Analysis and Improvement of a Rubber Agglomeration Manufacturing Process using a Discrete Event Simulation Model

Ricardo Campos Maia

Dissertação de Mestrado

Orientador na FEUP: Prof. Mário Amorim Lopes

Orientador na empresa: Mike Bain

U.PORTO
FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

Mestrado Integrado em Engenharia Mecânica

2017-06-23

Aos meus pais

Resumo

Um aumento da concorrência global, aliado a níveis de consumo cada vez mais altos, aumentou a necessidade das empresas em produzir produtos em maiores quantidades, com melhor qualidade e em espaços de tempo mais curtos. Desta forma, é necessária a adoção de estratégias que permitam obter níveis mais altos de eficiência.

O projeto foi realizado numa linha de produção de cilindros de borracha, cujo objetivo principal se baseou na análise e melhoria do processo produtivo recorrendo a uma ferramenta de simulação. Estando a ferramenta criada, foi possível estudar a reengenharia do processo experimentando várias estratégias produtivas. A simulação é vantajosa na medida que possibilita o teste de diferentes cenários sem afetar a produção, e consequentemente sem custos associados.

A principal adversidade está relacionada com os diferentes valores das taxas de entrada e saída de matéria-prima nos silos. Uma taxa de saída mais elevada cria um défice produtivo que esgota o material disponível nos silos, forçando uma mudança de produção. Esta situação atrasa a produção uma vez que se produzirão artigos não urgentes, para stock, até os silos serem reabastecidos.

Recorrendo ao modelo desenvolvido foi possível identificar ineficiências no processo de carregamento dos silos que restringia o fluxo de entrada e reduzia os ciclos produtivos. Ao eliminar tais ineficiências, concluiu-se que a produção poderia ser estendida pelo tempo desejado. Assumindo tal situação, pode-se descartar o cenário que contemplava a adição de um novo silo. Por outro lado, concluiu-se que ao implementar tal melhoria seria possível estender a produção a dois turnos diários, sem falhas de matéria-prima.

Ao analisar o processo produtivo foi também identificado o gargalo do mesmo. Procedeu-se à simulação de dois cenários distintos, representativos de aumentos de velocidades de produção diferentes, de forma a avaliar o impacto que teriam na disponibilidade da matéria-prima. Concluiu-se que apenas era vantajoso aumentar a velocidade de produção se fosse mantido um turno diário, aliado a um aumento da taxa de entrada de material nos silos.

Recorrendo ao OEE pode-se analisar as perdas ocultas de produtividade. Os resultados obtidos mostram que a baixa disponibilidade do equipamento proporcionava a maior oportunidade de melhoria. As principais razões estão relacionadas com os tempos de transição entre séries e paragens não planeadas. Na linha procedeu-se à implementação de vários aperfeiçoamentos, de forma a proporcionar um ambiente mais organizado e limpo aos operadores.

Os objetivos do projeto foram alcançados e é expectável que os resultados obtidos possam permitir à empresa perspetivar as consequências que advêm da implementação de várias estratégias produtivas.

Abstract

An increasingly fierce global competition and high product demand has forced companies to produce more goods, with a better quality in less time. To achieve this, new strategies that grant higher efficiency levels, had to be enforced.

This project took place in a rubber agglomeration manufacturing line. The main goal was to analyse and improve the productive process recurring to a simulation tool. Once the tool was created it was possible to reengineer the process by experimenting with different scenarios. It has the advantage of testing different alternatives without disrupting the production line and consequently with no associated costs.

The main issue was related with the difference of material rates, in and out of the silos. A higher out-rate creates a material deficit that drains the silos after a few days, forcing production to be adjusted. This delays production as it will be manufacturing non urgent stock articles until the silos levels are replenished.

With the model it was possible to identify inefficiencies in the material loading operations that hindered the in-rates and shortened the production lifecycle. By addressing this issue, production is expected to be able to resume for the expected duration. Therefore, the testing scenario that simulated the impact of adding an extra silo was discarded. On the other hand, a double daily shift could be enforced without expected material shortages.

Afterwards, the production process was examined and the "Bottleneck" operation was identified. Two distinct scenarios, representing different production speed increases, were tested to evaluate their impact on raw material availability. It was concluded that only by maintaining a single shift and enhancing loading operations could the speed increase benefit the process.

The OEE tool was applied to unveil hidden productivity losses. It was disclosed that the main issue relied on the low availability rates. The main reasons were related to changeovers and unplanned stops. On the production line, some improvements were made in order to provide operators with a safer, cleaner and more organized working space.

The project's objectives were accomplished and it is expected that the obtained results could offer the company an insightful perspective on the consequences of implementing different productive strategies.

Acknowledgments

Firstly, I would like to thank Amorim Cork Composites for providing me with a fulfilling and dynamic working experience overseas, where I had exceptional conditions to develop my project.

I would like to extend my gratitude to all the members of ACC USA that made it easy for me to adapt to a new reality, in such a welcoming and supporting manner. I would like to give a special thanks to Mike Bain for its availability and constant support throughout the duration of the project.

To my professor, Mário Lopes, I would like to thank for guiding me towards simulation modelling, that I found out to be such an interesting and useful skill to learn. Thank you for mentoring me throughout the entire process and for always being available in such short notices.

I would also like to acknowledge Nanci Carvalho, for the constant monitoring which made me feel supported during the entire experience.

Last of all, I would like to thank my close family for always supporting me in every aspect of my life and encourage me to constantly step out of my comfort zone to pursue my goals. Thank you for all the opportunities given throughout my life, which defined my journey and myself as a person.

INDEX

Abbreviations

ABM - Agent Based Model

ACC - Amorim Cork Composites

APE - Absolute Percentage Error

BB - Big Bag

EBM - Event Based Model

MAPE - Medium Absolute Percentage Error

MTS - Make To Stock

MTO - Make To Order

OEE - Overall Equipment Effectiveness

TOC - Theory Of Constraints

TPM - Total Productive Maintenance

WIP - Work In Progress

List of Figures

List of Tables

1 Introduction

The production of rubber cylinders is a highly complex process, involving heavy industrial equipment that is part of a stationary manufacturing structure with an inflexible layout. Changes to the production process may require shutting down the line for days, if not weeks, which would incur in huge costs, and eventually a failure to fulfill production orders in time. However, such scenario should not lead to inaction, in this way avoiding improvements altogether that could contribute to a more efficient production process, saving scarce resources or increasing production throughput. Hence, addressing this problem without disrupting the production with experimentation requires a method capable of simulating and inspecting the rubber production process, while at the same time providing the tools to experiment with changes and measure their potential impact on key indicators.

In this dissertation we devise a simulation-based method to reproduce the rubber cylinder manufacturing line, and illustrate its application on a real case study. We validate the model by comparing virtual and real production times, and once deemed to be accurate we experiment with several potential improvements, measuring their impact. We believe this methodology may be a sound contribution to the rubber production industry, helping to improve the production process in a controlled and prudent manner.

1.1 Aim of the thesis

The present project was developed at the Amorim Cork Composites (ACC) manufacturing plant, in Wisconsin, USA. ACC is a Portuguese company, part of the Corticeira Amorim's group. Although the company's main business is cork, this plant is directed towards the manufacturing and processing of rubber agglomerates products. The respective production line will be the project's central focus.

Its primarily objective is to scrutinize the productive system and seek improvement opportunities, while eliminating inefficiencies, as well as projecting the consequences derived from implementing different production strategies.

1.2 Amorim Cork Composites – a brief introduction

Amorim Group

Amorim Group is a Portuguese multinational company that had its roots in the cork business back in the 1870's under the name of "Corticeira Amorim". Although still being its core business, the group aimed at a business diversification process in the early 1960's. Now the Amorim Group has well established positions in sectors as distinct as the financial, textile, communications, tourism and real estate, being one of the most dynamic and well succeeded groups in Portugal.

Corticeira Amorim

The company is the worldwide leader in the cork sector. Guided by a vision of sustained growth and quality excellence in their products, the company grew internationally to a global scale. The mission is to: *"Add value to cork in a competitive, distinctive and innovative way that is in perfect harmony with nature"*. It currently holds 83 companies, 29 industrial plants, 44 distribution companies, 11 joint ventures and 258 main agents spread throughout the world.

Amorim Cork Composites

Amorim Cork Composites (ACC) is a subgroup of Corticeira Amorim that resulted from the merge of 2 of the group's now defunct companies (Amorim Industrial Solutions and Amorim Indústria). Its main business is composite cork and arose from the need of reusing the waste that came from the bottle cork industry. It is also responsible for constantly seeking new applications for cork that can be used in an increasingly higher number of products. Their mission is: *"Reinventing how cork engages the world"*.

In 2007 an overseas facility in Trevor, USA (former Amorim Industrial Solutions) was added to ACC. This plant's main business is rubber agglomeration manufacturing, which transforms reground rubber granulates into finished goods that may include: flooring material, underlays, rubber blocks and logs, among others. Although there is no cork production in Trevor, the plant often imports sizable amounts of this material from Portugal, enabling it to hold a share of the American cork market.

ACC USA – Agglomeration Sector

The plant is divided in three main areas: Agglomeration, Transformation and Storage and Shipping operations.

The project was developed in the main production area of the plant: the rubber agglomeration manufacturing line, also designated as the "Mold Room" and represented by Figure 1. In this place, a transformation process turns rubber buffing into rubber blocks or cylinders (Logs). After being produced these materials follow through to the remaining sectors, so they can be transformed into finished items, stored and shipped.

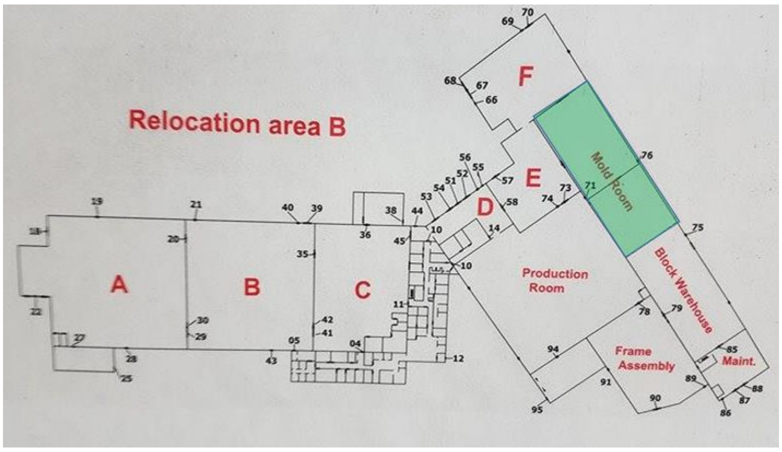


Figure 1 - "Mold Room" location

All of the plant's productivity depends on the efficiency of this manufacturing process as it is the first step of the interdependent internal productive chain. Without it, all the subsequent sectors would starve. Therefore it is on the company's best interest to reduce inefficiencies and extend production time within this sector, thus improving efficiency and productivity. This will have a positive effect which will be reflected on the entire plant's performance.

Operations are run 6 days per week and three different product types are manufactured during that period. A problematic situation arises during the Log production days, which occupy production during 3-4 days a week. When producing Logs, the silos, which store black buffing, are drained at faster rates than they are refilled, creating a deficit. This deficit will eventually cause the silos to be emptied, forcing production to be temporarily switched to low-priority colored buffing products, while they are being refiled. This causes urgent orders to be delayed and the production schedule to be hampered.

1.3 Project Objectives

The proposed project main field of action would concern the Rubber Agglomeration manufacturing line process, during the production of Rubber Logs. With the objective of improving the process in its whole, several objectives were set:

1. The first, and most relevant goal, was to develop a simulation model that could reproduce the productive system with accuracy. This would allow for a complete process analysis without any associated costs and without disrupting the actual productive system. After being created and validated, this tool would be used to test the following scenarios and its respective impact on the black buffing material availability:
    - 1.1. Extended production cycles, with more efficient loading operations;
    - 1.2. Use of an extra storage material;
    - 1.3. Double daily shift implementation;
    - 1.4. Production speed increase;
2. Identify the causes and extent of hidden productivity losses using an OEE analysis;
3. Apply LEAN methods to the sector:
    - 3.1. Improve work conditions on the line by using the 5S methodology;
    - 3.2. Suggest Standard work to eliminate inefficiencies on the line and prove that a better performance levels can be achieved.

1.4 Methodology

The simulation project was divided in five main stages: Identifying the company's requirements, developing a strategy to represent the productive system in a simulation tool, gathering the necessary data to do it and creating the respective model, executing and validating it, and lastly experimenting various alternatives and analyzing the respective results. This was based on a methodology by (Rabe, Spieckermann, & Wenzel (2009), represented by Figure 2. At the same time a 5S methodology was followed to improve working conditions within the production line.

- **Phase 1** – The first phase involved the full understanding of the complete productive process, as well as the company's needs for the sector;
- **Phase 2** – Defining the plan of action. This phase involved depicting the most relevant processual phases that should be portrayed in the model;
- **Phase 3** - After having a strong understanding of the process and having a plan defined, all the relevant data started being gathered, which would be later applied to the model. Concurrently, a conceptual model started being developed. Meanwhile, several line improvements opportunities were identified;

- **Phase 4** - After having the model created, the prepared gathered data was added, generating a functional tool that was later validated recurring to production sheets;
- **Phase 5** – By having an executable, validated model new production strategies could be simulated and their results analyzed. Production line improvements were also implemented in this phase.

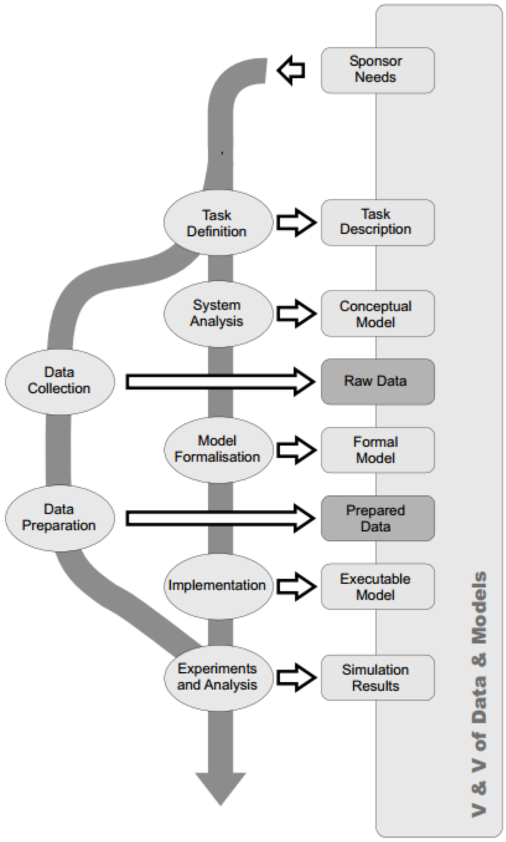


Figure 2 - Simulation model creation methodology by Rabe, Spieckermann, & Wenzel

1.5 Dissertation structure

This project is divided in 6 chapters. The following two chapters present the initiation phase that preceded the development of the simulation model. On Chapter 2, a literature review regarding the state of the art of the most relevant themes is addressed, while Chapter 3 exposes the production's line current situation. Chapter 4 presents and explores the developed simulation model, followed by Chapter 5, which exposes several testing experiments made and their respective outcomes. On Chapter 6 the project's conclusions are presented and possible future works are suggested.

2 Literature review

2.1 Production and Operations management

Operations management is the group of managerial systems and processes responsible for the production of goods and services. It differs from other management areas due to the involvement of both people and equipment (Stevenson, 2009). Therefore, there is a need to create strategies that englobe both of these elements within the organization. Lately, there has been a wider number of researches that, in addition to focusing just on the equipment elements of the productive chain, also start considering the impact of the human element (Westbrook, 1995).

Production, or manufacturing, involves the transformation of raw material (input) into a finished good (output). This transformation process involves several phases and distinct resources. There is also a need to assure quality standards, therefore production control is mandatory throughout the entire process.

By going through this transformation process, value is being added to the product, which will be reflected on the amount customers will be willing to pay for it. Expectedly, this value will be higher than the sum of all the input related costs, resulting in profit for the organization (Stevenson, 2009).

During the course of the years, the manufacturing industry as evolved in order to cope with the increasingly demanding challenges of the modern world. Consequently, new and more efficient production methodologies were created and adopted.

2.2 Analytical methods applied to Production and Operations Management

In order to properly assess a productive process, it is necessary to use a method capable of producing an acceptable outcome. This method should be able to reproduce the productive process accurately, as well as being able to reengineer it if needed. The most widely used methods are the following:

- **Process Mapping**. It is based on a workflow diagram with the main purpose of providing a clear understanding of the productive process. It relies mainly on the use of flowcharts. The main difference between industrial and digital process mapping resides on the fact that it identifies the participants alongside the processes. It is divided in three major phases that involve the creation of three respective models: “As-Is”, “To-Be” and “Bridging the Chasm” (Okrent & Vokurka, 2004);
- **Value Stream Mapping**. It is the analysis of a group of actions (value added and non-value added actions) required to move a product through the complete production flow: from raw material to finished product. It displays the process’s “big picture”, allowing focus to be drawn on improving the process as a whole, instead of targeting smaller individual parts (Rother & Shook, 2003);

- **Simulation Modelling.** It accurately represents a production process. It will allow for the testing of several alternatives without associated costs and without disrupting the production line. It is useful to test the impact that a preplanned measure will have on the system, as well as improving it by detecting and eliminating inefficiencies (Pedgen, Shadowski, & Shannon, 1995);
- **Bottleneck analysis and theory of constraints.** The system's bottleneck is the most time consuming operation, which hinders production rates and will cause material accumulation before its respective station. The theory of constrains is a sequenced method designed to analyze and improve the system's constraints, improving performance and efficiency (Lanke, Hoseinie & Ghodrati, 2016).

2.2.1 Process Mapping

The main objective of Process Mapping is to use diagramming tools, such as flowcharts, in order to display all the possible processual outcomes of every operation, enabling an organization to improve its efficiency. By having processes identified, as well as inputs, outputs and decision points, it is possible to attain a clearer global perspective and assess if and how improvements can be promoted inside the organization. According to Okrent & Vokurka in 2004, process mapping can be divided in 3 phases.

Phase 1- "As-Is" Model. It is vital to understand how processes are currently performed and the main reasons for it. All the interconnections between processes should be sequenced according to their execution order. This will allow for the detection of non-value added activities that can be reduced or removed, when transitioning to the "To-Be" model.

Phase 2 –To-Be" Model. Firstly, while creating this model the main focus should be on identifying the critical, strategical, business processes. Next, a flowchart with no constraints should be elaborated. Then, taking into account all of the system's restrictions, a simplification process should take place to reduce and simplify the process before automating it.

Phase 3 - "Bridging the Chasm" Model. It is the intermediate model that will allow for a smooth transition between the two previous phases, without major productivity losses.

This reengineering method has proven to produce adequate results for every company in need of more efficient processes. By identifying the current process flows it is possible to locate inefficiencies and aim for the desired objectives, following a structured transition. Although it can be used in both information and material flow projects, it has predominant applications on the information flow field.

2.2.2 Value Stream Mapping

It surfaced alongside the Lean methodology in order to redesign the productive systems in a more efficient manner. What differentiates VSM from other processes is that it focuses on representing the two main flows involved in any industry: information and material flow. Its main goal is to grant visibility to the entire process, so it can be studied and improved as a whole, detecting inefficiencies and disconnected manufacturing flow lines.

In order to do so, it has to consider all the activities required to manufacture a product. These can be divided in: value added activities and non-value added activities. The first group gathers all the operations in which the final result differs from the initial result, in both shape and value. These include all the processing operations required to transform raw materials in marketable items, for which clients are willing to pay for (Singh, Garg & Sharma, 2011).

The second group is considered to be included in one of the Lean methodology's three main wastes: Muda. It states that any activity that does not add value to the product is a waste of resources and should be reduced or eliminated. It is often related to excessive transport movements, of parts and resources, prolonged waiting times and inaccurate production planning. This will cause inventory surplus and overproduction, reducing the production flow and increasing Work in Progress (WIP). Although some of the non-value adding activities are necessary to establish a production system, others can be significantly reduced (Pinto, 2008).

According to Rother and Shook in 2003, every VSM project is based in five different phases:

- **Selection of the product family**. It is vital to extend the analysis to all the variants within the same product family, which share flow routes throughout the manufacturing process;
- **Current state analysis**. Evaluate the current situation by integrating all the relevant parameters and processes in a map that reproduces the entire system. All the flow stages must be represented, as well as the duration it takes for each operation to be completed. In order for VSM to produce accurate results there must be a rigorous data gathering procedure. These will have a major effect on the conclusions drawn from the method. Poorly collected data will consequently result in a poor decision making process. As the process's inefficiencies are revealed by the collected data a strategic plan for improvement should be commenced;
- **Future state analysis**. The future state analysis includes a redesign of the productive process that should embody several Lean principles. Firstly, there should be a lower reliance on forecasts as production rates should directly represent real product demand based on orders. This production adjustment is represented by *takt* times. Implementing a *pull* system is also a critical step in the process. Material must not accumulate in-between operations, creating Muda by increasing WIP. It should only advance if the following station is vacant. Cycle time decreases and changeover reductions implementation could further benefit the productive system;
- **Designing a plan of action**. A plan must be drawn to expose how the Future state situation will be achieved. A chronogram including every relevant transformation time frame should also be contemplated;
- **Implementing the plan**. The last phase includes the execution of the previously delineated plan and the result's evaluation.

Application of VSM in the industry

In terms of application, VSM has been widely used in several industries over the last two decades. The revamping of a distribution network for electronic components was reviewed by Brunt, Sullivan, Hines in 1998, which involved a prior analysis of the current stream flow and was proceeded by the implementation of an improvement plan that englobed dozens of suppliers. Taylor (2005) studied how a value stream analysis allowed the discovery of hindering system inefficiencies in a complete food supply chain, which involved all the processes from the farmer to the final client. Another project, using VSM in the food and drinking sector, detected significant improvement opportunities while reducing and eliminating non value added activities (Melvin, Baglee, 2008). Also, by using the VSM a forging industry was able to surpass their inability to reduce wasteful operations by identifying their causes and eliminate them. Reductions on both set up and WIP levels were also attained (Sahoo, Singh, Shankar & Tiwari, 2008).

VSM and Simulation modelling

Both of these methods are often used together in order to produce a more robust analysis of a company's situation, complementing one another. After addressing the VSM current state situation and identifying the critical points in terms of improvements opportunities, a simulation model was created to test and analyze the outcomes of such measures without disrupting the production line of a Taiwanese plant (Huang & Liu 2005). In the process sector, a simulation model was developed to provide an insightful perspective of the benefits of implementing *Lean* measures with a before and after scenarios display. These opportunities were identified via VSM (Abdulmalek & Rajgopal 2007). In a construction industry there was a need to increase material flow, which was achieved by studying various production scenarios on a simulation model. It was concluded that the system would become increasingly leaner if material spent lesser time on the value stream (Al-Sudairi 2007). A discrete event simulation modeling applied to a VSM process was able to increase the efficiency levels of a warehouse distribution center by identifying and eliminating faulty operations. These methods can be used separately or combined to identify and improve ineffective situations. Both are powerful tools that provide high value by granting an insightful viewpoint to the production's current issues and the respective impact of alternative solutions.

