Universidade de Aveiro Departamento de Economia, Gestão, Engenharia Industrial e Turismo
2018

PEDRO MANUEL GOMES FERREIRA

MELHORIA DE EFICIÊNCIA INDUSTRIAL NUMA UNIDADE DE PROCESSAMENTO DE BORRACHA

IMPROVING INDUSTRIAL EFFICIENCY IN A RUBBER PROCESSING JOB SHOP

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Relatório de Projeto apresentado à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia e Gestão Industrial, realizado sob a orientação científica da Professora Doutora Ana Raquel Reis Couto Xambre, Professora Auxiliar do Departamento de Economia, Gestão, Engenharia Industrial e Turismo da Universidade de Aveiro.

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agradecimentos

À minha orientadora, Ana Raquel Xambre, pela disponibilidade e auxílio prestado ao longo deste projeto.

Ao diretor de operações da Procalçado, S.A., José António Silva, pela oportunidade dada e pela confiança depositada em mim.

À minha orientadora na empresa, Denise Tavares, e ao Hélder Barreiros, por todos os ensinamentos que me transmitiram e por me ajudarem a crescer como profissional, e pessoa.

À Adriana, por partilhar este percurso comigo e pela motivação.

Aos restantes membros da Procalçado, S.A., pela colaboração e disponibilidade que mostraram ao longo deste período.

Aos meus amigos, pela força que me dão todos os dias.

À minha família, por todo o apoio e motivação que me deram ao longo do meu percurso académico.

palavras-chave

Lean Manufacturing, Eficiência Industrial, TPM, Melhoria Contínua. Sequenciamento de produção.

resumo

Atualmente, para as empresas se manterem competitivas no mercado, necessitam de responder às necessidades do cliente em termos de nível de serviço, variedade da procura e qualidade do produto. Para isso, metodologias como a filosofia *lean* são aplicadas de maneira a melhorar processos, a aumentar a utilização dos recursos e a reduzir desperdícios. Este trabalho foi desenvolvido numa unidade da Procalçado, S.A., empresa pertencente à indústria do calçado. A empresa pretendia encontrar soluções para a elevada complexidade de operações e atrasos de produção na sua unidade de processamento de matéria-prima, que tinha como clientes internos duas unidades de produção de solas de borracha.

O projeto teve como objetivo melhorar o fluxo de produção na unidade de processamento de borracha, por forma a reduzir o WIP e os *lead times* de produção.

Neste sentido, os processos operacionais no setor foram analisados e documentados. As causas do problema em questão foram identificadas, sendo que, finalmente, foram propostas e implementadas medidas de melhoria para a unidade. As melhorias apoiam-se em ferramentas *lean*, bem como em métodos de sequenciamento de produção.

Essas ações de melhoria resultaram numa redução da taxa de reprocessamento de materiais devido à implementação de uma cultura de manutenção preventiva em equipamentos, à criação de sistemas de gestão visual e à organização do espaço e dos postos de trabalho. Além disso, os níveis de WIP reduziram substancialmente, com o auxílio de um maior controlo de produção resultando na libertação de espaço na unidade.

keywords

Lean Manufacturing, Industrial Efficiency, TPM, Continuous Improvement. Sequencing.

abstract

For companies to remain competitive in these days' market environment, they must respond to client needs in terms of service level, demand variety and product quality. As such, methodologies like lean philosophy are used with the intent of improving operational processes, increasing the use of resources and reducing waste. This work was developed in a production unit belonging to Procalçado, S.A., a company in the footwear industry. The company wanted to find solutions for the high complexity of operations and production delays in its raw material processing unit, which had two rubber sole production units as its internal clients.

The project's goals were based on improving production flows in the rubber processing unit, thus reducing WIP and production lead times.

With this in mind, the existing operational processes in the unit were analysed and documented. The initial problem's causes were identified. Finally, improvement measures for the unit were proposed and implemented. Lean tools and production sequencing methods supported these implementations.

Those solutions resulted in a decrease in product reprocessing, thanks to the creation of a preventive maintenance culture, a visual management system and an overall improvement in organization of space and workstations.

Furthermore, WIP levels were reduced substantially, with an improved production control and improved product flow.

Contents

List of Figures

List of Tables

1 Introduction

Much like the majority of other current industries, shoe production is competitive, there are numerous direct rivals, and consumer requirements must be met. While in the past companies focused on mass production, their attentions have shifted elsewhere. To remain competitive in this new market environment, an emphasis must be placed on quality, service level and product variety. In recent years, the shoe industry has experienced a spike in terms of product customization and functionality, while maintaining sale prices. Shoe sole production follows the same rule, as buyers more and more seek shoes with personalized soles – multicoloured, different formats, engraved lettering. As such, it is imperative that companies adapt to this situation by redesigning their processes, enabling them to satisfy most of their customers' needs.

1.1 Context

This project was developed at Procalçado, S.A., within the scope of the curricular internship which is part of the master's degree in Industrial Engineering and Management at the University of Aveiro. Its aim is set on improving operational processes in one of the company's departments - which is responsible for processing raw material and supplying internal clients (downstream production workstations). The company's modus operandi is based on satisfying every client's needs equally. These needs translate into orders which vary in production complexity and quantity. As such, the department faces a challenge of delivering every order in time, whilst assuring product quality.

The main problems associated with the department are high amounts of work-in-progress, a high rate of material rework and reprocessing, an overall lack of workspace cleanliness, and general disorganization. As such, the main objective of this project is to come up with solutions that can solve the problems at hand, to reduce production lead times, and satisfy downstream demands at a steady rate, thus improving workflow.

1.2 Methodology

Initially, the current state of operations was diagnosed. Data on operational times, movement and material flow was collected, analysed and documented. Furthermore, every operators' feedback was collected, to allow a better understanding of the production process, both in general and in specific details. Progress metrics were defined to quantify the department's evolution: amount of intermediate stock (work-in-progress), machine stoppage times, scrap rates, rework and reprocessing percentages of total production and overall production lead times.

Improvement proposals to the department's problems were thereafter presented. It is important to note that all proposals are subject to the administration's approval, depending on resource availability and implementation costs. Hence, they will fall under two categories: implemented and suggested proposals.

1.3 Document Structure

This work will be divided into five main chapters. The first chapter contains a brief introduction to the project, its context and the methodology used to carry it out. In the second chapter, all theoretical foundations of the project will be explained, divided into two main categories: lean principles and production planning and control. The company will be presented in the third chapter, along with the focused department's productive process. Furthermore, the sector's identified problems will be documented in detail, preceding all proposed improvement measures. The fourth chapter presents the actions that were suggested but are not yet implemented. The last chapter contains a short overview of the project as a whole, and final reflections.

2 Literature review

In this chapter, the main theoretical concepts that were relevant for the project at hand will be presented and discussed. Furthermore, some projects and works from other authors that cover these concepts will be presented and analysed.

2.1 Lean

The term "lean" was first coined by John Krafcik, and introduced by James P. Womack, Daniel Jones and Daniel Roos (1990), as an alternative to mass production principles. Womack defines lean thinking as an antidote to waste, as it provides a way to do more in less time (and less equipment, space, and resources, in general). Furthermore, all this can be achieved while guaranteeing customer satisfaction (Womack & Jones, 2003). In general, lean aims to create more value to customers with fewer resources, with a systematic approach. Although it was developed for the industry sector, lean has been shown to be effective when applied in the service and public sectors (Marsikova & Sirova, 2018). Because lean is based on simple principles and practical methodologies, it can be applied to virtually any industry. The five principles of lean are as follows (Womack & Jones, 2003):

- Value – The starting point for lean thinking, which begins with defining value for products in terms of specification and capabilities. The company must comprehend the customer's perspective, thus identifying processes which add value to the product, minimizing associated cost and waste.
- Value Stream Mapping – Value stream is defined as the group of actions and processes necessary to place the product (or service) in the hands of the customer. In manufacturing terms, this translates into transforming raw materials into a finished product and delivering it. The goal here is to identify value-adding activities, activities that don't add value, and necessary but non-value adding activities.
- Flow – The previous principle is continued as the value stream must follow a smooth progression from start to finish. In sum, the value chain should include the least amount of non-value adding activities as possible, so that value-creating processes can be linked in a non-disruptive manner.
- Pull – A production system where downstream processes define production demand when needed.
- Perfection – When all four previous principles are identified and implemented, the newfound processes must be monitored, maintained and be subject to additional improvements, until perfection is achieved.

Applying lean principles has yielded results in various forms, in different industries. Detty & Yingling's simulation studies (2000), show that operational performance can be improved by applying lean principles in a manufacturing plant in several areas: decrease in inventory levels, lower changeover and order lead times and reduced variability in supplier demand. In the service sector, Stadnicka & Ratnayake (2017) present their findings on applying VSM and VSA (Value Stream Analysis) in a Polish telecommunication service provider. By evaluating the current state and analysing it, an improved value stream map was developed. The results show that the service lead time of the company decreased by 37%, by applying a Kanban system. Elsewhere, in the healthcare sector, Matt, Arcidiacono, & Rauch (2018) have found that applying lean principles in patient flows in hospitals resulted in several benefits. This methodology included six different phases – developing a lean strategy, lean training, current state analysis, future state implementation and definition and leadership awareness training. By introducing new triage and queue management systems, the authors reported a 17% reduction in patient lead times.

Lean includes several tools and methods that help companies implement the aforementioned five principles. In the following subchapters some of those lean tools that were applied in this project will be presented.

2.1.1 The Seven "Deadly" Wastes

There are seven wastes associated to manufacturing systems and operations in production that were first identified by Ohno (1988), and thereafter reported by Womack & Jones (1996). These include:

- Overproduction – the continuation of operations after demand has been satisfied, resulting in increased inventory.
- Waiting – refers to periods of inactivity in a downstream process due to the failure of delivery by an upstream process.
- Transport – adds no value to the process and should therefore be minimized.
- Over processing – the use of operational processes that are not required, thus creating more product than what is valued by the customer.
- Inventory – all types of product (raw material, work-in-progress, finished goods) which aren't required to fulfil customer orders. These require much needed space and additional material handling.
- Motion – refers to the extra movement done by operators and equipment to carry out tasks. This adds no value to the product.
- Defects – products that do not meet customer specifications or expectations.

2.1.2 The 5S

This methodology originates from Japan and focuses on eliminating waste and improving productivity in manufacturing operations, through five distinct phases (Womack & Jones, 2003). The phases are presented in italic in their Japanese translation:

- *Seiri* – Sort. In the first phase, items that are unnecessary in the workplace are identified with a red tag. Afterwards, a dedicated area is created where these items are deposited, awaiting further inspection. The goal is to eliminate items that are considered disposable, therefore clearing the workspace. In a manufacturing scenario, excess raw material, semi-finished products and tools are considered viable candidates for disposing.
- *Seiton* – Straighten. The remaining items are organized and set in order, placing them in their designated location. This can be achieved through visual identification. Ensuring *seiton* is valuable for reducing wasted time in operations and setups.
- *Seiso* – Shine. After sorting all the necessary materials, the workplace is thoroughly cleaned. Equipment and machines must be constantly clean to avoid variability and failure. Furthermore, a cleaning and maintenance culture is implemented.

- *Seiketsu* – Standardize. The fourth phase focuses on creating a preventive maintenance culture that aims to preserve and maintain control of the three aforementioned phases. This includes setting objectives and goals, work instructions, checklists and other documentation.
- *Shitsuke* – Sustain. The last step in implementing 5S can also be the most challenging. It focuses on addressing the need to perform 5S on a systematic basis, through regular audits.

2.1.3 TPM

Total productive maintenance (TPM) is a Japanese philosophy based on productive maintenance concepts, first created in 1971, which focuses on improving equipment effectiveness, eliminating breakdowns and promoting autonomous maintenance by operators (Ahuja & Khamba, 2008). By including all employees in improving equipment availability, TPM tries to bring the best out of every machine and device, in order to achieve economic efficiency, whilst lowering operational costs and maintenance costs (Ahuja & Khamba, 2008).

TPM is divided into eight basic elements (often referred to as "pillars") which serve as the philosophy's building blocks (Borris, 2006). In order to successfully implement TPM, all eight pillars, identified in Figure 1, must be continuously connected throughout the deployment phase (Bartz, Cezar Mairesse Siluk & Bartz, 2014). According to Borris, (2006), each can be explained as an area of responsibility, although they often overlap: Initial Phase Management is the planning pillar of TPM, where every stage of production is considered and analysed, in search of ways to improve the current system. Health and safety is very important, as it is closely related to having zero accidents in the work place. Education and Training ensures procedures are passed along and absorbed by workers. Autonomous Maintenance deals with empowering workers and increasing their skills, to a point where they are able to carry out basic maintenance procedures on their own equipment. Planned Maintenance searches for equipment breakdown causes, with the aim of implementing solutions to avoid future failures. Quality Maintenance analyses potential productive variations that affect the quality of the product itself, whether it is a component issue, or an equipment design one. Furthermore, once these causes are identified, cross-functional teams are put together to implement possible solutions. Focused Improvement deals with systematic efforts to eliminate waste and improve conditions in a continuous manner. Finally, each of a company's department – purchasing, scheduling, quality – has an impact on production, hence the identification of Support Systems as a pillar for TPM implementation.

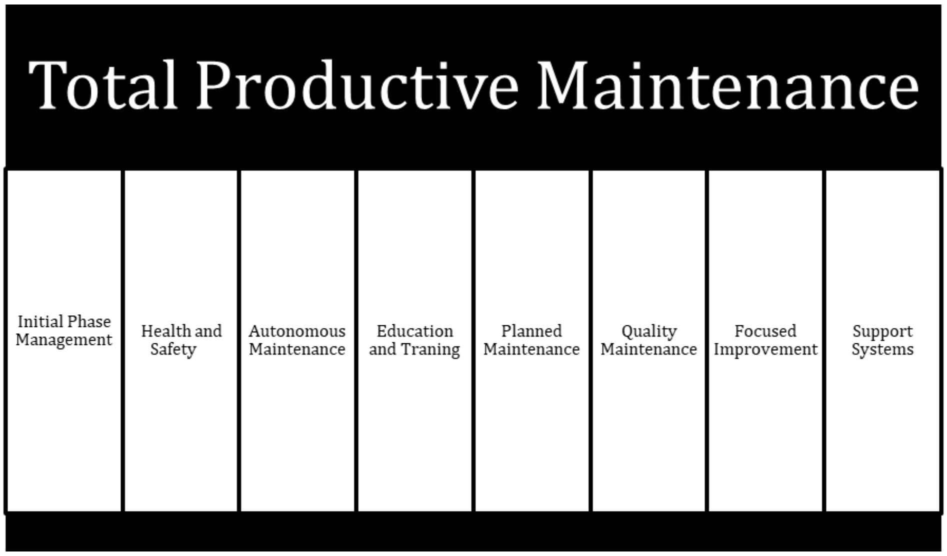

Figure 1 - The pillars of TPM (adapted from Ahuja & Khamba, 2008)

2.1.4 Layout

According to Stevenson (2008), a plant's layout can be defined as the configuration of departments, work centres and equipment. Layout decisions are important, as they require a substantial amount of investment, long-term commitments and have an overall significant impact on short-term operations' cost and efficiency (Stevenson, 2008). As such, the redesign of current facilities can be attributed to inefficient operations and changes in methods and equipment, which are the two main reasons found in the case study described in this report.

Plant layouts can be divided into three basic types (Stevenson, 2008):

- Product-oriented: normally found in highly standardized and repetitive processing operations. Jobs are divided into several tasks, requiring highly specialized labour and equipment. These systems deal with a high volume of product flow. Typical system arrangements include production and assembly lines. The shortcomings of these layouts are based on inflexibility to volume changes and shutdowns. Furthermore, a larger emphasis (and cost) is placed on preventive maintenance practices.
- Process-oriented: layouts that facilitate products or services with a high variety of processing requirements. Job shops and flow shops are included here. These types of systems are much less vulnerable to shut down, as compared to their product counterparts. However, because equipment is not dedicated and is usually grouped into functional departments, materials are moved through longer distances, which leads to higher handling costs.
- Fixed-position: these layouts are commonly found in large construction projects. Items which are being worked on remain stationary, forcing the movement of equipment, materials and workers.

The efficiency of a plant's layout is normally measured in terms of material handling costs, where three parameters are considered to calculate said costs: interdepartmental flows, f_{ij} (the amount of product flow from i to j), unit-cost value, c_{ij} (the associated handling cost to move one unit from i to *j*), and interdepartmental distance, d_{ij} (Meller & Gau, 1996). Therefore, material handling costs are directly proportional to the amount of distance one product unit must travel and the amount of product flow. The objective function that aims at minimizing layout-related costs is typically defined as:

$$Min\ Z = \sum_{i=1}^{m} \sum_{j=1}^{m} f_{ij} c_{ij d_{ij}} \tag{1}$$

Where Z represents the material handling cost for the current plant layout. Several procedures have been developed to objectively optimize plant layouts, through computerized algorithms, such as CRAFT (Computerized Relative Allocation of Facilities Technique) and SLP (Systematic Layout Planning) (Meller & Gau, 1996).

2.2 Production planning and scheduling

Thomas & McClain (1993) define production planning as the process of determining the amount of production for the next *planning horizon* – future time periods where production will occur. Furthermore, in production planning, important factors such as expected inventory levels and resource (both workforce and machinery) usage are determined. This is done by analysing future demand and the production facility's current state (Thomas & McClain, 1993).

Scheduling, on the other hand, is concerned with allocating resources to work tasks over a given time period. Its goal is to optimize predetermined cost-related objectives (for example, minimizing the number of tasks completed after their respective due dates). In most manufacturing systems, scheduling plays an important role, as it interacts with both long-term planning functions and production shopfloor management (Pinedo, 2008). Detailed task scheduling also contributes to operations control and efficiency, as it takes into account machine breakdowns, high priority job (machine processing task) arrivals and unexpected processing times (Pinedo, 2008). The role of scheduling, and its presence in manufacturing companies is exemplified in Figure 2.

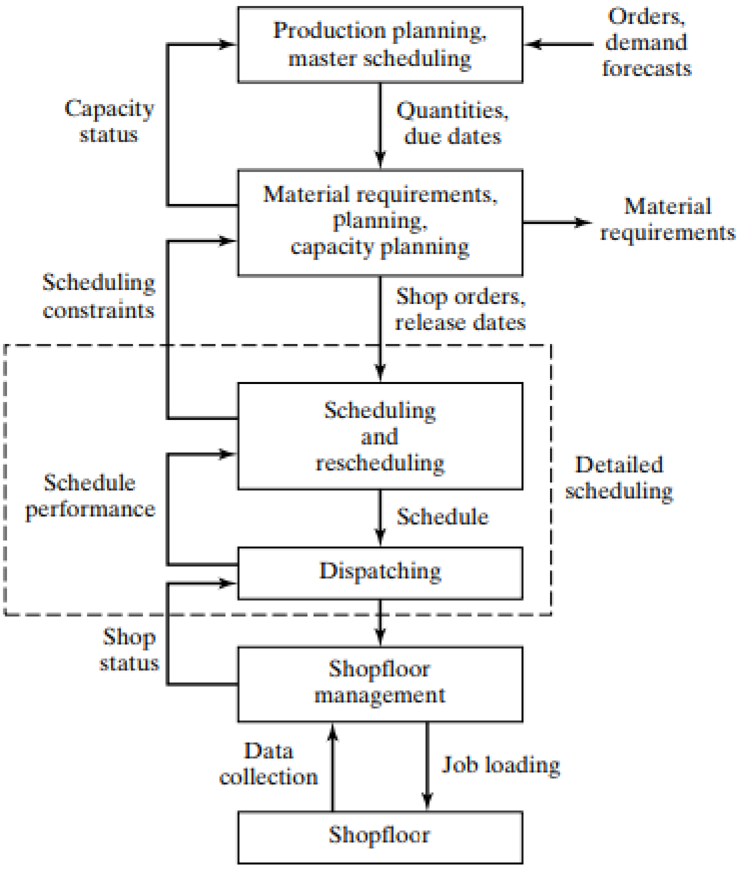

Figure 2 - Information flow in a manufacturing system (Pinedo, 2008)

2.2.1 Sequencing rules

Sequencing rules are decision rules that assign priorities to incoming processing orders at a manufacturing unit or workstation (Rewers et al., 2018). The most relevant rules for this work are presented below:

- SPT (Shortest processing time) – sequences incoming orders in nondecreasing order of processing time (Baker & Trietsch, 2009). As such, the priority is given to orders with the lowest operational time, with the aim of minimizing the average cycle time for task completion, and the percentage of delayed tasks in an order pool (Rewers et al., 2018).
- LPT (Longest processing time) – as opposed to SPT, this rule aims to reduce machine changeovers by giving priority to orders with the longest total processing time (Barbosa, Costa, Fátima, Souza & Pereira, 2010). It is an efficient method when applied to systems containing various machines and equipment (Rewers et al., 2018).
- FIFO (First in, first out) – the first order to arrive at the shop is the first one to be processed, thus ensuring minimized queue times (Barbosa et al., 2010).
- EDD (Earliest due date) – priority is given to orders with the earliest delivery deadline dates, with the aim of reducing order lateness (Barbosa et al., 2010). In a system where setup times

are very small or even negligible, EDD tends to be the optimal sequencing rule (Baker, 1999).

2.2.2 Family and batch order scheduling

In batch manufacturing (which is present in this work's case study), there is an ever-present trade-off involving production efficiency and due-dates. In the pursuit of high levels of efficiency, batch sizes are made larger so that there are less setup changes. This can, however, delay jobs past their due dates due to extended production runs in the same setup. Conversely, when jobs are intended to be finished in time, batch sizes are made smaller, so that job priorities can be shifted according to the most urgent job requirements. This leads to excessive priority shifting, numerous setups changes, and an overall loss of production efficiency. Therefore, a scheduling procedure is required to minimize the effects of this trade-off.

