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ASSESSMENT OF PRODUCTION PLANNING STRATEGIES THROUGH SIMULATION

A TISSUE PAPER MILL CASE STUDY

Dissertação no âmbito do Mestrado em Engenharia e Gestão Industrial orientada pelo Professor Doutor Samuel de Oliveira Moniz e apresentada no Departamento de Engenharia Mecânica da Faculdade de Ciências e Tecnologias da Universidade de Coimbra.

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Assessment of production planning strategies through simulation: A tissue paper mill case study

Dissertação apresentada para a obtenção do grau de Mestre em Engenharia e Gestão Industrial

Avaliação de estratégias de planeamento de produção através de simulação: Caso de uma fábrica de papel tissue

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“If you torture data long enough,
it will confess”

Ronald H. Coase, in Essays on Economics and Economists

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Abstract

Pulp and paper manufacturing systems have been struggling in the implementation of efficient operational strategies. Amongst the sector, multi-stage and multi-product production systems are common. The object of this study is an integrated tissue paper mill, which commercializes products from two stages of production: intermediate material and finished product. Its production resources are being poorly seized, having to deal with relatively low productivity and high occupation rate at the inventory between stages of production.

A discrete-event simulation model of the system was developed to address the trade-offs between each of its elements, while assessing the efficiency of the current production planning methodology. This analysis has shown that the main constraint to the overall performance of the system was the low productivity of the last production stage, which mainly relied on the high level of inventory kept. Then, two complementary production planning heuristics were developed, in order to improve the material flow between production stages. The proposed planning methodology has significantly improved the throughput capacity of finished products, while decreasing the average occupation rate of the intermediate inventory. Further considerations are performed regarding the suitability of the framework for the current profile of the demand processed by the system.

Keywords: Simulation, Production Planning, Process Industry, System Analysis.

Resumo

Os sistemas de produção de papel e celulose têm encontrado dificuldades na implementação de estratégias operacionais eficientes. No setor, é comum a produção por várias etapas e de vários produtos. O objeto de estudo desta dissertação é uma fábrica integrada de papel *tissue*, que comercializa produtos em duas etapas de produção: material intermédio e produto acabado. Atualmente, a tecnologia avançada de que dispõe não está a ser aproveitada, tendo que lidar com baixa produtividade e alta taxa de ocupação no inventário entre as etapas de produção.

Um modelo de simulação baseada em eventos discretos foi desenvolvido para analisar os *trade-offs* existentes no sistema, sendo avaliada a eficiência da metodologia atual de planeamento de produção. Esta análise demonstrou que o principal constrangimento ao desempenho global do sistema é a baixa produtividade da última fase de produção, que se sustenta principalmente no elevado nível de stock. Em seguida, duas heurísticas de planeamento de produção complementares foram desenvolvidas, de modo a melhorar o fluxo de material entre as etapas de produção. A metodologia de planeamento proposta melhorou significativamente a capacidade de processamento de produtos acabados e reduziu a taxa média de ocupação do armazém entre as etapas de produção. Considerações adicionais são realizadas a respeito da adequação do método desenvolvido para o perfil atual de procura de material intermédio processado pelo sistema.

Keywords Simulação, Planeamento da Produção, Indústria do Processo, Análise de Sistemas.

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ACRONIMS

ACD – Activity Cycle Diagram

BOM – Bill of Materials

CPO – Converting Production Order

CPOF – Capacity Planning by Overall Factors

DES – Discrete Event Simulation

EDD – Earliest Due Date

EGR – Expected Gross Requirements

ERP – Enterprise Resource Planning

ET – End Time

IWL – Internal Workload

JR – Jumbo Roll

KPI – Key Performance Indicator

LCD – Life Cycle Diagram

LGV – Large Goods Vehicl

MRP – Material Requirement Planning

MWL – Máximum Workload

SD – System Dynamics

ST – Start Time

SKU – Stock Keeping Unit

TPO – Tissue Production Order

TWL – Total Workload

1. INTRODUCTION

Digitalization has numerous advantages related to the ability to effectively and analytically manage manufacturing processes. Operational managers have the rule of realizing those benefits by finding the best overall conditions at which the system performs most notably, according to the specific business goals. Through data streamed from the manufacturing systems, mathematical models are often developed to generate data-driven decision-making support, which may aid the management at all planning levels (Baid and Nagarur, 1994).

The present work intends to describe the development and application of a framework capable of evaluating the performance of production systems under distinct conditions defined by the decision-maker. The object of study is a paper manufacturing company, which is inserted in the process industry sector. Diverse issues regarding the incapacity of reaching satisfactory utilization rates of the facility's resources have motivated this study. The reasons for this detriment are analysed in detail, being them closely related to the accomplishment of an adequate inventory policy and an effective production planning methodology.

Usually, in these cases, modelling the complete system is required to account for intricate dynamics between its elements; and the capability of getting a significant model abstraction is critical for developing an adequate representation of the real system (Van de Mortel-Fronczak *et al.*, 2001). Furthermore, a consistent reproducibility is required to allow a thorough analysis of a large number of working conditions, each representing a distinct decision instance. Thus, the adopted methodology was Discrete-Event Simulation (DES), which allows an accurate representation and understanding of the system and enhances the possibility for a comprehensive scenario analysis (Banks, 1998).

On a first approach, the simulation model serves as a current system analysis tool that receives as inputs the actual working conditions of the manufacturing system, according to the current operations management policies followed by the company. This first modelling step ensures visibility throughout the entire production system, enabling a broad perception of its production capabilities and constraints. Further on, experiments are performed to understand the underlying trade-offs to be accounted for when managing the production system so as to aid the search for satisfactory productive conditions. Then, two complementary heuristics are developed based on the results from the previous analysis. Lastly, those are tested in the simulation model and a comparison of performances between the current and the proposed production planning methodologies is conducted.

From the production management decisions range, this study focuses on the small to medium-term decisions, encompassing the problem of production sequencing at the low-level production planning. The principal milestone is set on the demonstration of the worthiness of a simulation approach as primary tool for dealing with those issues, by obtaining valuable improvements to the overall manufacturing system.

The remaining structure of the dissertation is composed of 4 chapters. Firstly, in chapter 2, it is presented a background to the work developed, based on previous publications from the subjects addressed. Then, chapter 3 exposes the object of study, a tissue paper manufacturing system. After presenting the operations executed at the studied system, it is performed a description of the development of the proposed methodology, simulation modelling, in chapter 4. In the following segment, chapter 5, the results from the implementation of the simulation model are addressed. Lastly, some final remarks are stated in chapter 6, being discussed the results from the study.

2. BACKGROUND

This second chapter consists of establishing a literature background to support the resolution of the problem at hand. Therefore, the theoretical knowledge required to understand the work of this dissertation is presented here by addressing previously published works in relevant research fields.

Regarding the case study, it is relevant to address the published work related to the operations and production management in the process industry and the concrete case of the pulp and paper industry. Hence, there is a need to perceive the actual managerial problems faced in those industries, along with the approaches and solutions formulated for its resolution. Furthermore, the proposed methodology, simulation modelling, requires a concise acknowledgement of its foundations and the developed work in the field to assimilate relevant concepts and outline the intended approach.

2.1. Process industry

Process industries are defined as industrial systems that "add value to materials by mixing, separating, forming, or chemical reactions where processes may be either continuous or batch" (Blackstone, 2013). In this category are sectors as pulp and paper, chemical, pharmaceutical, and food (Marques et al., 2020). This industry is considered of intensive capital, and most of its sectors present a high product volume with low-profit margins. The production systems are mainly characterized by continuous or batch production instead of discrete production. Herewith this distinction, allied with other particularities from each sector, it is required a focused approach when implementing operations management tools (Dennis and Meredith, 2000).

In process industries, inventory keeping usually constitutes the large majority of the materials' lead time, i.e. time between the entrance in the system as raw material to the exitance as finished product. Adding this to the long changeover operations times and costs between production orders, and to the low material efficiency, the ratio of value-added operations can be diminished to about 1 to 5% of the total lead time of the product (Shah, 2005). Some of the most influential factors related to the degrees of freedom regarding the inventory management at these systems are the transportation cost, the capital intensity, the demand uncertainty, the gross margin and the price volatility (Moser et al., 2017).

By the end of the XX century, differentiation strategies through a large product variety, often referred to as mass customization, were adopted by a large parcel of the process industry sectors. This mass customization, on an industry guided by high volume and low-profit margin product policies, presented a new challenge for the managers of those industries: the achievement of a high-volume and high-variety production through manufacturing flexibility (Berry and Cooper, 1999). The cited work has presented an analysis of the impact of a large product mix in the performance of process industries, which often are constrained by a considerable duration of its setup operations. As a result, the batch size is established as one of the main influencing factors of the system's productivity, since smaller batches require more setup operations. Furthermore, it is highlighted the necessity of an alignment between the product variety strategy and the manufacturing system's capabilities to produce in an efficient way, i.e., manufacturing flexibility.

This issue of establishing a product mix that is congruent to the system's manufacturing flexibility was, since then, addressed considering distinct perspectives. Al-Aomar (2000) approaches this problem by, on a first instance, applying a Linear Programming (LP) model and, a priori, integrating its solution on a Discrete Event Simulation model. The LP solution defined the initial product-mix, which is then tested in the simulation model, which assesses the system's response to those conditions. While this study was oriented to the classical view of profitability, others were focused on distinct objectives for similar problems. Scoping at the process industries, some alternative objective functions were the profitability computation of process measurements (Mattila et al., 2011) and the environmental sustainability of the product-mix (Galal and Moneim, 2015).

2.1.1. Production planning and scheduling

Naturally, a large product variety on a system with sequence-dependent changeover times (as it is common amongst process industries) raises relevant issues related to the production planning of such systems (Moniz et al., 2014). Most of the companies in this sector attempt to minimize the overall changeover time and cost by planning campaigns, i.e., planning several batches of the same product or products of the same family (items between which the changeover time is relatively low). Furthermore, the usual presence of distinct product stages in the system (between the raw materials and the finished good), characteristic from the process industries, hinders the management of productive resources and the allocation of materials. Susarla and Karimi (2011) approached this issue, developing a Mixed-Integer Linear Programming (MILP) model for an integrated campaign planning and resource allocation on a multi-product multi-stage batch plant. The developed model delivers production campaign plans on a time horizon of 1 to 2 years, integrating material and equipment allocation, maintenance operations, new products release, and inventory keeping decisions and constraints.