2.2.3 Simulation modeling

Simulation modeling reproduces a real world process over time, which is displayed in a digital format. It allows data gathering and an insightful representation of every stage of the process modeled, culminating in the observation of key behaviors (Pedgen, Shadowski, & Shannon, 1995; Schelling, 1978). Being a valid imitation of the process it has the advantage of experimenting, creating and optimizing every possible situation. Scenarios can be tested, without any disturbance or risk to the actual system (Pedgen, Shadowski, & Shannon, 1995). The model assumes an abstraction level, which may vary in each case, and has to be defined strategically beforehand. However, every model will always be less complex than their real world counterpart (Borshchev, 2013).

The models can be divided regarding their dependence on time, by being static (independent) or dynamic (dependent). A dependent model can still be classified as discrete or continuous, depending on how the time scale is considered. By further scrutinizing a discrete model, a differentiation can be made, depending if a system alteration was time or event-triggered, by having event-driven or time-stepped simulations (Mourtzis, Doukas, & Bernidaki, 2014).

Events

An event is an occurrence that takes place in a specific time frame, although it does not have any duration (Bækgaard, 2004). It is vital to understand the causes, consequences, relation between events and types of events to fully comprehend the process (Granat, 2006). "Equipment starts moving" and "Button is pressed" can be seen as phenomenon examples. Phenomenon are categorized as events when it is assumed that any further division has no real value, therefore their duration is suppressed. Events can be seen and may trigger activities. On the other end, activities are event-triggered and event-interrupted (Bækgaard, 2004).

Modeling types

Every model must be created to serve a well-defined purpose, with a clear objective, while being based on an existing system. This will influence the choice of method, regarding the abstraction level required. There are three main methods, and whilst "System Dynamics" is recommended for strategic, high abstraction modelling, Agent-Based and Discrete event modelling focus on more detailed, tactical or operational scenarios, at the meso or micro levels (Borshchev, 2013). Figure 3 illustrates the main differences between the approaches.

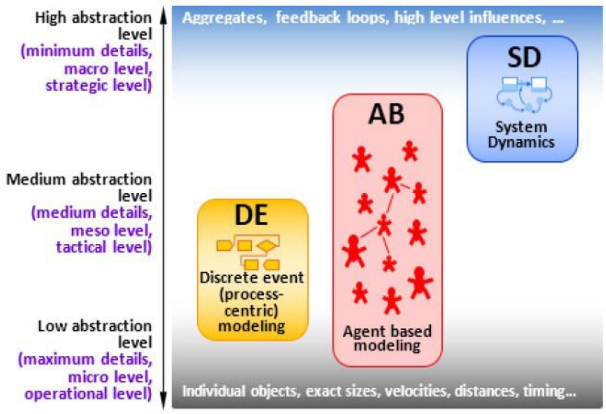


Figure 3 - Simulation approaches comparison (Borshchev, A. (2013))

Agent-Based Modelling

We can separate these last two approaches by the way a system is looked at. If there is a deeper understanding of the object's behavioral qualities, when compared to the general system dynamics, a bottom-up perspective should be considered. An Agent based model (ABM) would be the most appropriate (Baldwin, Sauser, & Cloutier, 2015). These objects are referred as agents and have their own behaviors, which can be pre-defined by a set of rules.

Usually, agents also have a notion of state and will act accordingly (Borshchev, 2013). "An agent is a distinct software program that represents social actors which may be people, animals, organizations or any individual system" (Baldwin, Sauser, & Cloutier, 2015). By connecting this autonomous agents it is possible to study their interactions with each other and with the environment they are in, which can have its own dynamics as well. A spreading epidemic model would be a suitable example for an agent based model (Borshchev, 2013).

Event-Based Modelling

The event-based models (EBM) represent a sequence of events that are performed across entities, having an instantaneous impact on the process and a change in its state (Borshchev, 2013). Rather than being action programmed like the ABM, the EBM are reaction programmed, passive, so it is vital for the modeler to correctly map the states and events of the system (Baldwin, Sauser, & Cloutier, 2015). Any action will be determined by the process flowchart, which will not allow any independent behaviour (Borshchev, 2013). When creating the model, there is simplicity associated with EBM, not only on the process modelling itself, but also because there is no interest in the internal states of the system, only in observable events that trigger the reactions. This allows for an easier, more convenient, method to validate the testing model. A manufacturing industry, where there is a transformation of raw materials into finished products throughout several phases, it is a suitable EBM example (Baldwin, Sauser, & Cloutier, 2015). A comparison between these two types of models is displayed in Figure 4.

Event-Based (Discrete) Modeling	Agent-Based Modeling
Macrospecifications reveal microstructures (top-down view)	Microspecifications generate macrostructure (bottom-up view)
Externally observable phenomenon (events)	Autonomous decision making entities (agents)
Programmed response to discrete events	Programmed functionality of agents
Events adhere to system-level observable information	Agents adhere to behavioral rules (boundedly rational)
System of interest changes state in response to events	Agents function independently and flexibly
Event impacts the entire entity	Agents interact as distinct parts of simulation
Simplicity in modeling inputs, state, and outputs	Simplicity in modeling rules
Internal behavior is unknown	Events emerge
Easy to test	Difficult to validate

Figure 4 - Comparison between ABM and EBM features (Baldwin, Sauser and Cloutier, 2015).

Discrete Event Simulation

The discrete event simulation (DES) is also known for solving complicated issues that otherwise would not be possible just owing to analytical human abilities. In complex process industries it would not be possible to monitor the effect that every minor change would have on the system, without computer assistance. It allows for a transparent view over every stage of the process, therefore allowing for a clear bottleneck identification. It also comes as a valuable tool in terms of decision making processes (Donhauser, Rackow, Hirschbrunn, Schudererb, & Franke, 2016). Different situations regarding investment, resources allocation and optimization policies using DES are an increasingly common practice in the industry (Gomes, & Trabasso, 2016).

Another advantage of the DES arises in plants where the layout is inflexible and Lean principles and Toyota Production System measures cannot be applied to their full potential. A rigid sub process machine disposal and a heavy goods transportation system would benefit most from organizational measures rather than optimization measures (Donhauser, Rackow, Hirschbrunn, Schudererb, & Franke, 2016).

Alternative Simulation Approaches

Multimethod approaches can also be an interesting choice regarding complex industries with large scale manufacturing systems. According to Sadeghi, Dauzère-Pérès, and Yugma (2016), who conducted a study on the semiconductor industry, if there is a need for flexibility (ABM), as well as the need of queues and discrete events processing (EBM), a combination of the two methods can be applied. A process can be modelled inside the agents, through discrete events, or having the agents become entities that go through different stages while using the system. This allows to overcome the shortcomings presented in the EBM for large scale systems, regarding modelling time and costs (Sadeghi, Dauzère-Pérès, & Yugma, 2016).

There is another option for industries that deal with bulk or high speed flows (e.g. mining, oil and packaging industry), where EBM is not fully adjusted or too slow. It is called Discrete Rate Simulation and it is a continuous modelling approach which can support discrete events as well (Siprelle, & Phelps, 1997). The main drawback is the loss of information inherent with the use of a continuous system. (Donhauser, Rackow, Hirschbrunn, Schudererb, & Franke, 2016). The solution would be a mesoscopic approach mixing both discrete events and continuous modelling, which were studied by Reggelin, & Tolujew (2011) and Terlunen, Horstkemper, & Hellingrath, (2014), although with lack of reliable information due to their continuous model base. (Donhauser, Rackow, Hirschbrunn, Schudererb, & Franke, 2016). However, in a study conducted by (Donhauser, Rackow, Hirschbrunn, Schudererb, & Franke, 2016), a discrete model was used as the base, while also using a continuous model with a positive outcome and a reduced simulation time.

Available Simulation Software

With so many upsides related to the use of simulation-based technologies in the manufacturing industry, there is a need to compare the various digital tools available on the market (Mourtzis, Doukas & Bernidaki, 2014). A study was made comparing five popular software systems: "AnyLogic", "Arena", "Flexsim", "Plant Simulation" and "Witness", enhancing its strengths and weaknesses. The comparison process was divided in five main categories: "Hardware and software", "General features", "Modelling assistance"; "Simulation capabilities" and "Input/Output". The model used for the test was an adaption of a simulation model from Chryssolouris, Pierce and Dicke (1992) that studied a flexible manufacturing center. The rating scale ranges from 1 to 5 stars, being * Inadequate, **Adequate, ***Satisfactory, ****Very Satisfactory and *****Outstanding with the respective results being shown in table 1 (Mourtzis, Doukas & Bernidaki, 2014).

Table 1 - Comparison between the different available software (Mourtzis, Doukas & Bernidaki, 2014)

Criteria Groups	Comparison Criteria	Simulation Software Tools				
		AnyLogic	Arena	Flexsim	Plant Simulation	Witness
Hardware and Software	Coding aspects	****	***	**	****	**
	Software compatibility	***	**	***	****	***
	User support	****	**	****	****	***
General features	Purpose	General	General	General	General	General
	Experience required	***	****	**	***	**
	Ease of use	***	**	**	***	****
Modelling assistance	On-line help	****	**	****	***	**
	Library and templates	***	**	****	****	***
	Comprehensiveness of prompting	***	**	***	***	***
Simulation capabilities	Visual aspects	****	**	*****	****	***
	Efficiency	****	**	****	****	***
	Testability	****	***	****	****	***
	Experimentation facilities	***	***	****	****	***
	Statistical data	****	***	****	****	****
Input / Output	Input/output capabilities	****	***	****	*****	****
	Manufacturing capabilities	****	**	****	****	*****
	Analysis capabilities	***	***	****	****	***

It can be concluded by analyzing Table 1 that 4 out of the 5 options could be considered very satisfactory on their whole, showing a wide range of capabilities for the general user.

Data types

In terms of relevant data for simulation purposes, it can be divided in 4 groups. Input data regards buffer capacities, process times, resources speed, while output data is related to all the statistics collected after the simulation is over. The experiment data and the internal model data represent the other two categories. They account for the simulation's time horizon and the sub processes time, respectively. (Donhauser, Rackow, Hirschbrunn, Schudererb, & Franke, 2016).

Conclusions must be drawn only by having an accurate and precise simulator that provides accurate results. A poorly calibrated model will produce inadequate results that will end in a poor decision making process. Therefore, there is a need for model verification and validation. Rabe, Spieckermann, & Wenzel (2009) recommend a model for creating and validating simulation tools with several phases, providing a structured, step-by-step guide which allows every activity to be proven and every result to be validated.

DES Case studies

Simulation modeling has been widely applied in the resolution of several improvement challenges on manufacturing industries. The discrete event simulation models become relevant when there is a need to analyze a sequenced productive system, which is performed across several entities and causes the process's state to change. This is the case of the manufacturing industry (Borshchev, 2013).

Byrne & Heavey (2006) applied a DES model to a supply chain which quantified the cost reductions associated with the implementation of an enhanced forecasting model and information flow. It was proven that all parties would benefit from a more active information share alongside the supply chain.

Regarding the production planning field, a Chinese telecommunications manufacturer used a DES model to simulate the current plant's situation, which faced high WIP levels (Kadipasaoglu, Xian & Khumawala, 1999). After testing the current scenario, three other scenarios, containing slight modifications (inventory and batch sizes variations, bottleneck identification), were tested. The simulation model allowed to test the impact of several production strategies that could produce both financial and operational benefits to the company.

Mendes, Ramos, Simari & Vilarinho in 2005 used a DES model alongside analytical models to allow for a production line to adapt to the current demand. Different settings could be tested, with the aid of the simulation tool, in order to maximize the production's line use in different scenarios without disrupting the line.

A DES system was created by Son, Wysk & Jones (2003) to promote the real time control of a discrete parts manufacturing plant. It was created due to the high costs of control software development and maintenance issues, and it features the first successful implementation of a real time complex control system, which was automatically generated.

DES also proves to be a valuable tool when it comes to workforce planning, as Zülch, Rottinger & Vollstedt analyzed in 2004. The model was used to explore the innumerous possibilities of schedules allocation and their respective resources. After the situation was optimized, it resulted in an enhanced organizational structure that allowed for a more competent re-assignment policy.

A simulation model was used by Roser, Nakano & Tanaka (2006) in order to test the impact that a larger capacity buffer would have on the system's performance. The model tested several combinations that provided enough data so that the ideal buffer position within the productive line could be found.

De Ruyter, Cardew-Hall, & Hodgson (2002) displayed the potential of simulation techniques applied to the quality control department of an automotive stamping plant. The model provides enough data to conclude that a low cost quality control increases the total quality cost, as many items need rework.

It can be concluded that simulation modeling, specifically DES, can be successfully applied to a wide array of fields, contemplated within the production and operations sectors of a manufacturing plant.

In terms of the rubber production process, the following articles using some form of simulation were found:

Isayev, Yushanov, & Chen (1996) proposes a simulation model capable reproducing a technology applicable to rubber tire recycling and other rubber wastes. The model tests how cavitation inside rubber particles can be used in the rubber's devulcanization process. The created model was successfully validated by generating acceptable results when compared to the experimental data gathered.

Rafei, Ghoreishy & Naderi (2009) studied how different features and parameters could influence the rubber curing process, which was simulated through an advanced computational technique. Its main goal was to replicate the behavior of a thick rubber product inside the mold during the cure and post-cure stages. The created model produced accurate results when compared to experimentally measured data.

Deng & Isayev in 1991, developed a simulation model based off finite-elements and finite-difference methods in order to tackle the challenges faced on the injection molding of rubber compounds. The study focused on two rubber compounds and their respective mechanical properties. The model's produced outcome helped attaining the mold's temperature, for which the properties and cycle times are optimal.

Later, a finite element simulation software was used by Felhõs, Xu, Schlarb, Váradi, & Goda (2008) to better comprehend the viscoelastic behavior of an EPDM rubber under dry rolling conditions. Through simulation, is was possible to determine the material's viscoelasticity, as well as its behavior under strainful conditions. It proved to be a valuable tool when analyzing rubbery material's viscoelastic properties.

2.2.4 Bottleneck analysis and theory of constrains

The bottleneck is the operation in the system that limits the production flow. This constraint affects the production rate and therefore the system efficiency itself. The material flow is affected, being slowed down or even stopped, as the input rate is higher than the output rate. It can be identified as the operation that keeps material waiting. The bottleneck is the weakest link on the productive chain, in terms of effectiveness and performance (Lanke, Hoseinie & Ghodrati, 2016).

It is not possible to completely remove bottlenecks from the system as, once performance is increased and constraints eliminated from one operation, the bottleneck will shift towards the new least efficient one. This will be continuously repeated (Taj & Berro, 2006).

The theory of constraints (TOC) is a structured process in which the main goal is to detect the bottlenecks on the production chain, as well as analyzing any possible interrelation between them. It started as a production planning tool and has evolved into a widespread management philosophy focused on continuous improvement, present in every sector, from production to marketing and accounting.

The main drive force behind its success was: “The Goal”, a book by Goldratt and Cox written in 1984 to inform managers about what would end up being TOC. It lays on a five step cyclic process named “The five focusing steps”, which are the following:

1-Identify the system’s constraints

2-Decide how to exploit the system’s constraints

3-Subordinate everything else to the above decision

4-Elevate the system’s constraints

5-Repeat the process

TOC is an on-going process focused on how a system is affected by its restrictions, aiming to reduce them in a continuous cycle. When correctly implemented, it brings companies benefits, such as reductions in inventory and operation expenses, while increasing production rates. The system’s production rate is defined by the production rate of the constraint operation, so in order to increase efficiency it is necessary to identify and eliminate it. That is the TOC goal which will help companies achieving their goals, thus becoming more competitive (Şimşita, Günayb, Vayvayc, 2014).

2.3 OEE indicator

The Overall Equipment Effectiveness is a performance indicator widely used in manufacturing industries. It is a part of the TPM (Total Productive Maintenance), which is a system focused on improving the production rates mainly through preventive maintenance measures. OEE was created as an evaluation metric for TPM. It was first implemented on the semiconductor industry and is now used among industries with mainly automatic processes (Jeong & Phillips, 2001).

It is a powerful and simple tool that provides companies an insightful look at all the hidden production losses on their processes. This tool depends on accurate data gathering to be reliable. OEE is a ratio between all the time spent producing quality approved products and the scheduled time to do so. It is the result of the multiplication of three efficiency factors: Availability, Performance and Quality as showed in Figure 5 (Hedman, Subramaniyan & Almatrom, 2016). Each one of these three factors is related to 2 of 6 production losses which are the following:

1. **Availability losses**

    1.1. Setup and adjustment time - It is also referred as planned stops and include every period of time when the equipment is ready to run but is idle. It can include setup, changeovers, cleaning, planned maintenance and inspections.

    1.2. Equipment failure - Every period of time that the equipment is not able to run due to technical issues. It is also referred as downtime or unplanned stops. The main reasons account for material shortages, breakdowns and corrective maintenance (Hedman, Subramaniyan & Almatrom, 2016).

2. **Performance losses**

    2.1. Idling and minor stops - Stoppage on the equipment that has a duration of less than two minutes and can be fixed by the operator. Product overflow and material jams, as well as misplaced machine elements can cause these losses.

    2.2. Reduced speed - Every time the equipment is running slower than it was designed to. The main causes are poor maintenance, cleaning and operator inexperience (Hedman, Subramaniyan & Almatrom, 2016).

3. **Quality losses**

    3.1. Process defects. Defective products that need to be scraped or reworked. Operator errors and equipment misalignment are probable causes.

    3.2. Reduced yield. All the products that are produced during a stable state is reached, under suboptimal conditions. It includes all the scrapped parts and the ones that need rework (Hedman, Subramaniyan & Almatrom, 2016).

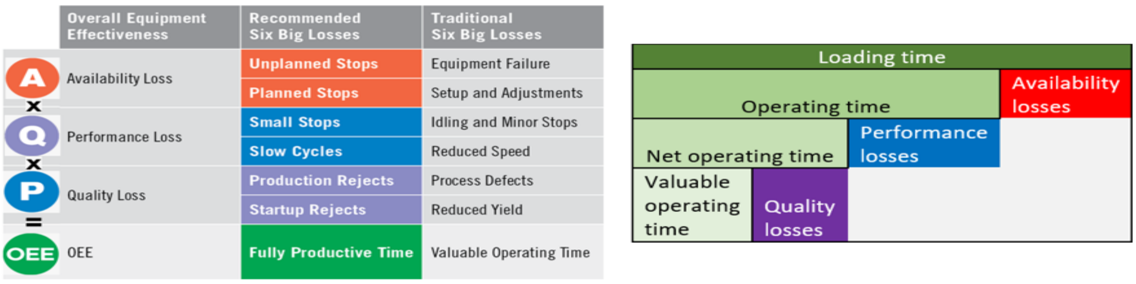


Figure 5 - OEE time losses overview

The availability factor is a ratio between the operating time and the loading time. The loading time is the available time to produce, excluding planned activities as breaks or planned maintenance. The operating time will account for the available time, minus the amount of time spent on unplanned and unproductive activities, such as: breakdowns, changeovers and corrective maintenance (Jeong & Phillips, 2001).

The performance indicator is the ratio between the actual production capacity and the planned production capacity. It subtracts the micro stops and low cycle times from the operating time, resulting in the net operating time. Lastly, the quality factor is a proportion between the quality approved parts produced and the total amount of parts produced. The valuable operating time is the time left for quality production after all the losses are taken into consideration as it is shown on Figure 8 (Jeong & Phillips, 2001).

The OEE value will be the result of the multiplication between the three efficiency factors. The world-class goals for the discrete manufacturing industries regarding OEE factor levels are the following: Availability-90%, Performance-95%, Quality-99%. This will result in an OEE=85%. Although it is important to achieve certain numbers, one should not focus only on them, but try to implement continuous improvement strategies and increasingly more ambitious targets. (World-Class OEE, n.d).

3 Case study

3.1 Production policy and demand levels

ACC's current production policy is divided in Make to Order (MTO) and Make to Stock (MTS) orders. The company is currently unable to rely solely on a MTO policy, although it is recognized to be the optimal situation.

One of the reasons for this situation to happen is the tight delivery lead times, which have been significantly reduced over the past few years due to the emergence of digital trading platforms like Amazon. In order to keep up with the competition, ACC is forced to compromise on delivery lead times, which are shorter than production lead times.

By doing so, production would inevitably fall behind if no stocks were maintained. With the current productive time and current accepted delivery times, there is no optimization possible that could grant an exclusively successful MTO policy.

Therefore, there is a need to rely on forecasts and maintain stocks of certain items. Production shifts between the two policies daily, in order to fill stocks and complete orders. Due to an experienced staff, production planning has achieved success by keeping up with demand. Although this will prove to be a more complicated task in the future, as demand is expected to rise, as well as reference numbers.

That is why it is vital to analyze alternatives that would enable production time extensions, and raw material to be available during the complete production expected time. It is critical to have conditions that would allow production deadlines to be met.

3.2 Production line overview

The company produces several different types of Logs, with individual requirements. These include different chemical formulas, densities, distinct raw material weight usage and different system requirements.

The system requirements include all the parameters of a specific reference that will cause the production time to vary. One of these parameters is the height of the product that can range from 33'to 51' inches, although the diameter remains constant throughout all products. Other parameters include: baking time, the number of material loads necessary to produce a single unit, EPDM usage, among others.

Figure 6 shows how Log production is divided by products. They were gathered in 13 main groups, each one representing a specific product. Some products have more than one size, which would increase the number of considered references to 24. These references would represent 94% of all the produced items during the year 2016.