In sequencing terms, this problem is characterized by the following conditions (Baker & Trietsch, 2009):

1. There are, simultaneously, *n* jobs available for processing;
2. Machines can process, at most, one job at a time;
3. Job setup times are independent of job sequence and are included in processing times;
4. Machines are continuously available;
5. Machine operations run with no interruption.

Grouping jobs is an alternative strategy which is necessary in the presence of setup times on a machine (Baker & Trietsch, 2009). A job belonging to a particular family does not require an additional setup when following another job of the same group. However, when changing the production order to a job belonging to another family, a changeover is required. Hence, it makes sense to schedule job families in this type of environment (Baker & Trietsch, 2009). Baker (1999) proposes a solution wherein each job family is scheduled in one batch, a Group Technology (GT) sequence. By this rule, all jobs within their family are sequenced from earliest to latest due date. Then, families of jobs are sequenced in the same manner (Baker, 1999).

3 Case Study

In this chapter, the company where this project will be presented, firstly with a brief historical overview, followed by a description of its current operations in different departments. The production process for its SBR products will be overviewed, followed by a detailed explanation of the specific production processes within each department that deals with SBR materials. The SBR mixing production unit will be thoroughly explained in a specific subchapter, followed by identified problems associated with the unit itself. Afterwards, another subchapter will present solutions found to counteract said problems.

3.1 The company

Procalçado, S.A. is a shoe and shoe component manufacturer located in northern Portugal. While this work focuses on its SBR (styrene-butadiene rubber) sole production department, the company also produces goods in other different materials, each one having its own separate department: PVC (polyvinyl chloride), EVA (ethylene-vinyl acetate), TPU (thermoplastic polyurethane), TR (thermoplastic rubber, also referred to as thermoplastic elastomer - TPE).

In March 1973, José Pinto and Álvaro Moreira, two former employees at VALCOR, which was then the leading shoe component producer in the country, decided to form their own firm. Thus, “For Ever” was born. At first, the company only produced shoe moulds. In 1978, the company acquired 50% equity of VALCOR, and started producing soles under the brand CPM – Correia, Pinto & Moreira (the three surnames of the brand’s owners). Two of the owners would soon leave the company, leaving José Pinto with full ownership. He would create the PROCALÇADO group in 1984, for shoe component production, and the PROBOL group in 1989, a company specialized in rubber production. The three groups were aggregated under the name For Ever Group in 1990.

Currently, it is Portugal’s leading sole producer, with over fifteen million Euros in annual revenue, and five million pairs produced per year. Over three hundred people are employed and the manufacturing area spans over 18000 square meters. The group currently owns three distinct patented brands, Forever, WOCK and Lemon Jelly. While Forever focuses mostly on rubber sole production for several shoe brands, WOCK is well-known for its professional footwear, found in hospitals and kitchens, bringing safety and comfort in a unique style. The latter is an exclusive brand for female footwear. The company is present in over fifty markets, with a strong presence in footwear fairs and expos. Its structure is visible in Figure 3.

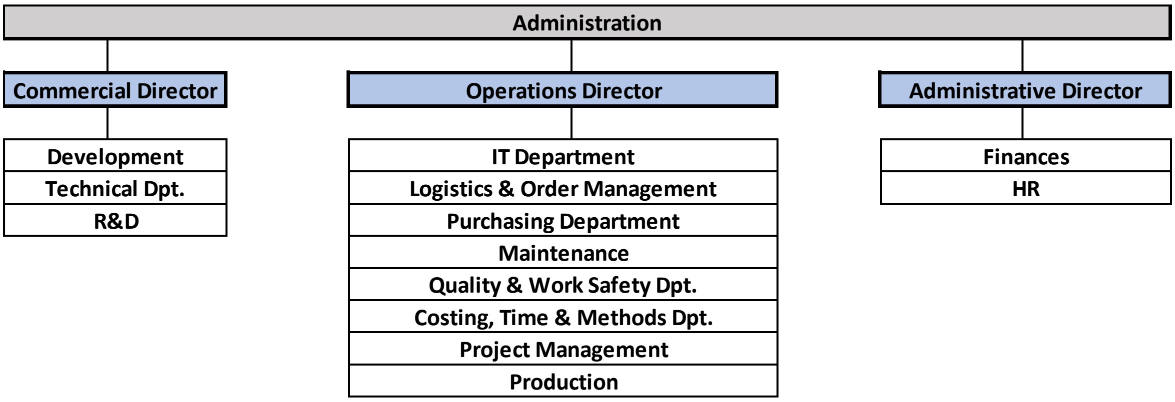

Figure 3 - Organizational chart

Eleven different sectors comprise the company's grounds, each depicted in Figure 4. The administrative offices are located on the far left (1), over the R&D laboratory, IT, marketing and design offices. Incoming raw materials are stored in warehouses number 2 and 7. Sectors which work with SBR rubber are marked with number 4 (SBR Compression), 6 (SBR Mixing) and 3 (SBR Injection). Finished goods are stored in warehouse number 5, which is also the facility where PVC soles are produced. Warehouse number 8 is home to the maintenance department, as well as the TPU sole finishing line. TPU soles are produced in sector number 10, next to the TPE production sector (11). Finally, EVA footwear is produced in the bottom right sector (9).

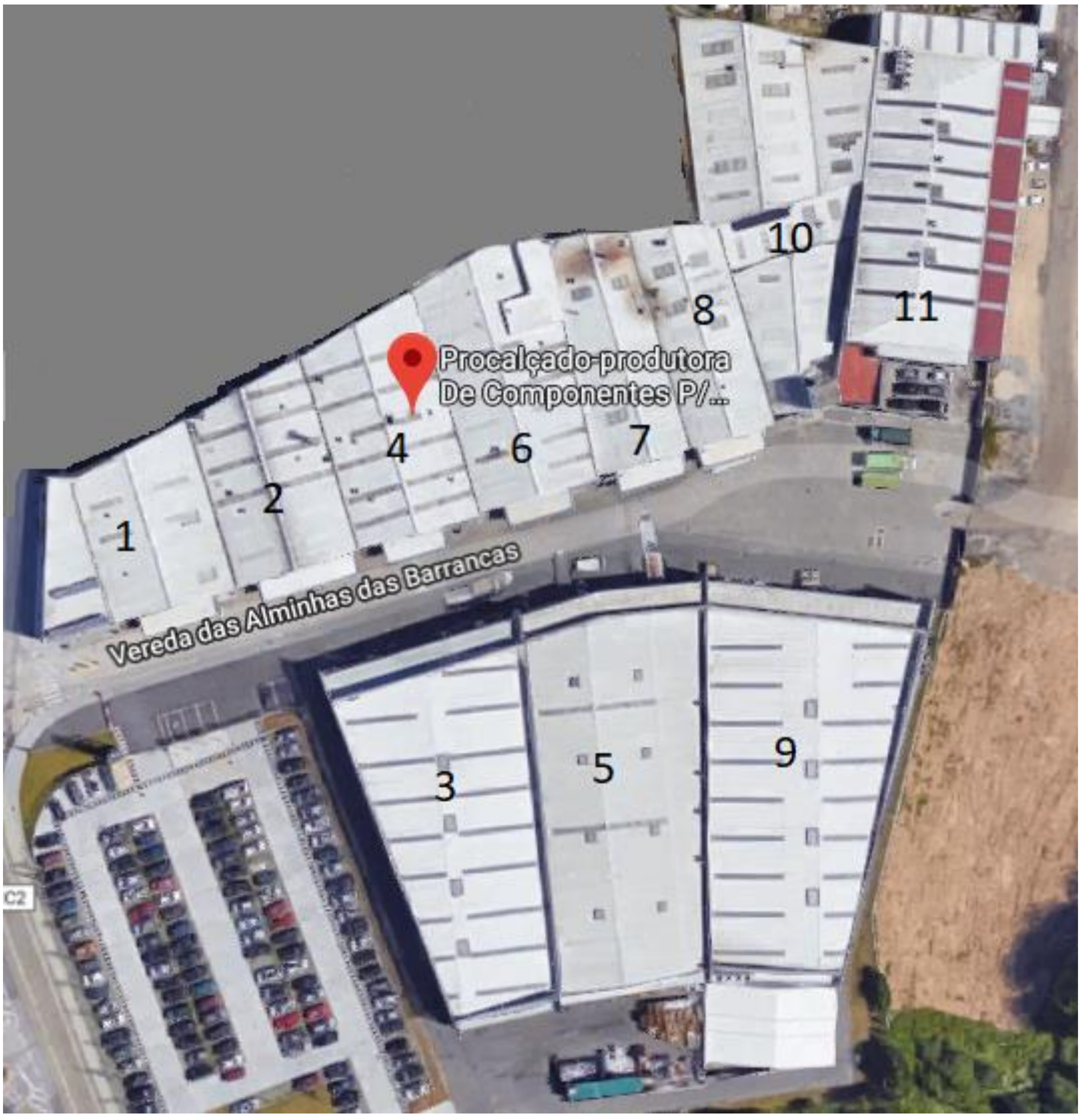

Figure 4 - Aerial shot of company departments (Google, 2018)

Each production department has its own characteristics and unique type of product. SBR, being the oldest department, has had its own raw material processing sector since the start. Naturally, as the company expanded, it diversified in terms of business areas, specifically in purchasing. Each department has its purchasing team, which has allowed for greater flexibility in terms of acquiring raw material from suppliers. Table 1 presents a summary of relevant information for all departments.

Both SBR departments serve external clients as well as internal ones. Shoe producers acquire rubber soles for their own manufacturing purposes. On the other hand, some Forever brand shoes, which are produced internally, are also made up of SBR soles. In general, SBR is very versatile, which leads to its diverse application in footwear. TR is a lighter and cheaper alternative to vulcanised rubber, commonly found in fashion and children's footwear. It is used in an injection process and it has very good slip resistance. TPU is commonly found in sports soles, noted for being incredibly oil resistant and, like TR, it is also injected. EVA materials follow a compression moulding process and are also found in sports footwear. While it is more flexible than TPU, repeated impact leads to smaller longevity. Finally, PVC is an inexpensive polymer found in plastic piping which also has its use in outsoles and work boots.

Table 1 - Summary of each department's activity.

Department	Raw material processing	Production rate (units per month)	Number of employees
SBR Compression	In-house	120000	67
SBR Injection	In-house	100000	28
TR	Imported	50000	22
TPU	Imported	55000	25
EVA	Imported	85000	52
PVC	Imported	50000	23

3.2 Production process – SBR

As previously mentioned, SBR sole production is mainly in-house, meaning raw material processing has its own sector, which in turn is connected to both sole production sectors. Production orders are created by the production planner, once a customer order is received. This person is responsible for converting customer orders into production orders and allocating them to a specific machine. To do this, the planner follows a set of criteria such as mould availability, production delays and production capacity. Once production orders are released, feedstock necessities are generated and made available to the mixing department's production planner in the form of a detailed list. To ensure that the moulding machines are constantly supplied without any rubber shortages, production orders for the mixing facility are planned two days in advance. All three sectors (SBR Compression, SBR Injection and SBR Mixing) are interlinked with a shop-floor application that runs through the company's network. In said application, operators can log in to their workstation, using their operator number, and view the progress for their ongoing production orders. Each department has its own dedicated shop-floor screen shared on multiple monitors.

Once rubber is made available by the mixing department, it is then separated into boxes according to each production order and its needs. Once the person responsible for this procedure finishes the separation process, rubber is stored in a cold-air room in a specific location which is linked to the box. Operators in the compression/injection sectors can request rubber for the following production order through their screen, if the current workable rubber does not exceed production capacity for the next two shifts, ensuring production is levelled on both sides. Each sector has one person responsible for carrying rubber from the mixing sector to workstations that have pending material needs. Once the rubber arrives at its destination, it is associated to the workstation (through the shop-floor application), eliminating pending requests.

Sole production is possible through two distinct ways: compression and injection. Compression machines are older than their counterpart but are larger in quantity. Furthermore, rubber is fed in two different ways, as will be explained in the following chapters. Machine operators load compression moulds with workable rubber and initiate production cycles that vary due to sole model differences.

Once a sole is produced, it is transported to the finishing line. Operations here include the removal of excess rubber and painting. Additionally, the line has an inspection post that detects imperfections on the sole. In case there is one, it is promptly rejected. Soles are then packaged and sent to the finished goods warehouse. The injection sector follows the same process, having its separate finishing line. The overall production process is visible in Figure 5.

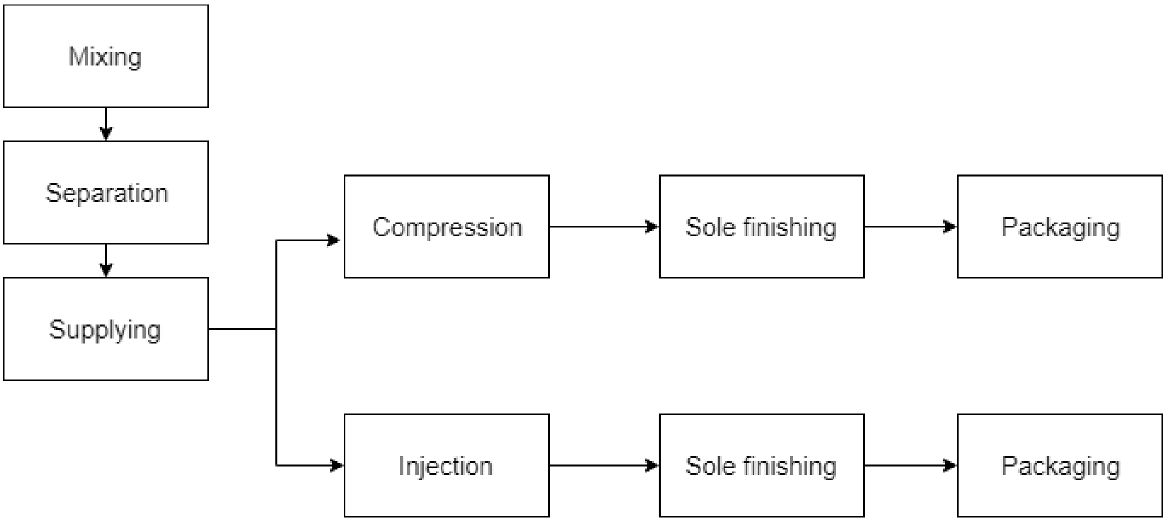

Figure 5 - General production process for SBR soles

3.2.1 SBR Mixing

This is the manufacturing unit responsible for supplying moulding machines of both departments with workable rubber, and the one where this project will focus. The mixing unit is the starting place for the production process, transforming feedstock into intermediate rubber compounds which in turn are cut into preforms. It employs 22 operators divided into two eight-hour shifts. In terms of machining equipment, it comprises one Banbury component mixer, four mixing cylinders and four cutting machines, three of which are semi-automated – Barwell Preformer 1, Barwell Preformer 2 and the Injection Cutter. The department also includes specific storage areas for semi-finished compounds, although these can be found virtually anywhere across the floor – a problem that will be assessed in following chapters. One of the storage areas is reserved for basic rubber compounds – material used in the start of the production process, while the others contain leftovers from the cutting process for both Barwell Preformers. Manual cutting operations are performed on both tables. Finished rubber is stored in a cold-air room and made available for the compression department, while rubber assigned to injection machines has its own storage area. The department's layout is visible in Figure 6.

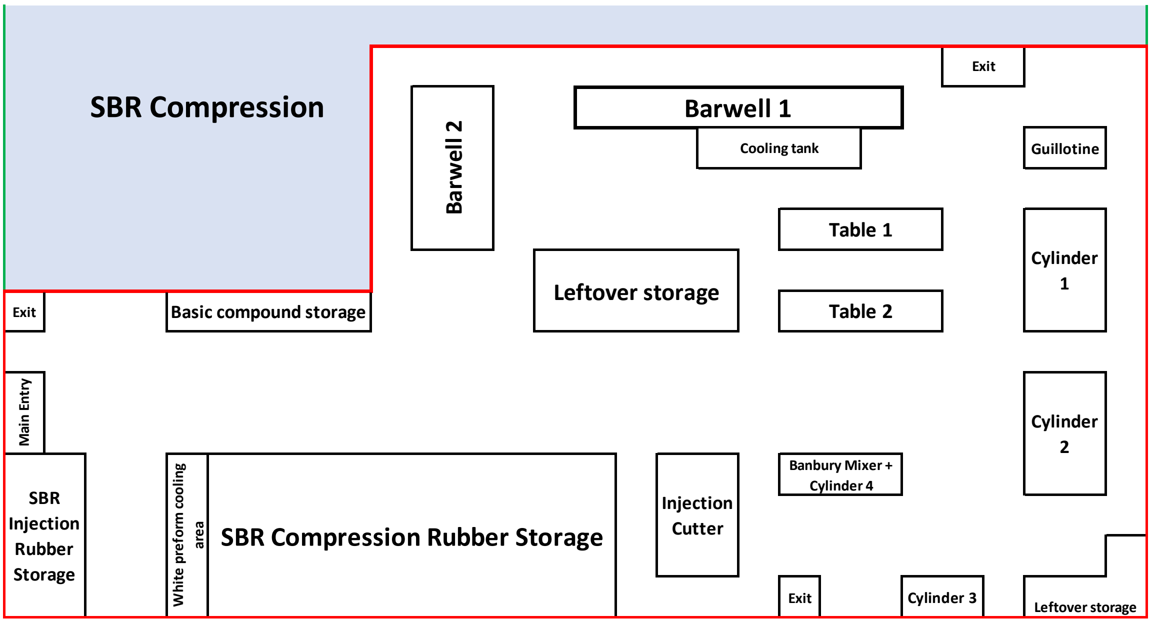

Figure 6 - SBR Mixing department layout

The sector currently produces, on average, 125 rubber compounds per day, 13 of which are considered reprocessed compounds – compounds which have been rejected by the quality department due to falling out of predetermined specifications and are thus required to be reprocessed. Reprocessing falls into three main categories: over-accelerated compounds, slow compounds and off-coloured compounds. The first two are related to the compounds' physical dimensions, which are controlled by the quality department using a rheometer. Deviations from the standard can occur when adding the wrong amount of accelerator during the component weighing process. Weather also plays a part on the compound's physical qualities, as higher temperatures diminish the rubber's lifecycle. Likewise, off-coloured compounds are also attributed to faulty weighing of components. In this case, dye quantities must be extremely precise to match a colour's formula, otherwise defects are expected. Additionally, rubber contamination can happen anywhere during all mixing operations due to sub-par cleanliness in machinery, cutting equipment or the general vicinity. Off-coloured compounds are determined by colour differences between produced compounds and the defined standard. The distribution for each rework category, in percentage, is found in Figure 7. This data is available in SAP's production report module and has been continuously updated since November 2017.

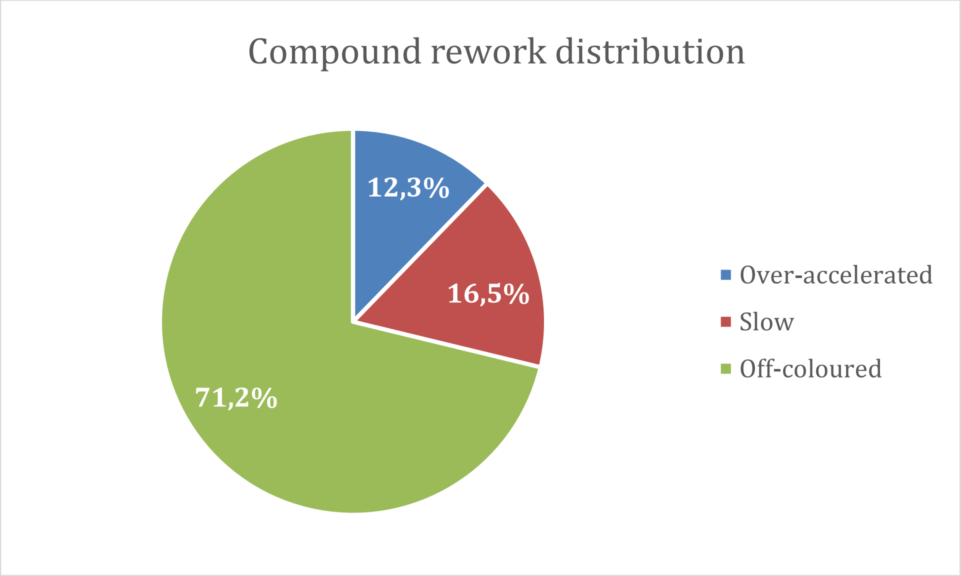

Figure 7 - Compound rework categories and their frequency

3.2.2 SBR Compression

This production unit is responsible for manufacturing rubber soles and sole prototypes for external clients. It is divided into five groups of machines, being that each machine comprises several working moulds. Because this is the company's oldest production unit, it also has the oldest machines. The majority of sole producers worldwide have resorted to injection machines, as they produce at a faster rate, and have a lesser percentage of defects. While compression machines are slowly becoming obsolete, their production is still within acceptable limits. In this unit's case, there are 32 fully operational moulding machines, each one comprising four moulds. Ignoring moulding changes, mould testing and material shortages, there is a maximum potential of 128 moulds simultaneously producing soles.

Each group serves a different purpose in terms of produced sole models. Machines that belong to groups A and B mostly work with smaller production orders, resulting in a higher number of changeovers per shift. Group C machines are responsible for producing sample soles and prototypes. Additionally, new moulds are tested here. Group F produces multi-coloured soles, while Group G deals with large orders. For most models, each machine has a capacity of 30 pairs of soles per shift. Rubber is compressed within steel moulds, shaping it according to a specific sole's requirements, such as weight, diameter and length. Three operators work in groups A and B, each one allocated to four machines, while group F also comprises three operators. Groups C and G have two working operators each.