The planning process comprises production, distribution, sales, and inventory decisions based on market information (i.e., aggregate or capacity planning). From these operational plans, the sequencing of individual operations and assignment of resources over time are scheduled in detail, on a shorter-term (disaggregate planning). Omar and Teo (2007) presented a hierarchical model for an integrated solution of both problems in a multi-product batch process environment. Kallrath (2002) developed a mathematical programming approach, presenting a model founded on MILP and weight-integer goal programming. Nevertheless, as stated by Kallrath (2002), solution optimality is unusual on the scheduling problems since process industries often prefer qualitative goals, such as reliability and robustness, rather than the usual quantitative objectives: minimal makespan, minimal operating cost, or maximum profit.

Some distinct common issues were later addressed to cope with the flexibility requirements of the process industries. Focusing on dealing with demand uncertainty, planning inadequacy, and production capability imbalance, Feng et al. (2011) presented an optimization method centred on minimising inventory costs and reaching an optimal production load rate. The developed mathematical model has proved to be efficient in approximating the difference between the production volume and the actual demand (aided by an improvement of the sales forecasting), as well as in reducing the average inventory levels, hence the inventory holding costs.

By developing a MILP discrete-time formulation, Moniz et al. (2013) addressed the short-time scheduling problem in general multipurpose batch plants. This model has presented new types of constraints for the modelling of common process industry features. Those encompass sequence-dependent changeovers, temporary storage in the processing units and lots blending.

In addition to those issues, the material flow and properties from a significant parcel of the process industries raise further constraints to the production planning at those manufacturing systems. Being the “rough” transformation of materials (involving state changes) one of the main characteristics of this sector, it is understandable that the manufacturing processes are susceptible to a lower material efficiency than most discrete industries (Shah, 2005). One of the direct results is a higher rejection rate due to quality flaws, leading to the necessity of reprocessing. The consequences of this recurrent issue on process industries were summarized in Flapper et al. (2002), whose analysis was segmented according to specific features of the most common types of process industries.

2.1.2. Inventory management

Quite often, inventory management is separated from the production planning process. However, both activities should be performed in cooperation since, depending on the production planning methodology, different levels of inventory must be kept in order to reach a satisfactory service level. In the particular case of process industries, much due to the significant changeover times and costs, an inadequate production planning may lead to undesirably high inventory levels, thus additional costs for the company.

Dennis & Meredith (2000) presented a framework for the classification of integrated Production and Inventory Management (P&IM) systems in this sector. The method was established by defining the following key variables to distinguish those systems:

- level of detail and frequency applied on the generation of material and capacity requirements.
- level of detail and frequency applied on the tracking of material and capacity consumption.
- control of the Work-In-Process (WIP).
- percentage of material and capacity control tasks that are computerized.

Through the exploitation of those factors with data gathered from 13 industries, 19 P&IM systems were distinguished, which later resulted in 4 clusters of identical managerial features: common, WIP-control, computerized, and simple. In the first (the most usual), the raw material requirements are generated on a fixed interval reorder point and updated on a daily basis; the tracking of material consumption is performed through the record of standard consumptions with periodic adjustments; Capacity Planning by Overall Factors (CPOF) is applied for the establishment of capacity requirements; and the labour and machine hours are tracked individually for each product reference.

The regularity of multi-stage production systems at process industries often results in an abundance of inventory keeping throughout the system. As a matter of fact, inventory keeping accounted for more than half the net working capital of those industries, by the year of 2013 (Moser et al. 2017). Usually presenting intermediate inventories of distinct Stok Keeping Units (SKU), the material allocation problem constitutes one of the main issues approached by the process industry-oriented research field. This problem consists of assigning raw materials or semi-finished products that are part of a product's recipe from a production stage ahead to specific orders. Amongst these problems is inserted the surplus inventory matching problem, which must be considered previously to the production planning process (Kalagnanam et al., 2000). More recently, Li et al. (2020) approached the problem by adapting the economic theory of two-sided matching, conceptualized in Roth (1985). This theory focuses on exploiting the relation between two disjoint agents and establishing an outcome that is satisfactory for both parts. The developed work has proved the adequacy of this formulation to the process industries, which regularly dispose of significant intermediate inventories of semi-finished products.

Nevertheless, regarding integrated production-inventory planning tools, its applicability in the sector has raised some barriers, primarily due to the industry features of sequence-dependent changeover times, recycling flows, and instability of the generated production plans (Moniz et al., 2014). Hence there is a necessity for simpler planning methods that present more flexible solutions and that approach those features in a practical manner. Ashayeri et al. (2006) have addressed this suitability problem, by developing a cyclic production-inventory planning and control model for the process industry environment. Results show that capacity was increased, material requirements became more predictable, lead time was reduced, and the stability of the workload and workforce requirements was improved. Furthermore, the transposition of the method to the real-world industries is facilitated, since the framework may be implemented on a spreadsheet, similarly to most of the sector's current production planning methodologies.

2.1.3. Pulp and paper industry: tissue paper manufacturing

Following the trends from the process industry, several research works are oriented toward mathematical optimization approaches. However, the companies of the sector have found difficulties in the employment of such methods in the manufacturing system, mostly due to the highly variant lead times, aggravated by the uncertainty related the productive equipment's availability (Malik and Qiu, 2008). The most common measure taken to mitigate the impact of this variability is the determination of contracts with flexible due dates along with the clients/distributors. Björk & Carlsson (2007) presented a MILP approach to understand the trade-offs between production planning and inventory management in those environments so that relevant advantages could be taken from this flexibility. By developing two identical models: one without flexibility in the lead times and the other with a reduced, yet present, flexibility (1 day); the overall savings from the producer through flexible due dates were approximately 24% superior.

Deriving from significant costs in transportation of materials, vertical integration strategies are quite common amongst this industry, such that the most acknowledged taxonomy at the research field is "pulp and paper industry". This nomenclature accounts for the transformation of wood into pulp, which later is processed into large-dimension paper rolls (usually referred to as "jumbo rolls"), as well as the energy production, from biomass. Being this a capital-intensive industry, production planners seek the maximization of throughput while satisfying the customers demand. As a result, most of the work regarding the production planning at pulp and paper industry focus on the sort-term production planning and scheduling (Santos and Almada-Lobo, 2012; Figueira, Oliveira Santos et al., 2013; Figueira, Furlan et al., 2013).

Concerning tissue paper, the manufacturing systems are characterized by a multi-stage, multi-product, and batch production. Encompassing pulp and papermaking processes (may or not be integrated), this sector extends the transformation process by converting the jumbo rolls into products like napkins, kitchen rolls, toilet paper, and towels (finished products), commercialized in typical grocery shops. As a result, the chain of production present various decoupling points, dealing with demand from both stages of the material/product: jumbo rolls and finished products. These features originate the need for intermediate inventories and their integration in the up and downstream production planning process. Research work has been focusing on this integrated view of tissue paper mills, encompassing strategic planning and short to long-term production planning, mostly through mathematical optimization (Westerlund et al., 2006; Teksan et al., 2013).

Further work has been published addressing the productivity of the last stage transformation process, referred to as "converting" (Cigolini and Rossi, 2004). At most industries, this stage is composed of multiple highly automated transformation lines, designed with the purpose of accomplishment of mass volume demand yet lacking flexibility to deal with a significant product variety efficiently. Identically to other process industries, the significance of changeover times and costs hinders this flexibility, generating a conflicting trade-off between product variety and productivity.

2.2. Simulation modelling

Simulation is an adaptable computational procedure that represents a phenomenon or a system (Pidd, 1998). For the context of this dissertation, the representation of systems should be the singular focus. A system is defined as a collection of entities that act and interact together in a way that a specific task is completed, or a specific goal is accomplished (Law, 2015). The process of system analysis comprises a wide range of possibilities when selecting a methodology to follow. This selection should be made considering not only the characteristics of the system in question, but also the motivation for the analysis. Law (2015) summarized the most common approaches applied in this context (Figure 2.1). On a first level, the analysis may be performed by experimentation, either on the actual system or through a model representation of the system. The first is considerably more constrained than the latter, since that type of analysis may hinder the performance of the system during the period of experimentation. Amongst the experimentation on a representative model of the system, the type of model is distinguished between physical and mathematical. Here, the nature of both problem and system should dictate which approach is more suitable for each case. At last, mathematical models may be analytical or simulation. This last branching usually is decided based on the complexity of the system, which results in an identically complex model. For the cases where the system is relatively simple, analytical solutions are preferred, since better solutions are more easily obtained. On the other hand, when the complexity is increased, analytical models, for most of the cases, require a higher computational capacity than the simulation approach. Pidd (1998) reinforced this idea by highlighting simulation as the most appropriate approach for complex problems with a large set of parameters, assuring low costs and a better understanding of the interaction between the system's components.

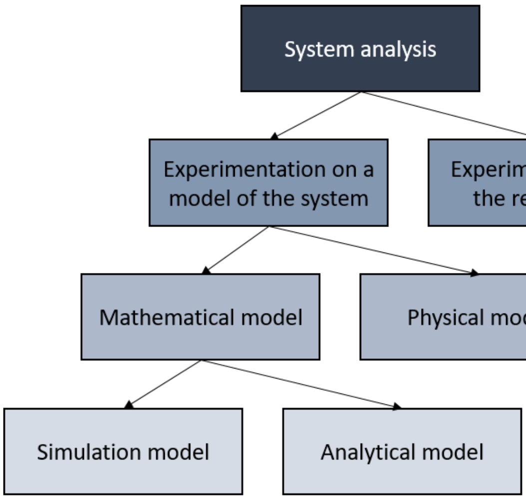

Figure 2.1. Approaches to system analysis (Adapted from Law, 2007).

2.2.1. Simulation models and their elements

Preceding the development and analysis of a simulation model, it is required an understanding of the available modalities of modelling, as well as of the elements of the models. Law (2015) proposes three dimensions for model classification: static or dynamic, deterministic or stochastic, and continuous or discrete. The first dimension is related to the evolution of the model through time. While dynamic models represent a system whose state changes over time, static simulation models represent the state of a system in a particular instance, i.e. time has no influence on the state of the model. The following dimension regards the presence of randomness in the model. The outputs from deterministic models may be obtained through similar analytical models, since there is no variability (randomness) in the elements of the model. On the other hand, stochastic models will be subject to the probability that is processed amongst the components of the model, requiring a thorough statistical analysis of multiple replications for the validation of the results obtained. At last, the continuity-discretion dimension is related to the time-advance mechanism through which the simulation run evolves. At continuous models, time advances continuously, resulting in a continuous update of the model state. In opposition, at discrete models, the advance of time is performed discretely, resulting in state updates.