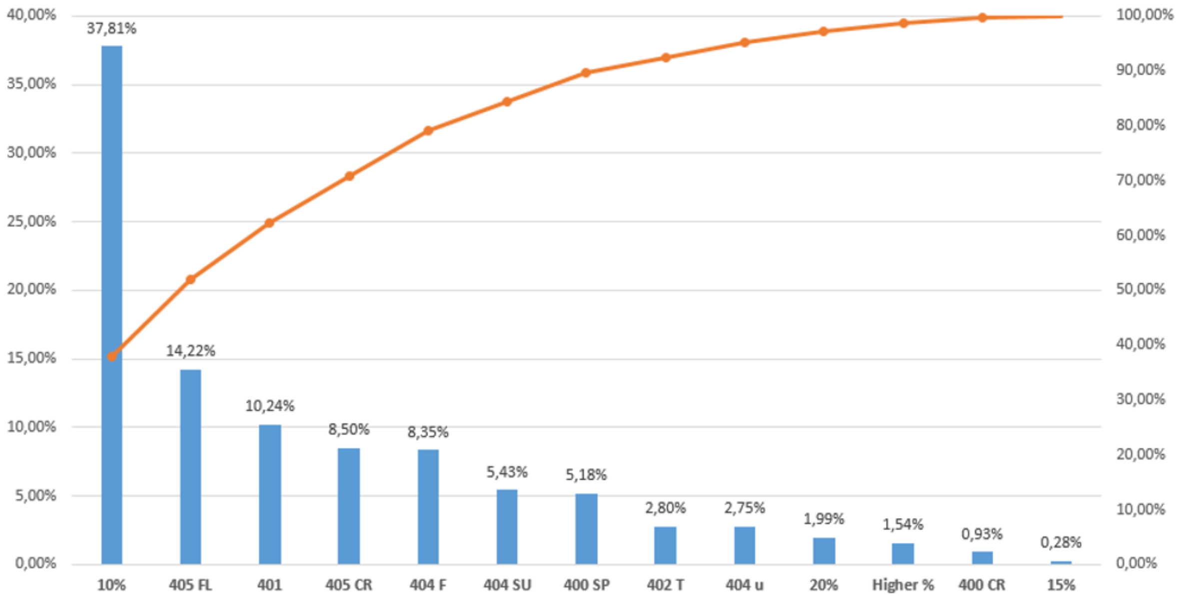


Figure 6 - 2016 Production share by reference

3.2.1 Productive process

Logs are produced exclusively during 3 to 4 straight days a week. There is only one unfazed shift enforced, with a current workforce of three experienced operators, although new personal was being trained during the duration of the project. In order to produce Logs there is a manufacturing process involved that transforms raw material into finished product. The most important aspects of this process are have been identified and analyzed.

Raw materials

Log production requires three different raw materials displayed in Figure 7. They are stored on the adjacent hall and are transported to the room whenever they are needed and are the following:

-**Rubber buffing**, which may be being colored or black. This material is kept inside Big Bags (BB) prior to be introduced in the system. It is the main raw material, which in most cases is responsible for more than 90% of the total weight of the cylinder. Black buffing is the most widely used, high quality buffing, while Colored Regrind buffing (CR) represents a material of variable color and lower quality, used in some references.

-**EPDM**, which are stored in pallets. Each pallet is composed of 40 plastic bags, with same color material. This component is what grants Logs its colors. It may or not be necessary in every product and can be used in different combinations and amounts (10%-90% of the final product weight). Extra information regarding raw materials is available on Appendix B.

-**Binder**, which is stored in liquid containers. It acts as a glue that provides consistency to the mixture when exposed to high temperatures.

Figure 7 - Raw materials: buffing stored in BB's, EPDM and binder

Production Phases

1-System loading

1.1 Buffing starts flowing into the system when BB's are hung by a hoist directly above the "Bagoff" mechanism, represented in Figure 8. The mechanism has the same function of a funnel, as it channels all the raw material towards the pipe system and into the silos. In order for material to start flowing there are some preparation operations that need to be performed by the operator. Only one bag can be used at a time. There is one separate loading station for CR and black buffing material.

1.2 Regarding the EPDM's, the pallets have to be transported via forklift to the room, where they are stored. Then the bags of the necessary color will be discharged manually to one of the three tanks that can withhold a small volume of bags. As there is no EPDM silos, the material will flow to a scale and then it will be automatically displaced to the mixer, when needed.

1.3 The liquid containers keeping the binder are directly connected to the system and are replaced when empty. There are always 2 containers on site so production is never hindered when there is a need of replacement.

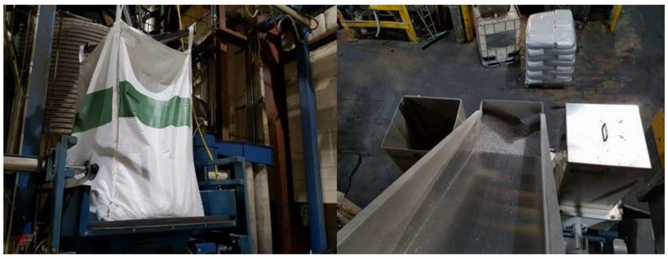


Figure 8 - Bagoff equipment and EPDM tanks

2-Silos

There is a total of four available silos, two for black buffing and two for CR. Each pair has a capacity to withhold 29000 pounds, capable of keeping the approximate volume of 14 BBs of material. Each pair is connected between them and the PLC program is designed to consider each pair of silos as one. That means that material will be loaded and unloaded through both silos, of the same pair, at the same time, reducing waiting times. They will act as the production system's buffer. Figure 9 represents the plant's silos.

3-Scales

When material processing operations performed by the press terminate, a specific amount of material will automatically flow from the silos (or the tanks, in the EPDM case) to the scale. This amount varies from product to product. When the desired amount is reached, the connection with the silos will cease and material will flow towards the mixer. After the complete load of material reaches the mixer, the Binder pump starts working, transferring the required amount to the same equipment.

4-Mixer

The mixer tank is a cylindrical equipment that will amass all of the 3 inputs, scrambling them by using centrifugal force, in order to produce a homogeneous mixture. The mixing process will last for 60 seconds and will start immediately after the binder reaches the tank. The sum of all the input weights combined will result in the load weight. If using EPDMs on a percentage higher than 20% of the total weight, the bags will have to be loaded manually into the mixer, which is displayed in Figure 9.

Figure 9 - Silos and mixing process

5-Press

The press is responsible for the compression of the load coming from the mix tank into the mold. When the material stops falling, it will trigger the beginning of a new cycle, by allowing material to flow from the silos to the scales again. There are several consecutive processing operation that will occupy the press before a log is ready to move to the oven.

6-Oven

After being processed, the molds with the recently poured and compressed mix are transported to the ovens to be heated between 4 and 5 hours, depending on the product. There are two ovens with a capacity for nine molds each. This process is vital, as it is in the oven at high temperatures that the binder will have its deepest effect on the mixture, hardening it and providing enough consistency so that it will be transformed into a solid piece.

7-Demolding

The last phase of the process starts when the molds are pulled out of the oven and into the demolding station. They are transported on top of a cart which moves within a rail. In the station, the mold is separated from the finished product using a horizontal press, which extracts the material, detaching it from the mold. After the operation, the mold is placed on the same track where it will queue until needed to hold the next round of material, therefore completing a cyclic movement. The finished Logs, after being demolded will be stored in an adjacent warehouse. Figure 10 represents such operation.

Figure 10 - Oven loading and demolding operations

3.2.2 Production area constraints

While producing Logs there are several operations that occur at the same time. Some are independent, and others are triggered by subsequent tasks that allow them to resume. These operations are grouped within one of the three sector's areas displayed in Figure 11.

-Loading area. This area is composed by all the elements responsible for the transport, storage and deployment of all the three raw materials in the system. This section has no restriction as it is of the operators responsibility to prepare, refill and transport every empty container when is necessary. This should be the main priority in order to keep production flowing during the longest period of time;

-**Processing area**. This area is composed by the press, the scales, the mixer and the system that allows for the movement and transportation of the molds between work posts. Materials can only enter the mixer when the previous load is completely deployed on the mold. When this happens materials (buffing and EPDM's) will be transferred from the scales to the mixer. When this operation is completed binder will start flowing inwards;

-**Demolding area**. The operator in charge for this operation is responsible to remove the molds with material from the oven, demold it, and transport it through a rail system to the press's proximities. It is the most physically demanding operation in the sector. The operation is dependent on the available molds ready to be pulled out of the oven, after baking. The activity will always require significant less time to complete than the press processing operations. The operator's main goal is to never let the press processing operation starve, if there are available molds. In there are not, production will stop until the resource is available again.

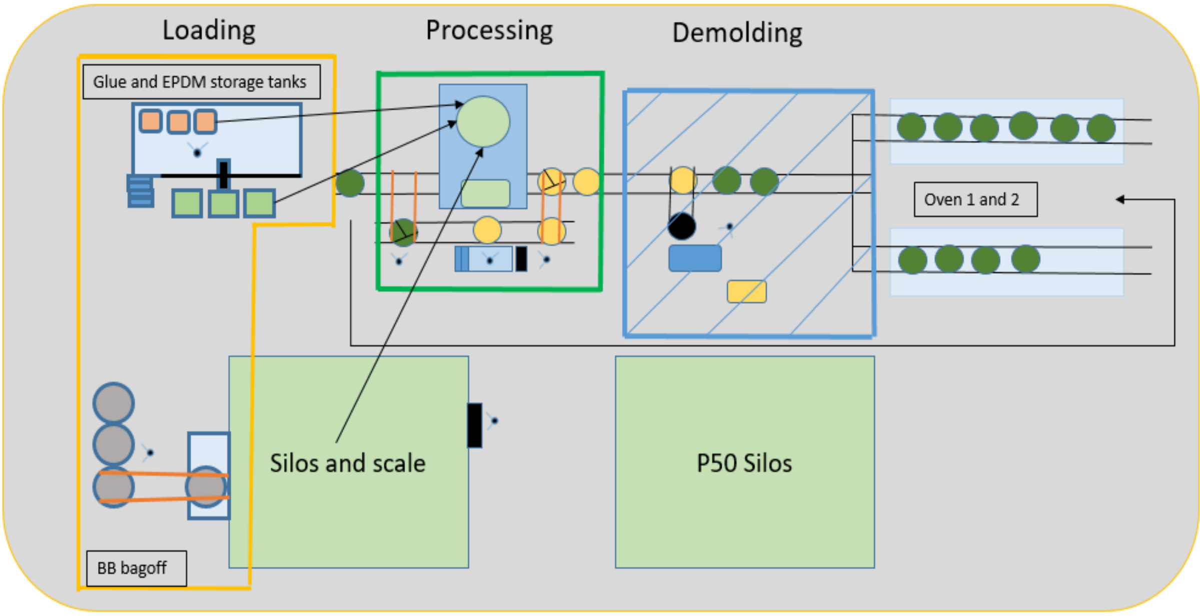


Figure 11 - Sector division by areas

3.2.3 Key parameters that influence production planning

When planning production one must be aware of the main parameters, inherent to each reference, to maximize production rates. There is no linear dependency among them, as none fully depends on another. These parameters are the following:

1. **Raw material** consumption. Each reference has an exact amount of raw material needed to produce a single unit. This will influence the silos consumption rates and their production length;
2. **Number of loads**. Each product will have a specific amount necessary of loads to be completed. Each load will dump a predetermined amount of material into the mold;
3. **Baking time**. There are two default possible baking times. Usually the smaller units will be retained in the oven less time than the bigger ones. This parameter can cause starvation due to limited amount of molds;

4. **Number of molds**. There are only 26 molds, and one mold can only contain one cylinder, regardless of its size. There has to be a careful production planning in order not to run out of molds and stall production. Although the smaller cylinders require less buffing, it will also require less time to be processed. This situation could cause the oven to be the bottleneck of the process and starve all of the following workstations;
5. **Cleanout logs**. Every time there is a need to change the EPDM color or combination a cleanout log has to be created. These Logs only use black buffing and are responsible to absorb all the leftover material on the piping system from the previous series. This will eliminate color contamination between series. This products are not a resource waste, as they are marketable.

The processing time of each Log is dependent on the number of loads, material consumption and operations order. Operator's performance can influence the production rate as well. Changeover times between series also negatively influence productivity.

3.3 Black buffing amounts deficit

The main challenge that the sector was facing occurred only when the production was directed towards the black buffing Logs. The raw material input rates on the system were lower than the output rates when producing the most demanded units. This situation created a deficit in available material amounts, which caused the silos, acting as buffers, to be drained at a faster rate than they could be refiled.

Eventually, production had to be readjusted on the fly to other products, including CR products. This hindered product time deliveries and created inefficiencies by producing less urgent items to stock. The main objective of this project is to extend black buffing related production time and find solutions to improve efficiency within the sector. As a second goal, there was also a need to study how different production scenarios would affect buffing availability and production extension.

BB loading operations

Before tackling the black buffing silos usage rates problem it was mandatory to understand the prior operation, responsible to load black buffing into the system. This operation is divided in the four stage represented by Figure 12, which involve:

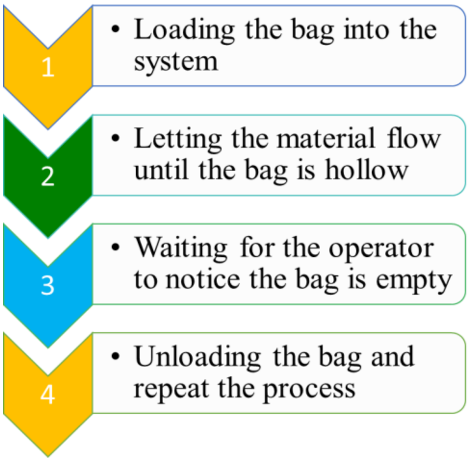


Figure 12 - The 4 stages of the bag loading operations

Stage 1 and 4 can be grouped in one single task that shall be denominated as "Transportation", representing the movements done by the hoist while loading and the unloading the bags from the system's entry. Stage 2 accounts for the duration of time that the bag is deploying material to the system being named as the "Material Flowing" operation.

Once the bag becomes hollow, operators are responsible to proceed to change it. However they take a considerable amount of time to notice that material is no longer flowing out of the bags. The duration of this period is represented as the "Waiting" share. A complete cycle will consist on the following three phases displayed in Figure 13.

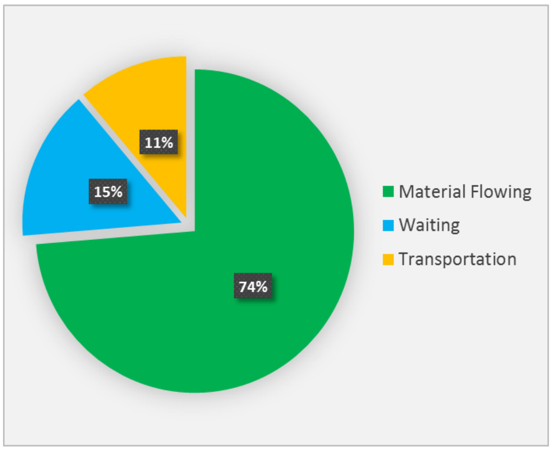


Figure 13 - Loading operations duration breakdown

Therefore, we can conclude that the material is only flowing through the system 74% of the time. This is an alarming scenario as 15% of the total time is completely wasted, impairing the production system, creating buffing shortages and reduced production lifecycles. It is believed that the real waiting percentage is even higher than the one presented, as operators often noticed that they were being observed and proceeded to change the bags. The transportation share could only be removed if substantial investments to the production line were to be made.

4 Simulation modelling

Now that the current situation is properly identified and assessed it is necessary to develop a tool that allows to test the impact that different productions strategies would have on buffing availability and production extension. Therefore, a simulation model was the chosen method to tackle this case.

The manufacturing process studied in this project consists of a series of events that will eventually transform a collection of granulates into a finished rubber cylinder. Although the process may be "continuous" in time, it is possible to abstract ourselves from this paradigm and depict the most significant moments that will produce changes within the system and alter its state. The Discrete Event modelling is a process-centric type of simulation in which the considered production line would fit in. It focuses on mimicking every relevant stage of the process by executing tasks in a certain sequence, creating dependencies upon each other, serializing events and collecting "real time" data when being simulated.

4.1 Model overview

The model creation was only possible after having a strong understanding of the productive process, which allowed for the identification of the most pertinent and impactful operations that were to be featured. As a consequence, this tool does not encompass the totality of the production settings and details. The software used in the project was AnyLogic, which uses Java as its programming language. Besides being able to program in this language, it also grants the access to several logic blocks libraries in which the system will be built upon

At the time of its creation, the model was divided in two main interfaces, with specific purposes. While the "Main" interface was used to create the logic blocks sequence that mimics the real productive process, a second one was designed to be a visual and a dynamic representation of the actions performed in the "Main" interface.

4.2 2D Interface

This 2D representation of the process, featured in Figure 14, has all of the main features displayed. The most relevant equipment and working areas used in the manufacturing process are identified, as well as every major operation necessary to produce a rubber Log. These operations are numerically ordered according to the order of the productive process. Material transport movements and tanks current filling levels are dynamically portrayed throughout every simulation run.

It is also possible to analyze, in real time, the total amount of different materials that have gone through each phase of the process. A counter was added to determine, at any given time, the number of finished goods produced and in storage during the simulation run ("Logs Produced"). On the other hand, the amount of "Processed Logs" represents the number of products that currently occupy molds, but are still going through the productive chain. The designed layout accurately duplicates the plant's real layout as it was intended to approximate the simulation model as far as possible to its real world counterpart.

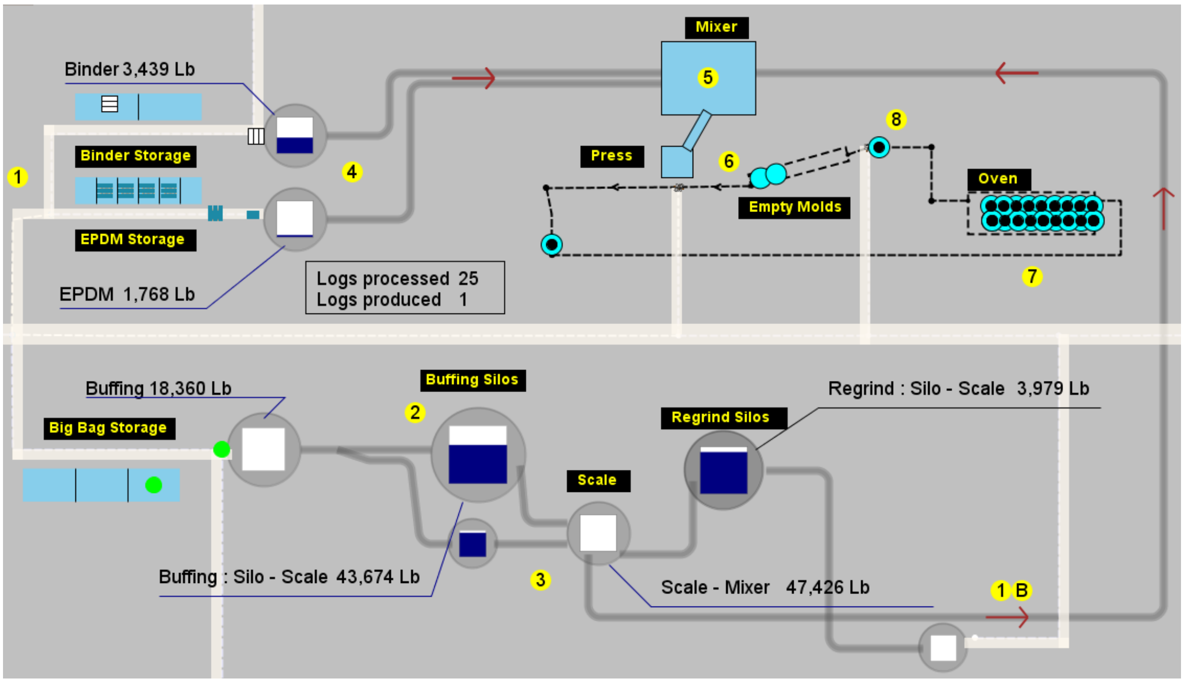


Figure 14 - 2D productive process representation

The operations sequence followed in the process is the following:

1- Raw materials are transported from the adjacent warehouse into the temporary storage sites, before being introduced in the system. Each one of the three materials is represented by three different icons. 1-B represents the same loading operations performed for CR products;
2- As the bags become hollow the material starts flowing to the silos, causing its volume to increase. On the other hand, as production resumes a specific amount of material is blown to the scale causing the opposite effect;
3- When the scale is filled with the required amount, the material starts flowing to the mixer emptying the scale, as it can be noted on Figure 40;
4- Binder and EPDM (if needed) are also added to the mixer;
5- The mixing process takes 60 second and will transform the three materials into an homogeneous mixture;
6- After a definite number of dump cycles a Log will be produced. This operations will require the system to both seize a mold and the press. If there are no empty molds available, production will stop;
7- After being processed, the mold with the respective mixture (blue circle with a black dot) will be transported to the oven, where it will remain until the mixture is solidified and a rubber Log is created;
8- In the demolding station there is a physical separation between the mold and the finished product. The mold, when is emptied (blue circle), returns to the "Empty Molds" site, completing an entire production cycle.

4.3 Main interface

Now that the animation interface was presented, it is essential to demonstrate what causes the actions displayed in such interface. These actions are the product of the interaction between a sequence of DES logic blocks.

4.3.1 Logical blocks libraries

The available blocks are integrated in specific libraries and the two that were used were the "Process Modeling Library" and the "Fluid Library". In the initial stages until material starts flowing into the system, the "Process Modeling library" was used. It captures with accuracy the sequences, events and resources of unitary solid entities throughout several stages. An entities list is displayed in Appendix A.

However, when the material starts flowing into the system it would be too demanding and unnecessary to simulate each granulate as a unit, while considering them all as a single agent would be imprecise. The Fluid library allows the modeling of a large number of discrete objects assuming a fluid-like type of behavior.

This library's blocks were used to simulate the stages comprehended between the material's entry on the system and Log processing operations. From that point on, blocks from the first library will be reused. The most relevant blocks of each library and their respective functions are displayed in Figure 15.