Moulding machines can be fed by rubber in two different ways: preforms (Figure 8) and short strips (Figure 9). Preforms differ in size, weight, shape, and any combination of the three makes it so that each sole produced may require a unique preform. Strips, however, are produced in the manual guillotine and generally do not differ in size or weight, as they are commonly used in prototype or sample sole production in Group C, or even mould testing, thus not requiring the same level of precision. Furthermore, strips are easier and faster to produce by the mixing unit, which reduces workload.

Figure 8 - SBR preforms in different variations

Figure 9 - SBR strips

The unit's layout is visible in Figure 10. Each block represents one workstation – a working moulding machine. Moulds are stored on the external areas of the unit, each with a specific location, which can be tracked via information system in a shop floor module. Group A and B are often considered a combined work group (Group A+B is the common notation), because three operators are allocated there, and are responsible for four workstations each. In group C, the four right-most workstations are usually allocated to sample production and mould testing, while the three remaining workstations are reserved for normal production. Groups G and F are set up in a peculiar way: one workstation extends to both sides, meaning two operators can operate the same workstation simultaneously, albeit in different moulds. The lanes where operators move around are represented in white blocks adjacent to the workstation groups.

The moulding process itself is quite simple: rubber preforms (or strips) are placed in the mould's cavity, ensuring it is totally filled. Then, the mould is manually closed by the operator, applying heat and pressure to the preform, allowing it to fill the cavity. After about ten minutes (this value depends on the produced sole model), the mould is opened, and the operator removes the moulded rubber and the excess that overflows from the mould. Finished soles are placed in carts and transported to the finishing area, where they are subject to additional work. Firstly, excess rubber is removed from the sole in a grinding operation. Four bench grinders (represented in red block) are manned at the same time. Then, the worked sole proceeds to a painting procedure, where imperfections on the sole are detected and covered up. Soles are then packaged and placed in a reserved area awaiting shipment to the finished product warehouse.

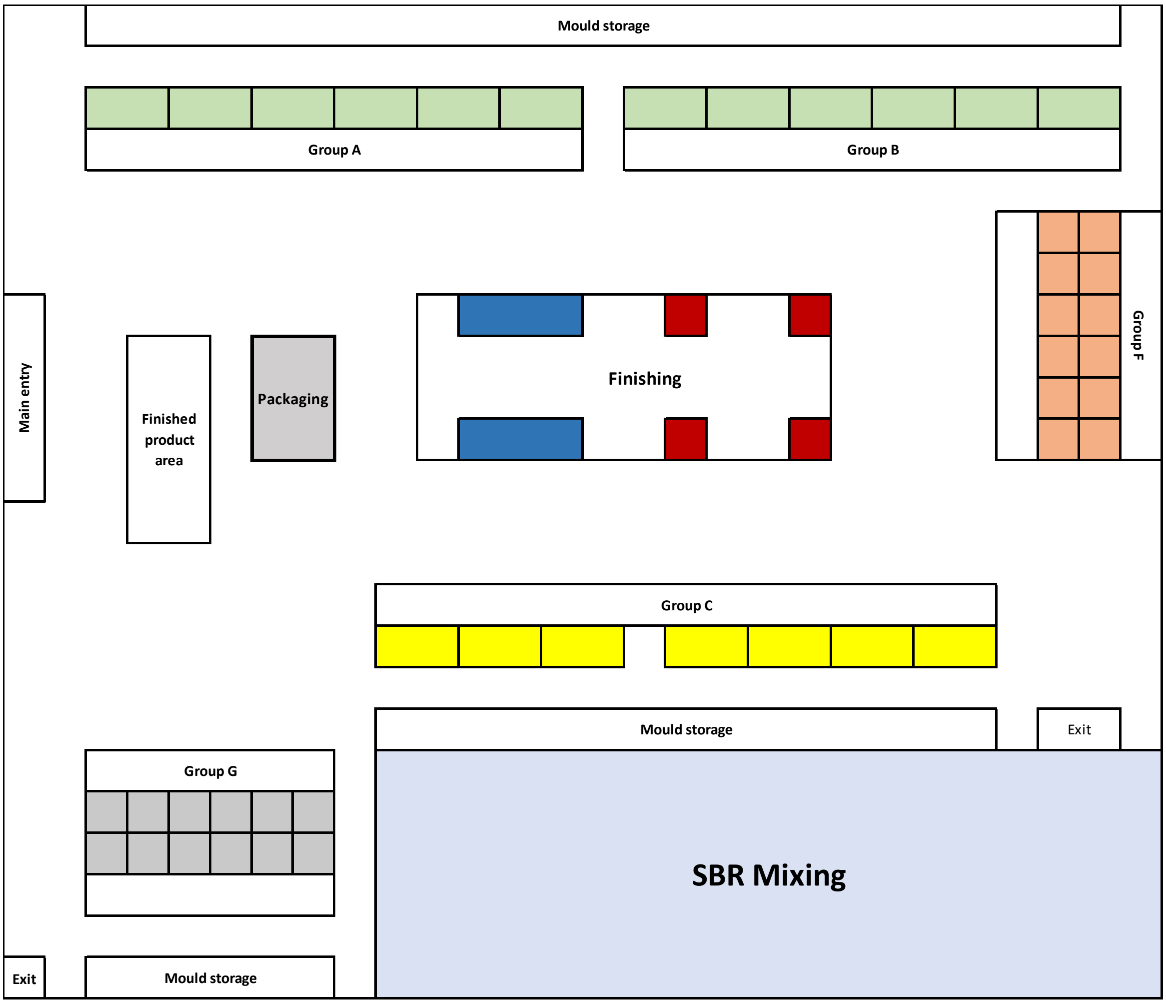

Figure 10 - SBR Compression department layout

3.2.3 SBR Injection

This unit, which is located in front of SBR Compression, also produces rubber soles, albeit using more advanced machines. These work using an injection process, thus having a shorter processing time than compression machines. The unit houses ten injection machines with two moulding cavities each. Rubber for these machines is produced in the form of larger, heavier strips (Figure 11). These strips are fed into a built-in screw which fills a barrel with an appropriate amount of rubber. The machine then places the rubber under more pressure than in compression moulding. Hence, the need for preforms is eliminated. Furthermore, production cycle time is lower which makes this a more economical approach to sole production when considering medium-high volume production. Additionally, there is minimal material waste. This unit has its own dedicated production planner, much like SBR Compression.

Figure 11 - Injection rubber strip

Unlike SBR Compression, where one operator is responsible for supplying workstations with workable rubber, this unit's shift supervisor is in charge of transporting materials from SBR Mixing to each machine, when needed. Rubber in the form of strips is placed behind each machine, awaiting its use after the current production order is finished. Injection machines are connected to a PLC screen, unlike their compression counterparts. Thus, operators control the machine's mechanical movements by operating said screen. Machines are not assigned to any groups rather, each has its own assigned number. Operators are spread evenly among all machines, with each one assigned to two separate workstations (e.g. operator A is assigned to machines 1 and 2, operator B is assigned to machines 3 and 4, and so on). Produced soles are placed in carts and transported to the unit's finishing area, where they are subject to the same operations as observed in SBR Compression. Finished soles are then transported to the finished goods warehouse. The unit's layout can be observed in Figure 12.

Because injection machines do not require preforms, there is minimal waste associated to this production system. Rubber is produced by the mixing unit in the exact amount that is required to complete production orders for a given number of soles, aside from a necessary additional percentage due to defects. Nevertheless, injection machines produce less defects than compression ones, because there is a lesser chance of human interaction with the production process. While the misuse of compression machines can lead to the breaking of moulds, substandard sole production, or ripped soles, injection machines are much more automated and self-sufficient. Injection machine operators simply load the rubber into the barrel, initiate production and repeat throughout the production order.

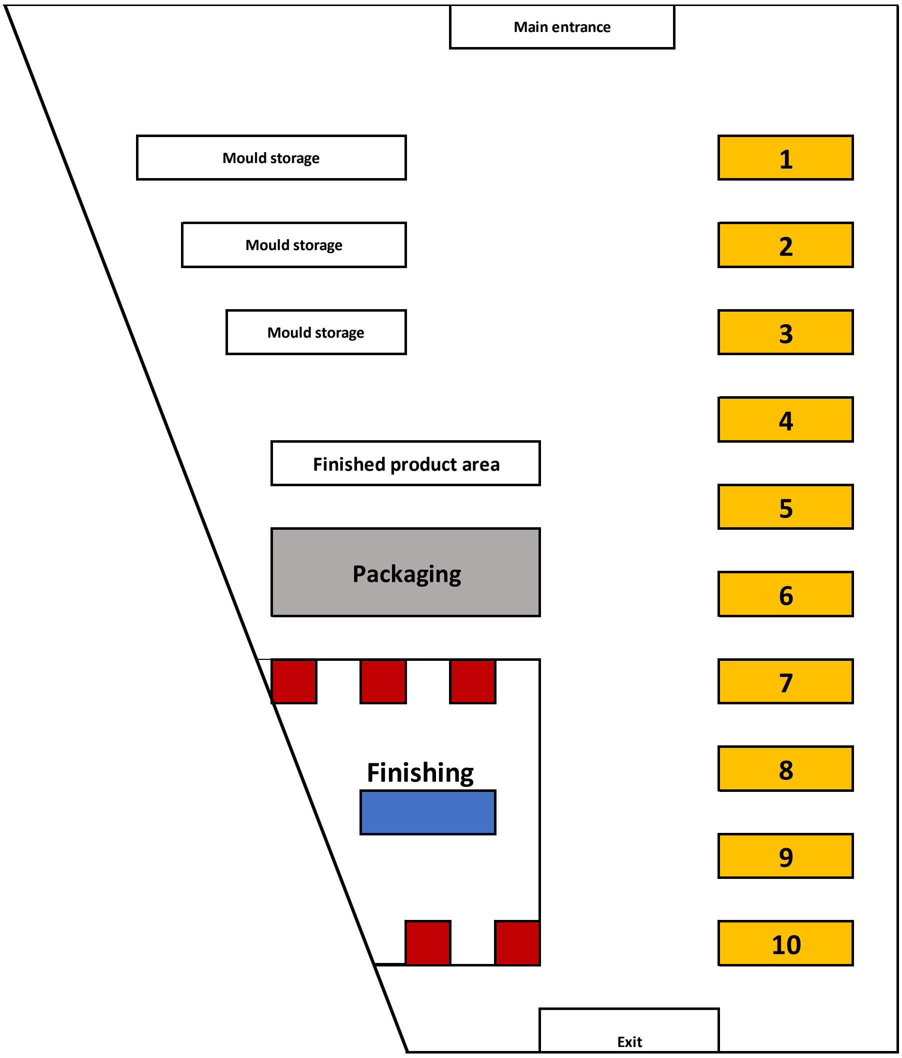

Figure 12 - SBR Injection department layout

3.3 Production process – SBR Mixing

Focusing on the SBR Mixing sector, where this project was developed, it is laid out as a job shop manufacturing system to accommodate a high complexity of products along with high order variability. The department's planner is responsible for releasing, from an order pool, three different production order lists to hand out to machine operators, plus an additional production order list to the component weighting staff.

The industrial process itself begins in the weighing room. Two processes occur simultaneously in this step: small and large component weighing. Two people deal with small components, while an additional operator weighs larger components. Whereas smaller raw components (silicon dioxide, dyes, accelerators, among others) are weighed in smaller quantities (up to a 100 grams), larger ones can range from 1 to 10 kilograms. Hence, smaller component weighing requires much more precision, as a small deviation in the formulas can greatly influence the intended output. Each compound's colour code has its own component formula, which is created by the head of the department. Basic compounds (pre-accelerated compounds with no colour) have their own nomination, as do specific colours. Therefore, an intermediate rubber compound is coded after both. For example, X150-430D rubber is produced with X150 basic compounds, by adding 430D colouring components. Each basic compound can be mixed with any colour dye, and each colour dye can be applied to any basic compound.

Larger components, such as the ones found in Figure 13 are put together in the Banbury mixer.

Figure 13 - Solid raw rubber

As the mixed product descends through the mixer, it arrives at the main cylinder. In a continuous mixing operation that takes under five minutes to complete, a basic compound is produced in the form of a large roll. It is then transported to a nearby table, where it is cut into smaller chunks, and subsequently stored in a water-cooling tank. The cooling process takes around three minutes to complete. The compound is then stored away for future use. It is important to note that there is a gap between this stage of the production process and the next. All the aforementioned operations are done in parallel to the next ones, as basic compound production follows an MTS (make-to-stock) production strategy. Conversely, intermediate compounds are produced following an MTO (make-to-order) strategy, according to daily needs. Because of this, there is a buffer between both production stages.

After checking the daily production plan, the current shift's team leader is responsible for organizing basic compounds so that the mixing cylinders are constantly fed, to avoid waiting idle times. The cylinder's operator mixes basic compounds with pre-weighted components, in an operation that lasts approximately ten minutes. Afterwards, the now-coloured compound is transported to one of the cutting machines, depending on the determined production sequence. Barwell preformers are the most complex machines, thus requiring a detailed explanation. When ready to insert the produced rubber compound into the machine, the operator must specify the preform's parameters (size, shape, weight) by typing them in the machine's PLC screen. Each sole model requires a different set of parameters. For simplicity's sake, the characteristics of a hypothetical model – Type A Sole – will be described. This example sole's characteristics are presented in Table 2, accompanied by a brief explanation of each one.

Table 2 - Type A sole characteristics

Colour code	**Model name**	**Sole size**	**Sole weight**	**Preform weight**	**Preform shape**
X150-430D	Type A	42	160g	80g	P3-2

With regard to colour mix coding, as explained earlier, colour codes are generated by the basic compound, preceded by the colour code. Each sole can be produced with various compounds of different colours, depending on customer orders. Each model is assigned to its specific denomination. The next four characteristics are interlinked with the downstream moulding process. Each sole is associated with its mould, wherein one mould can only produce one type of sole. Therefore, the sole must be produced exactly as its characteristics demand, so that the mould does not break or produce substandard soles. Preform is the name given to the rubber piece that is inserted in the mould's cavities. It has a predetermined weight and shape. Shape is given to preforms by a steel shaper that is inserted into the Barwell preformer's cavities, altering the preform's diameter and volume. These parameters are adjustable in both Barwell Preformers. All this information is available to the operator in the form of a shop floor application in a computer screen next to the cutting machine, along with production orders. When initiating the cutting procedure, preforms are sent to an automatic conveyor inside a structure, where they cool down. After reaching the end of the conveyor's path, they are stored in boxes by an additional operator and taken to the supply station. After finishing a production order, Barwell preformers produce leftovers from the cutting process. These leftovers are taken to the mixing cylinder, where an additional operation is performed. The leftovers are then stored in a shelf case next to the preformer, in case it's a coloured compound. If the compound is white-coloured, it is taken to a shelf case next to the mixing cylinder (marked as number two in the department's layout). After producing the specified amount of preforms, the machine operator is responsible for registering the amount of preforms produced in the LCD screen using the shop floor application.

The injection cutting machine follows a more automated process than the one previously described. It is composed of two smaller cylinders and a structure that allows the compound to experience a decrease in temperature. The machine operator simply places the compound between the cylinders, cutting it into a strip and placing it inside the structure. The machine then starts rotating, extending the strip's length until the compound fully leaves the cylinders. The operator then places the produced rubber strips in large boxes, and registers production in a nearby LCD screen. Boxes are then taken to their reserved storage areas.

Orders up to five kilograms in quantity require a manual cutting procedure, using a mechanical guillotine to cut rubber into small strips. Special orders, such as sample colours or rubber mixed with recycled components, also follow the same procedure.

Once the production order is satisfied (the amount of preforms or quantity in kg produced is complete) and registered, two production cards are printed carrying barcodes associated with a specific production order. Production cards carry the necessary information to the downstream process: date, colour code, model name, and compound production ID (the consecutive number of the same compound produced). The other barcode card is attached to a smaller compound piece reserved for testing. Once workable rubber arrives at the supply station, it is separated and packed into separate boxes, each belonging to a specific station in the moulding facility. This ensures that every production order in a moulding station is associated to incoming material. Finished inventory is transported and stored in a cold-air storage room, awaiting shipment to moulding machines. However, it is only made available once the quality department completes testing on produced rubber, awaiting approval.

Quality control consists in analysing produced rubber by comparing its physical characteristics with predetermined standards: acceleration, hardness and colour. Acceleration is measured using a rheometer, while hardness is calculated with a durometer. Colour control is performed in a two-step process. Firstly, produced rubber samples are analysed by using a spectrophotometer. The rubber's colour is quantified by the device, according to the CIELAB colour space convention. The output values are presented in three distinct values (L, a, b). Colour difference is then calculated by comparing these values to the pre-set values for the specific analysed colour. This difference is represented by a delta E value, which must be under a given numerical value so that the produced rubber is approved. Depending on tolerance limits, each colour code has its own delta E rejection limit. If the compound is rejected at this stage, it is subjected to visual inspection by the quality technician, wherein the sample is visually compared to existing colour benchmarks. If the responsible technician deems the sample to be within acceptable colour limits, he ignores the previous tests and approves the compound for production.

If a specific compound is rejected by the quality department, production orders for that compound are generated again and listed in the shop floor application, in a separate production list (visible in Figure 14) from the normal one. A reprocessing code is also generated, so that the necessary information is available to operators.

Data	Mist	Sola	TMold	Qtd	QtdP	Maquina	Tac	Sol	Mem	Pesc	Pesc	PRF	P	CodRe
2017-11-27	P233PR-201_PED	WAVA BOX-WV	S/NR	35	0	GC_M6_4		12	29	124	248	2		M015
2017-12-11	EVERGRIP 45AE VIRA-201_P...	TRIF T7	[illegible]	14	0	GF_M1_3		12	1429	60	240	4		M015
2017-12-14	PURA LATEX-6A0_PED	FANATIC	38	3	0	GC_M5_4	P2	2	1058	265	530	2		M003
2017-12-15	N383PR RASTO-201_PED	[illegible]	46	42	0	GF_M5_2		13	973	27	296	8		M015
2017-12-15	P234CAST-728A_PED	[illegible]	[illegible]	48	0	GA_M5_2		4	1841	135	270	2		M015
2017-12-18	CADS 65PR-201_PED	[illegible]	[illegible]	4	0	GB_M2_4		13		30	60	2		M007
2017-12-18	CADS 65PR-201_PED	[illegible]	3.5-...	4	0	GB_M2_4		13		30	60	2		M007
2017-12-18	CADS 65PR-201_PED	GABOR62-39-17	3.5-...	19	0	GB_M2_4		13		30	60	2		M007
2017-12-18	CADS 65PR-201_PED	GABOR62-39-17	3.5-...	10	0	GB_M2_4		13		30	60	2		M007
2017-12-18	CADS 65PR-201_PED	GABOR62-39-17	3.5-...	13	0	GB_M2_4		13		30	60	2		M007
2017-12-18	L120-519D_PED	FARY-SD	38	6	0	GC_M5_1		13	251	175	700	4		M003
2017-12-18	L153-634_PED	PZ CUP-ZU	43.5	6	0	GC_M5_1		4	1086	151	604	4		M003
2017-12-19	CADS 65COR-617D_PED	GABOR62-39-17	3-8-...	10	0	GB_M2_4		13		30	60	2		M015
2017-12-19	CADS 65PR-201_PED	GABOR62-39-17	3-8-...	10	0	GB_M2_4		13		30	60	2		M015

🟨 Para recuperação
🟥 Faltas

M003 - Cor não conforme c/ recup.
M005 - Lenta c/ recup.
M006 - Acelerada c/ recup.
M009 - Suja/Contaminada c/ recup.
M011 - Fora de prazo c/ recup.
M015 - Pedidos de Faltas

Figure 14 - Reprocessing list from the shop floor application

Each shift has its own person responsible for reprocessing compounds. Over-accelerated compounds are dealt with by adding a calculated percentage of rubber retardant to the rejected compound, mixing it in the cylinder once again. Conversely, slow compounds are mixed with a percentage of rubber accelerator, subject to the same procedure as before. Off-colour compounds, however, are more complex to solve. Firstly, tests are performed with smaller samples of the rejected compound (usually between five and ten kg) so, by adding other colour dyes in a smaller cylinder, reserved for reprocessing procedures, and mixing them, the pretended colour can be achieved. Then, the formula is replicated for the entire production order's quantity. The amount of time spent trying to refine the compound's colour ranges from a couple of hours to a whole week, depending on its complexity. Once the compound is successfully reprocessed in the cylinder, it follows the same process path. The production process for the department can easily be visualized in Figure 15.

