three global sustainability goals, particularly: SDG 3 (Good Health and Well-being): By minimizing employee exposure to potentially harmful substances, SDG 12 (Responsible Consumption and Production): By reducing material waste and improving the efficiency of filter usage, and SDG 13 (Climate Action): Through the reduction of CO_2 emissions in operational processes.

Furthermore, these practices reflect emerging best-in-class sustainability standards within the luxury leather goods manufacturing sector, where environmental responsibility is increasingly tied to brand value and consumer trust. It is recommended that similar industries integrate these improvements into environmental management systems, and supplier audits may magnify their long-term impact across the supply chain.

It is observed that the combined use of Lean tools and the Six Sigma methodology, commonly known as Lean Six Sigma, is a perfectly adequate strategy for addressing and improving the functioning of production lines, even in the case of luxury leather goods. Therefore, the case study reported here, despite being unique, can constitute a roadmap for the joint application of these tools and methodologies in other sectors, mainly sectors deeply supported in handcraft work, overcoming some existing doubts. To this end, a guide to the implementation of the structured DMAIC methodology in similar companies can be developed, following four recommendations:

- Develop training programs for workers and team leaders focused on DMAIC phases with particular emphasis on identifying waste and standardizing manual processes.
- Establish continuous improvement groups with representatives from production, maintenance, and quality departments to collaboratively map processes and collect data.
- Implement key performance indicators (KPIs) such as average filter replacement time, cost per filter, and its average lifespan, with weekly tracking and monthly review.
- Maintain a digital repository of successful DMAIC applications and practices in filter replacement and other manual processes to allow for replication and continuous learning.

Given the study findings and limitations, several research avenues can be pursued to further enhance the understanding and application of Lean Six Sigma methodologies in various industries, particularly in the luxury goods sector, as follows:

- Investigate how automation technologies (such as IoT, sensors, real-time monitoring systems, and artificial intelligence) can be integrated into the DMAIC phases to improve data accuracy and accelerate decision-making. This could enhance efficiency in repetitive or high-volume processes, including those within the artisanal luxury sector.
- Conduct comparative studies on the application of the DMAIC methodology across different industrial sectors, for example, contrasting artisanal manufacturing (such as luxury leather goods) with highly automated sectors, to identify critical success factors, limitations, and opportunities for adaptation.
- Explore the creation of indicators that combine operational performance with environmental and social metrics, aligning continuous improvement projects with the United Nations Sustainable Development Goals (SDGs).
- Investigate the long-term effects of implemented standardization, including its resilience to demand fluctuations, workforce changes, and the introduction of new products.

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References

1. Christodoulides G, Wiedmann K-P (2022) A roadmap and future research agenda for luxury marketing and branding research. J Product Brand Manag 31(3):341–350. https://doi.org/10.1108/JPBM-01-2022-3815
2. Morgan JP. (2023). What's next for the luxury market? Available: https://www.jpmorgan.com/insights/global-research/retail/luxury-market, Accessed on 15 Nov 2023.
3. Silva FJG, Gouveia RM (2020) Cleaner production – toward a better future. Springer Nature Switzerland, Cham, Switzerland, pp 1–420 (**ISBN: 978-3-030-23164-4**)
4. Porter ME, Kramer MR (2011) Creating shared value: redefining capitalism and the role of the corporation in society. Harv Bus Rev 89(1–2):62–77
5. van Voorthuysen E, Olsen J, Langley K, Lipski M, Subramanian K (2017) Design for scalability of industrial processes using modular components. Proc Inst Mech Eng, Part B 231(8):1464–1478. https://doi.org/10.1177/0954405415598893
6. Bagherpour M, Feylizadeh MR, Cioffi DF (2012) Time, cost, and quality trade-offs in material requirements planning using fuzzy multi-objective programming. Proc Inst Mech Eng B J Eng Manuf 226(3):560–564. https://doi.org/10.1177/0954405411424001
7. Sivaramkumar V, Thansekhar M, Saravanan R, Miruna JAS (2017) Multi-objective vehicle routing problem with time windows: Improving customer satisfaction by considering gap time. Proc Inst Mech Eng Part B 231(7):1248–1263. https://doi.org/10.1177/0954405415586608
8. Rosa C, Silva FJG, Ferreira LP (2017) Improving the quality and productivity of steel wire-rope assembly lines for the automotive industry. Procedia Manuf 11:1035–1042. https://doi.org/10.1016/j.promfg.2017.07.214