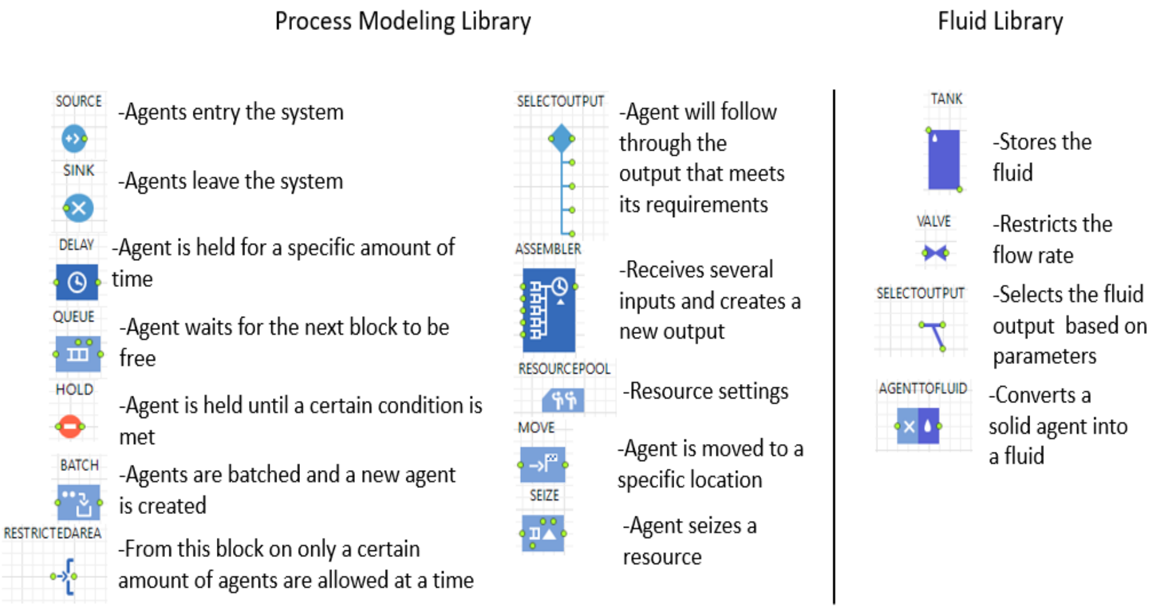


Figure 15 –Most relevant Anylogic blocks used from both libraries

4.3.2 Simulation process analysis

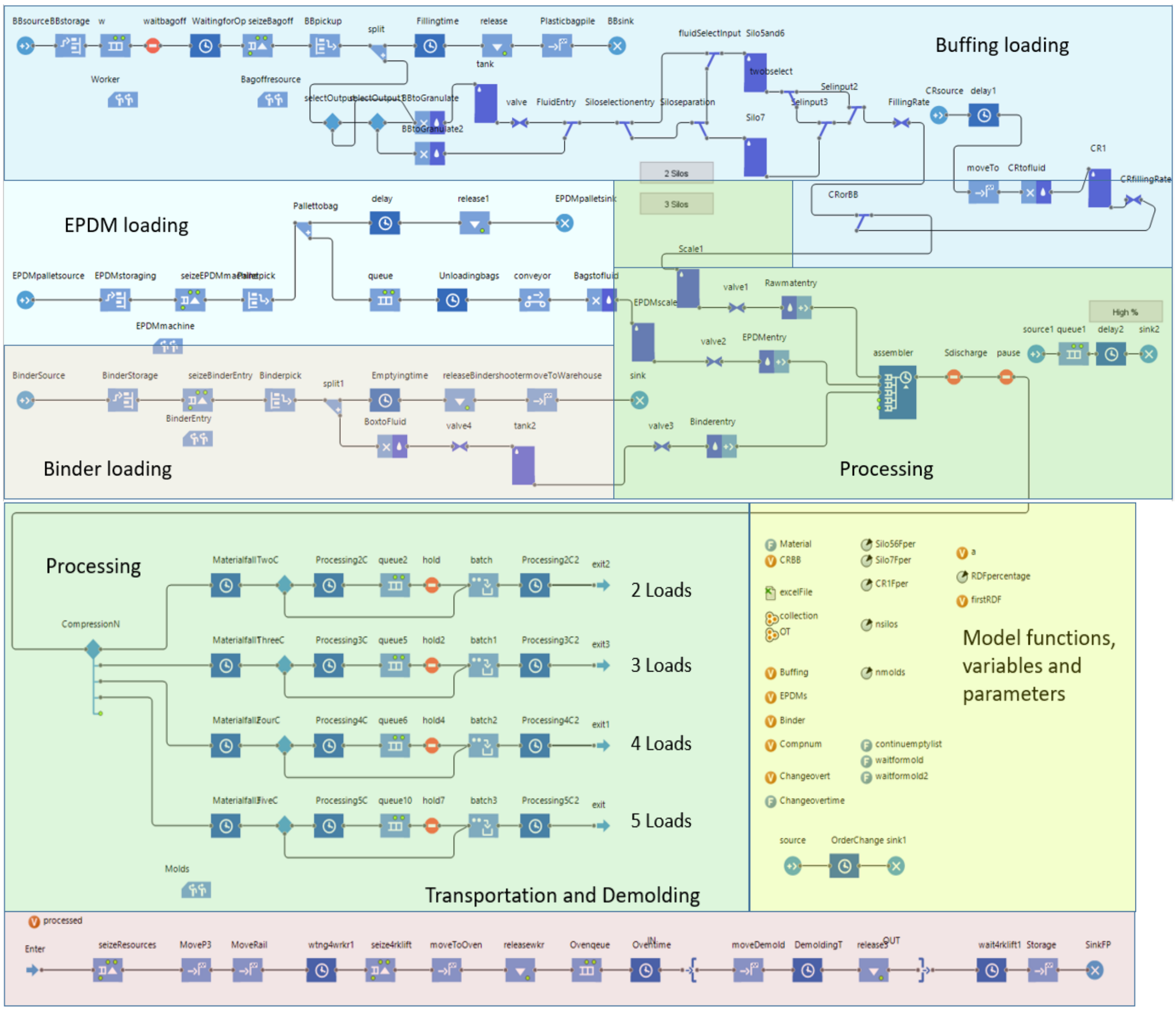


Figure 16 - Main

Figure 16 displays the DES block sequence scheme used to simulate the entire productive process with an uncounted number of production orders combinations. It is able to simulate the time needed to produce a certain set of products and its respective impact on raw material availability. The model can be subdivided in four main areas:

- **Raw material loading operations**. This area includes the loading operations of the three main components needed to produce rubber logs: Binder, EPDM and buffing. All the blocks encompassed in this area are part of sub-processes, representing their respective characteristics. Every sub process serves the common goal of providing input to the mixer, with each loading process having its own particular settings.

- **Processing operations**. These operations represent the core of the manufacturing process from the mixing operation, passing through all the subsequent phases, until reaching the point of having the mold filled with material and ready to be transported to the oven. Processing operations differ according to the number of compression cycles needed to produce a unit.

- **Transportation and demolding**. It represents the final group of operations that stage the latter phases of the production sequence. It features the mold transportation in and out of the oven, as well as the representative baking duration, terminating on the demolding operation.

- **Model functions, variables and parameters**. Within this section are all the variables, functions and parameters that allow the model to detect different production references and dynamically adjust the system to meet their requirements. These requirements range from the specific raw materials amounts needed to form a unit, to the required duration spent inside the oven baking, among many others. Each reference has its own independent characteristics.

4.3.3 Sub-processes

Having the main process identified and analyzed, it is relevant to proceed to a more in-depth examination of each one of the sub-processes included in this manufacturing line representation. The main objective is to grasp the relevant features of the actual process in each stage, and how they were transferred to the simulation model.

1- Raw materials loading operations

a. Buffing loading

Phase 1

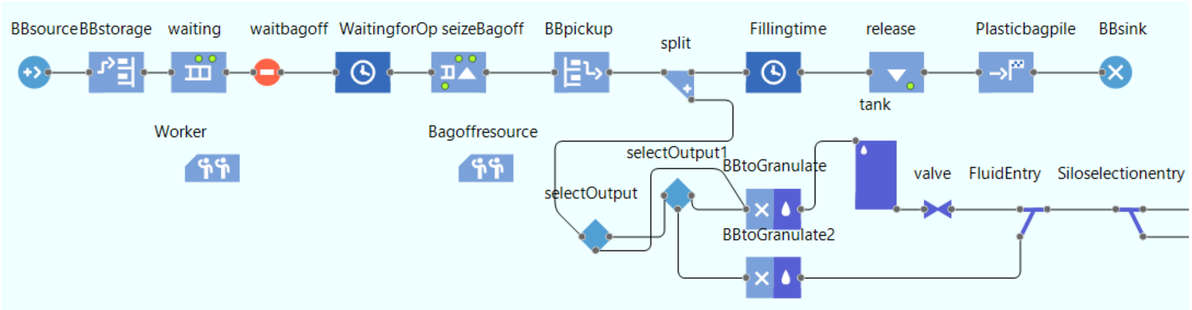


Figure 17 - Buffing loading block scheme, phase 1

The complete operation, represented by Figure17, is triggered by an inject function on the source block (“BBsource”). This will generate the first two black buffing entities that will be stored in a temporary storage space (“BBstorage”). This action will use a resource (“Worker”) to move the entities from the system’s entry point to the temporary storage space. The resource speed will not influence operations as all movements are set by “Trip Time”.

Next, the Queue and Hold blocks will not allow for more than one entity to advance to the next set of blocks if they are still occupied. It aims to represent the current bag loading situation, where no more than one bag can be used at any time. In order to do so, a resource is seized to grant its availability (“Bagoff”) and the material will be moved from storage to the equipment. Previous to that, however, there is a delay block that pauses the operations, which is used to simulate the time operators take to notice the bag needs changing.

Afterwards, two “Select Output” blocks are used to assure that the supplier usage ratio is fulfilled. The company currently uses two buffing suppliers with a 2:1 ratio that offer a slightly different weight amount per bag. The first block grants that the first used bag will always be from supplier 1, while the second block relies on a preset probability value that will direct the entity to one of the possible exits.

Depending on the output selected, a certain amount of time, represented by different transformation rates, will be required to transform the entity (buffing bag) into granulates. This will represent the time material is flowing into the system. To simulate this event, fluid library blocks were used to simulate the granulates fluid-like behavior. When material stops flowing it will trigger an action responsible for repeating the cycle, temporarily releasing the Hold block and letting other entities pass through, as well as generating another entity from the source. At the same time, the previous bag entity will be eliminated from the system.

Phase 2

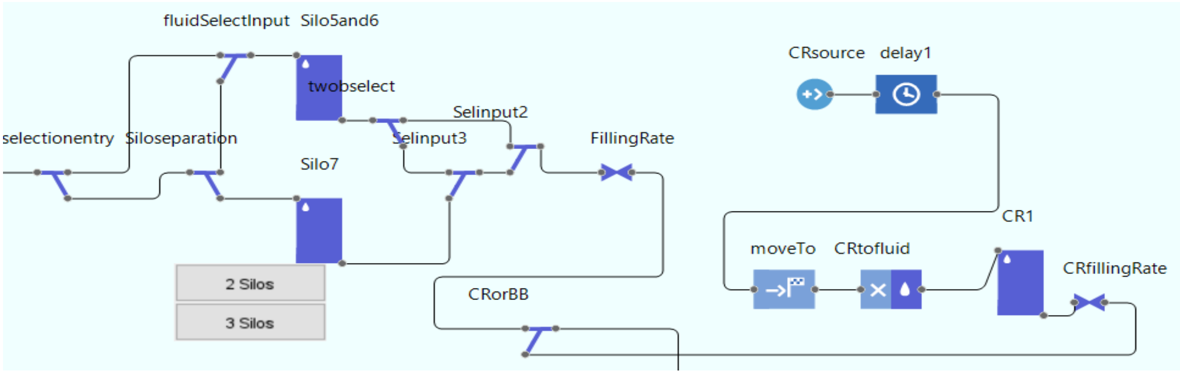


Figure 18 - Buffing loading block scheme, phase 2

The second phase, portrayed in Figure 18, commences with granulates, now considered as fluid, passing on to the silos. By default, the model is programmed to direct the material into Silo 5 and 6. In reality, these two silos are separated, but for modeling purposes they were considered as a unit, represented by the same "tank" block. As there was an intention to test the impact of having an extra silo, acting as a buffer in the system, a second block was modelled.

If a three silo usage scenario is planned, the respective button should be pressed, which will enable the system to fill and drain material from this extra block. Although "Silo 5 and 6" always have priority, the system will switch its input and output selection to the third silo if it is full or empty. The situation will be reversed in the opposite case.

The following valve ("Filling Rate") represents the rate at which the scales will be filled with material flowing from the silos. At the other side, an equivalent, although simpler, bag loading process is displayed. It represents the CR products loading process. In the end, it is represented by a Select Input valve ("CRorBB"), which will select which silo material will be drain from according to the reference being produced. This aims to emulate a real case scenario, where different references will use different types of rubber.

b. EPDM loading

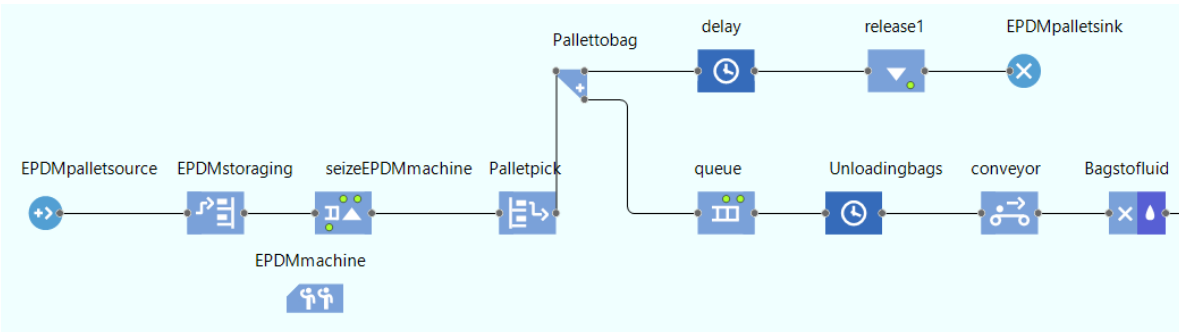


Figure 19 - EPDM loading block scheme

Similar to the black buffing loading operations, the EPDM are also drawn to the system via an initial "inject" function. The operations are similar to the previous case, except for the resources used. Instead of a "Bagoff" equipment there is an EPDM machine that needs to be available for the resources to be proceed, while workers will perform the transport operations.

The EPDM entity that will be sourced first will correspond to a pallet filled with EPDM bags. Only after being removed from the temporary storage to be put into use, will the entity be transformed in bags. A pallet consists of 40 bags, entities which will be created upon the Split block ("Pallettobag") and queued on the following block.

In the last stage, there is a delay block representative of the duration needed for operators to load the required bags into the tanks, which will restart the cycle when the operation is completed. A pull system is implemented, which will cause material only to be drawn when needed. This is accomplished by the use of a conveyor block that will hold the material flow every time the following operations are resuming. Once the EPDM is in the system it will also adopt a fluid's behavior, represented by the library's transition blocks. This process's representation is demonstrated on Figure 19.

c. Binder loading

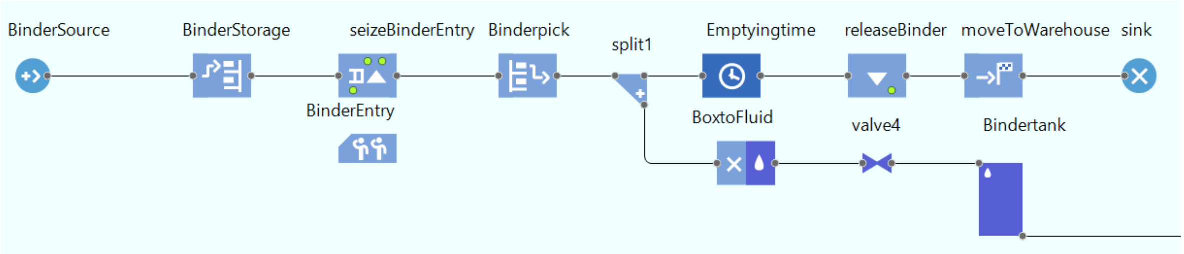


Figure 20 - Binder loading block scheme

Figure 20 represents the last of the raw material's loading operations, which uses Binder containers as entities. The first part of the scheme is similar to the other two, apart from the resource used ("Binder entry"). The main distinction occurs when the liquid inside the container is poured into the system's reservoir ("Binder tank"), eliminating the previous entity and adding a fluid to the system. A valve was created to assure that a new container will only be put into use when the reservoir is emptied, triggering an action that will restart a new cycle.

2- Processing operations

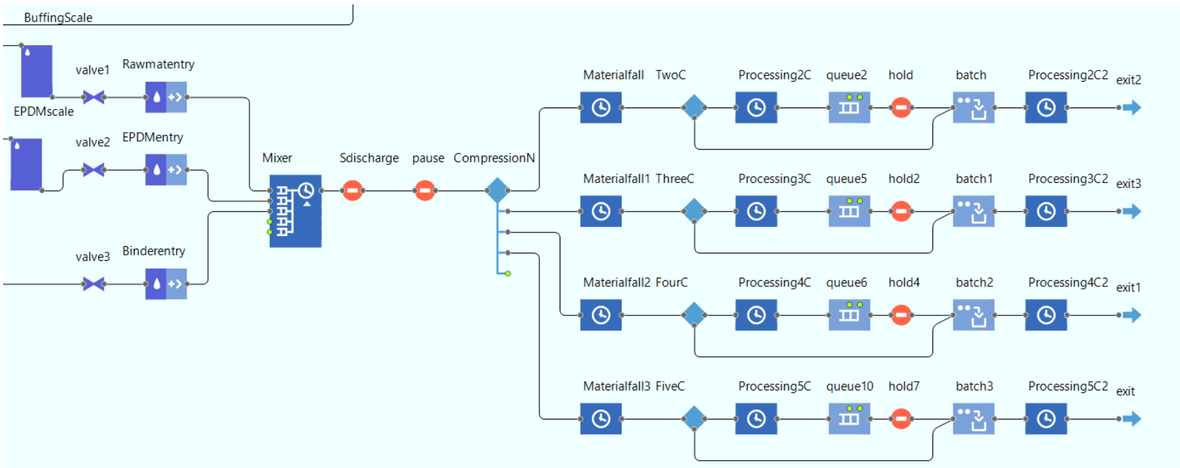


Figure 21 - Processing operations block scheme

The core group of operations required to manufacture a rubber log is displayed by Figure 21. The scheme has been reorganized to provide a more compact view of this operations group. It can be divided in two main phases: the operations that occur after and before the mixing.

Phase 1. Both EPDM and buffing flows will have material drained from the respective tanks and silos into the scales. Then, both valves 1 and 2, which are initially closed, will open to let material flow to the mixer. The flow rates are adjusted accordingly so that the same amount of material weight per second corresponds to the implemented rate on the plant.

The model is able to read the exact amount of weight needed to produce each reference. When that quantity is reached the valves will close again until the process is restarted. The process resumes, after which the material passes through this valves and reaches the mixer. Upon the completion of this operation valve 3 is opened, allowing the binder to be added to the mix tank that will process all the materials for 60 seconds.

Phase 2. After the mixing operation is completed it may or may not advance to the next stages, depending on the previous round of material having already exited the press processing operations. It resembles the production line, where no more than one block can be processed at the same time. If no processing operations are taking place, the Hold block ("Sdischarge") will release the material, enabling it to continue its process. The second hold block is then triggered and pauses the system for a specific amount of time. It is designed to simulate the downtime of the production line.

Depending on the number of material dump cycles needed to create a product, the model, according to the imported data, will align the material with the corresponding output. Each output has the same structure, starting with a delay block that simulates the time material takes to be dumped into the mold, which is followed by processing operations requiring the press. When it reaches the hold block it will trigger an action that will release the next load of material from the mixer ("Sdischarge" release). This cycle will be repeated until the last material load is dumped. When it happens the hold block will be released agglomerating material from all cycles and batching them on a mold. After further processing operations a Log unit is created. If there are no available molds the model will pause until the situation is settled.

3- Transportation and Demolding

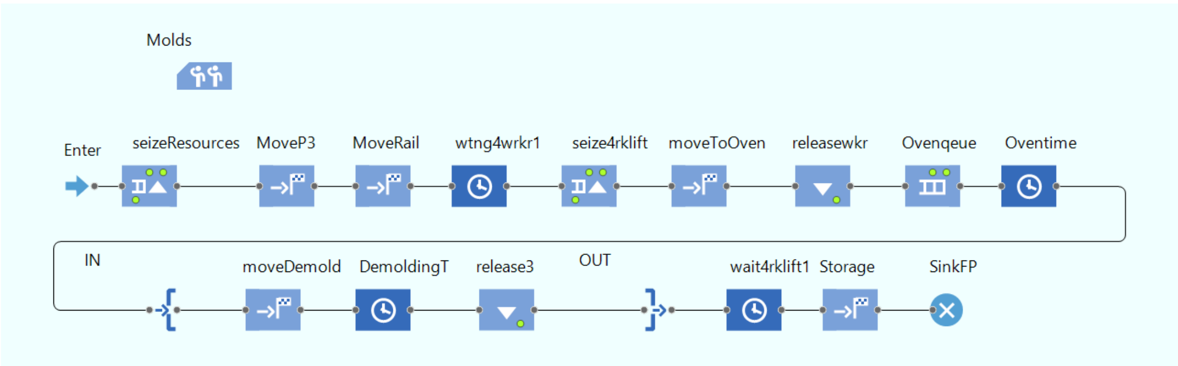


Figure 22 - Transportation and demolding operations block scheme

The last processual set of operations, portrayed by Figure 22, commences with an "Enter" block that will transfer the entity from any of the previous sets. It involves several "Move to" blocks that represent mold transportation movements and "Delay" blocks. While the first "Delay" block depicts the average waiting time needed for the operator to transport the mold into the oven, the second one represents the amount of time a log should be heated for. It is a variable parameter depending on the produced reference. The oven has a capacity for 18 molds, and if exceeded it will require material to queue until there is vacant space.

Lastly, the demolding operations take place within the "Restricted Area" blocks. These blocks have the sole purpose of only allowing the processing of a single unit between them, as it happens on the plant where no more than one unit can be demolded at a time. It involves the mold transportation ("Move to"), the demolding operation duration ("Delay") and the consequent release of the resource (Mold resource). Eventually, the mold will start a new processing cycle, receiving material from the mixer and the finish good will be stored.

4- Model functions, variables and parameters

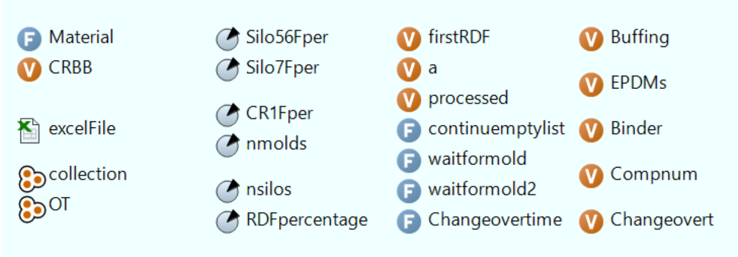


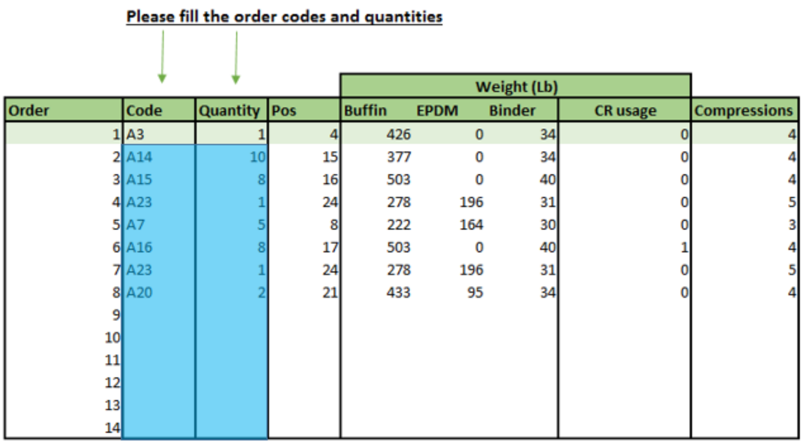
Figure 23 - Part of the model's control elements

This is the model's processing center. It includes variables, parameters, functions and collections, among others. It provides logic blocks with the ability to accurately simulate the production of more than 20 types of log products. As data is not inserted in the model, this sector's components act as a link between data on spreadsheet and logical block's actions. The process starts with the data entering on a separate document. Some of the model's control elements can are displayed by Figure 23.