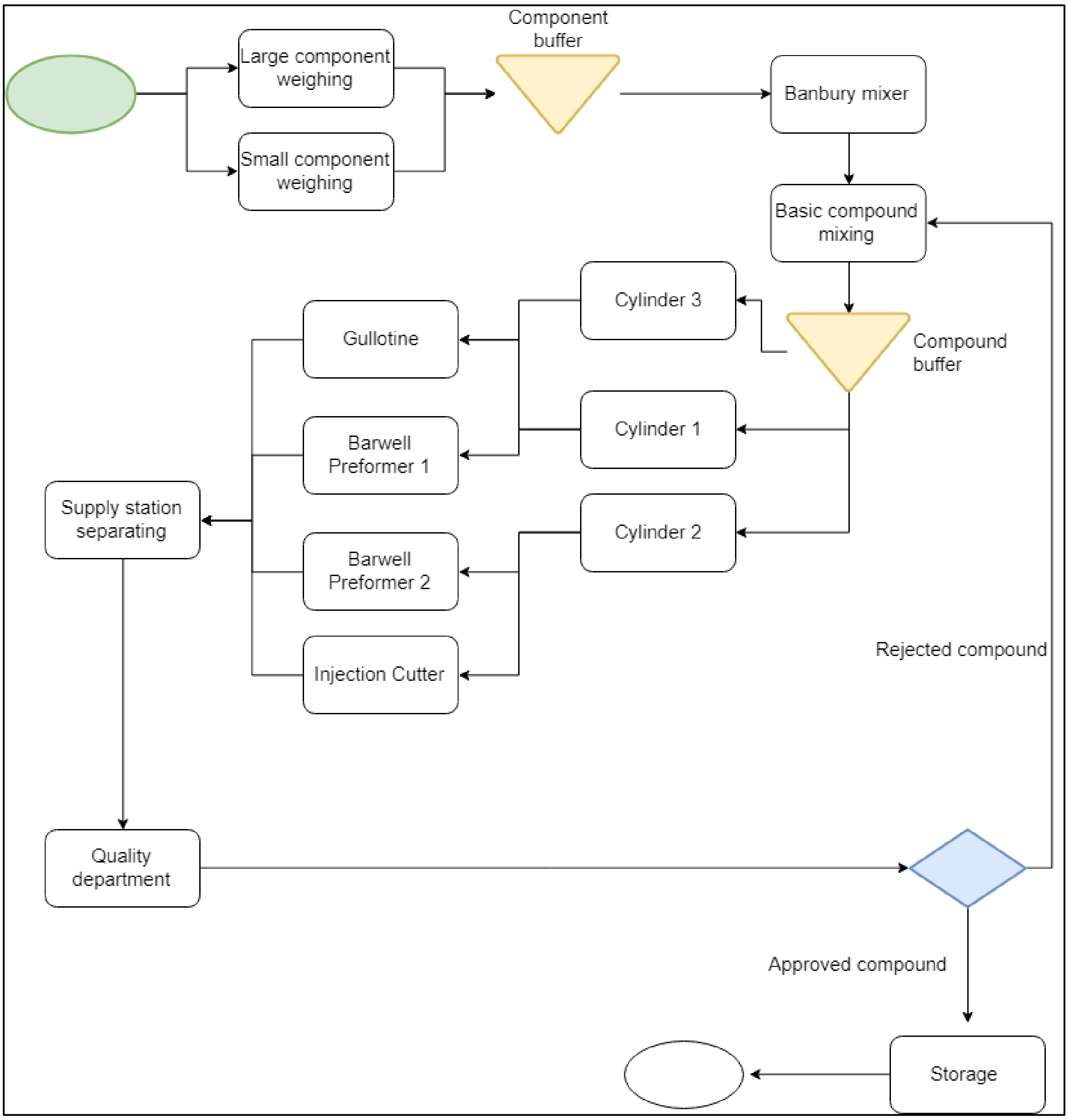

Figure 15 - SBR mixing production process flowchart

3.3.1 Initial performance

As the mixing cylinders possess the longest processing time in all operations, they were identified as bottleneck workstations. The department's current performance was then calculated, using maximum capacity production values for the mixing cylinders. Only intermediate compounds were considered as a product unit (one 50kg compound). Cylinder 1 and 2 are available full time across both shifts, whereas Cylinder 4 only produces intermediate compounds for one shift. Cylinder 3 was ignored in these calculations, as it is reserved for reprocessing, in a parallel production flow. Each cylinder has a production cycle time of 11 minutes per compound and idle time was ignored, assuming continuous basic compound feeding to the cylinders. These calculations are summarized in Table 3.

Table 3 - SBR mixing capacity

Equipment	Daily availability (minutes)	Maximum production capacity (units)
Cylinder 1	900	81
Cylinder 2	900	81
Cylinder 3	450	40
Total		**202**

Figure 16 shows the department's performance in terms of units produced (the dip observed in mid-December is attributed to the factory closing in the afternoon for holiday festivities). Data was collected from the second week of November onwards. The average for daily production in this period amounts to 125 units produced, including reprocessed units, which represents a performance level of 63%.

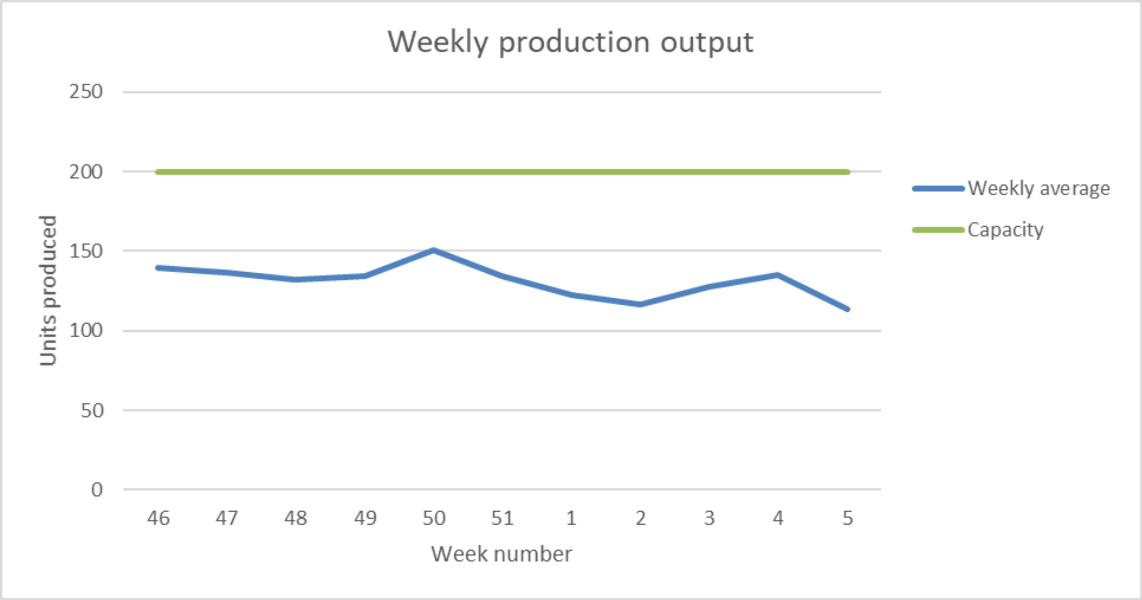

Figure 16 - Weekly compound production data for SBR Mixing department

In order to understand how the mixing unit affects both production units as a whole, further data was gathered on machine downtimes at both SBR Compression and SBR Injection units. Because the mixing unit isn't producing rubber at an optimal rate, it cannot keep up with downstream production and production orders fall behind schedule. As such, workstations stop producing soles, due to rubber shortages, for extended periods of time. Figure 17 shows the evolution of the average downtime per workstation (working mould), both in SBR Injection and SBR Compression. Data was gathered and analysed from November to February. As shown in the dotted line, the tendency was for these values to increase in the future. Data is available in SAP's production module, which is connected to the shop floor application used by machine operators. When rubber is not immediately available next to the respective workstation, an operator can stop a production order due to material shortage in the shop floor application. When material finally arrives, the operator can once again initiate the production order, thus closing the material shortage timer. SAP calculates the elapsed time and presents these results in its production module.

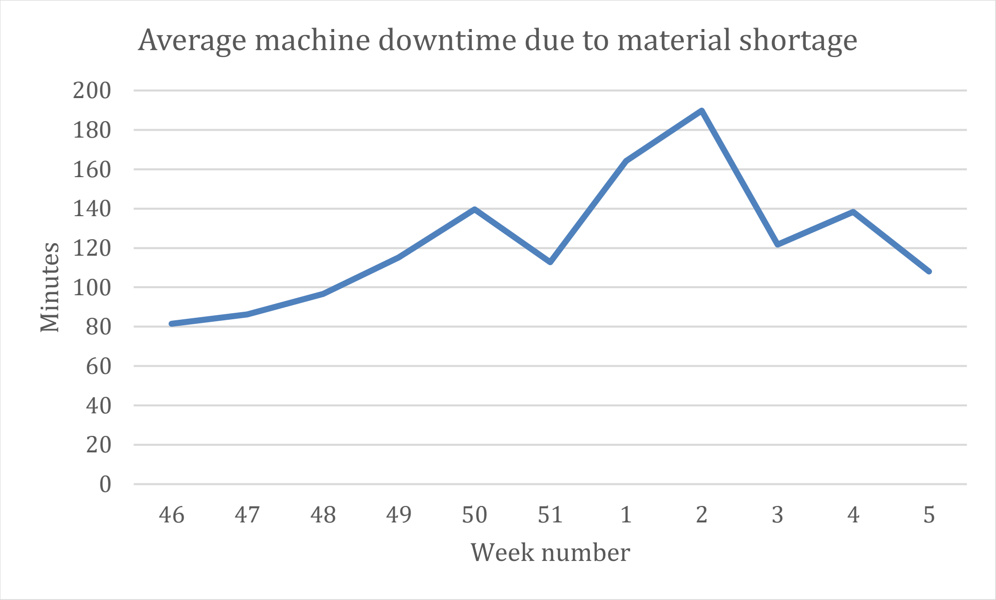

Figure 17 - SBR Compression and Injection machine downtime

3.3.2 Identified problems

During the initial diagnosis of the department, several problems were identified, in various areas. The most impactful ones are presented and segmented into different groups below.

3.3.2.1 Operations

As mentioned in previous chapters, basic rubber compounds are produced for stock. Because there is no production control or any sort of identification on these products, there is an excess of work-in-progress for these compounds. As of January 1st, the amount of basic rubber compound in inventory amounts to 11.900kg. Data on WIP was extracted from an SAP production module, which is linked to the shop floor application in the mixing unit used for registering basic compound production. With no adequate storage facilities, they are temporarily placed on the ground (see Figure 18) causing movement difficulties in the adjacent areas. Because there are plenty of different basic compounds produced each day, it is hard to distinguish each one visually. As such, operators tend to place paper sheets on top of compounds as a way to identify them. This, however, is not a regular practice, nor is it a very efficient one.

Figure 18 - Basic compound WIP

After completing a production order, both Barwell Preformers used in cutting operations produce leftovers, which are then taken to the mixing cylinder where they are processed for about three minutes and then stored away in nearby shelf cases (see Figure 19 and Figure 20). When a new production order arrives, requiring the same rubber that was stored, previous leftovers can be easily reintegrated into the mixing process. However, these are often stored without proper labelling or visual cues and, as such, it is difficult for an operator to locate leftovers for a specific rubber compound in the shelves, resulting in a significant amount of time wasted searching for them. Additionally, semi-finished rubber compounds, such as these, have a 15-day expiration date from the moment they are produced and after that they are considered waste. Some leftovers were found to be stored for over a month without any knowledge by the operators.

Figure 19 - Leftovers from Barwell 2

Each shelf case is dedicated to a Barwell Preformer: one is composed by white-coloured compounds, while the other one is filled with compounds of the remaining produced colours. However, these were very disorganized and confusing for someone unfamiliar with the production process. Colours were not organized, and some compounds had no identification whatsoever, meaning they could not be reintegrated. All of these factors result in larger production lead times, due to the time that is spent locating and reintegrating leftovers.

Figure 20 - Leftovers from Barwell 1

Without any knowledge of what compounds are present, or the date when they were produced, the risk of reintegrating expired rubber into the process is present. Therefore, it is likely that this practice leads to a number of off-coloured compounds produced. Despite having an expiration date, it is possible to reintegrate overdue leftovers in black-coloured compound production, as colour differences are barely noticeable in this case.

Compound reprocessing can be traced to various reasons, in different sections of the production process. Firstly, small component weighing can influence the intended output, as small deviations in quantities weighed result in large differences when the compound is being mixed in the cylinders, therefore, precision is key in this operation. Secondly, the Banbury mixer works in a closed environment, meaning the interior parts of this equipment cannot be reached, unless maintenance work is performed. Due to its constant production of different basic components during the day, there is the possibility that components remain inside the equipment, which in turn get mixed with components from another basic compound to be produced. Hence, variables such as colour and hardness will deviate from the expected output, as different components have different properties. The same principle applies to compound production in mixing cylinders. Without proper cleaning in the affected areas of the cylinder after each production cycle, remains from different compounds can reintegrate the newly produced compound, thus altering its intended colour. Rubber contamination is a constant problem in the production unit and has a significant impact on the amount of compound reprocessing. Work space and equipment cleaning is an afterthought to operators, who mostly focus on quantity rather than quality. Figure 21 shows the amount of reprocessing work required due to these factors. Although values varied from day to day, the average percentage of compound reprocessing of total production, during the month of February, was ten percent with an upward trend for the future, according to earlier data.

Compound reprocessing is dealt with in a parallel production flow to the main one, with dedicated resources. In terms of equipment, an extra cylinder (Cylinder 4) is dedicated to reprocessing. One person per shift is responsible for analysing off-coloured compounds and refining them until the intended colour is reached. Slow and over-accelerated compounds are reprocessed in the main production flow, by adding missing components, as explained in previous chapters. Although the reprocessing flow is parallel to the production one, production orders for these compounds and correspondent soles are delayed due to extra work that must be performed.

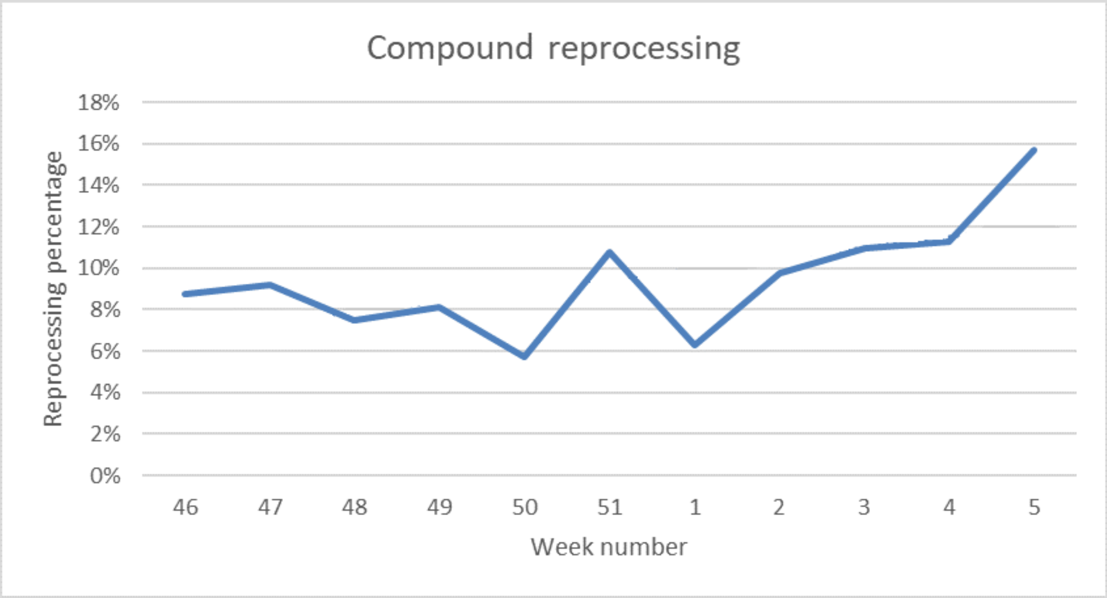

Figure 21 - Weekly compound reprocessing percentages from total production

Operations in the mixing cylinder are not adequately standardized, as the equipment's operating efficiency is very low, when considering it is the bottleneck workstation in the production process. Data was collected on both mixing cylinders' occupation during a week, namely worker movements and operations were detailed. Cylinder 1 was interrupted for a total 1h 48m, while Cylinder 2 was left unattended for a total of 4h30m. These causes for these idle times were categorized into five reasons (see Figure 22). Work preparation refers to times when the cylinders' operators had to prepare material for the next production cycle and includes locating and transporting basic compounds to the respective workspace, locating and transporting components, or registering production in order lists. Time spent transporting the produced compound to the cutting machine falls under the transporting category. The category marked in green refers to times when both cutting machine and cylinder operators performed shared tasks to ensure standard production. Inactive periods of time, where workers were not contributing to the production process, were also considered. Actions which did not fall under any of these categories were marked as "other". The values can be visualized in Figure 22.

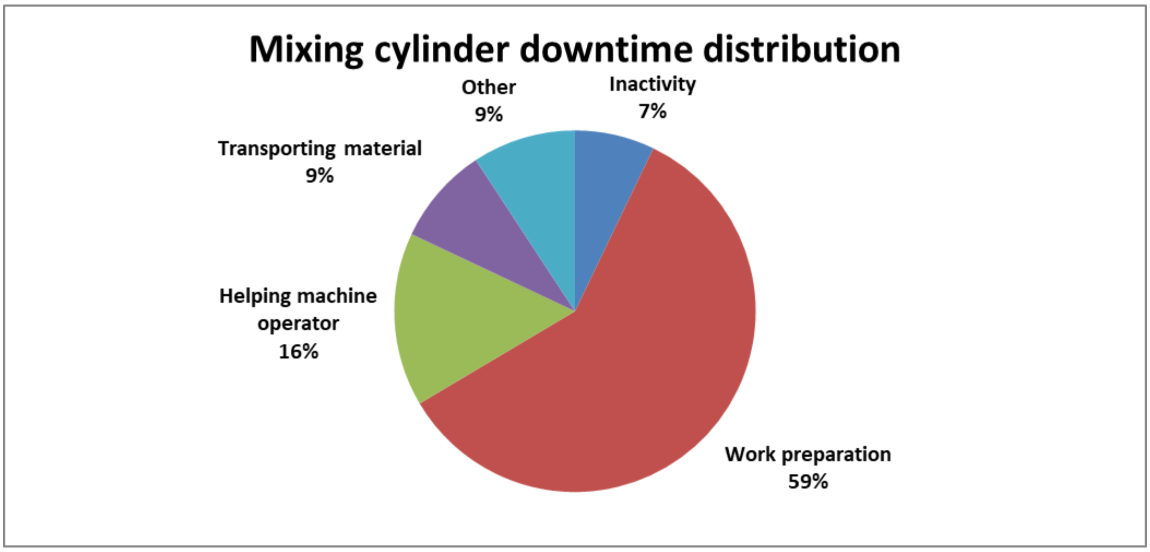

Figure 22 - Mixing cylinder downtime causes

Total observation time was fifteen hours. Dividing the overall idle time from the observed time results in the usage rate for these cylinders, which means the cylinders' effectiveness was just short of 58%.

3.3.2.2 Order sequencing

Operators do not follow a standard sequence to complete production orders and they rather rely on their experience to carry out tasks. When operating mixing cylinders, the most common procedure is to sequence work according to colour order, meaning operators will finish all compounds that share a colour family (beige, black, yellow), before moving on to another colour. This is done on the basis that colour changeover requires a lengthy machine cleaning process. However, this delays the process in general, due to priority orders being left behind in favour of less urgent ones. For example, on a given day, if the production list contains twenty black coloured compounds to produce with varying delivery dates and two compounds of different colours (e.g. red and green) with earlier delivery dates, operators will more often than not, produce the whole set of black compounds to avoid colour changeovers, both in the mixing cylinders and in the cutting machines. The result, however, is the delay in production for both red and green compounds, meaning sole production moulds will also be delayed due to material shortage. Although the time spent in colour changeovers is significant, the trade-off between that procedure and not producing the necessary material must be assessed.

Another common mistake done by operators is sequencing cutting operations without considering delivery dates. By doing this, operators are producing workable rubber for later orders, delaying sole production of orders dated earlier, thus delaying the delivery dates in general. As can be seen in Table 4, production orders, in this case, for the three earliest starting dates were ignored.

Table 4 - Example of a workstation with no available material for immediate production orders

Station	Order number	Sole model	Colour code	Size	Pairs to produce	Available rubber		Production starting date
GB_M2_3	1208938	GABOR 62-39-17	CADS65-617D	4	36	0	-36	14.12.2017
GB_M2_3	1208940	GABOR 62-39-18	CADS65-617D	4.5	36	0	-36	14.12.2017
GB_M2_3	1208941	GABOR 62-39-19	CADS65-617D	5	51	0	-51	14.12.2017
GB_M2_3	1211945	GABOR 62-39-20	CADS65-617D	4	18	19	1	18.12.2017
GB_M2_3	1211947	GABOR 62-39-21	CADS65-617D	5	15	16	1	19.12.2017
GB_M2_3	1213534	GABOR 62-39-22	CADS65-617D	5	3	4	1	19.12.2017
GB_M2_3	1213533	GABOR 62-39-23	CADS65-617D	4.5	3	4	1	19.12.2017
GB_M2_3	1211946	GABOR 62-39-24	CADS65-617D	4.5	6	7	1	19.12.2017
GB_M2_3	1213532	GABOR 62-39-25	CADS65-617D	4	3	4	1	19.12.2017

Without available rubber for sole production, moulds will stop altogether.

3.3.2.3 Equipment

Barwell 2 has a design flaw, which causes preforms to fall on the ground when exiting the machine cavity onto the preform receiver (this can be observed in Figure 23, in the area surrounded by the orange rectangle). Because of the high velocity of preforms exiting the preformer, and due to the green platform not being separated into enough dividers (signalled with blue arrows in Figure 23), preforms fall into a hole (represented by the orange box in Figure 23). Furthermore, this high velocity causes preforms to rebound on the green platform and fall onto the ground along the receiver’s side.