Regarding the elements of the model, Banks et al. (2010) distinguish the types: entities, attributes, activities, events, and state variables. Entities are the object of interest in the system and may be permanent, those which stay in the model from the start to the end of the simulation run; or temporary, those which enter and leave the system along the simulation run. Attributes compose the set of properties assigned to the model entities. An activity represents a time period of a specified length. Events are occurrences, at specific instances, that may alter the state of the system. And finally, state variables are the set of variables that describe the behaviour and state of the model at each instant.

2.2.2. Stages of a simulation study

Simulation modelling is usually a time-consuming procedure, which requires specialized training for the development of useful models (Law, 2015). Thus, the execution of a simulation-based analysis should follow some pre-defined stages, allowing for an efficient and accurate study. The definition of these stages has been reason for discussion amongst the academic field. Figure 2.2 and the listing below present the standard for the procedure of a simulation study, resultant from the crossing of proposals from various authors (Musselman, 1998; Banks et al., 2010; Law, 2015).

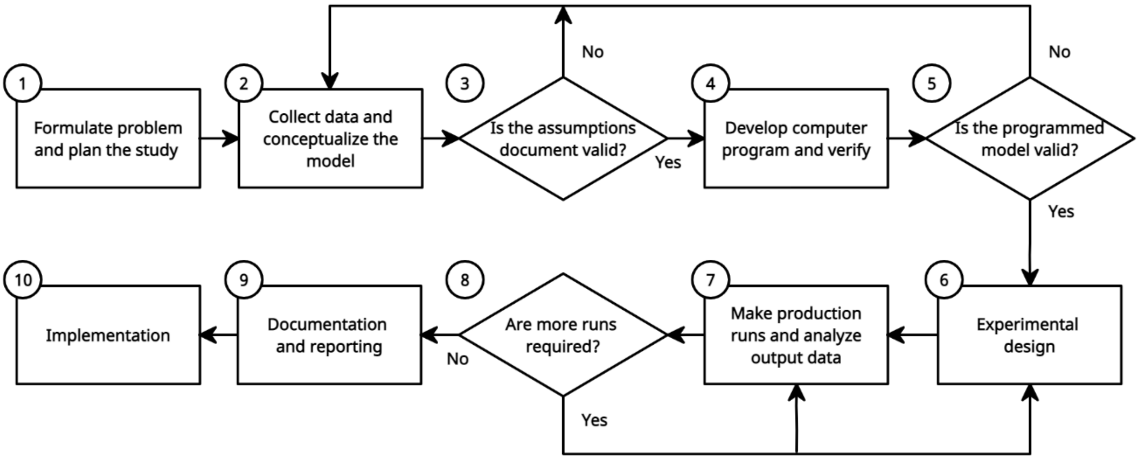

Figure 2.2. Stages of a simulation study (adapted from Banks et al., 2010; Law, 2015; and K. J. Musselman, 1998).

1. <u>Problem formulation and study planning</u> - the first step consists of concretizing the problem to be solved, clarifying the objectives and scope of the study, as well as planning the resources required for its execution.

2. Collection of data and conceptualization of the model – this stage consists of gathering information, near the system manager, regarding the operating procedures of the system in study. Being the overall activity of the system understood, the model should be conceptualized, assessing its level of detail and parameters, which should be synthetized in an assumptions document. From the data collected, the parameters of the model are specified.
3. Validation of the assumptions document – by presenting the assumptions document to the manager, insights are obtained regarding the validity of such assumptions. In case of invalidity, the step 2 should be reviewed.
4. Simulation model programming and verification – after validating the assumptions document, the conceptualized model is translated into a computer, which is programmed and verified (debugged).
5. Model Validation – in this step, pilot runs are executed in order to assess the quality of the representation of the system. If the behaviour and performance of the model are not similar to the ones of the system, a reformulation of the concept of the model may be required (stage 2).
6. Design of experiments – the alternatives that are meant to be studied with the simulation model must be determined and structured, as well as the length and the number of simulation runs that are to be executed.
7. Execution of production runs and analysis of output data – the analysis of the results from runs of the model serves to estimate measures of performance for the system designs that were established. Executing a thorough analysis from an enough number of production runs for each experimental design aids the differentiation of the studied alternatives and the highlighting of those which present a better improvement for the system.
8. Assessment of the need for more replications – from the previous analysis, the model user determines the necessity of a higher number of replications or additional experimental designs.
9. Reporting of the simulation study – In this step, the simulation program and the study progress is documented. This allows for future utilization of the model by other analysts, as well as further modifications to the simulation. In addition, this

reporting generates confidence in the study, bringing a consistent analysis to support the process of decision making.

10. Implementation of measures – The success of this last step is highly dependent on the assertiveness of the remaining steps of this guideline. Moreover, it is dependent on the follow-up of the study by the final model user, the decision-maker.

2.2.3. Discrete-event simulation and system dynamics

The most applied simulation modalities are the DES and the System Dynamics (SD). Both tools have emerged from the evolution of computational capacity over the years (Tako and Robinson, 2010). DES considers individual entities with a specific behaviour at discrete time instances. In addition, most of the application cases of the tool present a stochastic nature. On the other hand, SD simulation models are programmed as a set of stocks and flows, where the state changes occur continuously over time. Then, individual entities are not modelled, and the nature of most models is deterministic, even being possible the integration of random components (Law, 2015). Table 2.1 lists the features of each methodology. By crossing the features from each modality with the context of the problem to address, DES can be distinguished as the most adequate tool to be used for our problem.

Table 2.1. Characterization of DES and SD models (adapted from Tako & Robinson (2010)).

	DES	**SD**
Problem nature	Tactical-operational	Strategic
Variability significance	High	Low
System representation	Analytical	Holistic
Model complexity	Reduced scope, with large complexity and detail	Broad scope, general and abstract
Number of entities	Reduced	Large
Output data	Quantitative	Qualitative
Objectives	Comparison and optimization	Policy formulation

2.3. Simulation in operation and design of manufacturing systems

Simulation has frequently been employed in the industrial environment as a decision-support tool for the design and operation of manufacturing systems (Negahban and Smith, 2014). Being a flexible tool, simulation allows for integration with other decision-support frameworks, from algorithms to management tools. Those tools may be oriented for any of the three levels of managerial planning: strategic, tactical and operational (Baid and Nagarur, 1994). K. Musselman and Reilly (2002) have presented an exemplification where a simulation model was integrated in an Enterprise Resource Planning (ERP) system in order to improve the forecast and scheduling processes suitability to the system. In addition, simulation may be integrated with optimization methods, in hybrid approaches to problem-solving. The possibilities for the interaction between these two methodologies are wide, having it proved to be effective in addressing problems within production planning (Figueira and Almada-Lobo, 2014; Vieira *et al.*, 2019). This adaptability of simulation to distinct approaches was a fundamental factor for its role in the digital transformation of industry (Negahban and Smith, 2014).

Amongst process industries, simulation applications are also frequent. Venkateswaran and Son (2005) have presented a hierarchical production planning system developed through the integration of DES, for production scheduling, and SD for enterprise level planning. Also the scheduling and control on multi-product batch plants has been addressed through simulation (Castillo and Roberts, 2001; Van Beek et al. 2002). Here, the system analysis through simulation has shown to be adequate to non-discrete production systems, allowing for development of production strategies adapted for the system being studied. Mehra et al., 2006, for instance, presented a solution for the batch-size problem at a continuous manufacturing system. In addition, inventory management has also been addressed via simulation modelling, encompassing selection of inventory policies for multi-product plants and determination of the optimal customer order decoupling point (Sharda and Akiya, 2012; Zandieh and Motallebi, 2018).

2.4. Final remarks

In accordance with the literature review presented, simulation modelling comprises a suitable approach to the problem. On the one hand, process industries have shown resistance to applying the previously proposed planning methodologies, most of them founded on an analytical formulation basis. The difficulties in putting to practice such methods bring additional motivation for the exploitation of alternative approaches, which must be able to adapt to the characteristics of these type of systems. On the other hand, simulation modelling has regularly been applied to the design and operation of manufacturing systems, proving to be a valuable tool for obtaining a broad understanding of its operation. Through this acknowledgement of the system being studied, it is possible to develop heuristic rules to guide its operation towards improved performance. Therefore, this approach comprises a relevant opportunity for the application of such methodology on process industries, by defining heuristics suitable to the characteristics of the specific system instead of creating a purely analytical algorithm.

3. CASE STUDY

As the study object, it was considered the tissue paper manufacturing system from a Portuguese pulp and paper manufacturer, *The Navigator Company*. The case motivation relies on the difficulties found in exploiting the productive capabilities of a modern industrial complex. To better understand its current state, this chapter contains a description of the working environment and its elements.

3.1. The company

The Navigator Company started its activities in 1953, then by the name *Companhia Portuguesa de Celulose*, at Cacia, Aveiro, having its activity centred on raw pine pulp production. Along with its evolution, the company was recurrently a worldwide pioneer at the level of production processes as well as products developed, being, by 1957, the first producer of bleached paper pulp from eucalyptus. At the moment, *The Navigator Company* has industrial units in Cacia, Vila Velha de Ródão, Setúbal and Figueira da Foz. Following production chain integration principles, the company operates along every step of the life cycle of its products until the customer's purchase, acting in forest development and management, pulp, paper and tissue production, and energy generation. While managing 120 thousand acres of forest, its sophisticated and modern facilities allow for an annual capacity of 1.6 million tons of paper, 1.5 million tons of pulp, 130 thousand tons of tissue paper and 2.5TWh of electric energy.

The case study to the present thesis is the tissue paper production chain of the company, whose productive agents are the facilities located at Cacia and at Vila Velha de Ródão. From now on, these locations will be referred to as *Factory 1* and *Factory 2*, respectively. From those, the main focus will be assigned to the *Factory 1*, which is resultant from a recent investment from the company, as an effort of consolidation on the tissue market. This industrial complex consists of 4 distinct segments: wood reception and pre-processing, pulp factory, tissue factory and converting. The production flow from these complementary elements results in an annual transformation capacity of about 120 thousand tons of tissue paper in final products, in form of toilet paper, kitchen rolls and napkins.