Data inputs

Every product has a number of specific parameters that differ between them. All its related data are stored in Excel tables on an external document. From this document it is possible to choose what products to produce and the order at which they will be produced in order to simulate a production run. They are divided in 24 product categories that aggregate 94% of all the produced references in 2016. This document's template is exposed by Figure 24.

After selecting the products, their quantity and the order in which they will be produced, two production lists will be created. One will store data necessary for the system to read every time a material load passes through the Mixer, while the other has parameters to be read after a complete Log is formed. Both of the lists will be exported from the Excel spreadsheet to two "collections" present in the model.



Please fill the order codes and quantities

Order	Code	Quantity	Pos	Weight (Lb)			CR usage	Compressions
				Buffin	EPDM	Binder		
1	A3	1	4	426	0	34	0	4
2	A14	10	15	377	0	34	0	4
3	A15	8	16	503	0	40	0	4
4	A23	1	24	278	196	31	0	5
5	A7	5	8	222	164	30	0	3
6	A16	8	17	503	0	40	1	4
7	A23	1	24	278	196	31	0	5
8	A20	2	21	433	95	34	0	4
9								
10								
11								
12								
13								
14								

Figure 24 - Production planning template

Every parameter stored in the "collections" is associated with a dynamic system variable. These variables will assume the current first value of the list, on a specific column. At the end of each cycle, the first line of each collection will be removed and the following will take its place, repeating the cycle until it is finished. The "collection" size at any given moment represents the number of material loads left, while "OT" represents the number of products still to be produced. The parameters that do not have an assigned variable are "read" directly on a model block. There are also extra features added, as changeover times between series or customizable settings as number of molds available or silos filling rates. In Figure 25 it is shown how data is divided and categorized in the model.

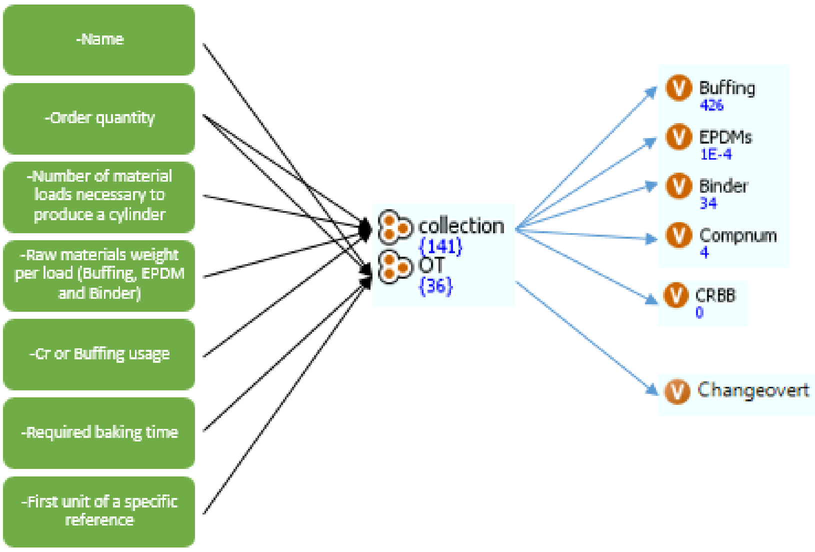


Figure 25 - Simulation model data inputs

4.4 Model validation

The software version used has a Fluid Library limitation of only one hour. As this time frame was too short to enable the evaluation of a daily production situation all the operations were set to run at a rate 10 times faster than reality. The model uses seconds as its time unit, therefore 1 second on the model will correspond to 10 seconds in a real situation. By doing this, the model will run for the exactly same 3600 seconds, but it will be able to simulate 10 hours' worth of production. This proved to be enough to simulate the great majority of the working days, however as there is a great variability in terms of working schedules production may last more than 10 hours in particular situations. When this situation took place the model was re run with the remaining production orders, and times were added to reach a final simulation value.

In order to validate the model, production sheets were used. The model was run for 50 dedicated Log production days. This number was thought to be sufficient, as it portrayed the sector's reality for over 3 consecutive months. These products are not exposed to seasonal fluctuations and maintain a steady demand year round. Other indicators might have been explored to validate the model (e.g.: silo's volumes), however the only available data was production time recordings and the respective quantities and references produced within that time frame.

Each production sheet has the references produced in the respective day, the order they were produced in, the quantity of products made in each series, as well as all the stops, and their duration. With that information it was possible to calculate the daily operating time for each one of the 50 days. All the daily data was introduced by the same order in the excel tool displayed in Figure 24. Then, the data was imported to the model, which was run sepparately for every day.

Table 2 - Part of the spreadsheet used to compare simulation runs with the daily production

Date	Units produced	Production time (h:m:s)	Simulation time (h:m:s)	Production time (sec)	Simulation time (sec)	% dif	Difference	Position
01/02/2017	21	05:30:00	05:22:05	19800	19325	2,40%	00:07:55	Under
02/02/2017	43	11:36:00	12:02:30	41760	43350	3,81%	00:26:30	Over
03/02/2017	31	07:54:00	07:44:37	28440	27877	1,98%	00:09:23	Under
04/02/2017	29	06:30:00	06:38:47	23400	23927	2,25%	00:08:47	Over
08/02/2017	34	09:12:00	09:23:07	33120	33787	2,01%	00:11:07	Over
09/02/2017	37	10:14:00	10:22:50	36840	37370	1,44%	00:08:50	Over
10/02/2017	23	06:36:00	06:21:45	23760	22905	3,60%	00:14:15	Under

Table 2 represents part of the table used to store the information regarding the obtained results for each day. It calculates the daily error by comparing the real production time and the time the model took to simulate the same situation.

There was the need to validate the model by applying a forecast method with a Scale independent Measure, and the Mean Absolute Percentage Error (MAPE) measure was the chosen method. It is one of the most widely used forecast measures and it will measure the sum of the average absolute error between simulation and real production times. As production time units will never reach any value approximate to 0, and Simulation and Production times will not differ greatly, the MAPE measure could be applied to this model. This enabled the testing of several hypothesis with a sufficient degree of trust.

Percentage Error

$$PE = \left(\frac{A-S}{A}\right) * 100 \qquad (4.1)$$

Mean Absolute Percentage Error (MAPE)

$$MAPE = \frac{\sum\lfloor PE \rfloor}{N} \qquad (4.2)$$

Where: A=actual value, S=simulated value and N=number of observations

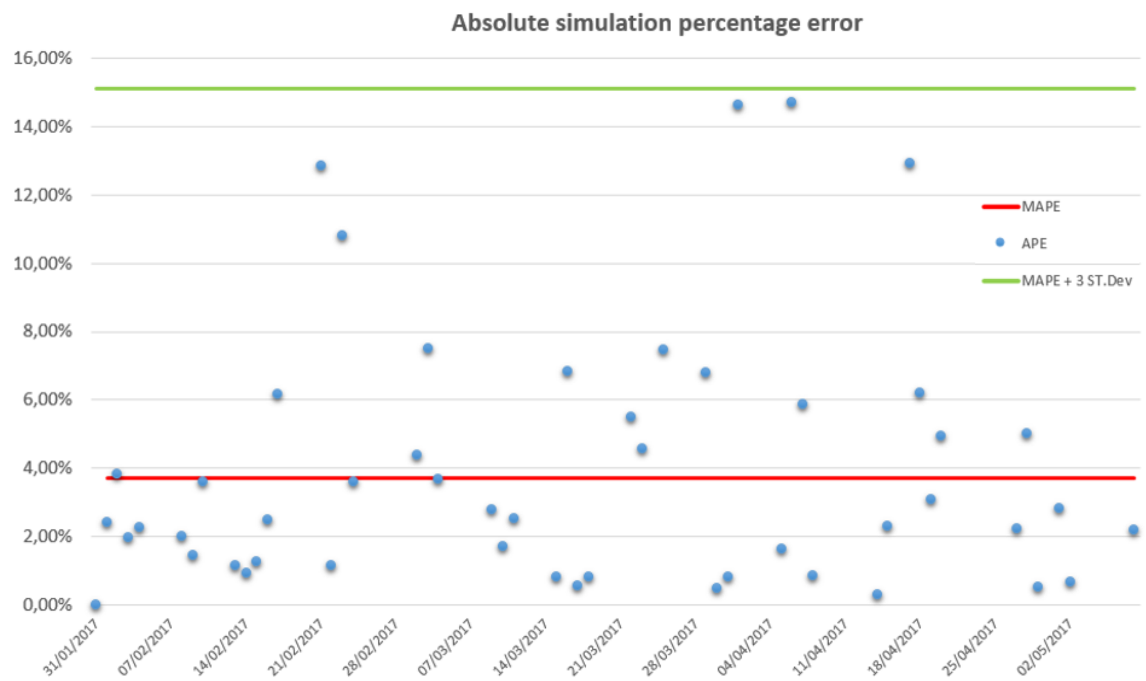


Figure 26 - APE obtained during 49 production days

Figure 26 displays the APE in each of the 50 days whereas Table 3 shows the statistical values obtained when comparing the sum of both simulation and real production times. Despite the initial population consisting of 50 production days, (displayed in Appendix C), it had to be reduced to 49, as there was an outlier that impacted significantly the results (22% APE) and had no apparent explanation. As it exceeded the APE plus 3 standard deviations value it was excluded. The before and after results can be compared by analyzing Table 3A and Table 3B, respectively.

Table 3 -Model validation data

A	Production time	Simulation time	B	Production time	Simulation time
Seconds	1540367	1494099	Seconds	1502207	1464570
Minutes	25673	24902	Minutes	25037	24410
Hours	428	415	Hours	417	407
MAPE	4,37%		MAPE	4,00%	
Standard Deviation	4,51%		Standard Deviation	3,71%	
MAPE+3*StandDev	17,89%		MAPE+3*StandDev	15,13%	
Production days(N)	50		Production days(N)	49	

4.5 Error discrepancy causes

There are several variables that can cause the model to produce a higher error when compared to the actual production times. These are the most common:

-**Unitary series**. A big number of consecutive unitary series will lead the model to produce a higher APE. Although an average changeover time has been considered while modelling, there are considerable variations between series that depend on a great number of situations and are difficult to estimate. The discrepancy is enhanced when special Log products are manufactured, with uneven production times. All the simulated days that had an APE over 10% share this characteristic;

-**Silos levels amount**. As the raw material amounts in the silos diminishes, the system may take more time to blow them through the pipe system, slowing the process;

-**Operators**. There are no fixed workstations as operators rotate throughout all of them in a week. Although being an experienced group there may be some delays caused by distractions and different performance levels.

5 Production improvement

5.1 Buffing consumption

In order to better comprehend the silos output situation, it is necessary to understand the different impact that each one of the 24 beholden products have on the silos levels. Simulation runs were made for every one of them, at cruising speed, in order to estimate production rates. No stops, initial variations or breaks were considered during the 3h worth of simulation per product. Production rates and other related relevant data for the company was retrieved. Part of it is shown in Table 4. Now it was possible to understand how production is affected depending on the products manufactured. As expected, all the references that have a positive impact on the silo levels are the ones that do not require black buffing. The values attained may experience a slight variation depending on the supplier bag types used. This document becomes relevant for the company as no information regarding production times and their respective impact on the silos existed thus far.

Table 4 - Production related data

Reference	Weigh variation/hour	Production rate	Production/3h	dif amount silos/unit	Min/unit	%variance on silos/hour	%variance on silos/unit
A15	-2870,00	4	11,5	-748,70	00:15:39	-10,05%	-2,62%
A17	-2653,00	4	12	-663,25	00:15:00	-9,29%	-2,32%
A18	-3383,33	5	15,66	-648,15	00:11:30	-11,85%	-2,27%
A19	-2531,79	4	12	-632,95	00:15:00	-8,86%	-2,22%

Now that the in and out silos rates are better comprehended we can conclude that:

-Material is flowing to the silos 74% of the time (44 minutes / hour, carrying approximately 4600 lb. / hour)

-Buffing requirements vary from 620-2012lb per Log (if CR Logs are excluded, which would use 0 lb. per Log) and unitary completion times range from 8-16 minutes, depending on the reference.

Figure 27 is an example of the simulated amount of black buffing in the silos over the course of three days. This simulation was done accordingly to the production sheet of the correspondent days (9-11 of March) in terms of references, series and operational time. It was assumed that the silos were full on the first day. Throughout set up and cleaning, loading operations were maintained.

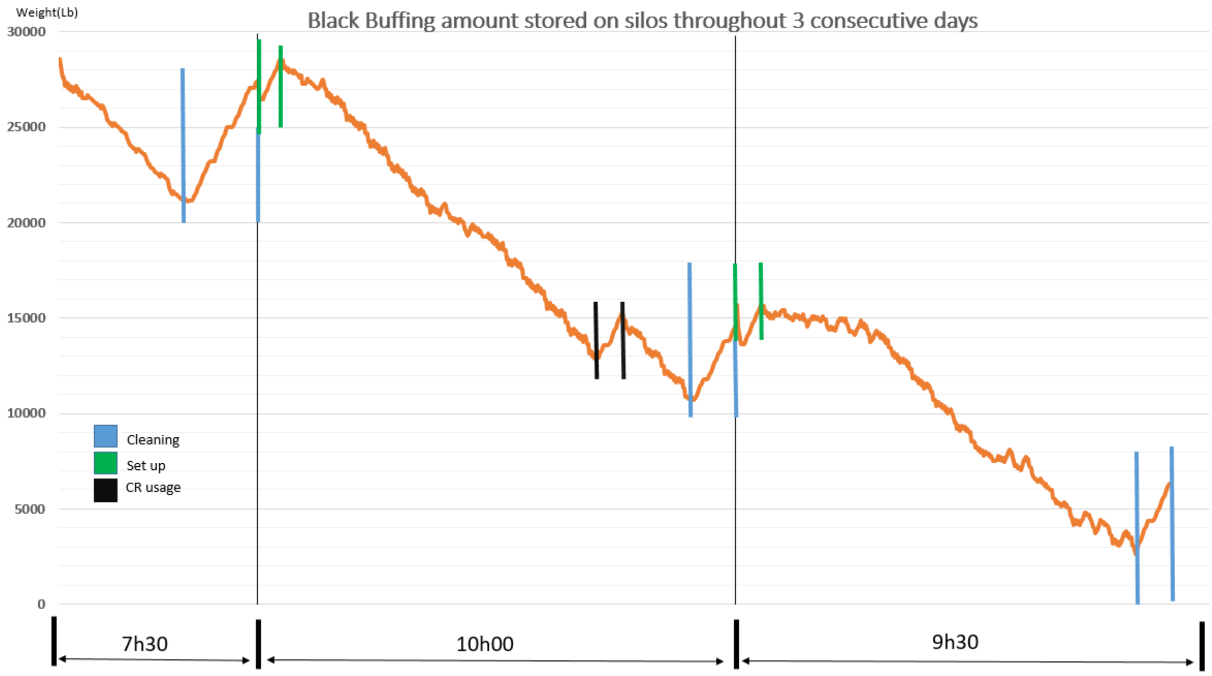


Figure 27 - Available amount of black buffing during a three day production sequence

From this graph it is possible to analyze the result that different series and products have on silos levels. There is a big contrast on what happened on the 10th of March, where a large amount of high demanding black buffing products were manufactured, with few changeovers, taking a considerable hit on the silos, and the first part of the 11th of March. In this case, levels remained almost unaltered as a consequence of several small series, which resulted in a higher number of changeovers. The products produced also required less material when compared to the previous set.

5.2 Loading scenarios

A normal Log run usually lasts between two and four days, depending on production planning and the availability of black buffing. It would be interesting to analyze how the buffing amount on the silos would vary if inefficiencies were to be eliminated. To study these situations and discover if production runs could be extended, and if so, for how long, three distinct loading scenarios were simulated:

1-Current situation: Divided in three phases: “Material Flowing”, “Transportation” and “Waiting”. It represents what is happening at the present;

2-Improved situation: In this hypothetical situation, operators would always be aware of when to switch bags and non-productive times would be reduced to transport movements;

3-Ideal situation: It is assumed that the process would never have to stop due to operator negligence and there would be two transport equipment that allow constant material flow. The following bag would always be loaded and ready to deploy material.

It was assumed that situation 3 would only be attainable after situation 2 is achieved and never as a direct alternative (removing the transportation times and still considering operator waiting times is not a practical solution). This would require a significant investment and the productivity returns would be lower than situation 2. Therefore, situation 3 is considered to be a second phase improvement operation after situation 2 is accomplished. Table 5 shows the differences between these 3 scenarios. It is relevant to state that situation 2 would not require any type of investment, just a better organizational strategy within the sector.

Table 5 - Comparison between the three different operations loading scenarios

	Material Flowing		Waiting	Transportation	Material weight amount loaded into the system (Lbs./Hour)		
Scenario	Min. / Hour	%	%	%	Total	Weight increase	Percentage Increase
Current	44	74%	15%	11%	4625		
Improved	52	87%	0%	13%	5449	824	118%
Ideal	59	98%	2%	0%	6000	1375	130%

* % refers to the occupied time percentage, within an hour, to perform a given operation

As it can be concluded by the presented data, only by eliminating the operator waiting time it is possible to deploy material for an extra 8 minutes per hour, increasing system occupation time in 13%. This situation would allow the silo to have 18% more material flowing per hour when compared to the current situation. Transportation percentage is increased in this situation because cycle time is reduced by eliminating the "Waiting" time share.

The ideal scenario shows even more impressive gains, by having material flowing almost constantly. However, physical restrictions on the system will not allow for a constant flow. This scenario grants a 30% increase in material flow amounts over the initial situation. It is expected that 6000 Lbs. of raw products could be loaded, representing approximately three full bags of material.

Figure 28 is an example of three consecutive production days that displays the comparison between the three presented scenarios (simulation of the silos buffing amount between February 8th and 10th). As it can be noticed, the silos ran out of material after the third consecutive production day in the current situation. The differences between the three scenarios becomes more evident over the course of the days. If by the end of the first day the material disparity in the silos is already considerable: 7500 Lbs. (1), it reaches a staggering amount of 17800 Lbs. by the end of the second day (2), which represents the amount contained in nine bags of material. The difference is more apparent when comparing the "Current" and "Improved" scenario, which would be the simplest to attain. The "Ideal" scenario shows even higher gains that are not as relevant. This happens because the mid solution is capable of extending production over the desired amount of time, without recurring to investments.

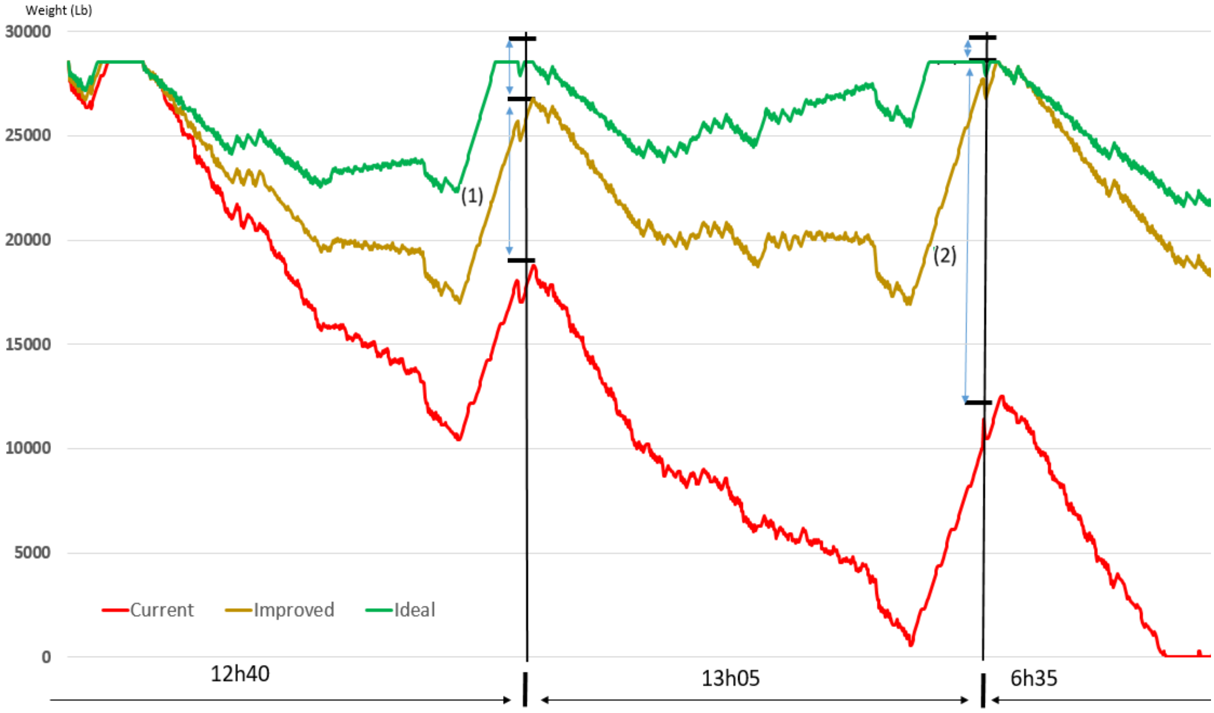


Figure 28 - Comparison of the different black buffing amounts available in each one of the 3 scenarios

These three days sequence is just an example as no production sequences are the same. Production days, client orders, series numbers, production sequence, downtimes duration, cleaning and set up times vary daily. This sequence was chosen because it can be considered as a realistic worst case scenario regarding buffing utilization. The three analyzed scenarios impact black buffing availability in a very disparate way. In Appendix E, the three scenarios analysis to the previous represented situation in Figure 27 is portrayed. After the study of several production sequences it can be concluded that the "Improved" scenario would allow management to produce the desired items without experiencing raw material shortages.

5.3 Black buffing exclusive production sets

It was also on the company's best interest to understand how the amount of raw material in the silos would be impacted if bag loading operations were sped up. Currently, in case of black buffing shortages, production is switched to CR logs. These products recurrently represent a deviation from the intended production orders schedule used to keep production running while silos are being refilled.

It is vital to understand if, in the case of waiting times being eliminated, there would be enough of a gain that allows silos to have sufficient material to continue black buffing related production. Or, on the other hand, by proving that the system would not be improved to an extent that would enable production to resume even if no CR production is intermixed.