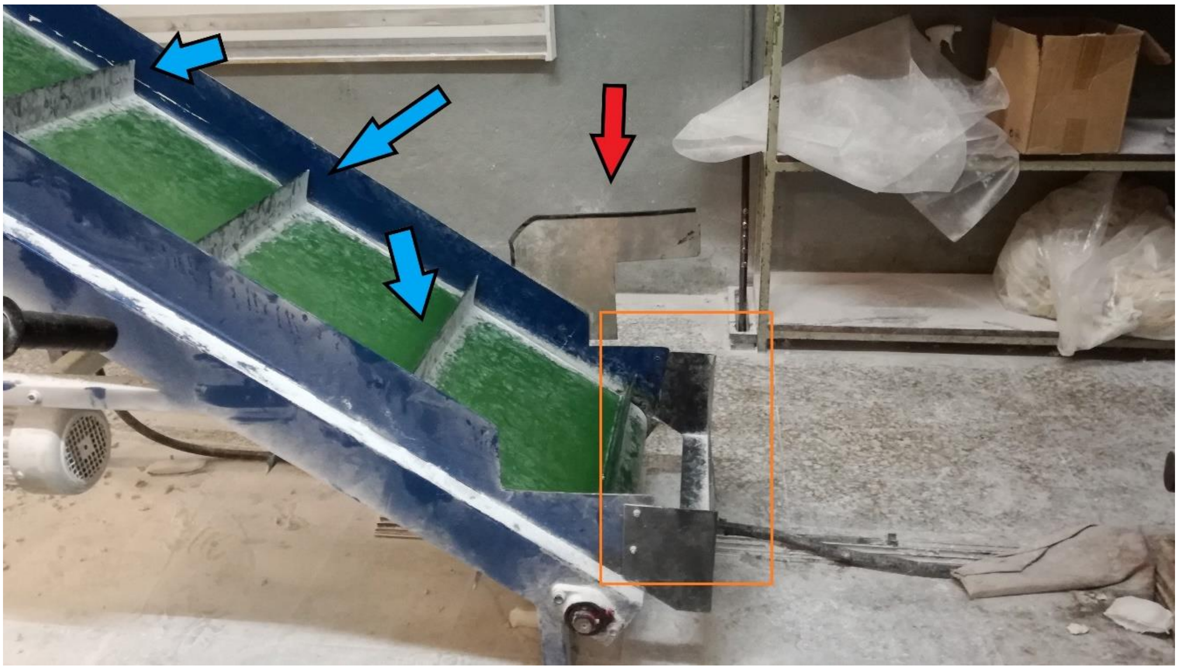

Figure 23 - Preform receiver design flaws

By falling onto the ground, preforms become contaminated because they remain in contact with the floor, thus being considered defects, and must be promptly sent to the reprocessing flow. However, operators tend to ignore this issue, and allow defective downstream in the process. When these contaminated preforms are moulded into soles, they will be promptly rejected due to the appearance of stains in particular areas of the sole, leaving the production order unfinished. A pilot test was performed to evaluate the initial scrap rate for model "PUBLICO SHORT" and it was found to be over 15 percent. Therefore, an initial "stop-gap" solution was designed: a couple of steel plates glued to each side of the preform receiver (shown in red in Figure 23). This temporary solution resulted in a decrease to 6 percent scrap rate. Data for the pilot test was gathered during one day of production for the sample model, before the implementation, and during two days of production after the implemented solution. Scrap rates for other core models during preform production were gathered for the following week of production and are shown in Figure 24. The sum of the amount of preforms for each of these models produced amounts to 80% of total production during the period of time when data was being gathered. A total of approximately 12000 preforms were observed during the observation phase.

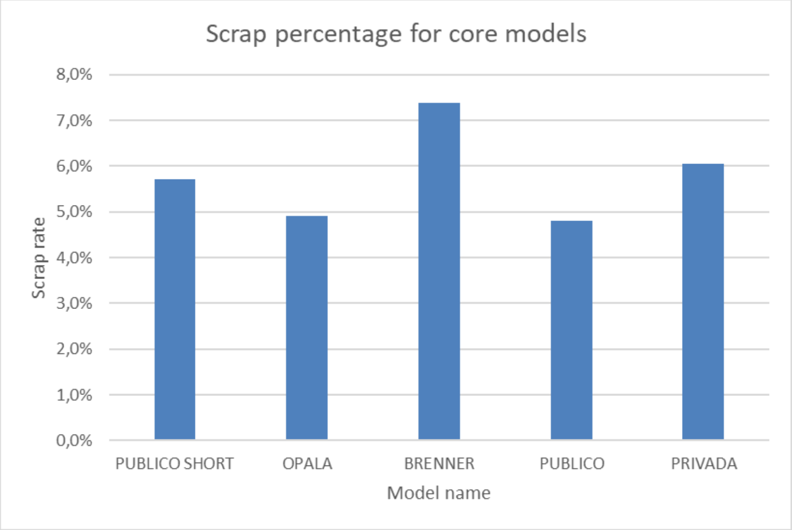

Figure 24 - Scrap percentage in preform production for core models produced in Barwell 2.

At the moment, the three main mixing cylinders do not have the required pace to feed cutting machines at a constant rate. The three machines are assigned to cutting operations in three different ways: The injection cutter produces all kinds of coloured rubber, Barwell 2 produces white-coloured preforms and Barwell 1 produces preforms of all colours, excluding white. Because one of the cylinders is dedicated to producing basic compounds during the first shift, only two cylinders remain to feed three cutting machines. The current practice is to divide Cylinder 2's production for both the injection cutter and Barwell 2, leaving Cylinder 1 for Barwell 1 and the manual guillotine. As such, it is common to find at least one of the machines temporarily stopped due to lack of incoming material. Data on machine downtimes was collected during two weeks for every first shift, thus achieving a considerate sample size (roughly one hundred total instances were recorded).

Machine downtimes were segmented into three categories: maintenance, absence, material. Maintenance refers to machine breakdowns, malfunctioning or standard maintenance procedures. Downtime associated to operators abandoning their workstation to perform activities anywhere else falls into the absence category. Finally, downtimes that were provoked by a lack of incoming compounds from mixing cylinders were categorized as material shortages.

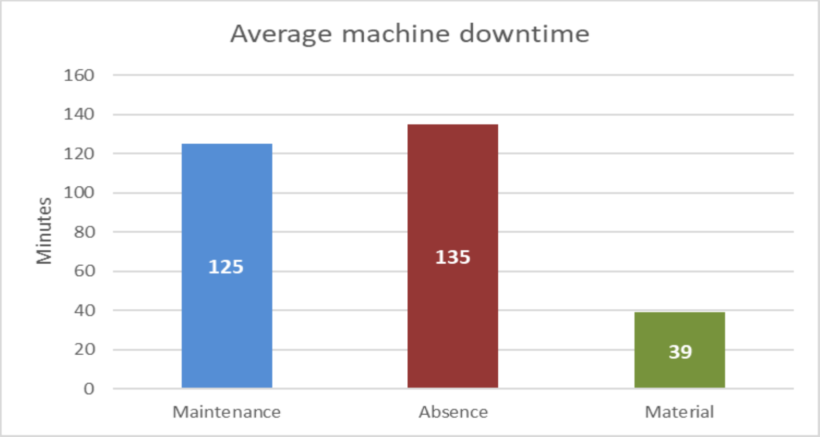

Figure 25 - Average machine downtime organized by category

Figure 25 shows the average downtime, in minutes, due to each category. Maintenance procedures were necessary interruptions in production, although the duration of each was longer than expected due to a lack of planned maintenance instructions. With that said, most maintenance operations were reactive rather than preventive. Time wasted due to absence was inflated in this period due to an unpredictable number of operators not showing up to work for personal reasons.

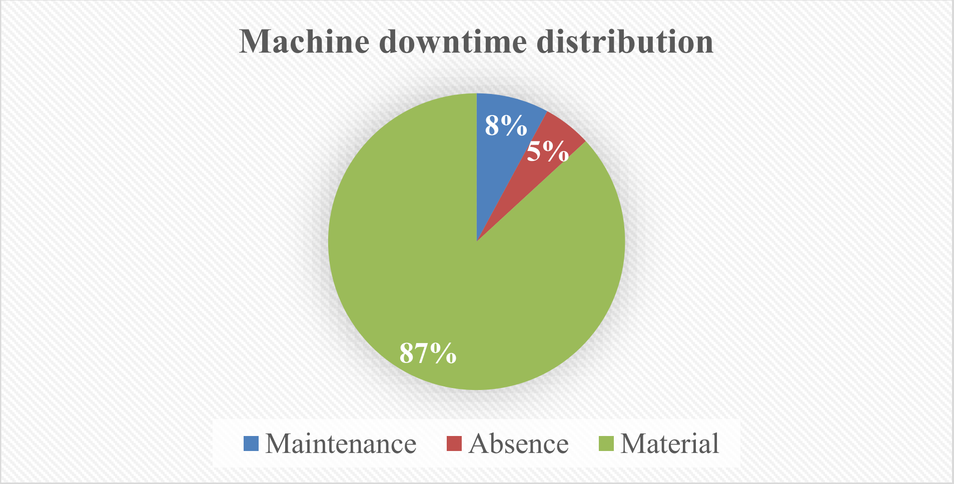

Figure 26 - Distribution of machine downtime categories

The frequency of stoppages distributed by the categorized reasons is shown in Figure 26. Although maintenance and absence had the longest stoppage times, their frequency was minimal when compared to material shortages. In this case, the cut-off time for material shortages was set at ten minutes, which is the average processing time for one compound in the mixing cylinder. Thus, stoppage times that were inferior to ten minutes were discarded in this analysis. Figure 27 shows the average downtime for each cutting machine for every recorded instance of an interruption in production.

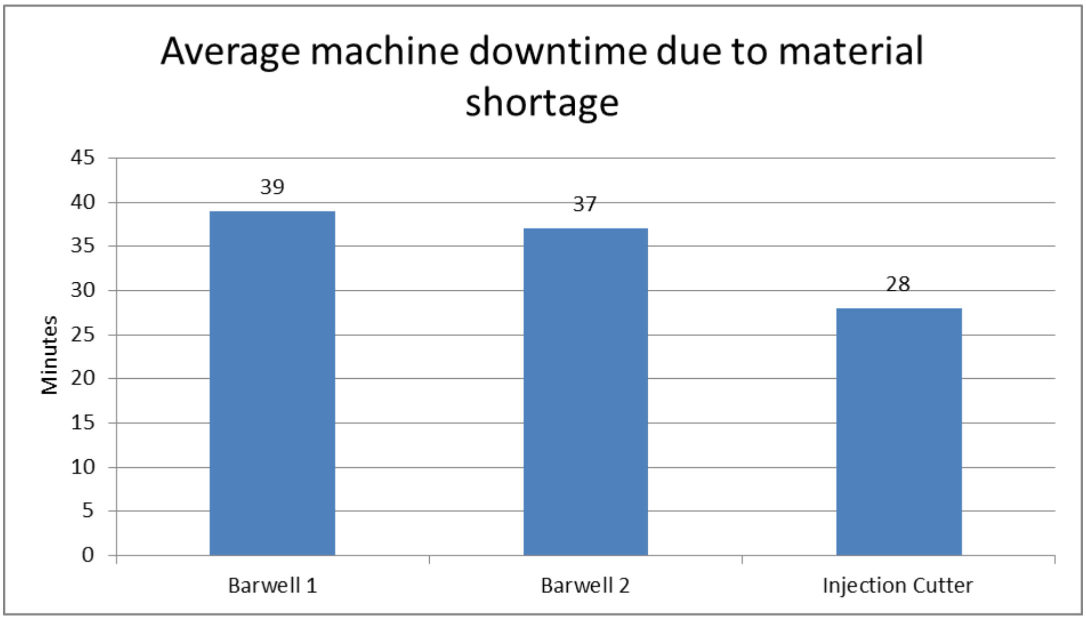

Figure 27 - Average downtime due to material shortage per cutting machine

3.3.2.4 Preform parameters

Without adequate preform shape or weight, moulding machines will produce defects, resulting in incomplete production orders. These orders are promptly rescheduled for the mixing department, further prolonging production lead times. An increase of rework in the unit further delays planned production orders, thus causing the department to fall behind schedule. Two factors greatly influence the amount of rework done:

- The current database has a lot of information gaps on preform parameters. This list must be constantly up-to-date so that operators can insert adequate variables into the preformer's system. Preform weights are only updated when moulding machine operators detect substandard soles and inform shift supervisors, who in turn inform the mixing department, to update the preform database. Furthermore, newer models, which require new moulds, don't have an associated preform weight. In this case, the shop floor application production list for such models will not have any information present, causing the operators to insert random parameters into the machine to avoid any stoppages.
- Both Barwell machines require an initial calibration procedure when the cutting sequence begins: operators weigh the first produced preform on a weight scale that is connected to the preformer's PLC system. If the preform's weight deviates from the target weight, the preformer automatically alters the cutting parameter. The operator repeats this sequence until the target weight is reached. The machine keeps running while the calibration procedure is done, meaning that all preforms which are produced, up until the target weight is reached,

do not meet specified standards. This has a larger impact when smaller production orders are being processed, because a larger percentage of preforms will be produced below the standard.

Figure 28 shows the evolution of compound rework percentages until February 1st. This metric is calculated by dividing the number of reworked compounds by the total production, in units produced.

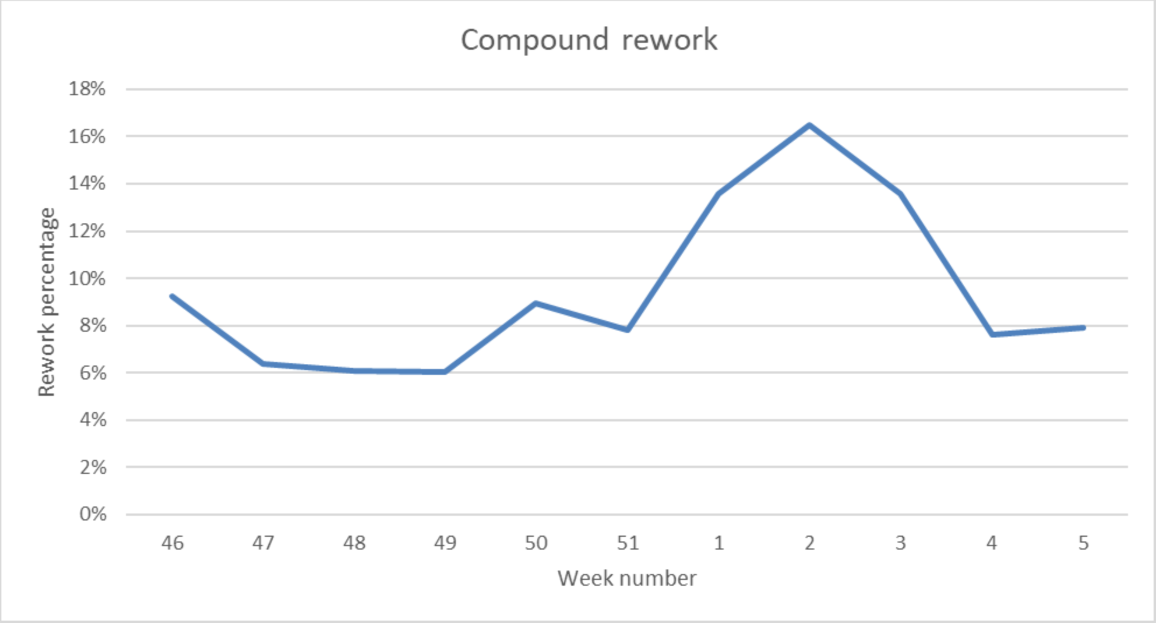

Figure 28 - Daily compound rework percentage

3.3.2.5 Layout

The current factory layout has not been improved in terms of material and movement flow. Figure 29 shows the average movement flow for a common produced compound in the department, where red arrows represent the initial and final movements. As can be seen, compound production flow is fuzzy and disorganized, which incurs in excessive motion, transport and long waiting periods. Starting in the Banbury mixer, basic compounds are mixed, descending to Cylinder 4 and then transported to the table that is nearest to Barwell 1. Compounds are then placed next to the semi-finished product storage area after cooling off. When needed, they are taken to one of the main cylinders, the first being the most frequently used cylinder. The now-coloured compound is taken to the Barwell machine. Noticeably, Barwell 1 is facing the wrong direction, as the product enters on its left side, exiting on the far right, and is finally transported across the unit.

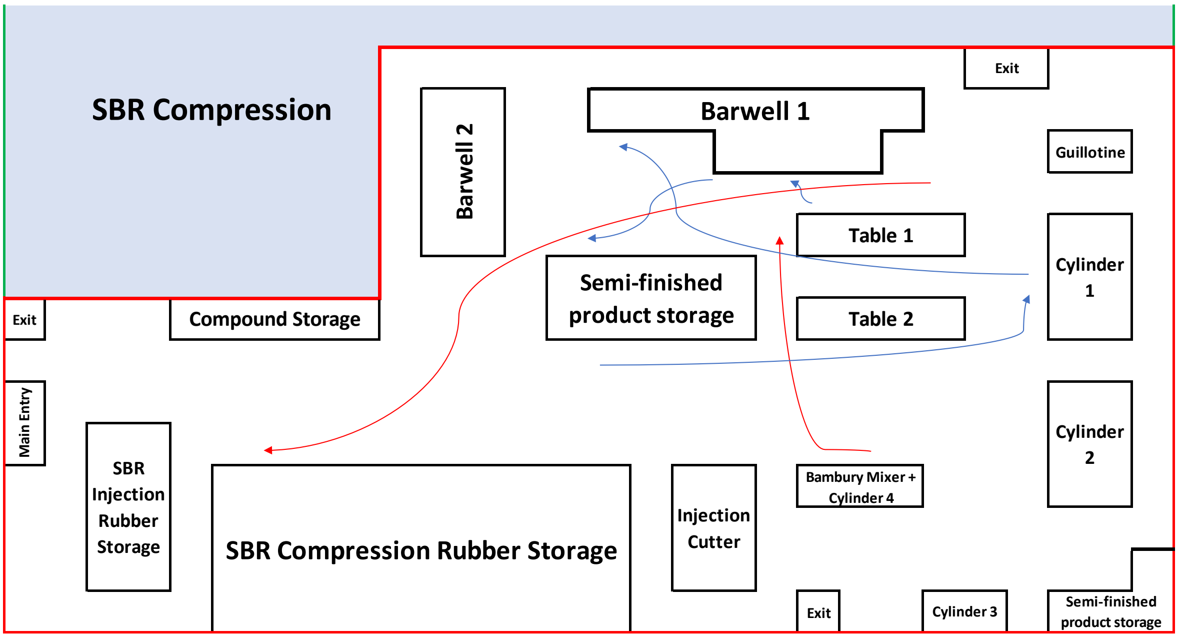

Figure 29 - Average movement flow of a compound

Distances between these points are visible in Table 5. Moving from Table 1 to the Cooling tank requires no movement, as both locations are next each other. Distances were calculated using AutoCAD software, simulating movement paths realistically. Flow is measured in units transported from one point to another. One produced unit corresponds to a full 50kg produced compound. Data was collected during two days of production in November. The global Z value for the current product flow is presented.

Table 5 - Average product flow for SBR Mixing

Banbury Mixer (starting point)	Table 1	Cooling tank	Basic compound storage	Cylinder 1	Barwell 1	Finished rubber storage
Distance (m)	7,1	0	4,2	9	15	25
Flow (units)	130	130	29	70	61	61

∑ Distance (m)	60,3
∑ Flow (units)	480,8
Z	28992

3.4 Implemented solutions

In this chapter, improvement measures that were proposed, and approved by the board, will be presented. The structure from the previous chapter is replicated, with each measure falling into a specific category. Specific metrics that were improved will be presented next to the implementation, whilst general metric improvements will be explained in chapter 4.

3.4.1 Operations

In order to ensure higher mixing cylinder usage and efficiency when producing coloured compounds, task descriptions for each operator involved in this part of the process were redefined. In order for this to be done, one operator in each shift was promoted to shift organizer. The person with this new role was responsible for preparing all pre-work for cylinder operators. This pre-work consisted in transporting basic compounds to the cylinder's side (which was, before this implementation, the cylinder operator's responsibility). Furthermore, shift organizers were responsible for placing mixing components near the basic compounds and ensuring that the right production sequence was followed. This eliminated all excessive movement and transport made by the cylinder operator, ensuring a greater cylinder efficiency. Figure 30 shows the improved operations visualized in the current layout. Basic compounds ready for production were placed in areas marked in yellow boxes. Blue arrows represent the movements made by shift organizers and improved basic compound flow after the storage buffer stage. Additionally, the responsibility of transporting produced compounds from the cylinders to cutting machines was also given to the shift organizer. However, given the number of tasks placed on this operator, transporting every compound is impossible. Therefore, this task was shared between both cylinder operators and the shift organizer.

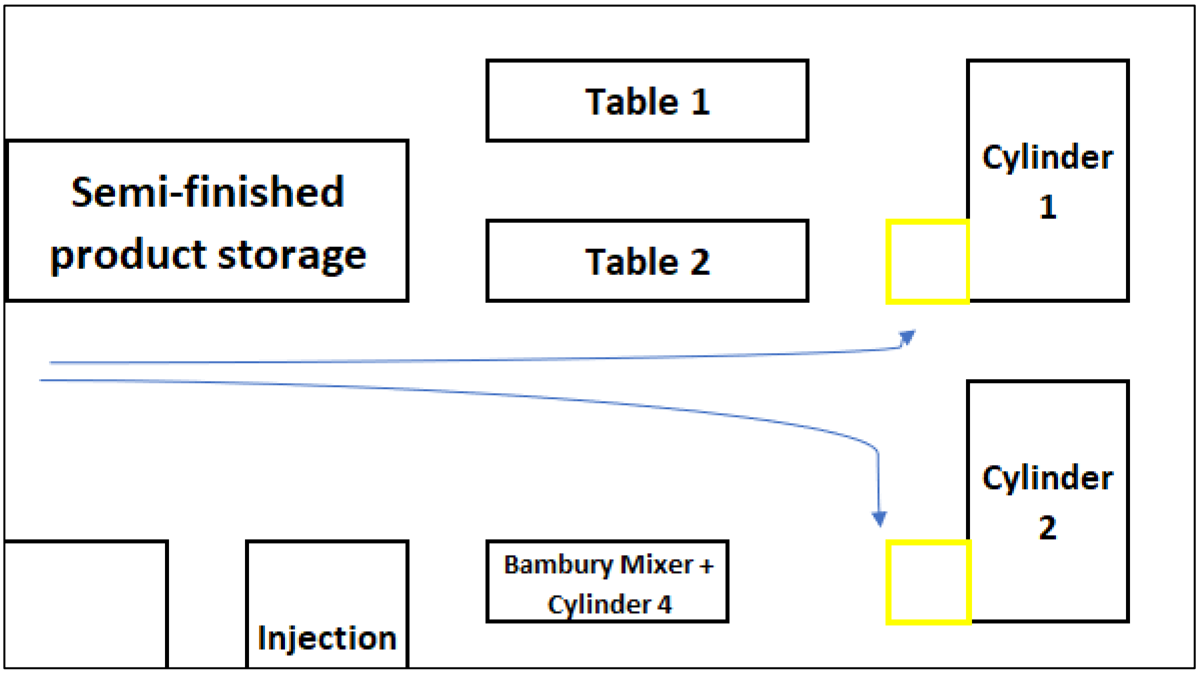

Figure 30 - Mixing pre-work

While this was the most impactful change in operator roles, others had to be adapted in order to maximize cylinder efficiency and compensate the shift organizer's previous role. Specifically, the responsibility for placing preforms in boxes at the end of the preform conveyor was split among

Barwell 1's operator and the person responsible for cutting basic compounds on the work station identified in Table 1 (represented in blue and green arrows, respectively, in Figure 31).