3.2. Tissue production chain

The tissue paper production chain is composed of 3 distinct stages: pulp treatment, tissue production and paper transformation. Resulting from the investment referred above, the *Factory 1* industrial unit, which previously consisted solely in the pulp factory, now contains a facility for the execution of each phase. Thereby, besides the increase of production capacity, the transportation of materials was facilitated, which in the pulp and paper industry may reach about 20% of the total operating costs (Blanco et al., 2004).

3.2.1. Pulp factory

At the pulp treatment stage, wood is received, trimmed, digested, bleached and cleared, resulting in paper pulp and fiber bundles, which are transported to the tissue production facility. Arriving at the *Tissue Factory*, the pulp and fiber bundles are pre-processed and stored in tanks, which feed the system with raw material. During this flow, the materials are refined, humidified and blended, assuring that the paper mixture produced has the correct properties, such as resistance, elasticity and softness.

3.2.2. Tissue factory

The tissue production process starts in this facility. This process is executed by an automated set of equipment that works continuously between batches of production: the *Tissue Machine*. The entrance of the paper mixture on the *Tissue Machine* chests initiates the production operation. While the mixture flows through the *Tissue Machine*, it is subject to processes of formation, drying and winding, resulting in a one-sheet large-dimensions paper roll, weighting approximately 6 tons, designated as the reel. From the entrance of mixture to the exit of the reel, the process takes approximately 1 hour, independently from the type of tissue paper being processed. After the process is complete, the reel is sawed in half, generating two identical intermediate SKUs, designated as *Jumbo Rolls* (JR). These JRs are categorized according to the tissue paper reference that they are composed of. This reference indicates the type of pulp mixture and the number of layers present in the paper sheet. The type of pulp mixture is a fundamental parameter, since it dictates the grade (weight per area, generally in g/m2) of each tissue paper. This characteristic is the single factor that defines the requirement of setup operations between production orders at the

Tissue Machine. The physical properties of the tissue paper and the production processes at this equipment result in the need for setup operations each time the grade is increased from one production order to the next. These setup operations consist mainly in the cleaning of the pulp chests and other components of the set of equipment.

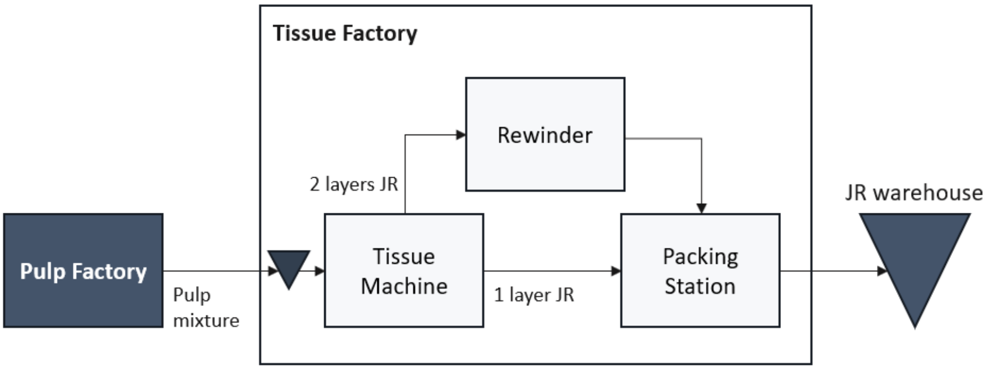

Figure 3.1. Material flow at the Tissue Factory.

For the cases where the JR specifications require a double paper sheet, the reel – set of two similar JRs – follows to the *Rewinder*, where the sheets are glued to one another, and then sent to the packing station. Otherwise, i.e. when the paper specification consists of a single sheet, the two JRs are transported directly to the packing station (Figure 3.1). After being individually involved in a plastic film, the JRs proceed to the autonomous intermediate warehouse (exposed ahead), being transported automatically by a chariot.

Regarding the quality of the processed materials, there is a factor to point out: web breaks. Web breaks are deformities that take place during the processing of a reel at the *Tissue Machine*, which lowers the quality of the paper and may even cause a rejection of the reel. Such rejections are dependent on the finality of the JRs, since each client has a specific tolerance regarding these flaws. Usually, the maximum tolerance from a standard customer is of 1 web break, yet there are others who may accept up to 3. Nevertheless, depending on the number of web breaks, a reel may yet be reutilized at a lower grade, on some occasions. If not, it must be directed to the pulp factory, where it will be humidified, and the tissue paper is reused.

3.2.3. Intermediate jumbo-roll warehouse

At this point, shop-floor workers at the *Converting Lines* (transformation lines of the next stage of production, which will be addressed ahead) are able to send material requests to the intermediate *JR Warehouse*, which autonomously delivers the roll to the line, with the assistance of a Large Goods Vehicle (LGV). This storage element has a capacity of 1212 JRs, stacked on top of each other, in a maximum of 4 levels at 303 locations. The inventory keeping resource behaves as a decoupling point, given that it is where the assignment of the rolls to a specific final product order takes place. Besides this demand of JRs from the next stage of production, the inventory kept in this storage unit must satisfy external demand as well. Identically to other process industries (Westerlund et al., 2006), the multi-stage feature of the production process allows the company to commercialize, not only the finished products from the last productive stage, but also intermediate materials, which in this case are the JRs. Along with this demand from external clients of JRs, further outgoing flows occur. Those flows are directed to *Factory 2*, which takes advantage from the higher throughput rate of the *Tissue Machine* at this facility. On the other hand, *Factory 2* also expedites JRs to this facility, mostly when the tissue requirements from the *Converting Lines* contain tissue paper with specifications that are not encompassed by the long-term production planning of the *Tissue Machine* at *Facility 1*, such as pink tissue paper. Each existing flow of JRs is represented in Figure 3.2.

Figure 3.2. Outgoing and incoming flows of JRs at the intermediate warehouse.

When entering this intermediate inventory point, the JR has already gone through the first decoupling process, which concerns the deliberation between exportation or internal consumption of the JR. In reality, this decision is taken during the *Tissue Machine* production planning, where one or more production orders are directly assigned to the external orders of JRs, for both clients and *Factory 2*. Consequently, the entering JRs are previously differentiated between internal consumption (at *Converting Lines*), exportation to *Factory 2* or exportation to a specific client.

The second and last decoupling point consists of a material allocation process of the JRs destined to be consumed internally, at the *Converting Lines* of *Factory 1*. This material allocation process is performed on a weekly-basis and is started by analyzing the planned converting production orders for the week to come. These forthcoming production orders are designated as “open orders”. Through an estimation of the tissue paper consumption resultant from the open orders of each production line, a certain number of JRs is assigned to each open order. Physically, the JRs remain in the *JR Warehouse*, however, they are already allocated to a specific final product, ending the process of decoupling.

3.2.4. Converting lines

The last productive stage of the manufacturing system consists of transforming JRs in the finished product, i.e. napkins, toilet paper and kitchen rolls. This process is commonly referred to as “converting”, hence the denomination of *Converting Lines*. At the moment, the converting facility of the industrial complex is composed of 4 lines that work continuously except for unplanned failures of the equipment.

On each line, there is a preparation area where the JRs (coming from the *JR Warehouse*) are unpacked, and their quality is verified. After this preparation process, 2 JRs are received in each of the 4 highly automated production lines – domestic #1, domestic #2, napkins and industrial. At the beginning of each line, there is a buffer of 2 JRs available, which must be renewed during the execution of the production orders, as the JRs are consumed (the entire material flow is schematized in Figure 3.3). For exemplification purposes, the tasks performed along with the domestics and industrial lines are briefly described in the next paragraph. The processes differ for the napkins line, since the final products consist of packs of folded paper sheets instead of a paper roll. Yet, the acknowledgement of the entire transformation process is not relevant to our problem.

For the domestics and industrial *Converting Lines*, the first process consists of unwinding the two JRs, whose paper type and number of layers might differ. Immediately ahead, the two resulting sheets are rewound together, forming a single paper sheet with 2 to 4 layers. This process is executed in parallel with the core winding, which creates a 2.6m wide cardboard core for the rolls. The following step is the tail sealing, which consists of the appliance of glue to the paper roll, from which comes out a 2.6 m wide paper roll with the diameter of the final product. At the end of this station, there is an intermediate buffer, referred to as “lung”, which allows the workers to make up for possible delays due to JR transportation, e.g., or even to prepare the following production order while the lung feeds the remaining steps of the line. Posteriorly, the large roll is sawed, resulting in multiple final product units, which are grouped, wrapped and palletized. At the two domestic lines, these last steps of grouping, wrapping and palletizing are performed in parallel, being the lines composed of one extra component responsible for each of such processes (these branches of equipment are designated as "legs"). Consequently, the production may proceed on one of the legs in the cases where the other stops working, in spite of reducing the throughput rate of the production line.

The characteristics of this set of equipment are mainly oriented for mass production, which is capable of accomplishing high throughput rates (Cigolini and Rossi, 2004). However, this high-volume production is only possible due to the specialization of the equipment on the specifications of each product that is processed. The primary result is that the productivity of the line depends on the reference being processed, since each one has its own specifications. In fact, for each product, each station of the production line has its own maximum throughput rate. Therefore, the bottleneck station of the production line, i.e. the station with a lower maximum throughput rate (thus, defining the production line's production rate), shifts between products.

Furthermore, as a result of the sophisticated equipment, the more distinct the specifications between two references, the longer the changeover operations between production orders will be. In order to deal with that, the converting references were grouped in families, that is, references between which the changeover time is relatively low. Aiming to mitigate the total time spent on changeover operations, the scheduling of orders of the same family consecutively is prioritized in the production planning process followed by the company.