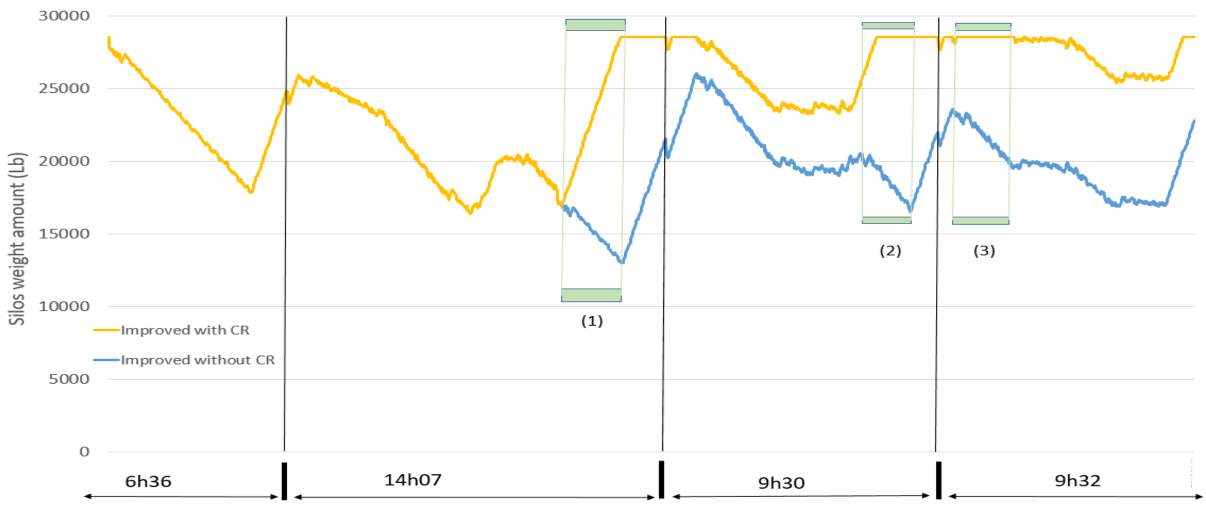


Figure 29 - Comparison of a production run simulating the impact of CR products

Figure 29 displays a four day production sequence that took place in the first days of February. During this sequence there are three time frames, within the green rectangle, which represent CR products manufacturing time. The yellow graph illustrates the amount of buffing in the silos assuming an "Improved" scenario, while following real production orders. On the other hand, the blue graph portrays the same case excluding CR production and replacing it by highly demanding buffing products.

The main aim of this simulation test was to prove that just by having a better organizational strategy inside the sector ("Improved" scenario) it is possible to grant the full availability of raw material throughout the production run. Therefore, management is expected to produce the ordered references without production shifts. Several sequences were simulated to reach this conclusion and there was an intent to study worse than reality cases by assuming that all CR products were superfluous, which is not the accurate.

5.4 Production hypothesis

As product demand is rising, there are some changes that are being considered to be implemented in the line in order to adapt production to an increasingly challenging scenario. There is a need to forecast the outcome and the impact that any of this proposed measures will have on productivity. Therefore, a number of different alternatives was simulated.

5.4.1 Testing Assumptions

All of the simulation runs were based on certain assumptions, which are expected to accurately reproduce the real production scenarios. In order to make up for any modeling errors, all tested scenarios were overestimated in order to produce a worse than reality results.

All simulation days were shorter than their real counterparts, as it can be analyzed in Table 6. Task’s duration was reduced during nonproductive times, when silos are being refilled and production is stopped. By doing so, in all tested scenarios, a large enough margin is created to accommodate any given modelling error.

Table 6 - Operation’s duration breakdown

	Simulation	Reality
Production time	08:40:00	08:40:00
Set up	00:30:00	00:30:00
Cleaning	01:00:00	01:30:00
Lunch Break		00:30:00
Unplanned Stops		00:30:00
Total	**10:10:00**	**11:40:00**

It was assumed that a production day would be divided in: Productive time (8h40) and non-productive time: Cleaning (1h00) and Setup (0h30) .This configuration is supposed to represent a harsher setup, by considering shorter Cleaning times and no maintenance or lunch breaks. During the entire 10h10 bags are loaded accordingly to the three previously exposed scenarios: “Current”, “Improved” and “Ideal”. Subsequently, there was a need to create 2 different production sets. As no production days are the same, these sets were based on the 2016 production quota by product. These production sets aggregate a group of series composed by a quantity of similar products (same reference). They are the following:

-**Extreme**. This consists of the worst possible case situation in terms of buffing consumption featuring two of the most demanding references and only 2 changeovers throughout the entire set. It is a fictional case just to test the maximum system capacity, as the probabilities of production being planned accordingly are extremely remote;

-**Mild**. This situation tries to emulate a demanding but possible production day. The fact that it is repeated during consecutive days makes it unlikely. It features the six products with the biggest production quota and includes a CR series.

These daily series were repeated for several days until the silos ran out of material. The quantities on each of the last series were overestimated so production would never stop before the established time (8h40). On the following day, production orders were repeated from the start, with the material amount left from the previous day. Starting from this point the following hypothesis were simulated.

5.4.2 Third silo addition

In the production room there are a total of six silos, two are used to store black buffing while other two store CR material. There is also an extra equipment that can be adapted to store black buffing. It was suggested to simulate the impact that a third silo would have in terms of production extent and if it would be a viable option to add it to the production system. During these simulations it was assumed that all the silos would function similarly. Several simulation runs were made to test the three loading scenarios while producing both sets.

Extreme set

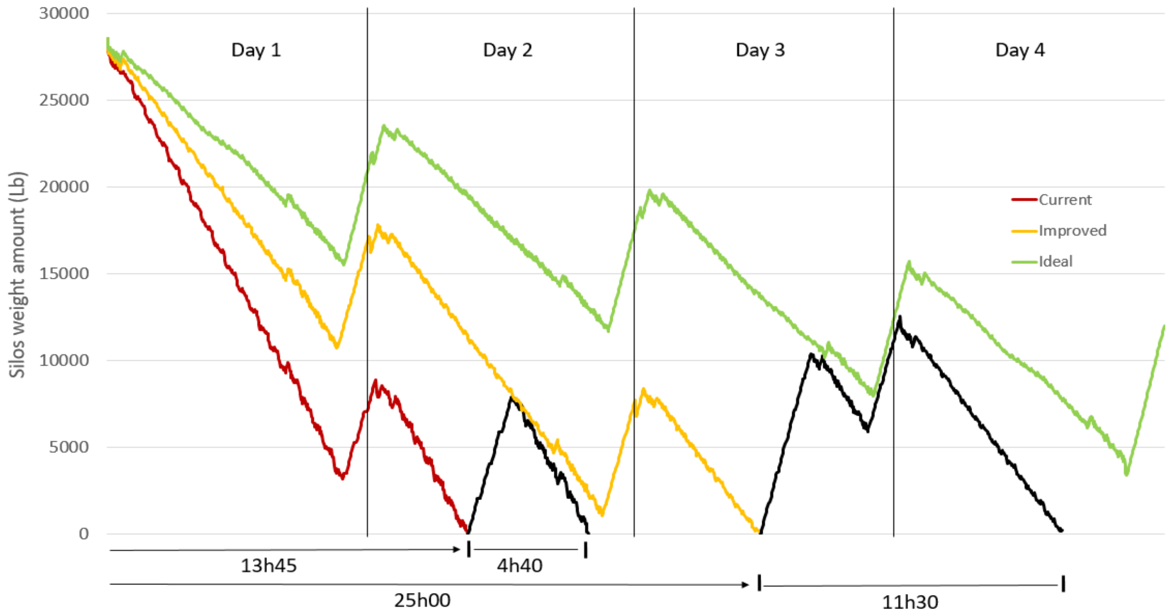


Figure 30 - Amount of buffing in the silos – Extreme set

The three scenarios are represented by their respective color while the impact that a third silo has in each situation is displayed by the black colored charts. Figure 30 represent the amount of material that is stored in the silos over the course of four production days (maximum number of consecutive production days per week). Different conclusions can be drawn from each scenario.

-Ideal: There is not a need to add an extra equipment as production is able to withstand even the longest production sequences;

-Improved: The added silo would enable the system to produce the great majority of high demanding combinations over the course of four days. However, as most sequences last an average of three days and do not include extreme sets, it is believed that implementing an "Improved" scenario while functioning with two silos, could tackle most of the production's challenges;

-Current: Current loading operations do not enable the system to produce consecutive demanding sets. Adding other silo would improve the situation, but it would still be considered unsatisfactory.

Mild Set

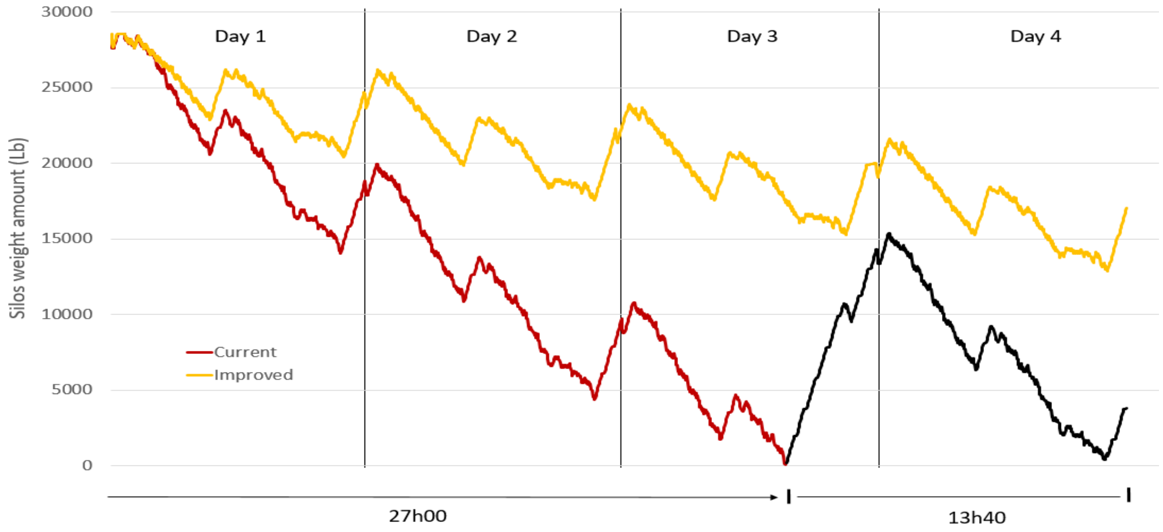


Figure 31 - Amount of buffing in the silos – Mild set

When simulating a "Mild" set, it is possible to observe, from Figure 31, that only two scenarios are considered. The "Ideal" scenario was disregarded because it can endure the most challenging set throughout four consecutive days. Examining the remaining options, it can be concluded that the "Improved" scenario can endure the maximum amount of production days, hence an extra silo is not needed. On the other hand, it is believed that current operations could undertake some production combinations, but it would be beneficial to add an extra silo to guarantee all "Mild" sequences.

Overview

Table 7 - General overview of the extra silo adding situation

Loading scenario	Mild Set			Extreme set		
	2 Silos	3 Silos	Prod. Time increase	2 Silos	3 Silos	Prod. Time increase
Current	27:00:00	M	**150,00%**	13:45:00	18:25:00	**133,94%**
Improved	M	M		25:00:00	36:30:00	**146,00%**
Ideal	M	M		M	M	

* M represents that a given scenario is capable of enduring production over the course of four consecutive days (Maximum)

Table 7 allows displays for the comparison among every simulated scenario. If production is running a Mild set it can be concluded that the most interesting option consists of implementing a better organizational strategy and achieving the "Improved" scenario, while maintaining the current number of silos. This allows for production to proceed during the maximum number of days encompassing all Mild-like production combinations without requiring expenditure. On the hand, to cover Extreme sets the best option would rely on improving both organizational and structural means within the room, achieving the "Ideal" scenario. An extra silo would not be required as the initial equipment is capable of producing during four consecutive days.

5.4.3 Double shift

As demand is expected to rise, the sector's single shift will not be enough to cope with the increasing work, therefore a need arises to study the impact that a second shift would have on raw material availability. Currently, production has been barely able to cope with demand and any drawback like power shortages, delayed raw material deliveries or equipment malfunctions have a major effect on such a tightly run manufacturing chain. Implementing a double shift would have significant implications on the sector, which are the following:

Advantages

- ✓ Standardized shifts. Daily schedule variability and irregular working hours would terminate allowing for a simpler organizational management and a consequent overtime pay reduction;
- ✓ 5 weekly production days. Currently the plant is operating during Saturday mornings;
- ✓ Extra capacity to cope with a rising demand or unexpected downtimes;
- ✓ Lower forecast reliance, as there is a bigger capacity to enforce a MTO policy within the proposed lead times. Forecasts cannot be fully dismissed, but can be reduced, leading to lower stocks levels.

Drawbacks

- ❖ -Not having enough orders to fulfill a full second shift, temporarily allocating staff on any other needing sector during part of the working schedule;
- ❖ -Not being able to enforce a 2^{nd} shift straightaway due to lack of trained personnel;
- ❖ -Lower morale due to reduced wages.

If a second shift was to be enforced, the shifts division would resemble the ones implemented in the subjacent Roll Splitting sector. The first shift would function during 8 hours, from Monday to Friday, and the second one during ten hours, from Monday to Thursday. It is expected that Log production would occupy three complete production days at most (six shifts). During simulation testing only the "Mild" set was considered as production would not reach its peak capacity with approximately the available production time.

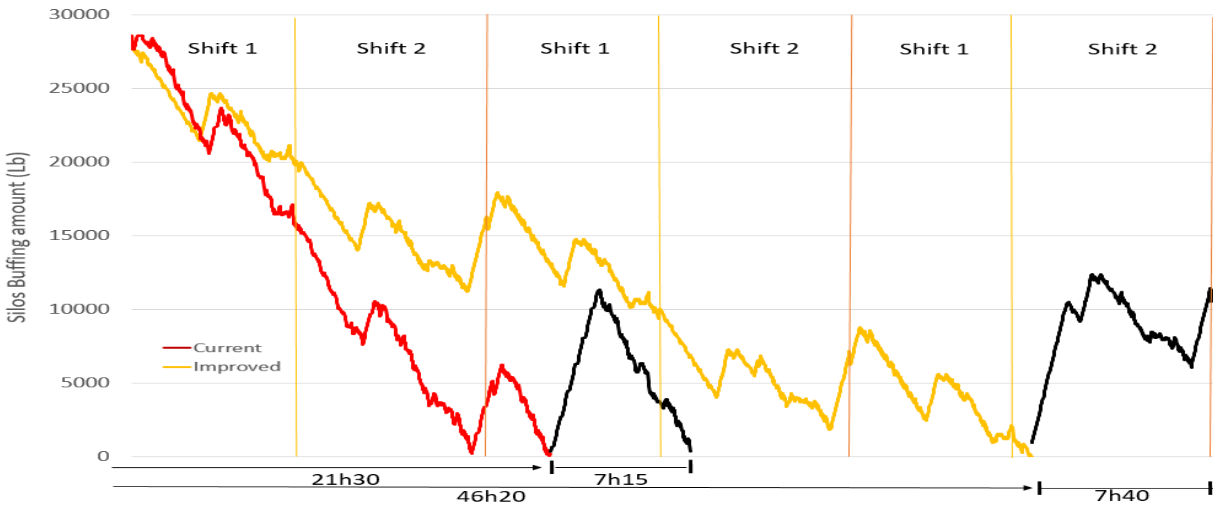


Figure 32 - Double shift - Mild Set - Current and Improved scenarios

Figure 32 displays two of the most relevant scenarios as the "Ideal" configuration would have material available for the entire six shifts. It is also portrayed the impact that adding an extra silo would have on both scenarios (represented by the black graphs). It can be concluded that, if loading settings remain unaltered (Current scenario), there are no conditions to enforce a second shift as buffing is expected to become unavailable on the beginning of the second working day. An extra silo would allow production to be barely lengthened but still producing unsuitable results. On the other side, the "Improved" scenario provides much more interesting results as it is predicted that production can withstand seven consecutive shifts. However, when initially implemented, this measure would not count with substantial orders to fill the entire two daily shifts. That means that this scenario will prove to be acceptable. Nevertheless, when both shifts are expected to run full time an extra equipment should be added to grant material availability during three complete days.

5.4.4 Bottleneck identification

Although this production line has been running for several decades, the system's bottleneck has never been identified. By identifying the operation that slows production it will be possible to further analyze if, and how, production can be increased. Therefore, an operation's duration breakdown, considering the most commonly produced four-compression log times, is displayed in table 8.

Table 8 - Productive process operations

Operation	Duration	Description
1	00:01:30	Buffing is blown from the silos to the scale
2	00:01:00	Scale is emptied as material starts flowing into the mixer
3	00:00:40	Time needed for all the material to reach the mixer after the scale is empty
4	00:00:35	Binder is added to the mix
5	00:01:00	Mixing process
6	00:00:30	Material is dumped into the mold
A	00:01:45	Processing activities between compressions
B	00:04:00	Processing between last and first compression of the following mold

The normal operations sequence is cyclic and follows a numeric order (1-6), from the first to the last compression. Any group of operations, represented by the same blue rectangle, cannot have two operations running simultaneously. The cycle will repeat itself according to the number of cycles required to produce a unit. However, there are some constrictions in the process, which are the following:

- Operation 1 only starts after operation 4 is terminated;
- Operation 2 only starts after operation 6 is terminated;
- Operation 6 can only start if Processing A or B is completed;
- Processing (A or B) starts right after Operation 6 is completed.

This causes the process to be interdependent, although without any material accumulation in any given operation. As the material is constantly moved between the six stages, there are some parallel processing operations performed by the operators that take place at the same time. Processing A and B represent different processing operations, which occur during the mid-production cycles and the initial and final moments of any log's production, respectively. "Processing B" will cause delays as material will be ready to be dumped into molds while there are still processing operations occurring. "Processing A" on the other will not cause any productive stall.

Due to the system's design and constraints there is no station that can be considered the bottleneck of the system. However, it can be concluded that the group that includes operations 2-4 has the longest total duration and it is the least interdependent which turns it into the most accessible option if production rates are to be increased.

5.4.5 Production Speed Increases

There were identified two relevant causes that delay production and if improved could produce higher production rates: "Processing B" and "Group 2" operations. The first represents a set of operations with little room for improvement as the press movement's account for a big percentage of the total time and this equipment is currently working at its maximum speed. On the other hand, it was identified an improvement opportunity on operation 2 that could reduce its duration in half (Stage 1). With extra investment a subsequent enhancement could be pursued on operation 4, reducing its duration to approximately 15 sec (Stage 2). This two phased hypothetical improvement plan aims at improving production rates based on real opportunity windows detected in the system.

Therefore, there is a need to simulate the system's response in terms of resources availability and conclude if production would be benefited or hindered by production speed increases. Table 9 displays the time needed to complete the two manufacturing sets in three different production speeds, which did not feature any stop so that a worse than reality scene was simulated.

Table 9 - Production speed increases comparison

Set	Improvement Stage	Duration (H)	Time reduction		Percentual Time Gain	
Mild	Present	10:43:20				
	Stage 1	09:12:30	01:30:50		14%	
	Stage 2	08:45:40	01:57:40	00:26:50	18%	4%
Extreme	Present	10:21:30				
	Stage 1	09:03:30	01:18:00		13%	
	Stage 2	08:29:30	01:52:00	00:34:00	18%	5%

By improving production speed to Stage 1 both sets would experience a reduction of approximately one hour and a half when compared to the current situation. This difference represents a realistic 10%-15% set completion time decrease. If Stage 2 was to be implemented, production time is expected to be reduced in two hours every ten and a half hours of production. Approximate results are anticipated for both sets. This would allow operations to save slightly under 20% of the time to produce the same number of products when compared to the current situation. However, as Stage 2 is supposed to be a subsequent stage, enforced only after Stage 1, an approximately 5% of the total time can be saved when improving from Stage1 to Stage2.

Resources availability

Nevertheless, there is a limited amount of resources linked to Log production that needs to be taken into account when considering production speed increases. The most relevant are:

-**Number of molds**. There is only a limited amount of molds and if production is not planned properly, it will stop. Faster processing operations may shift the production's bottleneck to the oven, which remains with an unaltered duration. It may retain a sufficient amount of molds that will cause production to pause.

-**Black buffing amount in the silos**. As production cycles are reduced it is expected that silos will be drained at a faster rate. It is vital to understand if an increase in production speed would not compromise the system's ability to resume production for the projected time.

When considering both of these resources availability there is a need to test how would each one of the loading scenarios ("Current", "Improved" and "Ideal") be impacted by production speed increases. This situation can be analyzed in Table 10, regarding buffing and molds availability, respectively.

Table 10 - Resource's Availability- Mold and Buffing

Mold Availability		Loading Situation		
Set	Production speed	Current	Improved	Ideal
Mild	Present			
	Stage1			
	Stage2			
Extreme	Present			
	Stage1			
	Stage2			

Raw Material Availability		Loading Situation		
Set	Production speed	Current	Improved	Ideal
Mild	Present			
	Stage1			
	Stage2			
Extreme	Present			
	Stage1			
	Stage2			

The bag loading scenarios were simulated for three production speed stages, regarding both resources, with distinct outcomes. The red rectangles indicate that there will be a lack of resource, the green color represents the opposite situation while the yellow color represents a scenario where the resource is scarce during a single production run.

It can be concluded that production will be stalled due to the lack of molds if increased to "Stage 2". This situation will occur in most testing scenarios. These results showed that implementing "Stage 2" would not be feasible as production would stop after a short period of time. Only with considerable investment could this situation be attractive. Therefore, "Stage 2" was disregarded. As "Current" scenarios have already been simulated, only two relevant options remain untested, which are the ones representing "Stage 1" for both loading scenarios and the two shift types.

Improved Scenario

In this section it will be studied if it is beneficial, in terms of production duration, to increase production speed without any physical improvements on the bag loading operations, apart from a better organizational strategy on the shop floor.