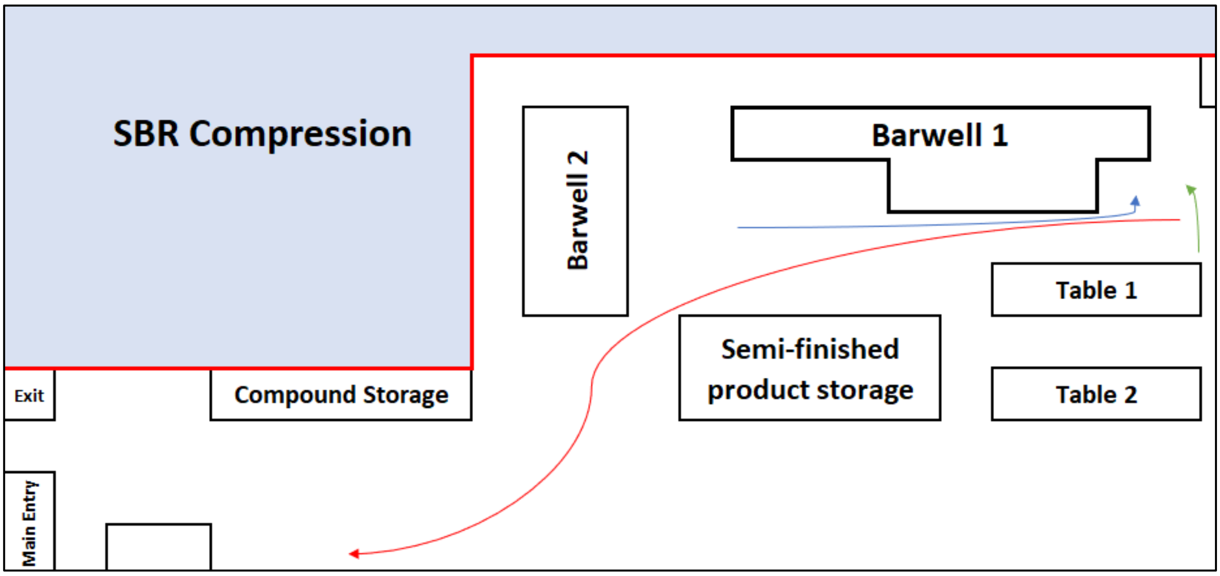

Figure 31 - Preform transport

At the end of a cutting sequence, whoever was idle from these two operators would transport preforms into the storage area (represented with a red arrow in Figure 31). Because both these operators' tasks have smaller cycle times than mixing cylinder production, there are time windows to perform other activities, such as these. Naturally, this required good communication and organization between all three people involved so that there aren't any overlapped activities. The results for this implementation are shown in Table 6. Values before the task reshuffling are compared to cylinder absence times after reorganizing operator tasks. Although there is a significant improvement in terms of usage rage and performance, these values are still suboptimal, considering the implementation had the ultimate goal of zero absence times for cylinder production. This discrepancy is explained by spontaneous events: worker absence was a significant factor during the implementation phase, which prompted the first shift organizer to dedicate time to cylinder production, filling in for absent cylinder workers.

Table 6 - Cylinder usage comparison

Cylinder efficiency		
	Before	**After**
Cylinder 1	01:48:00	00:32:30
Cylinder 2	04:30:00	01:25:00
Observed time	15:00:00	10:00:00
Efficiency	**58%**	**80%**

Both Barwell leftover storage shelf cases were organized by colour code, with each shelf being allocated to a specific colour code. Because some colours are produced more often than others, specific spaces had to be shared among a number of colours. Figure 32 indicates how the storage system for coloured compounds (non-black and non-white) was implemented.

500	500
600	700
600	900

400	800
700	600
900	600

Figure 32 - Coloured leftover storage (regular and opposite side perspective)

The amount of storage space allocated to each colour is proportional to the number of compounds produced per colour code. Figure 33 shows the distribution of coloured compounds produced during the year of 2017, with each element of the graphic associated to the actual colour (e.g. 800 is a yellow-coloured compound while 500 is a red-coloured compound).

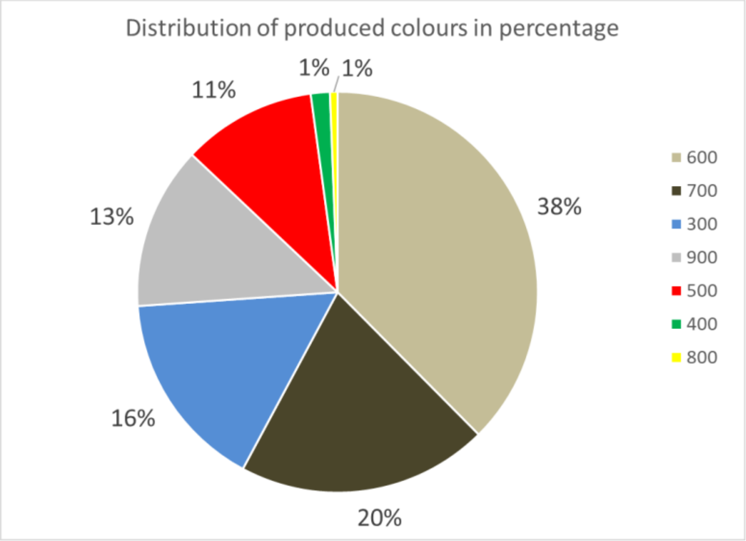

Figure 33 - Produced colour compounds and their distribution

This ensures a faster location of leftovers and better visual management. The same concept was applied to black-coloured and white-coloured compounds, each having their own storage location, although there is much less variety in colour codes in these cases. Whilst in the past, operators had to search for compounds of a specific colour anywhere in the storage unit, now the search range is smaller, making it easier and faster to locate compounds.

To further facilitate this process, a labelling system was created to associate a produced compound to its leftovers. When operators register production after the cutting procedure in the machine's LCD screen, a production card is printed. Following this implementation, operators now manually copy the production card in small pieces of paper card, placing them over the produced leftover. This tracking system provides much needed traceability of preforms to their original compound's leftover. When a compound is rejected by the quality department, all preforms which are stored, waiting for shipment, are identified and reprocessed. However, before this implementation, leftover rubber with the same origin as these preforms was left in the storage unit. Therefore, the risk of using leftover rubber for production could lead to more off-coloured compound production, and consequent reprocessing. This solution eliminates this risk, as leftovers and preforms carry the same identification cards. Hence, both can be separated and made available for reprocessing. Additionally, compounds with expired validity dates are easily identifiable, and separated.

3.4.2 Equipment

Following the success of the temporary solution found for Barwell 2's production problems, the equipment was further improved upon. A modified version of the preform receiver was designed. The number of separators was doubled, so that preforms exiting the machine would not slip into the gap at the bottom end of receiver. The spacing between separators was reduced significantly, as shown in Figure 34, marked in yellow. The material which was used to develop these extra separators (marked in red) was excess rubber from the production process, thus making it a zero-cost investment. Furthermore, new, higher side plates were attached to the receiver (marked in blue). This measure ensured that, when contacting the receiver, the preforms would not rebound to the side and fall out of the equipment entirely.

Figure 34 - Modified preform receiver

Data for this new implementation was gathered following the substitution of the previous receiver. The same five core models were studied during one week of production in February, to ensure greater accuracy in results. As can be seen Figure 35, the implemented solution greatly influenced the amount of rejected preforms, reducing the scrap percentage in all observed core models by nearly half (columns in blue are associated with scrap rates observed after the temporary solution was implemented). However, the chances of further improving the equipment are difficult, as the way it is built does not allow for more improvement actions. The gap at the bottom of the receiver remains the biggest cause for rejected preforms falling onto the ground. Nevertheless, reducing the amount of rejected preforms by half ensures a greater output of completed production orders and a reduction in reprocessed compounds. Workers were also instructed to promptly reject any fallen preform, as opposed to previous practices. A total of approximately 10000 preforms were considered during this observation period.

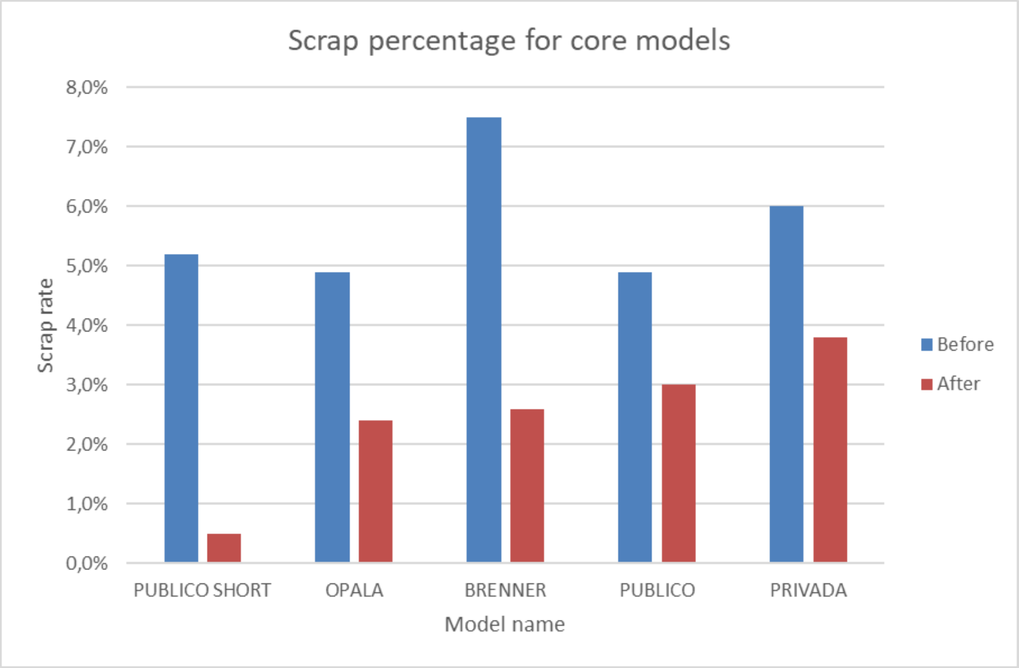

Figure 35 - Barwell 2 scrap percentage post-implementation

In an attempt to reduce the number of reprocessed compounds due to rubber contamination, an action plan regarding equipment maintenance and cleaning was also developed. This action plan consisted of a multi-step process that encouraged autonomous behaviour from collaborators, an increased focus on quality and general work space cleanliness. Prior to this implementation, every machining equipment in the unit was seldom cleaned, as the unit's philosophy was not aligned with these principles. As such, the action plan also served as a means to alter the current mentality of the department.

One of the potential factors for off-coloured compounds stems from rubber contamination, which can be traced to any equipment in the production process. Because machines are rarely cleaned or maintained properly, it is not uncommon to find compounds contaminated with external components to production, such as machining waste formed by residual rubber that is left uncleaned. These factors are also associated to a lack of an existing preventive maintenance plan, as these residues can be detrimental to normal machine functioning. As such, the first phase of the designed action plan was defined as identifying potential contamination areas in every machining equipment involved in compound production. Every equipment identified as critical to rubber contamination will be presented with a brief explanation of the potential contamination cause.

Mixing cylinders are the initial source of rubber contamination and possibly the most critical one, since there is a high variety of components used, as well as a high production output during the day. Produced compounds during the mixing operation are often in contact with the large tray indicated with a yellow arrow in Figure 36. Without proper cleaning, these trays will contain traces of previously produced compounds. The bigger the colour difference between previous compounds and the one currently being made, the bigger the chance that an off-coloured compound will be produced, since these traces can easily integrate the produced compound. As the process continues, the homogenized compound will be affected by the colour of the integrated traces.

Figure 36 - Mixing cylinder and potential contamination areas

The other potential contamination area in mixing cylinders is marked with a red arrow in Figure 36. Gears in the upper cylinders inherently produce residual substances during production. As these residues accumulate during production, the probability of falling into the lower tray rises. When in contact with produced compounds, residues will not homogenize with rubber. However, they will leave a noticeable stain in the compound, thus rendering it unviable for sole production. This is the case for all mixing cylinders, including the one involved in basic compound production (Cylinder 4).

For Barwell 1, rubber contamination areas lie in the extruding mechanism itself and the preform receiver, visible in Figure 37, which offers the perspective of the preformer when idle. The yellow arrow indicates the steel mould cavity that shapes outcoming rubber. Then, the rotating knife indicated with a red arrow produces the preform according to the predetermined shape and volume. The sequence is repeated throughout the production order.

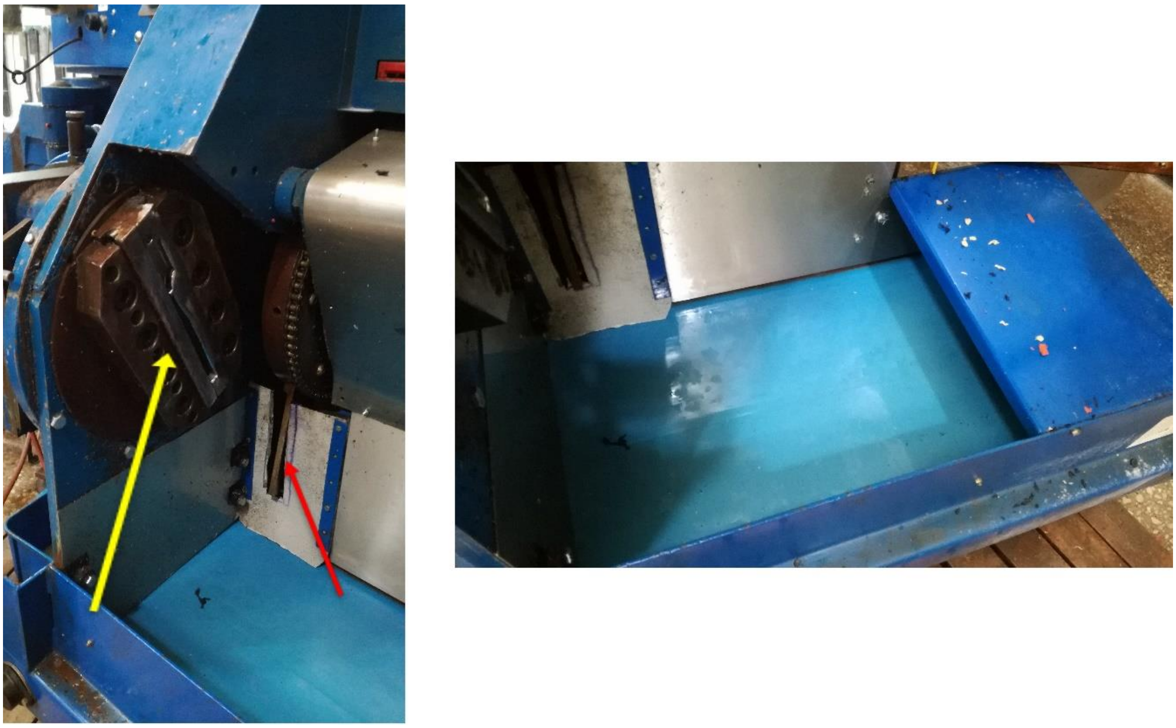

Figure 37 - Barwell 1 contamination areas

As the production order finishes, traces of the extruded compound remain both inside the cavities of the steel mould and on the cutting knife. If not cleaned properly, when producing a new compound, the risk of contamination increases because traces can be homogenized with new preforms, thus altering their intended colour. The second area of contamination in this equipment is the preform receiver, which can accumulate rubber traces and produces rust over time. Preforms that fall onto contaminated areas can experience a change in colour.

Following the cutting sequence, preforms are immediately sent to the closed cooling conveyor. The entrance is formed by a small tank filled with cold water designed to initially cool the preforms before entering the conveyor itself. It is not uncommon to find preforms which did not made their way inside, deep inside the water tank. If the water is not frequently substituted, it will become contaminated with traces from previously produced preforms. Newly produced rubber is in turn contaminated by the water, altering its colour.

Figure 38 - Cooling conveyor entrance

The conveyor belt itself is rarely cleaned, due to its location and the difficulty of reaching it. However, it's a potential source of rubber contamination as well, due to accumulated dust, residues, and rubber that stack up over time.

Following the identification of critical contamination points in the production process, the next phase of the action plan included the definition of machining equipment cleaning practices, and procedures to be followed by operators to ensure the plan is carried out. Cleaning practices were divided into three categories: routine, shift and general. Routine procedures were carried out during the day, between production cycles. Shift procedures refer to activities performed after each shift ended. Finally, specific days were reserved for cleaning purposes in the unit, generally during the weekends or holidays. Both routine and shift procedures are summarized in Table 7.

Table 7 - Cleaning procedures checklist for critical equipment

Equipment	**Routine procedure**	**Shift end procedure**
Mixing cylinders	Before starting production of a new compound, carefully clean the large tray below the cylinders, eliminating any traces of previously produced rubber.	Clean critical areas of contamination near the gear areas and eliminate possible residual substances. Leave the adjacent area to the cylinder clean and organized.
Barwell Preformer 1 (including cooling conveyor)	Before the cutting sequence for a new compound, remove any traces of rubber from the critical contamination areas: steel mould, cutting knife and preform receiver.	Replace the unfiltered water and remove any remaining preforms from the water tank. Clean the adjacent area to the preformer, as well as the external part of the conveyor.
Barwell Preformer 2 (including preform receiver)	Before the cutting sequence for a new compound, remove any traces of rubber from the critical contamination areas: steel mould, cutting knife and preform receiver.	Clean off any remaining dust or residual substances from the preform receiver. Leave the adjacent area to the preformer clean and organized.

Routine procedures were handed out in the form of checklists, with each operator having to sign his name, date and time after each cleaning procedure was made. General cleaning procedures were scheduled for every weekend during the month and were reserved for more lengthy operations such as cleaning the internal parts and components of the cooling conveyor, external cleaning of mixing cylinders and preformers and general cleaning of the work space. Workers were divided in rotating shifts of six, to ensure everyone was involved at some point during the month.

The action plan was designed in January and implemented in February. During January, workers were given instructions and training on equipment cleaning and possible compound contamination root causes. Weekly scheduled cleaning procedures started in the same month. Shift organizers were given the responsibility for managing checklists and weekly shifts, ensuring an autonomous environment.

3.4.3 Preform parameters

In order to avoid additional compound rework, several steps were taken to ensure both Barwell machines produce correct preforms. Firstly, the parameter database was completed by cross-referencing missing preform parameters with older databases which contained them. By doing this and filling missing parameter lines, operators stopped inserting random parameters in the preformers' PLC screens, thus avoiding substandard preforms. Secondly, regarding parameter adjustment, a procedure for preform parameter maintenance was created to ensure the correct weights were being used at all times. Figure 39 describes the preform weight adjusting sequence performed by the weight scale which is connected to the preformers' PLC. The vertical red lines indicate instances where manual adjustments were made by the machine operator.

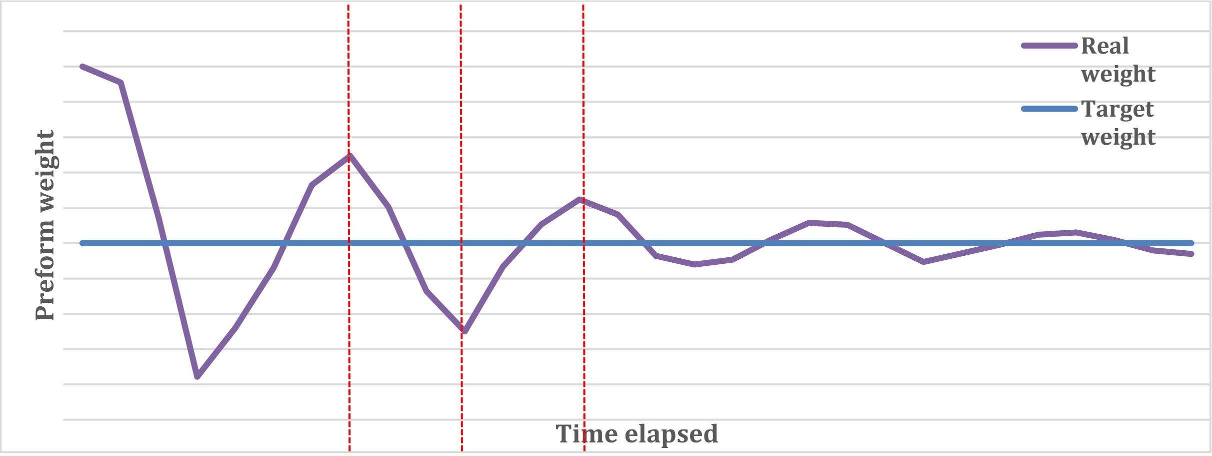

Figure 39 - Weight adjustment machine behaviour

The amount of adjustments needed for the preform's weight to approximately reach the target weight depends on the quality of the initial weight parameter that is set. Thus, the bigger the difference between the target weight and the initial preform parameters, the longer the machine will take to adjust its settings to achieve a given target weight. In sum, it is very important to have a quality initial weight to avoid producing a series of substandard preforms. To solve this, both preformers' operators were instructed to write down the achieved preform weight at the end of a cutting sequence, for a specific model and size. Operators would then insert the written weight and associated machine parameters into the memory slot reserved for the observed model. By doing this, the next cutting sequence for the same model will require less adjustments by the operator given the closeness between the target weight and the initial set parameters.