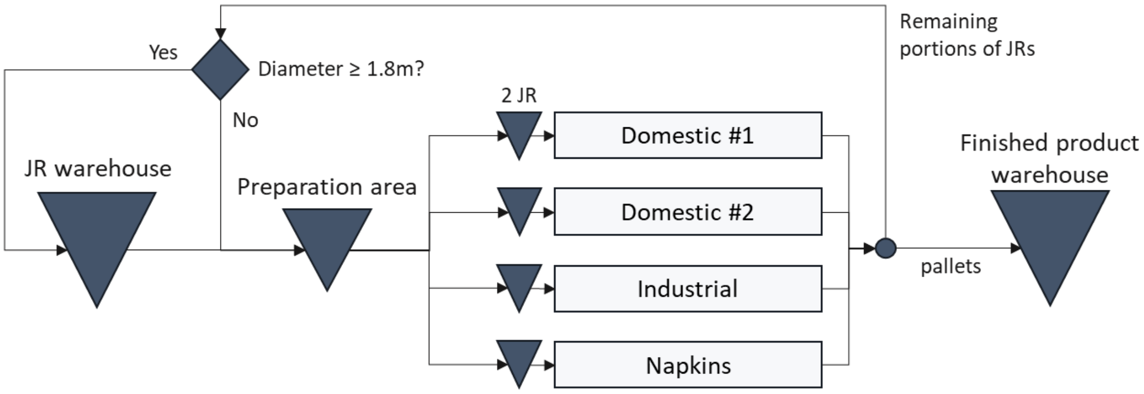

Figure 3.3. Flow of materials at Converting Lines.

3.2.5. End of production operations at the converting stage

From the entrance of the JRs to the exitance of pallets, the production process is automated, giving the workers the responsibility of control of the system's incomes, subsidiaries requirements, quality control, among other operational tasks. At the end of the palletizer, LGVs gather pallets of finished products, which are left at the pallet packaging station, located at the entrance of the final product storage. This last inventory keeping resource is automated and is responsible for autonomously preparing the transportation loads to be distributed later.

By the end of each production order, there may be some portion of one or both JRs left at the entrance of the production line. This occurs because it is not feasible to synchronize the converting batch sizes with the JRs dimensions, mostly due to the large dimensions of the JR. At that moment, the material flow is constrained by the characteristics of the handling system available. Ideally, the remaining part of the JR must be packed and transported back to the *JR Warehouse*, once again automatically, through the LGV. Yet, the available LGVs have a minimum grip defined at 1.8m diameter, which corresponds to about 62% of the standard JR diameter and 70% of the JR weight. Then, when, at the end of an order, a JR presents lower dimensions that those, it cannot be redirected to the *JR Warehouse*, being temporarily stored in the preparation area (Figure 3.3), until the execution of an order with the same tissue reference. This surplus material issue composes an important feature to be considered when developing the production plan and the allocation of JR to production orders, whose poor exploitation may result in unwanted and misplaced inventory keeping.

3.3. Production planning process

Regarding the flow of information during the production planning process, the acting parts consist of four distinct company sectors. The forecasting team delivers a monthly forecast to the high-level production planning team, based on various market analyses. In a first instance, this department studies the congruence of the current forecast with the forecast history and analyses the stock levels and the resulting coverage days for each tissue and converting reference. Furthermore, it receives information from the product development department, through which is decided the timing of the first production dates of the newly developed products. In the cases where the current forecast is not in line with the history, the development of a new forecast is requested to the forecast team. Otherwise, the high-level planning team decides, for the converting references, which ones must be produced and in which of the 2 facilities should they be produced. Being all the references from the forecast allocated to one of the facilities, or to both of them, the low-level planning department of each factory is in charge of performing the lot sizing and sequencing of the production batches, based on the finished product and intermediate JR storage levels.

After developing these monthly production plans, further reviews are performed every week to encompass urgent customer orders. The resultant weekly production plan is forwarded to the production department for approval, and, if successfully, the plan is implemented. The entire information flow is schematized in Figure 3.4.

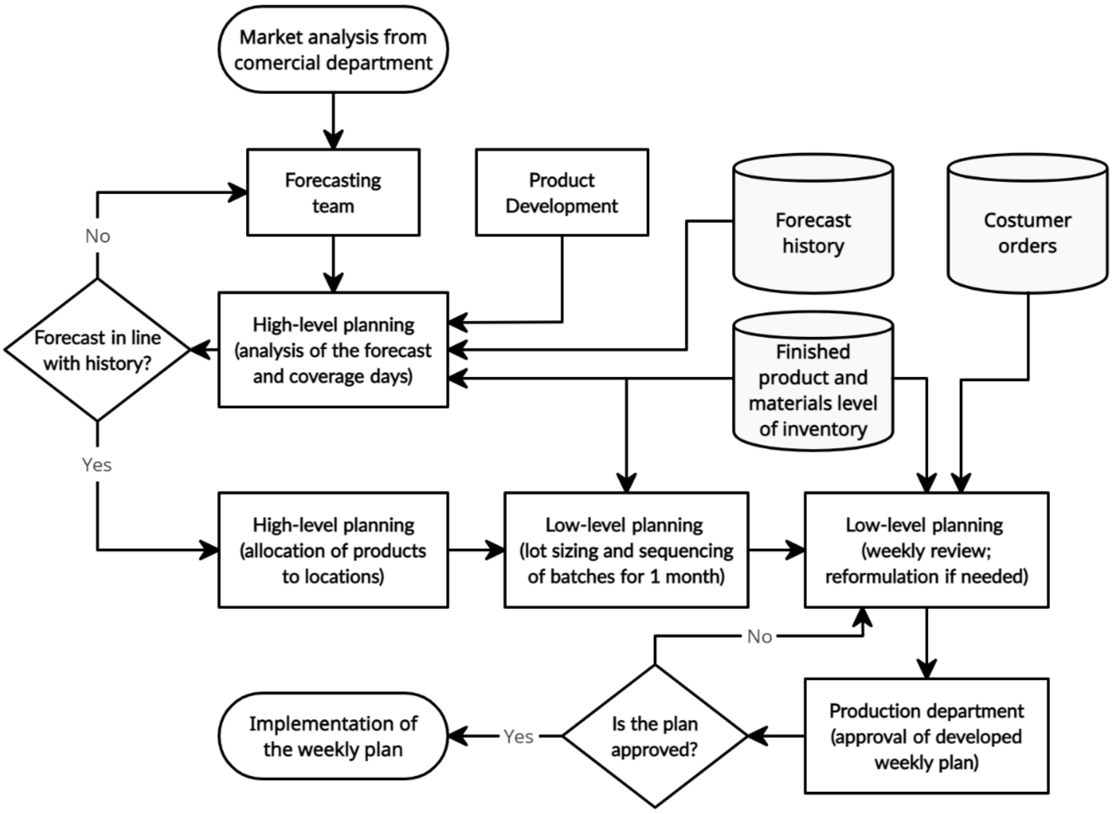

Figure 3.4. Information flow from the production planning process.

Considering the production planning process followed by the company, the most interesting step to integrate in this study is the component of the low-level planning. Since the decisions taken at the high-level planning, and above, constitute a distinct problem, the correspondent information flow and related decisions will not be addressed in our work.

Currently, the company develops monthly production plans to both *Tissue Factory* and *Converting Lines* through a capacity-constrained model on an Excel spreadsheet, which is executed accordingly to the monthly demand forecast and to the inventory level of each reference (tissue paper of the JRs for the *Tissue Factory* and finished products for the *Converting Lines*). This production planning methodology accounts for intricate system characteristics, such as the productivity dependence on the product sequence and the expected Overall Equipment Effectiveness (OEE) from each production resource. This type of methodology, although quite recurrent among process industries, is a highly time-consuming process, taking an experienced planner about 2 working days to complete one scenario of a feasible plan (Susarla and Karimi, 2011). In addition, the potential for human error, when applying this sort of planning framework, is increased compared to other methodologies.

In the case of the *Tissue Factory* production planning process, it is performed prior to the one of *Converting Lines*, which returns an estimation of the internal gross requirements of tissue paper over the month, updated on a weekly basis. Those gross requirements are then addressed by the material allocation process (open orders), from which are obtained the net tissue paper requirements, that must be either produced, at the *Tissue Factory*, or delivered from *Factory 2*. Lastly, the monthly production plan initially developed is reformulated to encompass the update from both the internal and tissue paper demands for that week. The result of this process (see Figure 3.5) is a detailed weekly production schedule, with differentiation of the destination (internal or external) for each production order.

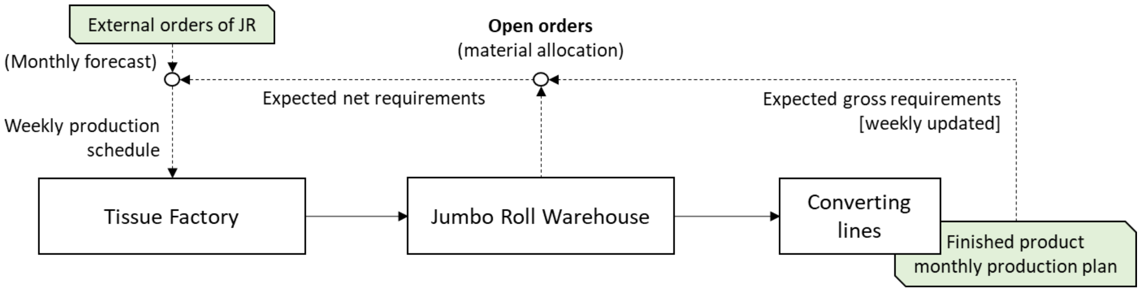

Figure 3.5. Tissue Factory production planning process.

3.4. Problem Statement

As referred above, the object of study consists of the papermaking processes at a recent tissue paper facility. The construction of this factory was mainly motivated by the necessity, from the company, to enlarge its production capacity so as to keep up with the increasing demand of tissue paper. Parallelly to the sales increase, the company had to deal with the emerging trend of mass product customization, which culminated in the processing of more than 900 distinct converting references during the year of 2020. As a matter of fact, this recent investment has made the difference in the company's annual tissue paper throughput capacity, having it more than duplicated. Nevertheless, the production performance of this modern manufacturing system is yet to be satisfactorily exploited, which enhances the motivation of the present work.