1. **Single Shift**

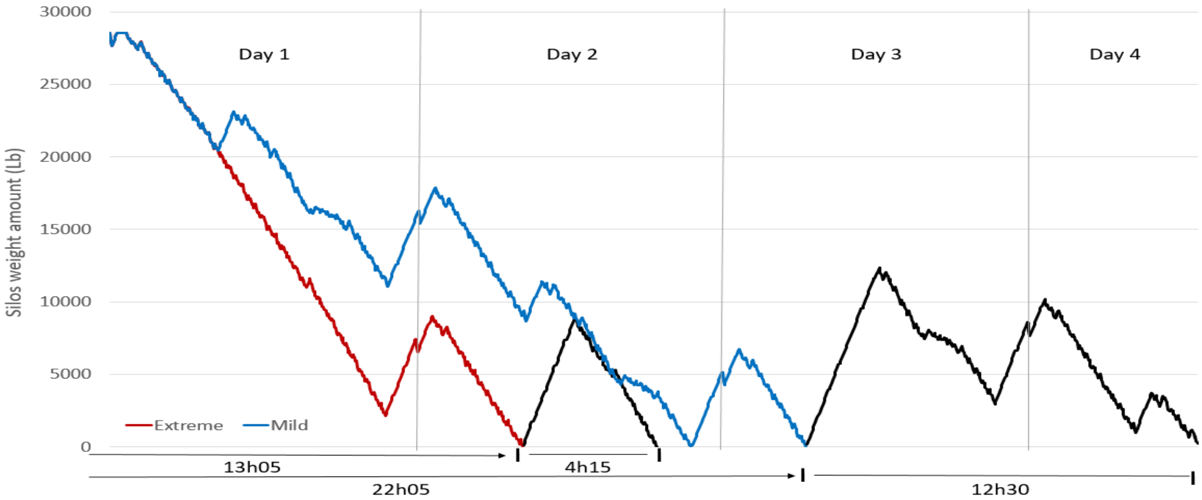


Figure 33 - Buffing amount on the silos - single shift - "Improved" – "Extreme" and "Mild" sets

Figure 33 represents an "Extreme" and "Mild" set over the course of four days while a single shift is implemented. The "Extreme" scenario would empty the silos on the beginning of the second production and not even by adding a third storage equipment would the produced results be interesting. On the other side, a "Mild" set would allow production to resume for a longer, still insufficient, period of time and only by adding a third silo could the operations be extended to endure almost the totality of four production days.

Production speed gains would not amend for the reduced time material will be available in the silos as it would evolve expenditure without any significant gain compared to the current situation, apart from the extra hours available at end of the fourth day.

Double Shift

Figure 34 displays the same situation but when, instead of a single shift, a double shift is implemented. Double shifts are much more demanding, as productive times are approximately doubled, while the number of nonproductive times, are maintained. This will cause the silos to run out of material even faster than on the previous situation. None of the considered situations proves to be acceptable as material becomes unavailable during the first shifts.

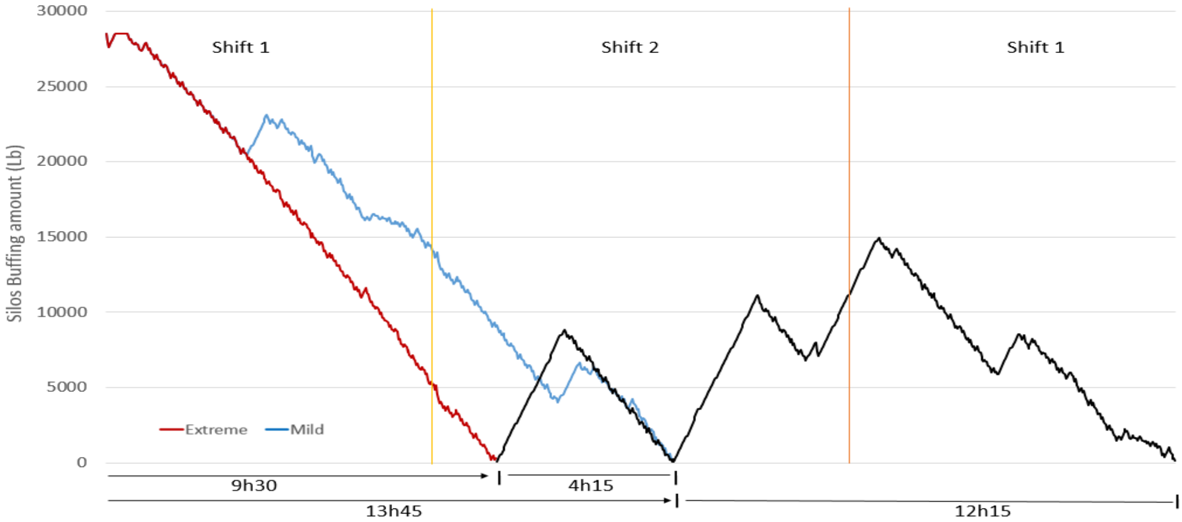


Figure 34 - Buffing amount in the silos - double shift - "Improved" – “Extreme” and “Mild” sets

It can be concluded that it will not be enough to just organize the production room without making any investments in equipment. A “Stage 1” improvement proves to be too demanding for any production set. Implementing a double shift under these conditions is strongly discouraged.

Stage 1 vs Current production speed – “Improved” scenario

Now that an analysis has been made on how quickly silos are drained when production speed is increased (Stage 1), it is relevant to understand if a faster production rate could compensate for shorter production available time.

Table 11 - Production length comparison between various tested scenarios on “Improved" scenario

Mild Set	Present		Stage 1	
	2 Silos	3 Silos	2 Silos	3 Silos
Single Shift				
Productive time	34:40:00(M)		18:35:00	29:35:00
Adjusted Productive time	**29:46:19**		**18:35:00**	**29:35:00**
Double Shift				
Productive time	42:50:00	49:30:00(M)	13:15:00	24:00:00
Adjusted Productive time	**36:47:08**	**42:30:40**	**13:15:00**	**24:00:00**

Table 11 was created with the purpose of comparing which situation would grant the longest productive time (which does not consider cleaning and set-up times), regarding production speed and number of used silos. Only the mild set was considered because of its higher resemblance with reality. In order to produce comparable productive times “Present” situations had to be adjusted according to rates displayed in Table 9. Conclusions were drawn by shift type.

-**Single Shift**. Current production speed should be maintained, as well as the current number of silos. This will enable for the most efficient production setting, extending the operations during four consecutive days without associated investment;

-**Double Shift**. In this case an increase in production speed will cause the system to underperform. Therefore, speed should be maintained in order to fully take advantage of productive time. It is believed that 2 silos would be able to tackle the great majority of productive combinations, however production can be extended by adding a third equipment.

All in all, it has been concluded that if no structural improvements are made in the bag loading operations, it is not advisable to invest in faster productive speed, as material will become unavailable too promptly to amend for any associated improvements.

5.4.5.1 Ideal scenario

In this subchapter, it will be simulated how production speed increases would impact the amount of material in the silos, if those are being constantly refilled.

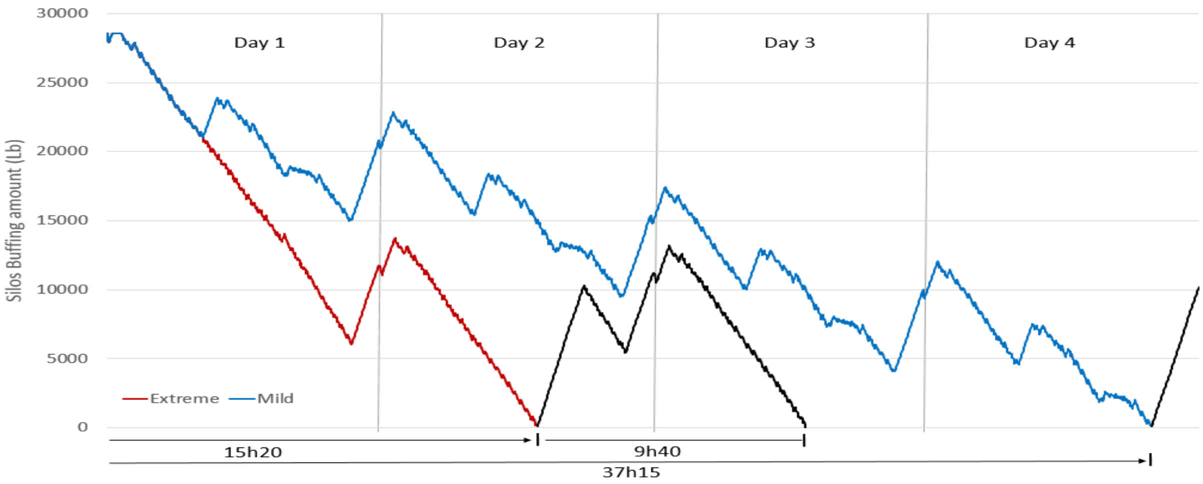


Figure 35 - Buffing amount in the silos - single shift - "Ideal" – "Extreme" and "Mild" sets

According to the outcome displayed in Figure 35, when operating a single shift, production proves that can endure the full four expected days when running a "Mild" set without extra storage equipment. This is the most probable combination and it produces encouraging results. By having shorter production cycles and achieving the maximum available time with no material shortages productivity is expected to peak. However this option comes associated with high investment costs on loading and processing operations.

A double shift implementation should be disregarded as it produces very poor results that would not be able to satisfy production's demands. The system is not currently able to have its daily productive time extended at the same time its processing operations are reduced.

Stage 1 vs Current production speed – "Ideal" scenario

It is important to understand how long production could last if loading operations are maximized (constant flow of material) and shorter production cycles implemented at the same time.

Table 12 - Production length comparison between various tested scenarios on an "Ideal" scenario

Mild Set	Present		Stage 1	
	2 Silos	3 Silos	2 Silos	3 Silos
Single Shift				
Productive time	34:40:00(M)		32:15:00	34:40:00 (M)
Adjusted Productive time	**29:46:19**		**32:15:00**	**34:40:00**
Double Shift				
Productive time	49:30:00(M)		24:00:00	41:20:00
Adjusted Productive time	**42:30:42**		**24:00:00**	**41:20:00**

Table 12 compares the expected available production duration before silos run out of material, in four distinct cases. The best alternative for each type of shift was analyzed.

-**Single shift**. In this case a "Stage 1" implementation would benefit the production system the most, as it would be able to resume production for the four maximum days while producing a greater amount of finished goods. Adding a third silo would grant an extra two and a half hours' worth of production per week which would not make up for the investment needed. The as-is situation also fills the maximum four days production time, however it will be less productive in the same amount of time;

-**Double Shift**. If a double shift is implemented, it would be advantageous not to increase production speed. This would cause silos to run out of material fasts producing poor results than in the “Current” scenario, even with the correspondent adjusted duration. The number of produced items would not amend for the reduced productive time, therefore being a worse alternative.

It can be concluded that production speed should only be increased if the number of shifts remains the same. From a financial perspective, it must be weighted if the extra hours of production time would produce a big enough return that would justify such investments. On the other hand, if planning of doubling the number of shifts, production cycles should not be shortened.

5.5 Achieving the “Improved” Scenario

As it was assumed that the bag loading operations function wastefully, it is vital to understand if operators have poor working practices or do not have enough available time to perform such operation when needed.

Each of the three operators occupies a certain workstation throughout a given day. Each workstation has a certain number of tasks that need to be performed in a certain order on every production cycle. These will be called the “Mandatory tasks”. Then, there are relevant tasks for log production that can be performed by any operator in the spare time between the mandatory tasks. It represents the group of tasks that have their own variable cycles and may or may not need to be completed every time a product is manufactured.

Table 13 - Occupied time percentage by each operator on a 4 cycle log

Occupied time	Operator 1	Operator 2	Operator 3
Mandatory	00:02:40	00:05:25	00:08:00
Variable	00:06:45	00:02:15	00:02:00
Total	00:09:25	00:07:40	00:10:00
Total available time	00:15:21	00:15:21	00:15:21
% used time	**61,37%**	**49,97%**	**65,17%**

In this analysis all of the operator’s tasks were listed and over timed to grant an acceptable working margin. Multiple combinations were tested, regarding the allocation of tasks to different operators working in different stations. Table 13 displays the used time percentage of each operator while producing each unit. The unit considered was the most common four cycle log. This allocation set simulates a much more demanding scenario when compared to the great majority of current situations. More tasks were required more often than in reality, causing an increase on the occupied time percentage produced results.

Even with an overly negative testing scenario the occupied time percentage would barely go over 60% of the total unit production time. Therefore, it can be concluded that operators have ample time to perform the required tasks within the designated time. However, this is not happening at the present because:

- Operators do not have any specifically “Variable” assigned tasks. The system is based on mutual help opening room to inefficiencies;
- No personal accountability. As no one is responsible to complete a designated task, the sense of obligation is diminished causing the working force to slack;
- Poor cooperation and team spirit. This is an increasingly degrading situation, as it causes individuals to be less motivated and less eager to help one another completing their tasks. Several initiatives to solve this problem have been tried, with little success.

Having the causes identified, several options were discussed in order to improve productivity and create standardization within the sector, which are the following:

- Assign specific tasks to a workstation. The operator working on a specific station during the day will be responsible to complete a set of “variable” tasks, therefore improving productivity by efficiently distributing the required tasks;
- Make personnel accountable. Giving workforce a sense of responsibility in their work is believed to have a positive impact in terms of productivity and product quality;
- Promote better communication between operators and the production planner so that problems and solutions can be easily identified and discussed;
- Raise awareness about the impact of not loading the buffing bags within the required time frame. Operators may not be familiarized on how deep of an impact the loading operation have on production throughout the days.

5.6 OEE analysis

In order to increase productivity even further and analyze hidden production liabilities, an OEE study regarding the whole system was made. Furthermore, to achieve those goals it is necessary to unveil the main reasons behind the unplanned breaks that pause production.

The analysis was made using 50 production sheets that represented Log production over the course of more than three months. Each one of these sheets display the list of production orders broken down in time frames. As production varies considerably every day, as well as schedules, number of productive days per week and unplanned downtime, there was a need to use estimated averages in every situation. The relevant OEE parameters are the following:

- **Loading Time**. Total daily dedicated time for Log production;
- **Planned downtime**. It includes Lunch breaks, clean ups and different set-up times. Changeovers between series were also considered as downtime, as the equipment is available for production while a new set is being programmed;
- **Unplanned downtime**. This group includes the sum of times spent with events that force production to stop, and require an intervention by the maintenance team. Material handling is also considered in this group, being an event that compels all operators to leave their stations and move material;
- **Operating Time**. It is considered to be the time equipment is available for production. It corresponds to the total Loading Time minus downtimes;
- **Performance losses**. As there is a wide variability in terms of produced references, each one with its specific completion time, there was a need to estimate an average default value to be used as a reference. This value was obtained by taking into account all of each reference’s production time and its respective production quota;
- **Net Operating Time**. Operating time minus the performance losses;
- **Quality loss**. All the logs produced are employed in the subsequent departments. Quality defects are scarce, and even when there is a flaw, the great majority of the product will still be used. Therefore, there are no rejected Logs and the Quality loss correspondent time will be null;
- **Valuable Operating Time**. Its duration it is identical to Net Operating time as no Quality time losses were considered. After all losses are taken into account this will be the remaining left over time used for production, during a day;

Figure 36 - OEE analysis results

Figure 36 represents the time breakdown per stage. Each one of these values is an estimated average based from the production data. It is also possible to understand that the biggest concern in terms of productivity losses results from Availability issues. An average of 34% of the total time each day is lost due to the system's inability to be able to produce.

Availability losses

Availability losses is what causes OEE to perform just slightly over 62%, which indicates that there is a clear margin for improvement. The other 2 parameters demonstrate that there are small or non-existing losses regarding Performance and Quality, respectively.

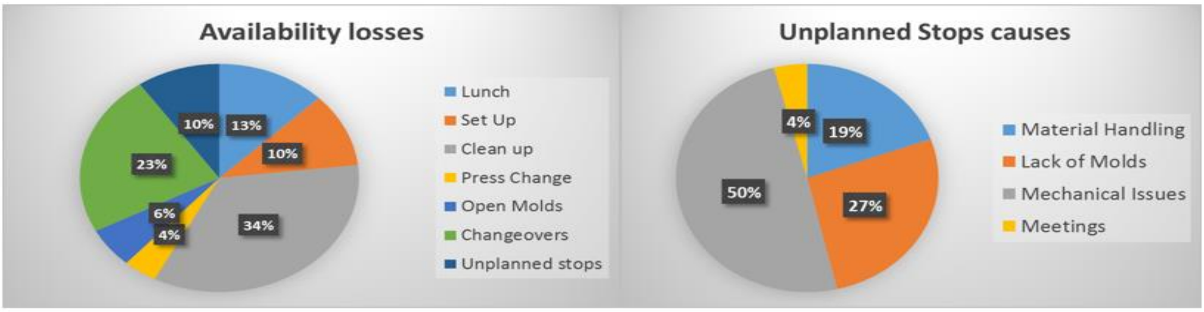


Figure 37 - Availability losses causes (A) and Unplanned Stops causes (B)

In order to understand what causes such a low Availability percentage all the causes and their respective impact are displayed in Figure 37.A. From all the displayed causes the three most impactful ones have been analyzed:

-**Changeover time**. It has variable duration depending on the produced references. It can be improved if all the required materials are available before starting the production of a new series. This can be attained with improved planning and organization. Its impact is augmented when producing small series or special product series;

-**Clean Ups**. This is a daily operation that occupies the operators between one hour and one hour and a half at the end of each day. This task's variability can be eliminated and its duration can be fixated in one hour by developing a cleaning strategy which would grant an extra daily half an hour of production time;

-**Unplanned stops**. Figure 37.B displays the unplanned stops main causes. It can be concluded that a better production strategy could reduce the percentage of time waiting for molds to be available and time operators spend transporting raw material. By implementing preventive maintenance, mechanical problems could be reduced, although most of the equipment is aged making it favorable for these types of situation. This stops, on average, account for approximately 5% of loading time.

If addressing this three operations carefully, productive gains should be attained with ease allowing production to be extended even further each day. Additional improvement measures have been proposed to enhance the productive system. These are displayed in Appendix D.

Conclusions

The project's objective was to improve the manufacturing of rubber agglomerates process by identifying improvement opportunities and eliminating inefficiencies, as well as expanding productions life cycles. Therefore, a simulation model was developed, which enabled the testing of a great variety of production scenarios and allowed for the following conclusions to be reached.

If material loading operations were prioritized and improved, production could be able to resume for the maximum required number of days. Therefore, there would be no buffing shortages and the system would be able to tackle the great majority of production combinations without draining the silos. Furthermore, it was concluded that by achieving this loading condition, production of non-urgent items could be eliminated, which would reduce production lead times. The need of a third silo proved to be unlikely and would entail significant investment costs, therefore being an unadvisable option.

By facing a growth perspective with an increasing number of production orders, there was a need to simulate the impact that a double shift would have on buffing availability. It was concluded that there would be enough raw material to resume production throughout the desired amount of consecutive shifts, as long as loading operations were improved. This is an acceptable outcome that would double production time.

On the other hand, by simulating a production speed increase with improved loading operations, it was concluded that production capacity would decrease. This would happen because silos would be drained at faster rates and the improved loading operations would be insufficient to keep production running. Therefore, better results could be attained by maintaining current production speeds. This conclusion is valid for single and double shift simulations.

However, by maximizing loading operations, which would allow material to be constantly flowing into the silos, productivity is expected to rise. This result is valid if the current number of shifts are maintained, increasing productivity by extending production time while reducing cycle times. Contrarily, if a double shift is enforced material would become unavailable shortly after production starts, proving to be an unacceptable strategy. Despite the different outcomes, production speed increases would always involve considerable expenditure and should not be considered a priority.

There were also implemented improvements on the job floor aiming at achieving a cleaner, safer and more organized working environment for the operators, while reducing performance losses. Moreover, production can be further extended by increasing availability rates, which are hindered by changeover times, extended cleaning times and equipment breakdowns.

To conclude, several production alternatives were simulated with the objective of extending production time while testing its respective impact on raw material availability. It is hoped that the produced outcome will aid production planning in the near future, providing enough data to support any decision made regarding this sector's production strategy.

Future work

As product demand is expected to increase in the near future, there is a need to further integrate all of the plant's sectors by promoting better material and information flows. To face this increasingly challenging scenario, some improvement projects can be developed in the following fields of action.

1. **Sales Forecasting**. An exclusively MTO policy can never be fully implemented as delivery lead times are shorter than production lead times. Therefore, there is always a need to rely on sales forecasts and have stock items. Nevertheless, the situation can be significantly improved, if forecasts and stock item numbers are supported by a scientific method;
2. **Warehouse layout**. Efficiency gains can be attained by reducing the number and length of trips used to load trucks and store material, by organizing items differently based on their turnover rate. There is also inefficiencies with the shipping process, as the currently used docks are the furthest from the warehouse. A layout design project is believed to considerably benefit the plant's logistical operations;
3. **Autonomous maintenance plan**. It was concluded that there is no implemented autonomous maintenance plan in the rubber manufacturing line. In case of unplanned stops, operators are supposed to call the maintenance team. Preventive maintenance routines are performed only once a month. It is believed that a number of unplanned stops can be reduced if operators were able to monitor and balance certain production related parameters on a daily basis.

References

Abdulmalek, F. A. & Rajgopal, J. (2007) Analyzing the benefits of lean manufacturing and value stream mapping via simulation: a process sector case study. *International Journal of Production Economics. 107*(1), 223–236. Doi:10.1016/j.ijpe.2006.09.009

Al-Sudairi, A.A. (2007) Evaluating the effect of construction process characteristics to the applicability of lean principles. *Constr Innov. 7*(1), 99–121. doi:10.1108/14714170710721322

Bækgaard, L. (2004). Event-Based Activity Modeling, *ALOIS'04 - Action In Language, Organisation and Information Systems*. Linköping, Sweden.

Baldwin, W. C., Sauser, B. & Cloutier, R. (2015). Simulation Approaches for System of Systems: Events-based versus Agent Based Modeling. *Conference on Systems Engineering Research, 44,* 363–372. doi: http://doi: 10.1016/j.procs.2015.03.032.

Borshchev, A. (2013). *The Big Book of Simulation Modeling: Multimethod Modeling with Anylogic 6*. North America: AnyLogic

Brunt, D., Sullivan, J. & Hines, P. (1998) Costing the value stream-an improvement opportunity. *Proceeding of the 7th Annual International IPSERA conference*, 80-88.

Byrne, P.J. & Heavey, C. (2006). The impact of information sharing and forecasting in capacitated industrial supply chains: A case study. *International Journal of Production Economics. 103* (1), 420–437.

Chryssolouris G., Pierce J., & Dicke K. (1992). A decision-making approach to the operation of flexible manufacturing systems. *The International Journal of Flexible Manufacturing Systems*, *4*, 309-330. doi: 10.1007/BF01324885

Deng, J. S. & Isayev, A. (1991). Injection Molding of Rubber Compounds: Experimentation and Simulation. *Rubber Chemistry and Technology*. *64*(2), 296-324.

De Ruyter, A.S., Cardew-Hall, M.J. & Hodgson, P.D. (2002). Estimating quality costs in an automotive stamping plant through the use of simulation. *International Journal of Production Research, 40*(15), 3835–3848.

Donhauser, T., Rackow, T., Hirschbrunn, J., Schudererb, P. & Franke, J. (2016). Valid methodology for using discrete event simulation to improve the resource consumption for the manufacturing of masonry units. *CIRP Conference on Manufacturing Systems, 41,* 57-62. doi: https://doi.org/10.1016/j.procir.2015.12.016

Felhõs, D., Xu, D., Schlarb, A.K.,Váradi, K., Goda, K. (2008). Viscoelastic characterization of an EPDM rubber and finite element simulation of its dry rolling friction. *Express Polymer Letters. 2*(3), 157–164. Doi: 10.3144/expresspolymlett.2008.21

Granat J. (2006). A Framework for Event Based Modeling and Analysis. *Journal of Telecommunications and Information Technology, 4,* 88–90.