Finally, a procedure was implemented regarding new sole models and associated preform weights. Whenever a new sole was developed, and its mould created, the operator in the production unit responsible for sole testing became responsible for registering experimental preform weights and shapes. After achieving the best combination of the two for sole production, the operator would be responsible for delivering these registration notes to the production supervisor, who in turn would insert preform parameters into the SAP system, thus ensuring production orders for newly created models would not be generated without preform parameters in the shop floor application for both Barwell Preformers.

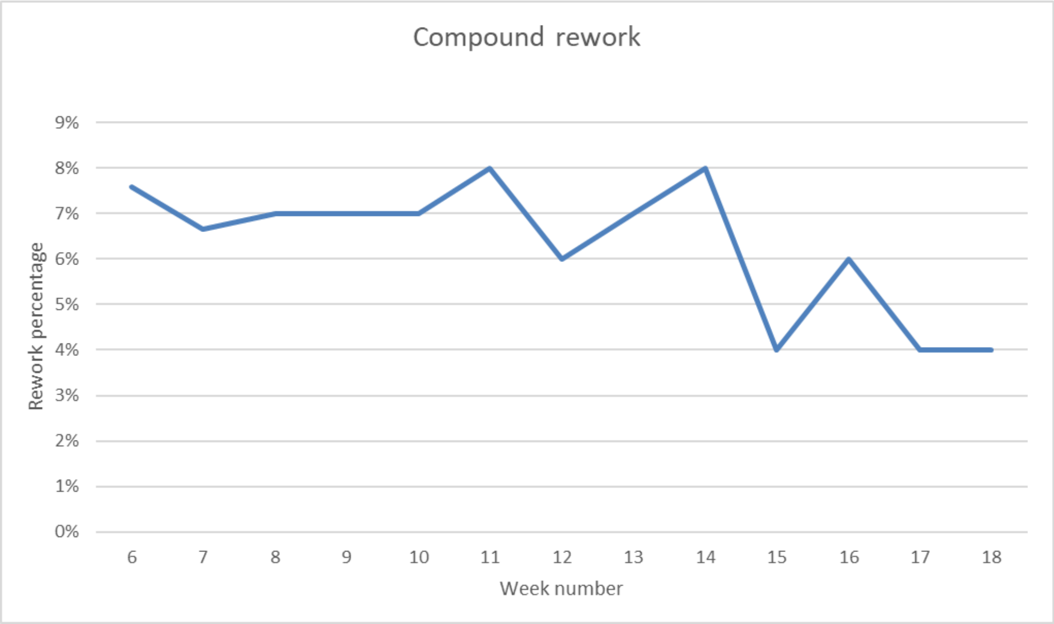

Figure 40 - Compound rework evolution

The evolution of compound rework percentages in shown in Figure 40. This implementation resulted in a significant improvement in this area. Prior to week 6, compound rework percentages fluctuated around the ten percent mark. After week 6, this value decreased to four percent, which represents a major improvement.

By producing preforms in the correct weight for sole production, the risk of substandard sole production in the compression unit is lower, as preforms will fit perfectly into mould cavities without any chance of overfilling the mould. Conversely, preforms below standard weight would cause the mould to exert unnecessary pressure on an insufficient amount of rubber, thus producing a defective sole. Defects can occur in the form of torn or severed areas in the sole. By producing soles with adequate preforms, the number of defected soles lowers substantially. Therefore, production orders are completed, without the need for generating additional rubber needs to compensate for defected soles. The mixing unit then benefits from this, resuming normal production without these additional requests.

Nevertheless, data suggests that there is still a certain fluctuation in the amount of rework done. Firstly, a number of diverse factors play a role in this, being that only one of them was controlled. Secondly, the measures taken to achieve correct preforms are very human-dependent. The bigger the effort made by operators to attempt to control preform parameters, the better the result. As the new procedure for preform control includes additional tasks for Barwell operators and given the number of pre-existent tasks allocated to them, it is expected that the preform control procedure will be gradually set. Furthermore, given the huge diversity in sole models, sizes and weights, the number of variables for preform control are too much to handle on a daily basis. However, it is expected that compound rework will lower in the future, as Figure 40 seems to indicate.

3.4.4 Order sequencing

Regarding daily production, a simple sequencing method was created to allow compounds to be produced in the right order in terms of delivery dates, availability and needs. Whereas in the past colour changeovers would seldom happen for production to run as smoothly as possible, this new order sequencing method generated more changeovers, but more compliance with due dates.

The method consisted of analysing daily production lists for the mixing unit and cross-referencing them with daily production lists for both compression and injection units. Firstly, data on future production orders without available rubber was retrieved, and then grouped by colour code family. Then, the average due date for production orders containing the same colour code family was calculated, for every production order, resulting in the creation of a priority list for families coloured compounds to be produced. Finally, colour codes belonging to the same colour family were ordered by the earliest due date. Therefore, a priority list was created for colour family groups and colour codes within those families. Table 8 is an adapted version of a daily production list which is handed out during morning planning meetings.

Table 8 - Production plan example

Production plan						**01/01/2018**
Workstation	Order nr.	Sole model	Colour	Colour family	Due date	Days to deliver
GC_M1_1	2595619	FANATIC	X120-695	600	02/01/2018	1
GC_M3_1	1207192	PUBLICO V2	E302-700	700	02/01/2018	1
GC_M3_3	1213129	PUB SHORT	K230-830	800	02/01/2018	1
GC_M3_4	1213880	BRENNER	L199-620	600	02/01/2018	1
GC_M3_1	1214956	OPALA V2	B04-201	200	05/01/2018	4
GC_M5_1	1215326	OPALA V3	L100-202	200	05/01/2018	4
GC_M8_3	1215352	PRIVADA	X120-696	600	05/01/2018	4
GC_M3_2	1214904	FANATIC V2	L120-302	300	08/01/2018	7
GB_M2_3	2589673	FANATIC V3	L120-606	600	09/01/2018	8
GC_M3_2	1214951	BRENNER SHORT	L120-700	700	09/01/2018	8
GC_M3_2	1214952	FANATIC SHORT	X120-850	800	09/01/2018	8
GC_M4_3	2600913	PUBLICO SHORT	X120-950	900	09/01/2018	8
GC_M4_4	2600914	PUBLICO SHORT	L160-101	100	09/01/2018	8
GB_M4_1	2599877	OPALA SHORT	L160-117	100	10/01/2018	9
GB_M4_2	2599876	OPALA V2 SHORT	L120-134A	100	10/01/2018	9
GC_M3_4	2600915	PUBLICO V2 SHORT	L180-190	100	10/01/2018	9
GC_M6_3	1210998	FANATIC V2 SHORT	P233-201	200	10/01/2018	9
GG_M2_2	2598698	FANATIC SHORT	P237-788	700	10/01/2018	9
GG_M3_3	2603459	PUBLICOSHORT	P232-720	700	10/01/2018	9
GG_M4_2	2594604	FANATIC	P604-120	100	10/01/2018	9
GG_M5_4	2598705	PRIVADA SHORT	L120-101	100	10/01/2018	9

The second to last column is automatically calculated by adding the average time needed to produce the number of soles from the production order to the present date. Every sole model in the database has an associated estimate production cycle time for one pair. The last column is then calculated by subtracting the due date from the present date. After this, the average delivery due date is calculated for each colour family group, as shown in Table 9. Because one of the mixing cylinders is reserved for white-coloured compound production (compounds with a family colour code of 200), those due dates are not considered in this analysis. Rather, they are analysed separately for each production order requiring a white coloured compound.

Table 9 - Average delivery due time for colour families

Colour family	Average delivery
600	3,5
800	4,5
200	5,7
700	6,8
300	7,0
900	8,0

After ordering delivery due times for each colour from earliest to latest, the production order for colour families is generated. Then, production orders for the selected colour families are carried out in the mixing unit based on delivery dates. The cut-off number for delivery days is 2, meaning production orders carrying delivery times superior to that number are postponed until all priority production orders are completed.

Table 10 - Production sequence for a given colour family

Production plan						**01/01/2018**
Workstation	Order nr.	Sole model	Colour	Colour family	Due date	Days to deliver
GC_M1_1	2595619	FANATIC	X120-695	600	02/01/2018	1
GC_M3_4	1213880	BRENNER	L199-620	600	02/01/2018	1
GC_M8_3	1215352	PRIVADA	X120-696	600	05/01/2018	4
GB_M2_3	2589673	FANATIC V3	L120-606	600	09/01/2018	8

Table 10 shows the production orders from the adapted production plan filtered by the priority colour family. The first two production orders are carried out, since they are due in less than two days. After that, production orders requiring yellow coloured compound production (code 800, the second in the priority list) due in less than two days are completed. The sequence is repeated until the daily production plan is finished. Production orders for white-coloured compounds are treated in the same exact manner, albeit without including the associated family colour code in the priority list calculations.

This is a modified version of batch scheduling. Downstream in the production process, moulds are supplied correctly and in the right order, while still achieving an acceptable number of colour changeovers in the mixing unit. In sum, setup changes are do not increase too much, and compliance with due dates is achieved.

4 Results and discussion

In this chapter, an analysis of the implementations made and their effect on the initial set of metrics will be presented, comparing the initial state and the situation observed at the end of the project. First more general metric improvements will be presented, to have a grasp on the current state as a whole, followed by more specific metrics. Improvements for these metrics also had a direct influence on the first ones.

4.1 General metric improvements

In terms of total output, the daily average for compound production was 132 units produced, from February 1st to May 3rd, as seen in Figure 41. When compared to the production rate in the first observed period (from November 13th to February 1st), daily output was increased by 7 units, which represents a 5% improvement.

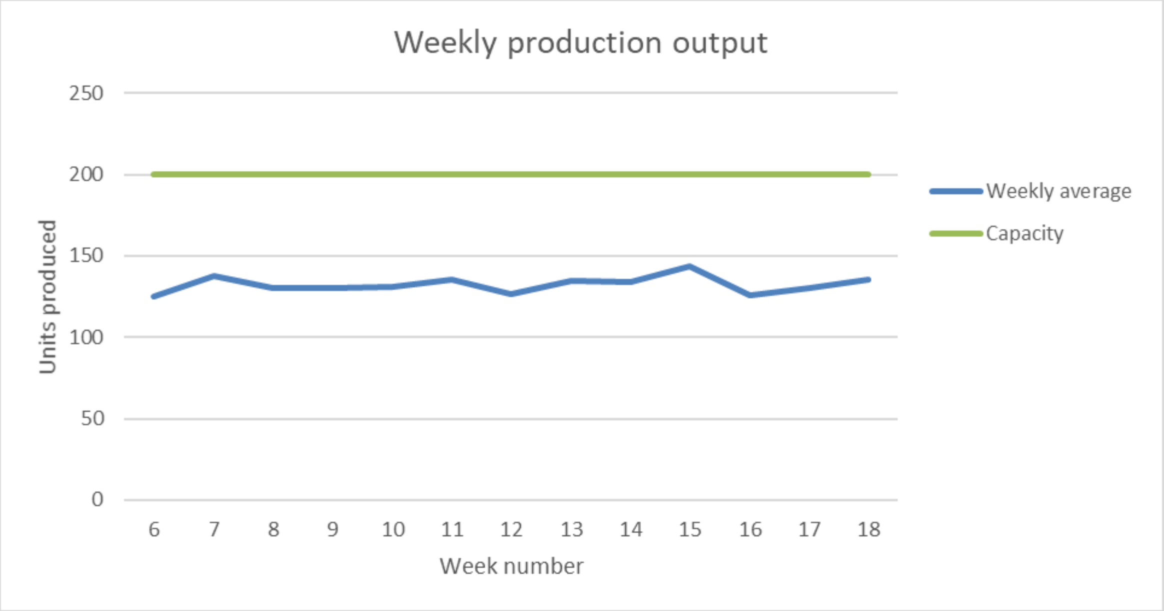

Figure 41 - Weekly compound production evolution

In general terms, all the alterations that took place in the unit did not lead to a significant increase in total units produced but there are several factors that can explain this, however. Firstly, the amount of pending production orders fluctuates during the year, as the footwear sales peak roughly at the end of each civil year, following a slight dip, and a secondary peak in the beginning of the summer. As such, the time period when data was collected during this project was not broad enough to serve as a viable comparison. Furthermore, data on production for the mixing unit was only available from November onwards, meaning that production numbers for the second half of the previous year were unavailable to perform an historical comparison.

Nevertheless, improvements were far more noticeable in other areas. Most notably, material shortages in moulding machines for both compression and injection units became shorter in duration, as can be observed in Figure 42. Whereas prior to the implemented solutions material shortages were frequent and rising due to pre-existent problems in the unit, the average machine downtime decreased over time, as every implementation started taking place. Better sequencing in the mixing unit had a major role in this, as production lists started being produced in a predetermined order, rather than in a random way. As such, the sequencing method prioritized batch production for compounds in an improved sequence. This also partially explains the small level of improvement in total output for the mixing unit, as more daily colour changeovers took place in this time period.

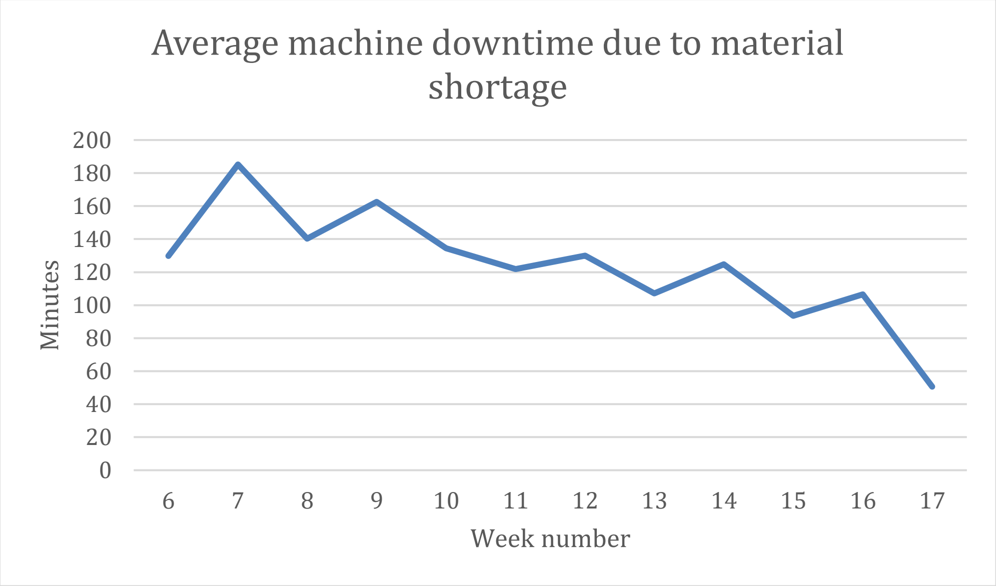

Figure 42 - SBR C/I machine downtime evolution

Basic compound WIP presented itself as a major problem in the unit, due to the implications in terms of available work space and movement difficulty, along with added stock retention costs. From the moment the basic compound is produced until it is used in intermediate compound production, it is considered work-in-progress material, as it is not a finished product nor a consumable one. Therefore, it was important to lower its values to improve flow within the unit. Figure 43 shows the evolution of basic compound WIP values since the start of the year. With a better production control and a feasible visual management system, a significant improvement was achieved, with the exception of a small uptick visible in the month of April. As of May, the total WIP amount for basic compounds was 10.000kg, which represents a 50% reduction since January.

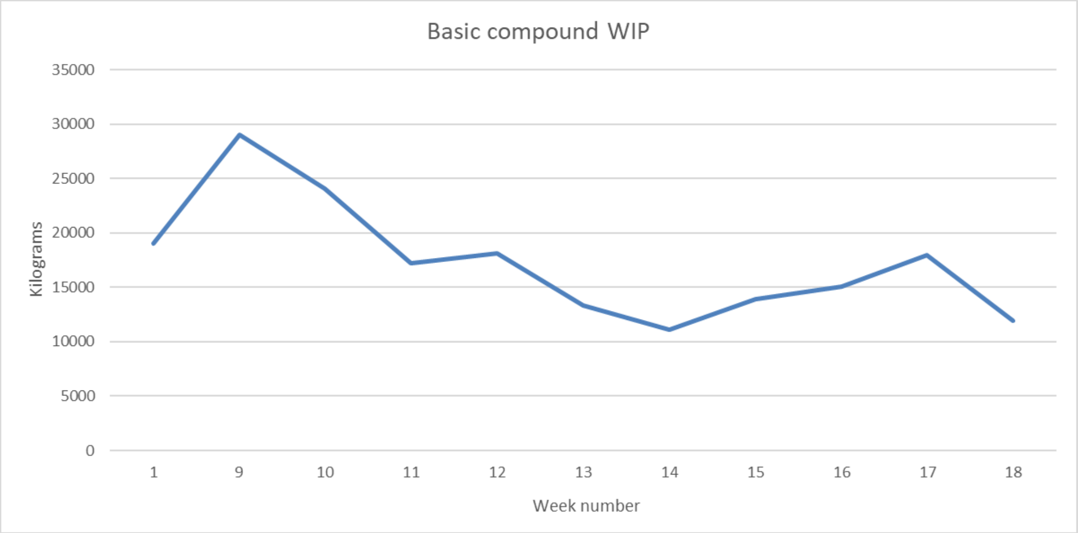

Figure 43 - Basic compound WIP evolution

Compound reprocessing was also an area with signs of improvement. Whereas the average percentage for reprocessed compounds from total production, from week 46 to week 5, was nearly ten percent, this figure lowered to 7,7%, which is a 2,3% decrease. Considering the observed daily output for compound production, this reduction in reprocessing percentage represents a decrease in four daily reprocessed compounds, meaning that the unit's production capacity was used for producing four additional compounds. Figure 44 shows this metric's improvement over the course of the second observed time period. Although there is a noticeable decrease over time, the mixing unit experienced a significant increase in reprocessed compounds from the ninth week until the twelfth. Although a number of factors is involved in this, the most reasonably explanation lies in the fact that this was the time period with the most varying colour production. A more diverse set of production orders in terms of coloured compounds were generated in this time frame, which coincides with sole production for the summer season, where demand for shoe sole colours is more disparate, in contrast with autumn and winter season colours – black, beige and grey. As such, an additional strain is placed on coloured compound production, with more precise formulas for component weighing, and a higher requirement for accuracy in mixing cylinder production. Additionally, this is also the time period where clients place more orders for prototype soles, meaning new colours are created and refined in these cases. As the refining process is made from scratch for new colours, it is hard to come up with the perfect formula for a new coloured compound, meaning the chances that compounds for these colours in production are rejected by quality standards are higher.

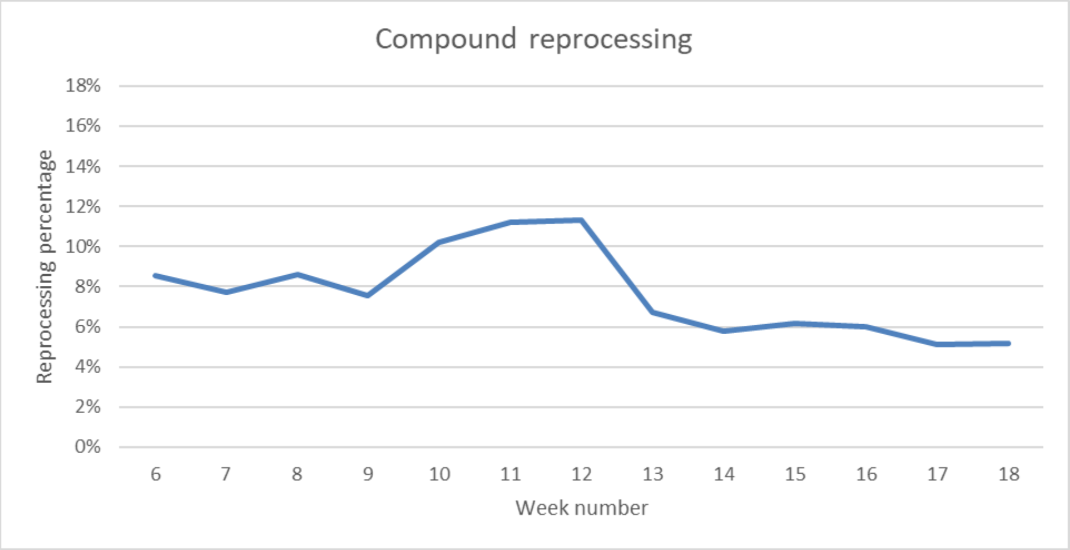

Figure 44 - Compound reprocessing evolution

In terms of reprocessing categories, the amount of off-coloured compound production decreased in about twenty percent, as observed in Figure 45. The reason for this decrease lies within most implementation targeting this category. By introducing a preventive maintenance culture with an emphasis on regular machining equipment cleaning and contamination avoidance, the risk of producing compounds with variations in the intended colour lowered. Furthermore, efforts were made to create a system where off-coloured compounds were easily traceable back to leftovers, thus eliminating them from the process altogether. It was important to prioritize decreasing the number of off-coloured compounds, compared to the other two categories. This is because the time spent refining colours in the process is much higher than time spent treating slow or over accelerated compounds. Whereas these are easily treatable by adding components such as accelerators or retardants, colour refining requires a lengthier procedure, and is more of a trial-and-error method. By partially eliminating off-coloured compounds, normal production is resumed and compliance with production due dates is achieved.