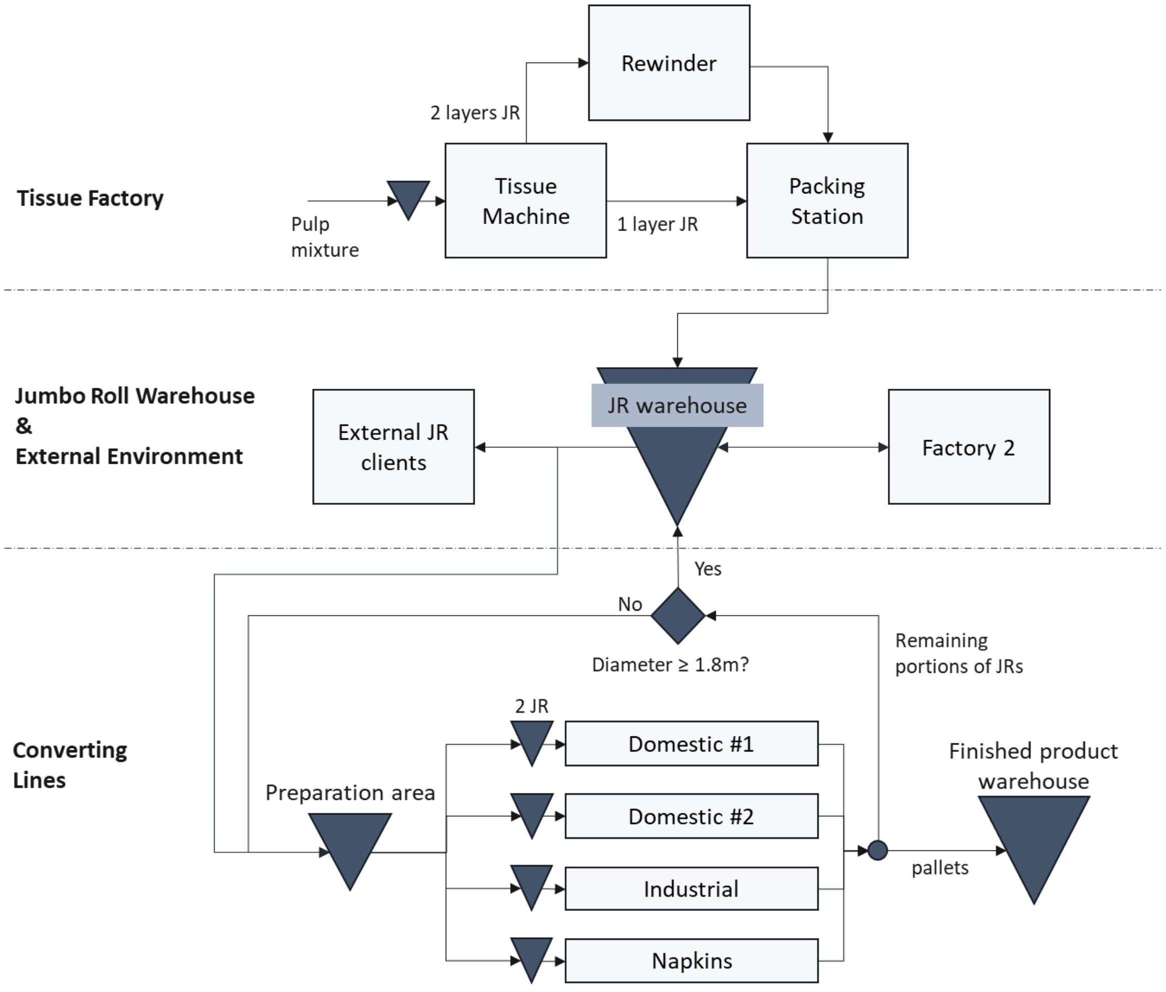

Figure 3.6. Flowchart of the entire manufacturing system.

The scope of this study was restricted to the production stages that could represent a higher impact on the operational performance (see Figure 3.6). The processes from the reception of wood up to the entrance of pulp in the *Tissue Machine* consist in the sourcing and pre-processing of raw materials. According to the company management, the availability of the raw materials should be considered consistent, withdrawing the interest of a possible sourcing strategy analysis. In addition, the production capacity available at the pulp factory is significantly higher than in the following stages. Thus, according to the Theory of Constraints (Goldratt and Cox, 2004) this element does not compose a constraint to the throughput rate of the downstream productive elements. Consequently, the scope of the study was restricted to the production processes inserted between the *Tissue Machine* and the end of *Converting Lines*. Those elements represent some of the papermaker's key resources, whose utilization rates strongly dictate the profitability of the facility.

Despite the effort from a few studies, led by the company, related to the development of adequate inventory policies, satisfactory minimum levels of inventory have never been reached, having those resulted in unfeasibly high occupation rates. Thus, some reference levels were determined in order to decrease the impact of disparities between the forecasts and the actual demand. Currently, the company struggles to keep satisfactory inventory levels, reaching an average of 85 to 90% of occupancy, which has recently motivated the creation of a taskforce to analyze alternative strategies to solve this inventory management problem.

One of the factors that cause this large inventory buffer comes from the low visibility of the tissue requirements coming from the *Converting Lines*, originated by its highly variant availability and product-dependent throughput rate. Besides the downtimes resultant from equipment planned or unplanned stops, the productivity of each converting line is highly influenced by the time spent on changeover operations between products of distinct families. Hence, the product sequence obtained from each production planning process constitutes a major influencing factor of the productivity at this last transformation stage, and consequently of the *JR Warehouse* state. An analysis of the trade-offs between inventory levels and productivity at *Converting Lines*, mainly affected by the production sequence and lot size, may bring relevant insights to the improvement of the system's productive capacity and reduction of inventory costs. Simulation modelling allows an integrated follow-up of the behaviour of every element of the system during the execution of each production plan, thus enabling the study of these trade-offs.

Regarding the production planning process, the actual methodology applied, a capacity-constrained Excel framework, is highly detailed, turning the file heavy and slowing the planning process. This blocks the possibility of a scenario analysis to aid the decision making at unforeseen occurrences, such as the failure of the execution of the production plan. Then, each time a significant unplanned situation occurs, the productive flow of the system is subject to the experience of the planners that are dealing with those random situations. Such occurrences are quite frequent, resulting in a regular reformulation of the production plan, sometimes requiring plan reviews on a daily basis. Having such a lowered visibility on the expected outcomes from the execution of the production plans may result in aggravating issues related to the reporting of materials and subsidiaries necessities which should be available, at least, one week before the time assigned to each production order.

Through a broader view of the system's expected response to each production plan, the company should be able to reduce costs in intermediate inventory keeping by increasing the productivity of each production line. Moreover, there is a clear necessity of a reformulation regarding the production planning process, which must benefit from a lighter planning method that enables the exploitation of multiple scenarios, mainly distinguished by the data entries applied, characterizing distinct forecasts. This more comprehensive perspective of future scenarios may bring to the planners an aid for production plan reformulation decisions, as they obtain insights into how the system is likely to respond to diverse scenarios that they might encounter.

Through a thorough integrated analysis of the entire manufacturing system, it is enabled an understanding of the inherent trade-offs between each segment of the production chain. By analyzing and exploiting those relations, improvement proposals may be formulated and assessed, aiding the company at the planning process along the manufacturing system.

In conclusion, the milestones of this project are listed:

1. **develop a simulation model** that allows for an overall perception of the information and material flows and its impacts on the current system's productive performance. At this stage, it is possible to obtain a prediction of the system's response for distinct production plans, which, on its own, may be a valuable tool to aid in future production planning processes;
2. **analyze the system's performance** under the current production policies and point out stations that require improvements;

3. **establish a range of influence** based on the characteristics of the system, defining the actual control properties which may be subject to proposals of improvement;
4. **develop proposals of intervention** for those control features, based on the analysis from the second point;
5. **implement those proposals in the simulation model**, obtaining the expected performance of the manufacturing system under the suggested measures.

4. PROPOSED METHODOLOGY

This chapter presents the methodology applied to solve the previously stated problem. Considering the actual planning framework, the flexibility required for a broader visibility over the production chain is not fully achieved. Nevertheless, such tool integrates an accurate capacity model of the system and years of experience from the planners at the company, which attaches a relevant credibility to the framework. Through simulation, it was possible to develop a virtual model of the manufacturing system, which behaves similarly to the factory. This simulation model, being validated and verified through the company's data, enables a scenario analysis of distinct production plans, developed by the Excel framework, which may act as a "prediction" of the response capability of the system to those plans. Furthermore, the understanding of the trade-offs between the elements of the system aids the search for efficient improvement proposals.

The model was developed through a python simulation package, SimPy[1], aided by an open-source data visualization framework, Streamlit[2]. Here, the conceptualization, development, and validation of the model, which compose some of the most relevant steps of the simulation study, will be exposed.

4.1. Simulation model conceptualization

This first step consists of outlining the structure of the model and obtaining the guidelines to develop the simulation.

4.1.1. Model scope and level of detail

When modelling systems with such complexity as the one present in the object of study, it is mandatory to restrict the model scope to the elements of the system whose influence on the problem is relevant. In fact, every simulation model should be as simple as possible in order to become a user-friendly and computationally viable analysis tool (Ward, 1989).

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[1] https://simpy.readthedocs.io/en/latest/

[2] https://streamlit.io/

Regarding the manufacturing system presented, a relevant source of complexity to the model may come from material and procedures specifications that do not benefit our analysis. Therefore, a model scope was developed by listing the possible elements to be considered and those that should be included and excluded from the model. Besides the restriction of the system to the processes between the *Tissue Machine* and the *Converting Lines*, previously justified, some details related to the production resources and material flows were excluded from the study. With the support of the company, the aim was to consider only the sufficient features to accurately model the system's capacity and its relevant influential elements. Table 4.1 summarizes the most relevant aspects that were excluded from the model scope, as well as the reason for exclusion.

Table 4.1. Exclusions from the model scope.

Element	**Reason for exclusion**
Layout distances and transportation	Material handling and transportation systems are highly automated, and activities occur in parallel with the production
Human resources	According to the company, workers do not compose a restriction to the functionality of the facility, since the quantity available at each shift is enough to keep every station running
Quality control (process)	Control activities are executed in parallel with the production and do not require extra transportation or production capacity
JR Warehouse infrastructures	Warehouse is autonomous, and the jumbo rolls are preserved through an oxygen suspension
Consumption of subsidiaries	The supply and availability of consumables is assured and does not compose an interesting element of study
Tissue Machine productive process details	Operations are performed in series, then each process is executed at the same production rate and has the same number of stops, since if one component fails or stops, the entire machine must stop
Tissue Machine maintenance requirements	Maintenance is performed once in a month, which, for the time horizon in study (1 month) is not relevant to consider
Final Product Warehouse	The analysis related to last inventory keeping element would significantly increase the complexity of the study, possibly harming its feasibility

Beyond the listed exclusions, it was required to establish the level of detail to apply on the modelling of the external entities of the system: *Factory 2* and JR clients. The only relevant features related to the external flows of JR to consider at the simulation model development are the incoming and outgoing rates or conditions of occurrences. Being so, the external environment, responsible for the external flows of materials, appears in the model conceptualization as a simple black box with specific demand and supply capability.