9. Moreira B, Gouveia RM, Silva FJG, Campilho R (2017) A novel concept of production and assembly processes integration. Procedia Manuf 11:1385–1395. https://doi.org/10.1016/j.promfg.2017.07.268
10. Harish D, Gowtham T, Arunachalam A, Narassima M, Lamy D, Thenarasu M (2024) Productivity improvement by application of simulation and lean approaches in an multimodal assembly line. Proc Inst Mech Eng Part B 238(6–7):1084–1094. https://doi.org/10.1177/09544054231182264
11. Araújo WFS, Silva FJG, Campilho RDSG, Matos JA (2017) Manufacturing cushions and suspension mats for vehicle seats: a novel cell concept. J Adv Manuf Technol 90:1539–1545. https://doi.org/10.1007/s00170-016-9475-6
12. Merlo E (2018) Italian luxury goods industry on the move: smes and global value Chains. Global luxury. Palgrave, Singapore, pp 39–63. https://doi.org/10.1007/978-981-10-5236-1_3
13. de Klerk HM, Kearns M, Redwood M (2019) Controversial fashion, ethical concerns and environmentally significant behaviour: the case of the leather industry. Int J Retail Distrib Manag 47(1):19–38. https://doi.org/10.1108/IJRDM-05-2017-0106
14. Prasad S, Khanduja D, Sharma SK (2018) A study on implementation of lean manufacturing in Indian foundry industry by analysing lean waste issues. Proc Inst Mech Eng, Part B 232(2):371–378. https://doi.org/10.1177/0954405416640169
15. Baines TS, Williams GM, Lightfoot H, Evans S (2007) Beyond theory: an examination of lean new product introduction practices in the UK. Proc Inst Mech Eng, Part B 221(11):1593–1600. https://doi.org/10.1243/09544054JEM871
16. Ball PD, Roberts S, Natalicchio A, Scorzafave C (2011) Modelling production ramp-up of engineering products. Proc Inst Mech Eng Part B J Eng Manuf 225(6):959–971. https://doi.org/10.1177/09544054JEM2071
17. El-Namrouty KA, AbuShaaban MS (2013) Seven wastes elimination targeted by lean manufacturing case study 'gaza strip manufacturing firms'. Int J Finance Manage Econ 1(2):68–80. https://doi.org/10.11648/j.ijefm.20130102.12
18. Gibbons PM, Kennedy C, Burgess SC, Godfrey P (2012) The development of a lean resource mapping framework: introducing an 8th waste. Int J Lean Six Sigma 3(1):4–27. https://doi.org/10.1108/20401461211223704
19. Dias P, Silva FJG, Campilho R, Ferreira LP, Santos T (2019) Analysis and improvement of an assembly line in the automotive industry. Procedia Manuf 38:1444–14552. https://doi.org/10.1016/j.promfg.2020.01.143
20. Mileham T (2007) Book review: essentials of lean six sigma. Proc Inst Mech Eng, Part B 221(8):1375–1375. https://doi.org/10.1177/095440540722100801
21. Murmura F, Bravi L, Musso F, Mosciszko A (2021) Lean six sigma for the improvement of company processes: the Schnell S.p.A. case study. TQM J 33(7):351–376. https://doi.org/10.1108/TQM-06-2021-0196
22. Mahato S, Rai Dixit A, Agrawal R (2017) Application of lean six sigma for cost-optimised solution of a field quality problem: a case study. Proc Inst Mech Eng, Part B 231(4):713–729. https://doi.org/10.1177/0954405417694060
23. Ferreira C, Sá JC, Ferreira LP, Lopes MP, Pereira T, Silva FJG (2019) iLeanDMAIC – a methodology for implementing the lean tools. Procedia Manuf 41:109–1102. https://doi.org/10.1016/j.promfg.2019.10.038
24. Rong K, Ding H, Song B, Gao J, Tang J (2021) Data-driven process control for manufacturing spiral bevel and hypoid gears by using design for six sigma (DFSS) considering numerical loaded tooth contact analysis (NLTCA). Proc Inst Mech Eng Part B 235(12):1875–1891. https://doi.org/10.1177/09544054211023625