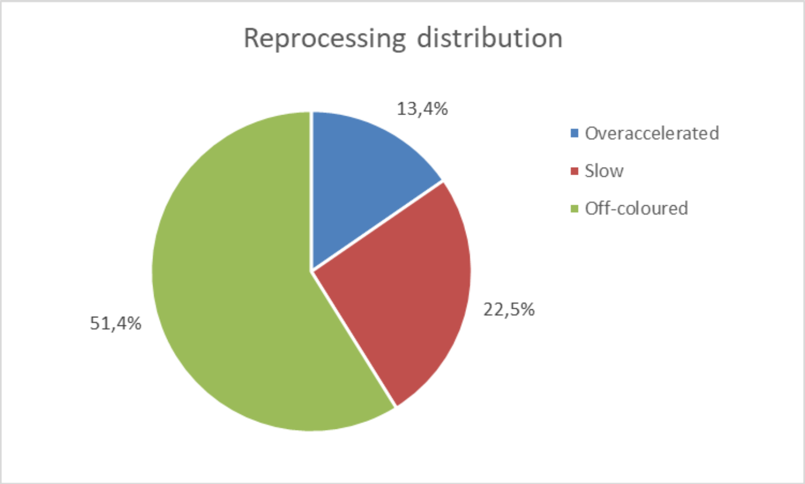

Figure 45 - Reprocessed compounds by category

4.2 Future implementations

In this chapter, solutions that were proposed to the board, but could not be implemented due to time or resource constraints, will be presented. As there are no practical results to go with the solutions, a cost-benefit analysis will follow each one to have a grasp at the return on potential investments.

4.2.1 Reprocessing

To further improve the unit's performance in terms of reprocessing percentages of total production, two different scenarios were created around two investment opportunities that complement current practices and procedures.

4.2.1.1 Scenario A – Colorimeter

A portable colorimeter, pictured in Figure 46, is a handheld colour-measuring device used in manufacturing, design and quality industries, whose function is to eliminate colour analysis subjectivity. It measures coloured objects in the CIELAB colour space to a high accuracy degree. Then, by comparing measured values to pre-set ones, a certain colour can be analysed by comparing the resulting delta E value and its tolerance. The device is usable in the rubber industry, and in this project's case, specifically by analysing produced coloured compounds immediately after being produced in the mixing cylinder being applicable to all colours.

Figure 46 - Portable colorimeter (source: Hach USA)

Its use would require a slight change in the production process, albeit an important one. As seen in Figure 47, the colorimeter would be set between mixing and cutting operations. After an operator produced an intermediate compound in one of the cylinders, he would then have to operate the colorimeter on the compound, thus reading its L*a*b colour values, akin to the current procedure in the quality department. After doing so, the operator would insert the resulting values in the shop floor screen next to the cylinders, before selecting the produced compound from a dropdown list. The values would be compared to the pre-set ones, thus creating a term of comparison. The resulting delta

E value from the comparison, together with the delta E tolerance limit defined for each compound colour, would indicate whether the compound was approved or rejected, and sent for reprocessing. This immediate quality control in the earlier stages of the production process allows a quicker response to reprocessing operations, saving unnecessary time spent on future operations.

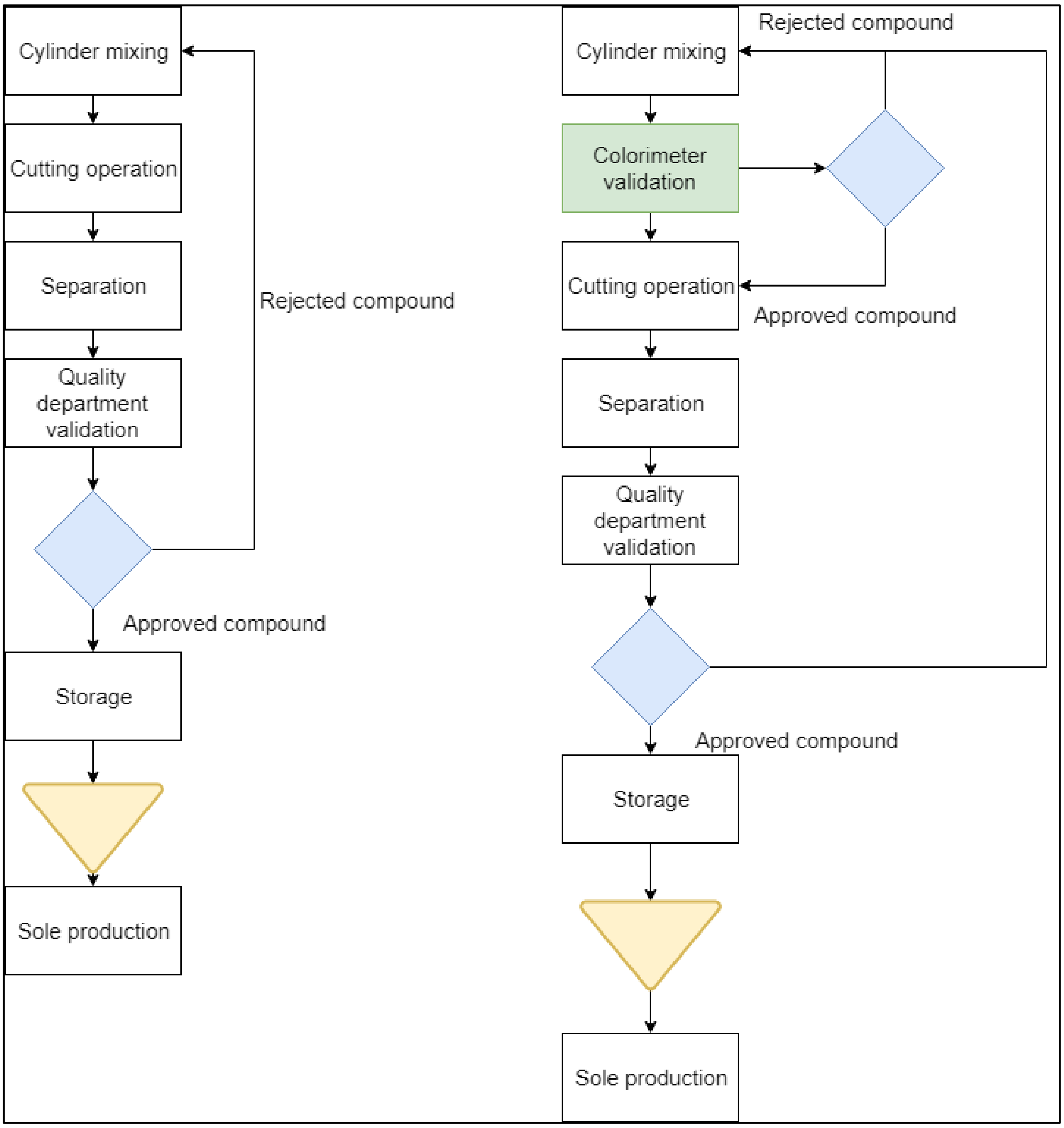

Figure 47 - Colorimeter process change

The return on this investment was then quantified. Firstly, the non-quality cost of reprocessing intermediate compounds in the unit was calculated (Equation 2). Only off-coloured compound production is considered. Dividing daily minutes available in a work day by the number of daily reprocessed compounds resulted in the average time spent reprocessing one compound. Then, the non-quality of one reprocessed unit was obtained by multiplying this value by the operations cost during one minute for the mixing unit. Multiplying this number by the number of daily reprocessed compounds results in the daily non-quality cost for compound reprocessing (Equation 3). Non-quality costs were calculated for the improved process, using new lead times by factoring in the colorimeter in the production process. Table 11 shows the current lead time production times for one intermediate compound. Data on this study was gathered during one week of production in order to obtain an approximate estimate of the exact lead times for production. The average time spent reprocessing one unit in the new process is obtained by simply subtracting the accumulated production lead time until the validation operation from the average time in the current process. Thus, Return on Investment (ROI) is calculated by subtracting daily non-quality costs for the new process from the current one (Equation 4).

Table 11 - Intermediate compound production lead time

Production Lead Time (1 unit)	
Cylinder mixing	00:04:00
Cutting operation	00:05:30
Order separation	00:05:00
Validation	00:20:00

Further gains are obtained by factoring in extra production that results from less reprocessed units. The calculations used to quantify the returns on this investment are listed below, while the projected ROI is presented in Table 12. The investment would be paid off by the end of the seventh month.

$$Reprocessing\ cost = SBR\ Mixing\ operating\ costs/\min x\ average\ reprocessing\ time\ in\ minutes \tag{2}$$

$$\text{Daily RP cost} = \text{RP cost x number of daily reprocessed units} \tag{3}$$

$$ROI = Daily\ RP\ Cost\ (colorimeter) - Daily\ RP\ Cost\ (no\ colorimeter) + extra\ production \tag{4}$$

The device requires an initial investment of €7000,00 and a yearly maintenance operation that costs approximately €1200,00 which is included in the monthly ROI table. ROI calculations exclude additional cost savings in machining equipment and decreased holding costs, as these were far less feasible to calculate. Extra production costs were firstly calculated by multiplying the amount of extra produced compounds by the average number of pairs produced with one compound, and then multiplying that value by the sales margin value for each produced pair.

In terms of layout and positioning, the colorimeter station would be placed between the three main mixing cylinders, to ensure improved movement flow for both operators and transported compounds. Training sessions would have to take place in order to inform workers on how to operate the device. Furthermore, the database for L*a*b colour values would have to be constructed for each coloured compound in the unit's database. Finally, the involvement of IT in this process is required to develop a shop floor module that calculates delta E tolerance limits based on the inserted values after each colorimeter reading.

Table 12 – Colorimeter ROI

Month	Net value
0	-7 000,00 €
1	-5 840,108 €
2	-4 680,215 €
3	-3 520,323 €
4	-2 360,430 €
5	-1 200,538 €
6	-40,645 €
7	1 119,247 €
8	2 279,140 €
9	3 439,032 €
10	4 598,924 €

4.2.1.2 Scenario B – EVA bags

These bags, pictured in Figure 48, also known as batch inclusion bags, are a popular choice in the chemical, rubber, food and ice industries. They are made of thin plastic that melts at low temperatures, allowing the inserted ingredients to be dispersed at the right time in the right amount.

Figure 48 - EVA bag (source: Modwrap)

In rubber compound production, EVA bags are usable for small component weighing. By including all ingredients inside one bag, they are guaranteed to be dissolved in the cylinder mixing process, when mixed with basic compounds, thanks to the plastic film's properties. Thus, a uniform mixture is ensured, and the chance for off-coloured compound production is lowered. Furthermore, operators working in mixing cylinders are far less exposed to potentially harmful chemicals and other ingredients included in compound production, since these will be in a closed environment, inside the bag.

In this case, the return on investment is calculated according to the decrease in percentage of reprocessed compounds from total production that stems from the usage of EVA bags. Two bag sizes are considered, one for smaller components and another one for bigger components.

The calculations are set in the same way as in the previous scenario: non-quality costs in the initial state vs. non-quality costs in the future state. For this scenario, however, the projected future state is based on setting objectives for the mixing unit. These objectives are based on decreasing the percentage for reprocessed compounds. Projecting these goals, considering a decrease in reprocessed compounds, the non-quality cost will be lower, thus lowering the daily reprocessing cost. Using Equation 3 and 4:

$$ROI = \ Current\ daily\ RP\ cost - objective\ daily\ RP\ cost + extra\ production \tag{5}$$

Gains from extra production are calculated in the same way as Scenario A. In sum, the better the performance of the mixing unit using these bags in terms of reprocessed compounds, the bigger the return. Two short-term goals were set: 5,5% and 5% of reprocessed compounds from total compounds, and a long-term goal was also set at 3,5%. Goals were defined as feasible and tangible for the unit.

The amount of EVA bags needed was calculated at 3000 small-sized bags and 6000 large-sized bags per month, based on the current production rate. Considering that the minimum order amount for the selected supplier is set at 20000 small-sized bags and 35000 large-sized, each with a minimum order cost of €2800, the unit would need a biannual supply to keep up with the current production rate.

Table 13 - EVA bags ROI based on goals

Month	5,5% RP	5% RP	3,5% RP
0	-5 600,00 €	-5 600,00 €	-5 600,000 €
1	-4 420,87 €	-3 969,605 €	-2 528,452 €
2	-3 241,75 €	-2 339,209 €	543,097 €
3	-2 062,62 €	-708,814 €	3 614,645 €
4	-883,50 €	921,581 €	6 686,193 €
5	-2 504,37 €	-248,023 €	6 957,741 €
6	-4 125,25 €	-1 417,628 €	7 229,290 €
7	-2 946,12 €	212,767 €	10 300,838 €
8	-1 767,00 €	1 843,162 €	13 372,386 €
9	-587,87 €	3 473,558 €	16 443,935 €
10	591,25 €	5 103,953 €	16 715,483 €

Table 13 presents the potential returns on the investments made in EVA bags, according to each set goal. In the worst-case scenario, the investment is returned after 10 months, whereas considering the most optimistic scenario, there is a payback only after two months. The negative ROI on the fifth and sixth months are explained by the required biannual reinvestment made in EVA bags to keep up with compound production. After the sixth month, the projected returns thanks to quality production will outweigh these reinvestments for future periods.

Table 14 presents a summary of both scenarios in terms of initial investments, recurring investments (maintenance for scenario A) and the associated payback for each. Both scenarios are worthwhile investments, although scenario A can be found more feasible and with less risk involved, since it is not dependent on any performance metrics, as is the case in scenario B.

Table 14 - Summary of investments

Scenario	Initial investment	Recurring investments	Goal (RP%)	Payback (months)
A - Colorimeter	€7000	€1200 per year		7
B – EVA bags	€5600	€5600 every 6 months	5,5	10
			5	4
			3,4	2

4.2.2 Layout

An improved factory layout was developed with the intention of improving product and operator movement flow, while still maintaining the unit's functionalities and machines. The current layout was deemed too disorganized, while the proposed one was more process-oriented. As can be seen in Figure 49, flows are much more linear and simple, as compared to the previous ones. Red arrows indicate the average movement flow of a produced compound similar to the one shown in previous chapters, while the blue arrows represent a parallel average production flow for a different compound.

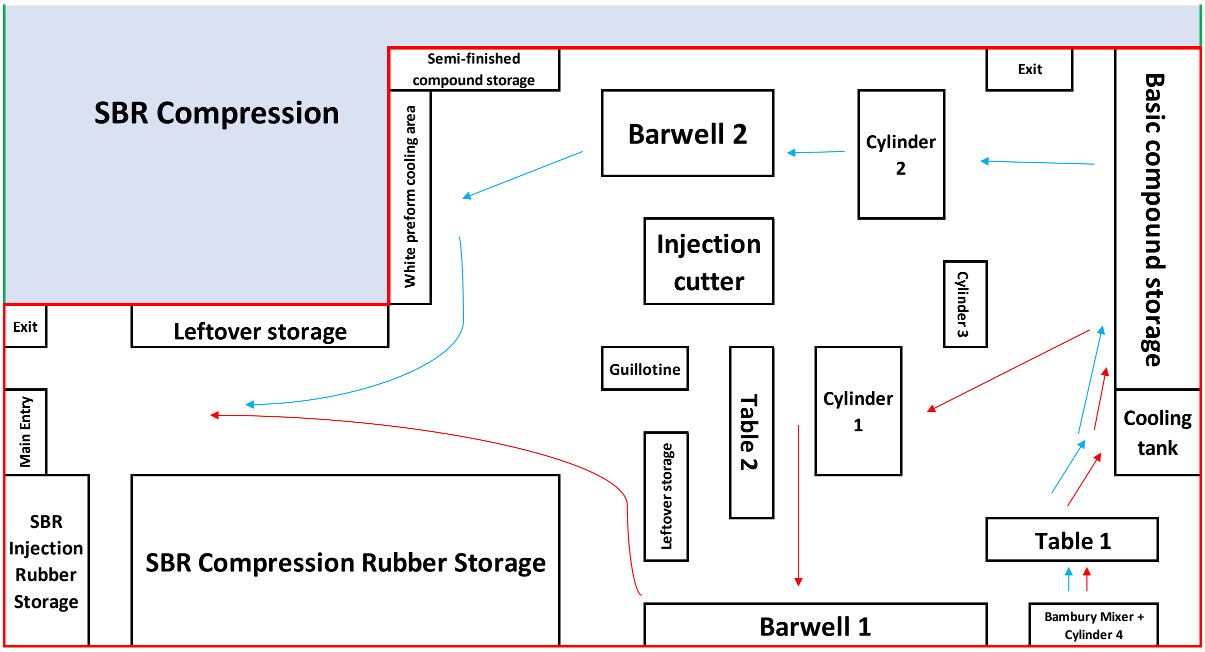

Figure 49 - Proposed new layout

Significant changes would need to happen, however, for this layout to be considered. Firstly, a new area for basic compound storage would be created, instead of storing basic compounds all around the factory, as in the current state. Secondly, almost every machining equipment would be moved from their current location. Because of the size and weight of these machines, moving them would present a somewhat difficult and costly operation. However, the layout change would bring several benefits. For starters, basic compound WIP would decrease drastically thanks to a dedicated storage area with a proper visual management system and a FIFO storage system in place. Distances travelled by operators would also decrease due to the process-oriented placing of machines. Furthermore, more open space obtained in this new layout would lead to a cleanlier work area. Table 15 shows the comparison between the current layout and the proposed one for the average flow of a produced compound.

Table 15 – Product flow for proposed layout

Banbury Mixer	Table 1	Cooling tank	Semi-finished product storage	Cylinder 1	Barwell 1	Finished rubber storage
Distance (m) - new layout	2,8	1	5,7	12,9	4,3	11,5
Flow (units)	130	130	29	70	61	61

∑ Distance (m)	38,2
∑ Flow (units)	480,8
Z	18367

The distance travelled in the new layout for the produced compound is over forty meters less than in the current one. Using Equation 1, and assuming unit-cost value, c_{ij}, is equal to one, the plant layout cost is decreased by 36% using the new layout proposal, by comparing the Z value for the new proposed layout with the one presented in Table 5. It is worth noting that this is the estimate for one example of a produced compound’s flow. Considering the remaining parallel flow of compounds that are produced simultaneously, the cost function would be reduced even further.

5 Conclusions and future work

This chapter's intent is to analyse the work's output in terms of comparing predefined objectives with the results that were observed over the course of the project's duration. Furthermore, future implementations that could benefit the company's long-term goals are included.

5.1 Main results

In this work, lean manufacturing tools and principles were studied and applied in a rubber processing unit for a sole production company. After extensive research, the most comprehensible tools were used to improve the unit as a whole. Furthermore, basic sequencing methods were used to improve due date compliance for internal clients' production.

The project's main objective was to come up with short-term solutions that could improve work flow in the production unit and reduce WIP, manufacturing waste and production costs. In general, all the types of waste included in this work's literature review were approached from an analytical point of view and dealt with by implementing cost-efficient measures.

The unit's current state was firstly diagnosed by calculating its production capacity and comparing it to the daily production output. By doing so, the unit's performance at its current state was measured. Since the unit works as an internal supplier to two other production units in the same company, a performance indicator that connected both production departments was presented. Thus, not only the unit's performance was shown, but also the effects it has on downstream processes. Following this performance study, the unit was studied from an operational process point of view, from the initial raw material weighing operations, all the way to the internal supply station. Data on parameters influential to the unit's performance was gathered, such as rework and reprocessing percentages from total production. They were then documented and improved upon with specific measures. Furthermore, basic operational processes were studied by analysing movement and product flow. Potential bottlenecks in the unit's operations were very diverse, hence the use of several different improvement measures.

Implementations were subject to the director of operation's approval, as well as the board's. Therefore, not all improvement measures were put into practice due to either time or resource constraints. The departure of the IT's main shop floor programmer played a significant role, as some of the proposed improvements had an IT component to them, by linking the company's SAP database to the production unit.

Nevertheless, several improvements were made to the unit. The amount of reprocessed production units lowered substantially due to the implementation and fostering of a preventive maintenance culture that emphasised work space and machining equipment cleanliness. Rework was also lowered, by implementing a preform weight control procedure. WIP in the unit was controlled by creating a visual management system and product location procedure. Finally, basic sequencing methods were used to ensure the unit supplied both production departments in the necessary order according to daily needs. In general, the unit was improved from a quality and organizational point of view.

However, daily output still fell short of the unit's capacity, and should be subject to further improvements.

5.2 Future work

Although some of the set objectives were achieved, much is left to improve in the unit:

- The factory's layout is disorganized and subpar in terms of product flow, available space for movement, machine placement, resulting in a substantial amount of waste in terms of transport and waiting times. A new layout was proposed, with signs of significant improvements in cost reduction. However, it is still subject to the board's approval, due to the difficulty and complexity of moving large-sized machines.
- Leftovers produced from cutting operations are now controlled, but still lack a connection to the shop floor application and SAP's database. By doing so, leftovers will easily be located and removed upon the rejection of a given produced compound by the quality department.
- The preventive maintenance culture procedures can be further improved by including the company's maintenance department. This is an important measure to ensure machining equipment is functioning in perfect conditions, thus avoiding potential breakdowns and malfunctioning. This measure would complement current regular cleaning practices.
- Reprocessing can be tackled by implementing either a colorimeter or EVA bags in the unit, or even both. The projected ROI from these improvements are shown to be positive, although there is a certain risk associated to EVA bags since they are objective-based, unlike the colorimeter's process change.
- Automating the used sequencing method is important to ensure better results and due date compliance. Creating an algorithm that uses due dates, production lead times and customer delivery dates as inputs, whilst taking into account different variables in production such as setup changes, could prove beneficial in this regard.
- Teamwork and worker motivation influence the outcome of the unit in terms of performance, as most activities require collaboration between two or more operators. Thus, instilling a friendly, well-spirited work environment is key for the unit to succeed. Extracurricular activities and team building exercises are potential sources of improvement in this area.

In general, the project was successful. Key improvement areas were tackled and dealt with, showing a significant effect in performance indicators. All improvement measures were well received and implemented with no resistance from all parties involved. Furthermore, future implementations were seriously considered for the near future.

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