4.1.2. Model entities

The entities of a simulation model constitute its essential parts, from whose definition and interaction result in the behavior of the system being modelled (Law, 2015). Those can be distinguished according to their durability in the system: the ones which are maintained in the system along the observation period are specified as permanent, while the remaining, which enter, go through the system and are deleted or excluded, are designated as temporary (Banks, 1998). In the present case, the group of permanent entities is composed of the various fixed production resources available, while the temporary entities represent each material flow throughout the system. Thus, considering the scope previously defined, the resulting model entities represented were grouped accordingly to Table 4.2.

Table 4.2. Entities of the model.

Permanent Entities	Temporary Entities
Tissue Machine	Tissue Production Orders
Rewinder	Jumbo Rolls
JR warehouse	Converting Production Orders
Converting Lines	
External environment	

4.1.3. Simulation model representation

Some of the most common tools applied to represent the simulation model, through graphical means, are the Life Cycle and the Activity Cycle Diagrams (LCD and ACD, respectively). Usually these graphs are composed of 2 elements: wait times and activities (Paul, 1993). However, the system in hand presents a considerable number of ramifications of flows, turning this approach inefficient and even confusing. Then, the developed diagrams result from a crossing between standard flowcharts and the notion of life cycle and activity cycle. These notions consist in the discrimination of the order of steps that each entity goes through during the time at the model (life cycle), and the overall activity of the system, defined by interaction between entities (activity cycle). For the context of this dissertation, the nomenclature will not be modified. From these diagrams, the flow of the entities in the model should be perceptible. Firstly, it is presented the life cycle diagram of each model entity, which displays every stage of the entity in the model. For the temporary entities, these flowcharts contain an initiation node (full black, at the left), as well as a termination node (black border with white center, at the right). These two nodes represent, respectively, the creation and the deletion of the temporary entity. Naturally, for the permanent entities, i.e., fixed resources of the manufacturing system, a termination node is inadequate.

The information flow is not a part of the diagrams, being excluded any activities related to planning or material allocation previous to the entities' physical state or location modification. Thus, there is no value in representing the LCD for the *JR Warehouse*, since its only physical activities are the reception and expedition of JRs. Likewise, the external environment does not execute any activities other than the reception and supply of materials, being also excluded. Also, the *Rewinder* was excluded from this representation since it functions as a simple server, which receives, processes and dispatches JR entities, and has no relation with the remaining entities besides the continuation of some of the *Tissue Machine*'s WIP. Yet, the flow around these elements may be deducted from the LCDs of the remaining entities.

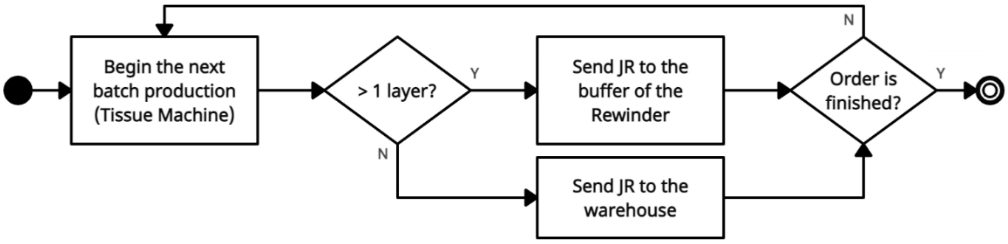


Figure 4.1. Life Cycle Diagram of Tissue Production Order entity.

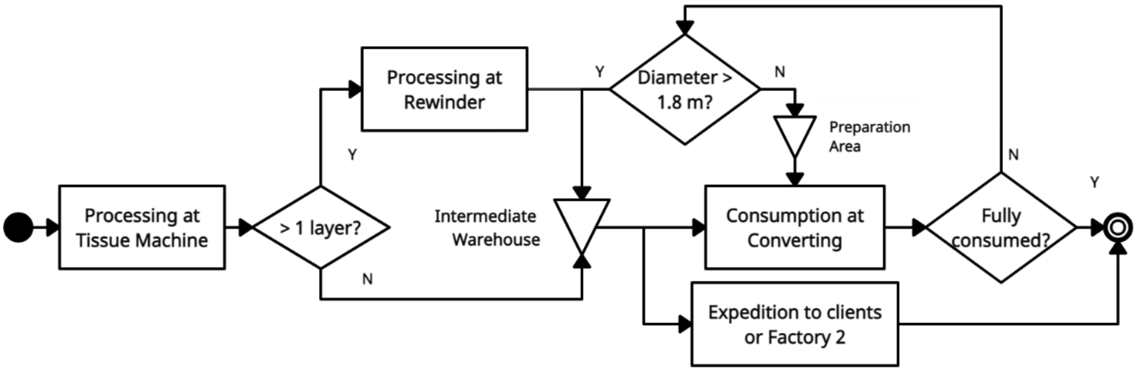


Figure 4.2. Life Cycle Diagram of Jumbo Roll entity.

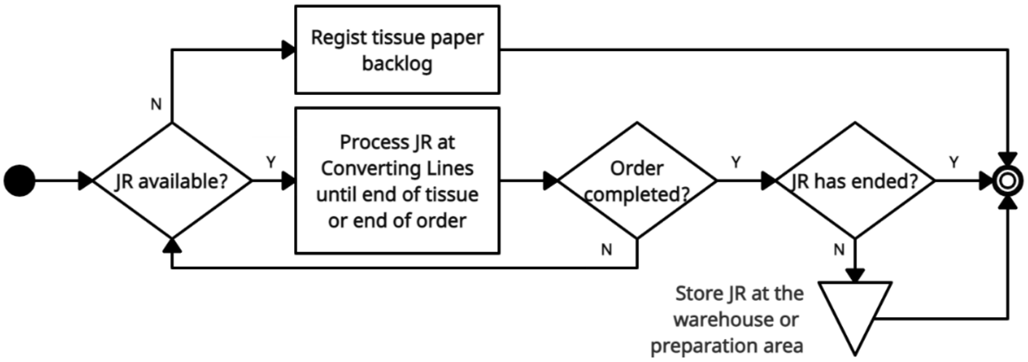


Figure 4.3. Life Cycle Diagram of Converting Production Order entity.

The LCDs above (Figure 4.1 to Figure 4.3) represent the stages and decision points of the material flow throughout the manufacturing system, which correspond to the activities performed by the temporary entities in the simulation model. The first the activities and decisions performed during each Tissue Production Order (TPO) execution. On the second, both the material assigning, and the inventory surplus issues are explicit, at the *JR Warehouse* and preparation area inventory points, respectively. Through the third, it is possible to infer that the execution of a Converting Production Order (CPO) will be segmented by the consume of JRs required to fulfil such order.

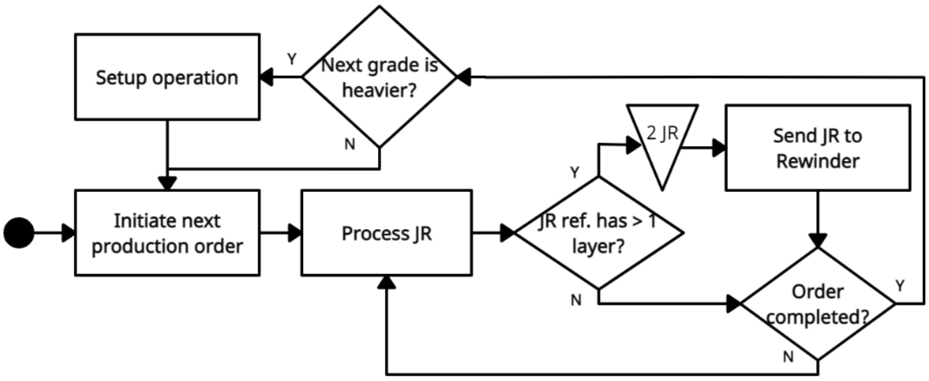


Figure 4.4. Life cycle diagram of Tissue Machine entity.

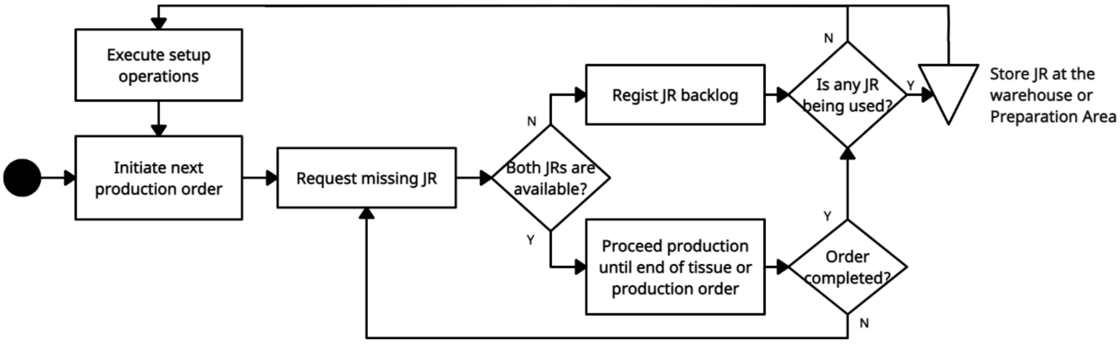


Figure 4.5. Life cycle diagram of Converting Line entity.

As for the permanent entities, its LCDs (Figure 4.4 and Figure 4.5) contain the sequence of operations performed during the production period. Besides the activities displayed, each element will be subject to the occurrence of equipment failures. Hence, these entities will present three distinct states along the simulation run: producing, setup or downtime.

In order to obtain a broad perception of the overall flow of entities (and materials), an ACD was created (Figure 4.6). This ACD composes the agglomerate of the previously shown LCDs, displaying the way in which each element is related. Here, for the elements which process more than one entity, a differentiation was established to clarify the destination of each entity type (TPO, CPO or JR).