25. Baptista A, Silva FJG, Campilho RDSG, Ferreira S, Pinto G (2020) Applying DMADV on the industrialization of updated components in the automotive sector: a case study. Procedia Manuf 51:1332–1339. https://doi.org/10.1016/j.promfg.2020.10.186
26. Ayeni P, Baines T, Lightfoot H, Ball P (2011) State-of-the-art of 'Lean'in the aviation maintenance, repair, and overhaul industry. Proc Inst Mech Eng, Part B: J Eng Manuf 225(11):2108–2123. https://doi.org/10.1177/0954405411407122
27. Costa T, Silva FJG, Ferreira LP (2017) Improve the extrusion process in tire production using six sigma methodology. Procedia Manuf 13:1104–1111. https://doi.org/10.1016/j.promfg.2017.09.171
28. Pereira MT, Bento MI, Ferreira LP, Sá JC, Silva FJG, Baptista A (2019) Using six sigma to analyse customer satisfaction at the product design and development stage. Procedia Manuf 38:1608–1614. https://doi.org/10.1016/j.promfg.2020.01.124
29. Behara RS, Fontenot GF, Gresham A (1995) Customer satisfaction measurement and analysis using six sigma. Intern J Qual Reliab Manag 12(3):9–18. https://doi.org/10.1108/02656719510084745
30. Nonthaleerak P, Hendry L (2008) Exploring the six-sigma phenomenon using multiple case study evidence. Intern J Operat Produc Manag 28(3):279–303. https://doi.org/10.1108/01443570810856198
31. Widiwati ITB, Liman SD, Nurprihatin F (2025) The implementation of lean six sigma approach to minimize waste at a food manufacturing industry. J Eng Res. https://doi.org/10.1016/j.jer.2024.01.022
32. Daniyan I, Adeodu A, Mpofu K, Maladzhi R, Katumba MGK-K (2022) Application of lean six sigma methodology using DMAIC approach for the improvement of bogie assembly process in the railcar industry. Heliyon 8(3):e09043. https://doi.org/10.1016/j.heliyon.2022.e09043
33. Gaikwad LM, Sunnapwar VK (2024) Validation of lean–green–Six Sigma practice model for improving performance and competitiveness in an Indian manufacturing industry. Int J Syst Assur Eng Manag 15:3508–3521. https://doi.org/10.1007/s13198-024-02357-0
34. Surjit R, Indu GM, Anusri Mahalakshmi B, Shubha Shree M (2024) Six sigma approach: a pathway to zero waste sustainable apparel industry. In: Muthu SS (ed) Zero waste sustainable apparel industry. Springer, Cham. https://doi.org/10.1007/978-3-031-76542-1_3
35. Silva IB, Cabeça MG, Barbosa GF, Shiki SB (2022) Lean six sigma for the automotive industry through the tools and aspects within metrics: a literature review. Int J Adv Manuf Technol 119:1357–1383. https://doi.org/10.1007/s00170-021-08336-0
36. Mitchell CV, Anderson AR, Romito K, Abadie WM, Phillips AK (2025) Employing lean six sigma strategies to improve operating room first case on-time starts: a case report. Periop Care Oper Room Manag 38:100473. https://doi.org/10.1016/j.pcorm.2025.100473
37. Gomez CR, Cardonell B, Pfeiffer K, Pond D, Ingebritson D, French BR, Siddiq F, Qureshi AI (2024) Optimizing workflow of urgent stroke endovascular intervention: a focused lean six sigma project. J Stroke Cerebrovasc Dis 33(3):107559. https://doi.org/10.1016/j.jstrokecerebrovasdis.2024.107559
38. Mistry KP, Jaggers J, Lodge AJ, Alton M.et al. (2008) Using six sigma® methodology to improve handoff communication in high-risk patients. In: Henriksen K, Battles JB, Keyes MA, et al., (eds). Advances in patient safety: new directions and alternative approaches (Vol. 3: Performance and Tools). Rockville (MD): Agency for Healthcare Research and Quality (US). Accessed on 22 Oct 2024.www.ncbi.nlm.nih.gov/books/NBK43658/