Goldratt, E. M. & Cox, J. (1984). *The Goal. Croton-on-Hudson*. (1º ed). New York: The North River Pres

Gomes, V. M. O, & Trabasso, L. G. (2016). A Proposal Simulation Method towards Continuous Improvement in Discrete Manufacturing. *49th CIRP Conference on Manufacturing Systems*, *57*, 270-275. doi: https://doi.org/10.1016/j.procir.2016.11.047

Hedman, R., Subramaniyan M. & Almatrom, P. (2016). Analysis of Critical Factors for Automatic Measurement of OEE. *Procedia CIRP, 57*, 128-133. doi: https://doi.org/10.1016/j.procir.2016.11.023

Huang, C. C. & Liu, S.H. (2005). A novel approach to lean control for Taiwan funded enterprises in mainland China. *Int J Prod Res. 43*(12), 2553– 2577.

Isayev, A., Yushanov, S. P. & Chen, J. (1996). Ultrasonic Devulcanization of Rubber Vulcanizates. I. Process Model. *Journal of Applied Polymer Science*. *59,* 803-813.

Jeong, K.Y. & Phillips, D.T. (2001). Operational efficiency and effectiveness measurement. *International Journal of Operations & Production Management*, *21*(11), 1404-1416. doi: 10.1108/EUM0000000006223

Kadipasaoglu, S.N. Xiang, W. & Khumawala, B.M. (1999). Batch scheduling in a multistage, multiproduct manufacturing system – an application. *International Journal of Operations and Production Management*. *19* (4), 421–436.

Lanke, A., Hoseinie, S. H. & Ghodrati. B. (2016). Mine production index (MPI)-extension of OEE for bottleneck detection in mining. *International Journal of Mining Science and Technology, 26*(5), 753-760. doi: https://doi.org/10.1016/j.ijmst.2016.05.050

Mendes, A.R., Ramos, A.L., Simaria, A.S., Vilarinho, P.M. (2005). Combining heuristic procedures and simulation models for balancing a PC camera assembly line. *Computers and Industrial Engineering*. *49* (3), 413–431.

Melvin, A. & Baglee, D. (2008) Value stream mapping: A dairy industry prospective. *Engineering Management Conference* EEE International. *28*, 1-5. Doi: 10.1109/ IEMCE.2008.4618003

Mourtzis, D., Doukas, M. & Bernidaki, D. (2014). Simulation in Manufacturing: Review and Challenges. *Procedia CIRP, 25*, 213-229. doi: https://doi.org/10.1016/j.procir.2014.10.032

Okrent, M. D. & Vokurka, R. J. (2004). Process mapping in successful ERP implementations. *Industrial Management & Data Systems, 104(*8), 637 – 643. Doi: http://dx.doi.org/10.1108/02635570410561618

Pedgen, C.D., Shadowski, R. P., & Shannon, R.E. (1995). *Introduction to Simulation Using SIMAN*. (2nd). New York: McGraw-Hill, Inc.

Pinto, J.P. (2008). *Lean Thinking: Introdução ao pensamento magro*. Lisboa: Edições Lidel

Rabe, M., Spieckermann, S. & Wenzel, S. (2009). Verification and Validation for Simulation in Production and Logistics. *SNE Simulation Notes Europe*, *19*(2), 21-29. doi:10.11128/sne.20.tn.09935

Rafei, M., Ghoreishy, M.H.R., Naderi, G. (2009). Development of an advanced computer simulation technique for the modeling of rubber curing process. *Computational Materials Science*. *47*, 539–547. Doi: 10.1016/j.commatsci.2009.09.022

Reggelin, T. & Tolujew, J. (2011). A Mesoscopic Approach to Modeling and Simulation of Logisitics Processes. *Winter Simulation Conference,* 1508-1518. doi: 10.1109/WSC.2011.6147869

Roser, C., Nakano, M. & Tanaka, M. (2006). Single simulation buffer optimization. *International Journal, Series C Mechanical Systems, Machine Elements and Manufacturing*. *48*(4), 763–768.

Rother, M. & Shook, John. (2003). Learning to see: Value-Stream Mapping to Create Value and Eliminate Muda. Cambridge: The Lean Enterprise Institute

Sadeghi, R., Dauzère-Pérès, S. & Yugma, C. (2016). A MultiMethod Simulation Modelling for Semiconductor Manufacturing. *IFAC-PapersOnLine, 49*(12), 727-732. doi: https://doi.org/10.1016/j.ifacol.2016.07.860

Sahoo, A. K., Singh N. K., Shankar, R. & Tiwari, M. K (2008) Lean philosophy: implementation in a forging company. *Int J Adv Manuf Technol*. *36*(5/6), 451–462. doi:10.1007/s00170-006-0870-2

Schelling, T. (1978). *Micromotives and Macrobehavior*. New York: W.W. Norton & Co.

Şimşita, Z. T., Günayb, N. S. & Vayvayc, O. (2014). Theory of Constraints: A Literature Review. *Procedia - Social and Behavioral Sciences, 150*, 930 – 936. doi: 10.1016/j.sbspro.2014.09.104

Singh, B., Garg, S. K. & Sharma, S. K. (2011). Value stream mapping: literature review and implications for Indian industry. *Int J Adv Manuf Technol*, *53,* 799–809. Doi: 10.1007/s00170-010-2860-7

Siprelle, A.J. & Phelps, R. A. (1997). Simulation of Bulk Flow and High Speed Operations. *Winter Simulation Conference.* 706-710. doi: 10.1109/WSC.1997.640942

Son, Y.J., Wysk, R.A. & Jones, A.T. (2003). Simulation-based shop floor control: Formal model, model generation and control interface. *IIE Transactions*. *35* (1), 29–48.

Stevenson, W. J. (2009). *Operations Management*. (10º). McGraw-Hill Irwin

Taj, S., & Berro, L. (2006). Application of constrained management and lean manufacturing in developing best practices for productivity improvement in an auto-assembly plant. *International Journal of Productivity and Performance Management, 55*(3/4), 332-345. doi: https://doi.org/10.1108/17410400610653264

Taylor, D. H. (2005) Value chain analysis: an approach to supply chain improvement in agri-food chains. *Int J Phys Distrib Logist Manag*, *35*(10), 744–761.

Terlunen, S., Horstkemper, D. & Hellingrath, B. (2014). Adaption of the discrete rate based simulation paradigm for tactical supply chain decisions. *Winter Simulation Conference in IEEE Press Piscataway,* 2060-2071.

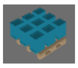
Westbrook, R. (1995). Action research: a new paradigm for research in production and operations management. *International Journal of Operations & Production Management*. *15* (12), 6-20. doi: doi.org/10.1108/01443579510104466

World-Class OEE (n.d). Consulted in http://www.oee.com/world-class-oee.html

Zülch, G., Rottinger, S. & Vollstedt, T. (2004). A simulation approach for planning and reassigning of personnel in manufacturing, *International Journal of Production Economics*. *90* (2), 265–277.

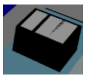
Appendix A: Model's Entities

To accurately simulate the sector's current operations several entities were created and used throughout the different processual stages.

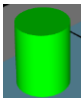


EPDM pallets – They will be transported from the room entry to their provisional storage site near the tanks. When used, a new pallet will be automatically available for transport;

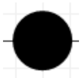
EPDM bags – Every pallet has 40 EPDM bags that are loaded individually into the system tanks. Each tank has a capacity of 5 bags, which is represented by a conveyor belt block in the model;



Glue Container – There are always 2 containers on site. Every time one is emptied a new will be available at the room entry for pick up;



Big Bags –This bags contain the buffing before they are poured in the system. They spawn at the room entry and will be transported to their "bagoff" sites;



Load- After the material is mixed and processed for 60 seconds a material load is formed.

Rounds – A group of loads will form a Round, which is a completed cylinder ready to be transported to the oven. The number of loads necessary to produce a Round will vary according to production references.

The agent's sequential use is displayed on figure 40, starting as raw material and terminating as a finished good.

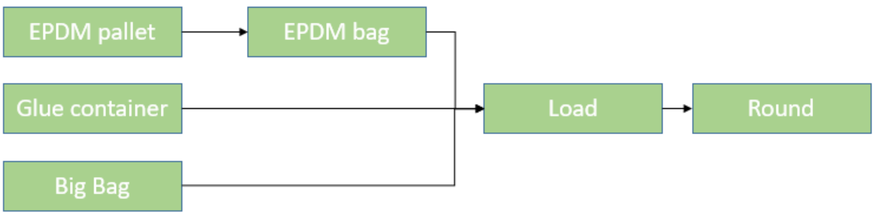


Figure 38 - Entities usage sequence

Appendix B: Raw Materials

Rubber buffing

Rubber buffing are rubber threads that result from grinding the outer layer of truck tires in preparation for receiving new layer. These threads are consequently vacuumed and go through a special process that will sort the material into various sizes. Dried and packaged, these rubber buffing are used in multiple applications including; pour-in-place playgrounds, running tracks, walkways, ergonomic mats, or may be used as raw materials for agglomeration processes. Figure 39 shows this raw materials general aspect.

Figure 39 - Black rubber buffing

EPDM

Plastics and rubber are both consisted of long chains of hundred thousands of small atoms which are connected to each other. The difference in characteristics however are determined by the monomers (like one bead or link of a chain) and the co-ordination of these. By taking different links to make the chain, it will result in a product with different strength, thickness and flexibility. By combining *Ethylene, Propylene* and a *Diene*, *Ethylene-Propylene-Diene-Rubber (EPDM)* will be created.

EPDM is a type of synthetic rubber is used in many applications from appliance hoses, radiator hoses in our cars, washers, refrigerator gaskets, tubing, pond liners, belts, electrical insulation, among many others. It is characterized to be resistant to a different range of temperatures as well as having great electrical insulation properties.

Appendix C: Model validation analysis with an outlier

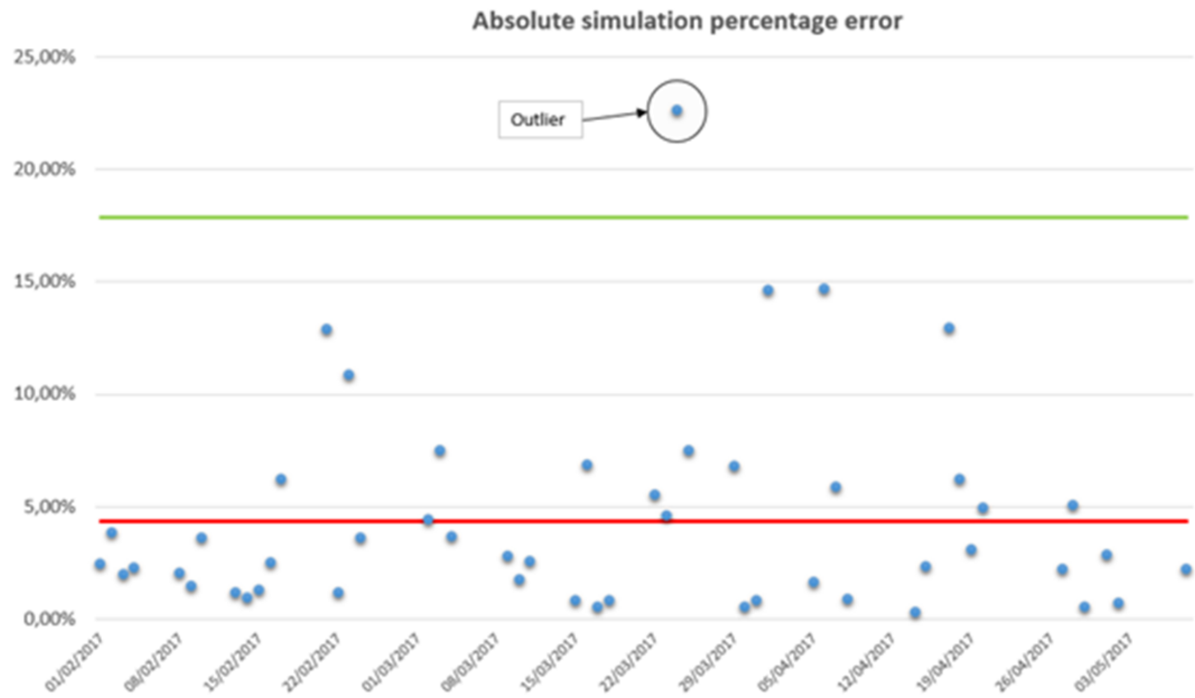


Figure 40 - 50 day APE analysis, with an outlier

Appendix D: Production line improvement suggestions

Some performance issues may be related with the poor space organization and general cleansing of the room. This type of conditions may take a toll on the operators moral and on the duration certain take to be performed. This sector is also aged, not having been updated for many years, which allows for various improvement opportunities to be made. Therefore several proposals have been made, which were approved. Some of them are already implemented and none involved significant costs. The importance of having a clean, organized working station was regularly transmitted to the operators as well as the subsequent benefits.

Each proposal is related with at least one of the phases of the 5S methodology, which are: Sort (1), Set in Order (2), Shine (3), Standardize (4) and Systematize (5). "Before" and "After" pictures are displayed in the following pictures to showing the organization improvement attained with some of the suggestions.

Proposal 1 – Remove everything that is not used from the room

As the agglomeration sector is located in a large area within the plant, there is plenty of room to store objects. Over the years several unuseful objects were added which created an unorganized and crowded space. Therefore, a myriad of objects had to be removed, from unsuitable tools to entire cabinets used to store worthless objects. Another objective was to remove every object that had a storage capacity, so that the situation could not be degraded over the years with the recurring accumulation of objects. This is the first stage of the 5S method, represented by Figure 43.

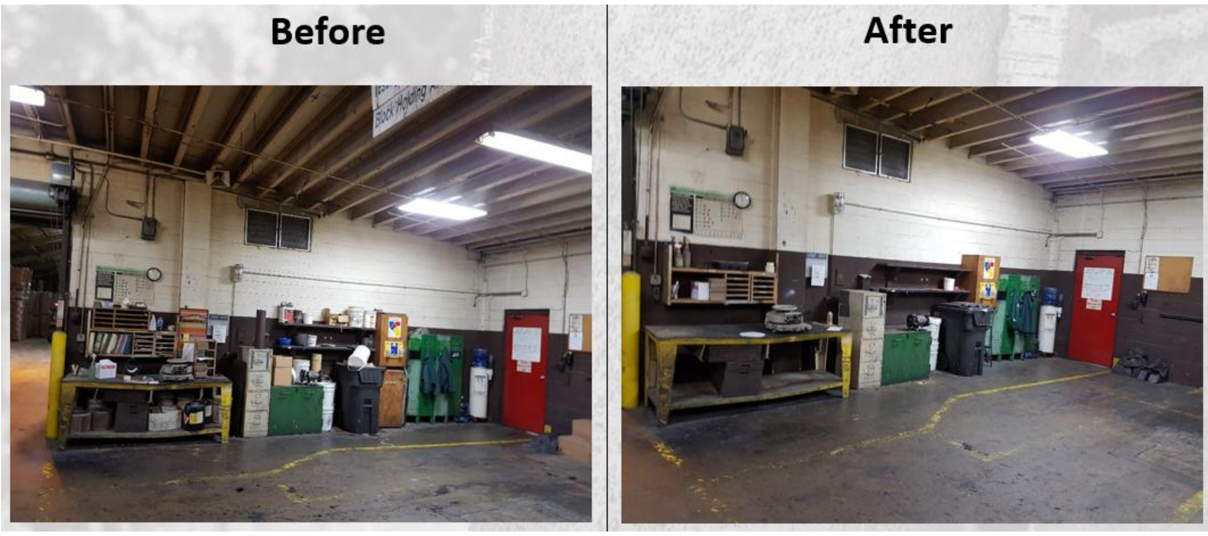


Figure 41 - "Before" and "After" pictures of the production's line storage area

Proposal 2 – Sort the crucial utensils

An effort was made to organize and clean all of the most used tools near the workstation to provide operators with an easy and more direct access to them. Refurbished drawers were made to keep tools clean and organized. These are displayed in Figure 44 .The importance of keeping the tools on the designated space was transmitted throughout the project so efficiency gains could be maintained. Several other items were properly stored as it is represented by Figure 45.

Figure 42 - Efficiently organized tools

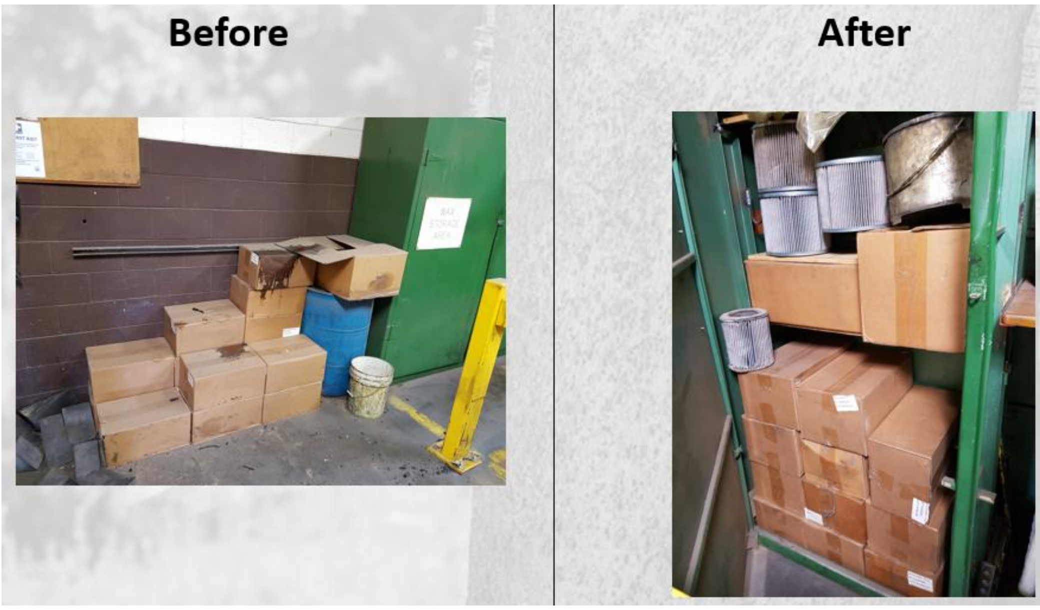


Figure 43 - Spare parts properly organized

Proposal 3 – Proper utensils storage

There was no designated space to store the brooms, which were recurrently left wherever. Spray cans had inappropriate storing space, which caused them to fall and break frequently. Hoses, Mold tops and large tools were spread throughout the room due to an undesignated storing space. Proper storage creation was suggested to fix this issue.

Proposal 4 – Restore lockers

The lockers operators use to store their personal belonging were deeply damaged and dirty. Solving this low cost matter is expected to increase workforce's moral.

Proposal 5 – Cardboard rack

The cardboards used in the identification painting process had no storage space, being left over the surrounding equipment or on the floor. Therefore, there was a need to create a rack that would allow operators to have them organized.

Proposal 6 – Electrical wiring cover

On the tracking system, used to move the molds, there were some electrical wires exposed. This is a safety concern that could jeopardize the operator's wellbeing. Maintenance was alerted and the situation was resolved.

Proposal 7 – Fans disposal

The room temperature is fairly high so there is a need to have an efficient cooling system in order to ensure good working conditions. Some of the cooling fans were initially broken, having been fixed, granting operators a cooler environment.

Proposal 8 – Baggoff support

The "Bagoff" equipment proved to be too high for operators to reach comfortably, when loading the new bags into the system. It was proposed that a portable stool was added, so operators could complete the task faster, safely and with less physical effort. The implemented improvement is displayed by Figure 46.

Figure 44 - Loading operations improvement measure

Proposal 9 – Audible alert

The addiction of a horn that would go off every time the bags are hollow is considered to be of major relevance as it would alert operators to switch the bags when needed. This alert would remain audible until the bag is switched, making operators perform the action as quickly as possible. This measure will allow the "Improved" situation to be reached with ease.

Appendix E: 3 Loading Scenario Analysis

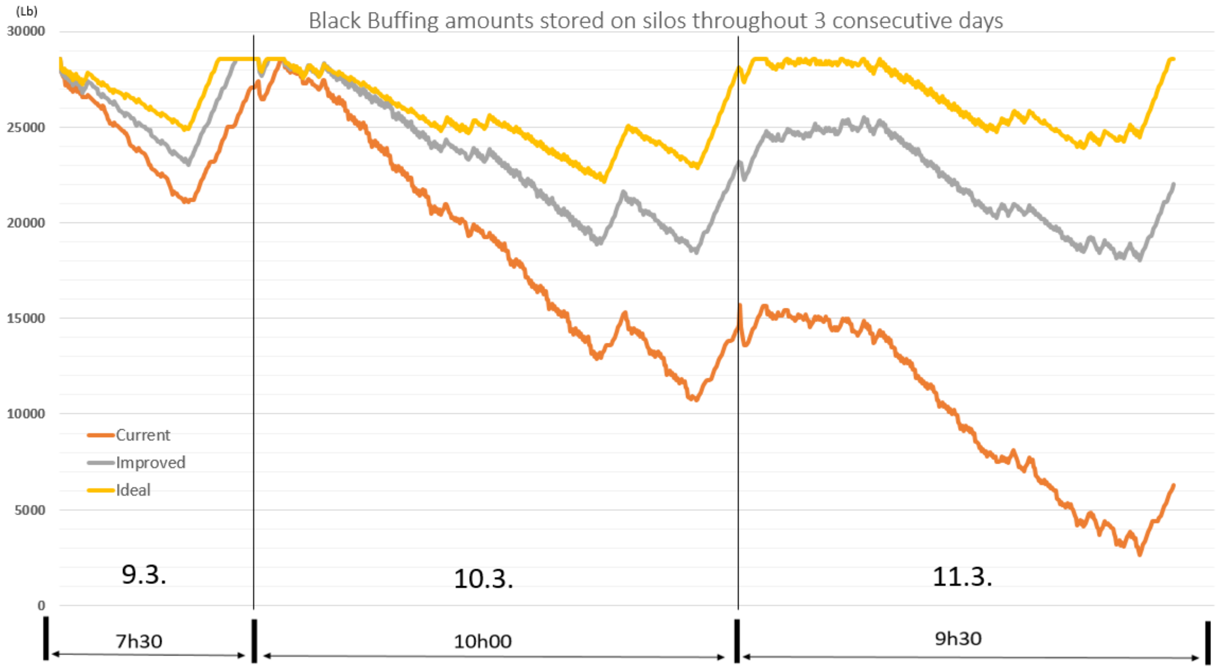


Figure 45 - Impact of the 3 bag loading scenarios on the silos levels