39. Proudlove N, Moxham C, Boaden R (2008) Lessons for lean in healthcare from using Six Sigma in the NHS. Public Money Manag 28(1):27–34. https://doi.org/10.1111/j.1467-9302.2008.00615.x
40. McDermott O, Antony J, Bhat S, Jayaraman R, Rosa A, Marolla G, Parida R (2022) Lean six sigma in healthcare: a systematic literature review on motivations and benefits. Processes 10(10):1910. https://doi.org/10.3390/pr10101910
41. Shokri A (2017) Quantitative analysis of six sigma, lean and lean six sigma research publications in last two decades. Intern J Qual Reliab Manag 34(5):598–625. https://doi.org/10.1108/IJQRM-07-2015-0096
42. Goh TN (2012) Six sigma in industry: some observations after a decade. Qual Reliab Eng Int 28(6):621–625. https://doi.org/10.1002/qre.1093
43. Jl D, Wang Z, Mcclellan DA, Langabeer JR (2010) The use of six sigma in healthcare management: are we using it to its full potential? Qual Manag Health Care 22(3):210–223. https://doi.org/10.1097/QMH.0b013e31829a838e
44. Costa T, Silva FJG, Ferreira LP (2017) Improve the extrusion process in tire production using six sigma methodology. Proc Manuf 13:1104–1111. https://doi.org/10.1016/j.promfg.2017.09.171
45. Silva FJG, Morgado L, Teixeira A, Sá JC, Ferreira LP, de Almeida F (2020) Analysis and development of a failure prediction model for electrical terminals used in the automotive industry. Proc Manuf 51:207–214. https://doi.org/10.1016/j.promfg.2020.10.030
46. Tissir S, Cherrafi A, Chiarini A, Elfezazi S, Shokri A, Antony J (2024) Lean six sigma and Industry 4.0 implementation framework for operational excellence: a case study. Total Qual Manag Bus Excel 35(9–10):1015–1053. https://doi.org/10.1080/14783363.2024.2351979
47. Rajak S, Kumar P, Modi A, Swarnakar V, Antony J, Sony M (2024) An assessment of barriers to integrate lean six sigma and industry 4.0 in manufacturing environment: case based approach. Intern J Comp Integ Manuf 38(3):386–407. https://doi.org/10.1080/0951192X.2024.2335969
48. Sordan JE, Oprime PC, Pimenta ML, Andersson R, Antony J, Garza-Reyes JA, Tortorella GL (2025) Lean six sigma practices supported by Industry 4.0 technologies: evidence from heavy vehicle manufacturers. J Manuf Technol Manage 36(2):504–533. https://doi.org/10.1108/JMTM-10-2023-0471
49. Bhat S, Gijo EV, Bha VS (2025) Benchmarking the best practices of lean six sigma in aerospace industry in India: a longitudinal multiple case analysis and roadmap for deployment. Benchmarking Int J Technol: Evid Heavy Veh Manuf 36(2):504–533. https://doi.org/10.1108/bij-06-2024-0511
50. Chandrasekaran R, Campilho RDSG, Silva FJG (2019) Reduction of scrap percentage of cast parts by optimizing the process parameters. Procedia Manuf 38:105–1057. https://doi.org/10.1016/j.promfg.2020.01.191
51. Gombojav D, Matsumoto T (2023) Multi criteria decision analysis to develop an optimized municipal solid waste management scenario: a case study in Ulaanbaatar, Mongolia. J Mater Cycles Waste Manag 25:1344–1358. https://doi.org/10.1007/s10163-023-01603-0
52. Sutthasil N, Chiemchaisri C, Chiemchaisri W, Tomonori I, Shabbir HG (2023) Life cycle greenhouse gas emissions of emerging municipal solid waste management options: a case study in Thailand. J Mater Cycles Waste Manag 25:662–673. https://doi.org/10.1007/s10163-022-01584-6
53. Svidroňová MM, Meričková BM (2022) Efficiency of waste management in municipalities and the importance of waste separation. J Mater Cycles Waste Manag 24:2644–2655. https://doi.org/10.1007/s10163-022-01511-9
54. Shah HH, Amin M, Pepe F (2023) Maximizing resource efficiency: opportunities for energy recovery from municipal solid waste in Europe. J Mater Cycles Waste Manag 25:2766–2782. https://doi.org/10.1007/s10163-023-01733-5
55. EPA – U.S. Environmental Protection Agency. (2021). Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste.
56. Aigner SN, García FD, Mansilla MA, Barros AB, Escobar M, Fernandez M, Bacigalupe A (2025) Reuse of leather waste into wood particleboards: physical–mechanical and thermal properties. J Mater Cycles Waste Manag 27:503–510. https://doi.org/10.1007/s10163-024-02131-1
57. Trubetskaya A, Ryan A, Powell DJ, Moore C (2024) Utilising a hybrid DMAIC/TAM model to optimise annual maintenance shutdown performance in the dairy industry: a case study. Intern J Lean Six Sigma 15(8):70–92. https://doi.org/10.1108/IJLSS-05-2023-0083
58. Knapić V, Rusjan B, Božič K (2023) Importance of first-line employees in lean implementation in SMEs: a systematic literature review. Intern J Lean Six Sigma 14(2):277–308. https://doi.org/10.1108/IJLSS-08-2021-0141
59. Eisenhardt KM (1989) Building theories from case study research. Acad Manag Rev 14(4):532–550
60. Voss C, Tsikriktsis N, Frohlich M (2002) Case research in operations management. Int J Oper Prod Manag 22(2):195–219. https://doi.org/10.1108/01443570210414329
61. Mayo E (2003) The human problems of an industrial civilization. Oxfordshire, England, UK (**ISBN: 978-0415604239**)
62. Womack JP, Jones DT (2003) Lean thinking: banish waste and create wealth in your corporation. Free Press, Washington DC, USA (**ISBN: 978-0743249270**)