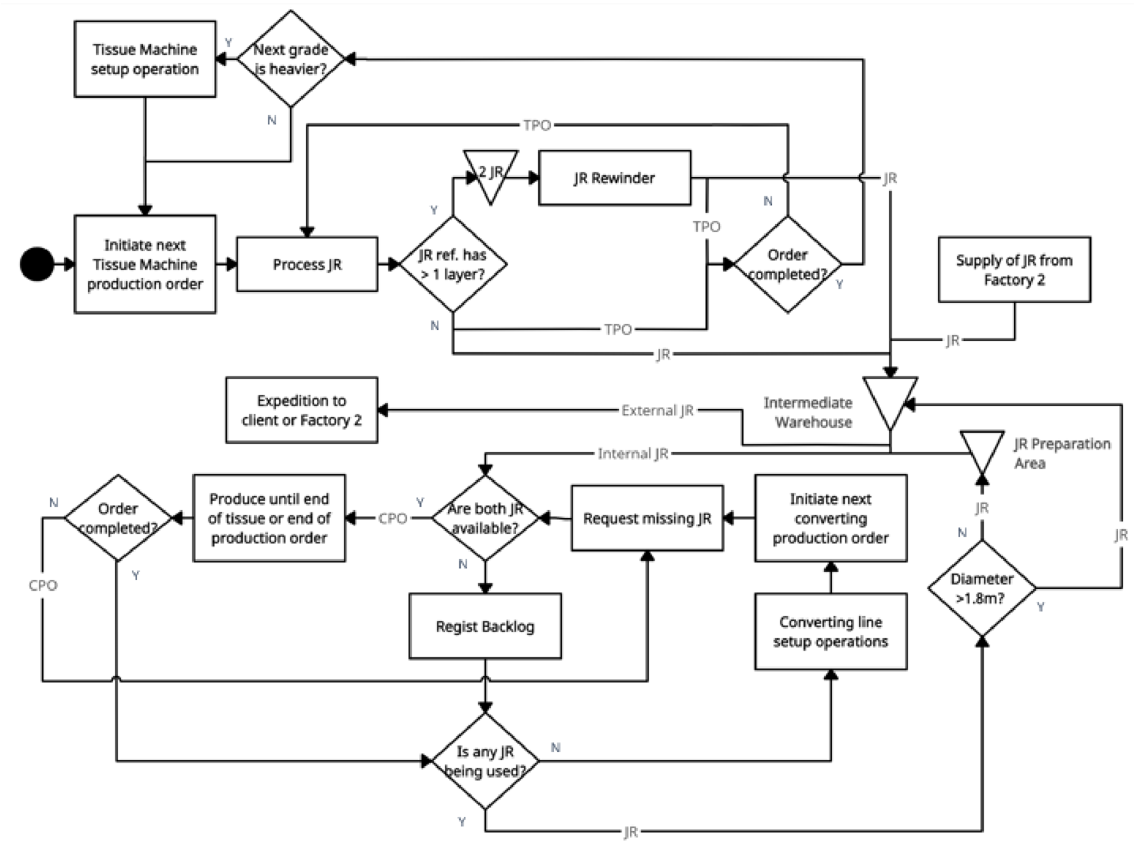


Figure 4.6. Activity cycle diagram of the manufacturing system.

4.1.4. Input modelling

Input data comprises one of the most influential elements when validating a simulation model (Law, 2015). For the system in hand, distinct types of datasets had to be gathered. Being one of the goals to test the system's response capability to a specific production plan applied, it was mandatory the access to an example of the production plan from both the *Tissue Machine* and *Converting Lines*. In order to model the flow of materials and its transformation, i.e. process of turning JRs into finished products at the *Converting Lines*, it was required to consider the Bill of Materials (BOM) of each converting reference. These BOMs, not only contain the types of tissue required to produce each converting reference, but also the value of the consumption rate when the production line is working at its maximum rate. Furthermore, as previously stated, one of the main issues to address is related to the productivity of the *Converting Lines*, which depends on the product being processed at each instant. Then, it was gathered information related to the *Converting Lines* productivity for each converting reference, as well as the setup matrix.

4.1.4.1. Production plans

One of the main milestones of this study consists of assessing the current production planning methodology and discussing possible alternatives to take advantage of the production system's unused capacity.

Tissue Machine

The *Tissue Machine* production plan is formulated based on the internal and external tissue paper necessities. Through the assessment of the inventory level for each tissue reference (at the *JR Warehouse*) and an estimation of the tissue consumption resultant from the execution of each *Converting Line* production plan, the internal tissue paper necessities are established. Meanwhile, the external necessities are defined based on the external demand of JR, as well as on the *Factory 2* intermediate inventory levels of JR (see Figure 4.7). The lack of consideration of the *JR Warehouse* inventory levels to the development of such necessities is due to the inventory management policy applied for these materials. In spite of being mostly produced to stock, the production orders of JRs (TPOs) at the *Tissue Machine* are assigned a specific customer or destination ahead of its execution. This allocation is performed to control the tolerance of the number of web breaks per batch. By previously knowing the maximum value of web breaks that each order can have, the production planning department can anticipate the need for reprocess of those orders. Nevertheless, if such threshold is surpassed, the JRs can be reassigned to another order that has a broader tolerance, or a lower grade.

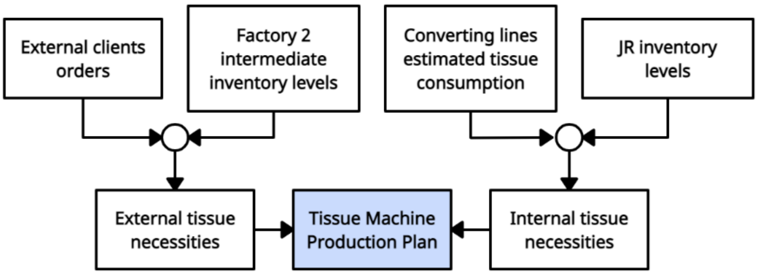


Figure 4.7. Current information sources of the Tissue Machine production planning.

This plan defines the production plan of the *Rewinder*, which results from the information cross between the *Tissue Machine* plan and the tissue references' BOM containing the number of layers per JR for each tissue reference. Through those files, considering that each tissue paper reference whose number of layers is higher than 1 must be rewound, it is defined the income flow at the *Rewinder*.

Since the internal tissue necessities are directly related to the inventory level of each tissue reference, it would be required to access such information to obtain a congruent production plan. Unfortunately, this data was not available. Hence, a reformulation had to be executed, by considering the internal necessities resultant from the inventory levels present in the simulation model, instead of the ones from the real system (Figure 4.8). Thus, the *Tissue Machine* production plan applied at the model validation is composed of the real system's external JR requirements, i.e., forecasted external demand (from both clients and *Factory 2*), and the simulation model pondered internal requirements. The concatenation of those two components in a single production plan was performed through a planning heuristic based on Earliest Due Date (EDD) rule.

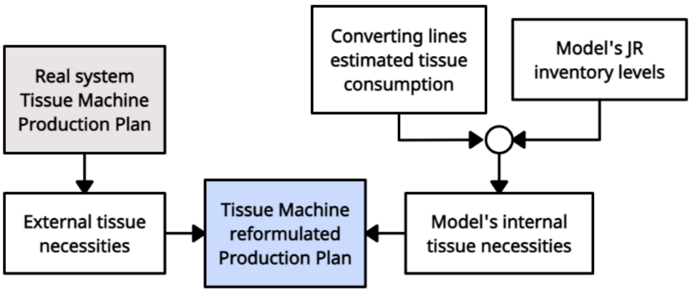


Figure 4.8. Updated information sources of the Tissue Machine production planning

Converting Lines

As stated in section 3.2, one of the most relevant issues to improve the production system's capacity is related to the *Converting Lines* productivity. This Key Performance Indicator (KPI) is directly influenced by the sequence of production, discriminated on the production plans. The plans obtained resulted from a regular planning process followed by the company, described in the section 3.3, and were applied in the model to validate the working conditions of the system.

In order to enhance the value from the simulation model, it had to present a facilitated insertion, pre-processing and application of these datasets. Furthermore, aiming at developing a framework capable of flexibly assessing different production plans, the model could not contain any barriers to handle these types of data.

4.1.4.2. Bill of materials

To accurately model the transformation process, it is required information regarding the paper consumption from each converting reference. In addition, it is required further data related to the output of each reference at the *Converting Lines* (pallets), since the packing and palletization layout is distinct to each reference.

All this information is available at the finished product BOM dataset, where the rolls dimensions, weight and palletization are defined for each converting reference. This spreadsheet is grouped according to the kind of production line in which each reference is produced: domestic, napkins or industrial. Having a verified information on the tissue consumption per converting reference, it is possible to estimate the internal gross tissue requirements resultant from a standard finished product production plan. These gross requirements are later analyzed and compared with the inventory levels of each tissue paper (JR) reference, from which results the internal net tissue requirements.

One more BOM was obtained, this time concerning the JRs. This data file contains the dimensions and properties of each type of tissue paper processed at the *Tissue Machine*. Through this information, it is possible to assess the number of JRs to produce as a function of the amount of tissue paper required.

4.1.4.3. Converting lines productivity and setup matrix

Another essential information for the model development is related to the capacity of the *Converting Lines*, whose throughput rate varies depending on the reference being processed. As previously referred, this equipment produces in series, which forces the line to work continuously, having its components processing at the same rate. Then, following the Theory of Constrains, the overall production line throughput rate is defined by its bottleneck, i.e., the component whose production rate is lower (Goldratt and Cox, 2004).

The productivity dataset, similarly to the one of finished product BOM, contains the maximum productivity levels for each converting reference, grouped by *Converting Line* in which it is processed. Through this data, it was possible to establish a reliable representation of the maximum production capability of the converting stage of the production chain. Beyond that, by crossing this information with the finished product BOM, the maximum tissue consumption rate for each reference can be defined. This allows an estimation of the tissue paper required for each interval of the production plan, thus relating the material necessities from *Converting Lines* with the production at the *Tissue Factory*.

The setup matrix is a fundamental data structure for the framework development, since it defines the productivity depending on the production sequence. Currently, a single converting reference is assigned to the napkins line, which erases the necessity for such information from that line. Beyond that, the finished product setup matrix of the industrial references is not available. Therefore, the production sequencing problem is restricted to the domestic *Converting Lines*, while the lot-sizing problem remains relevant for every other production line. The file obtained is composed of a matrix (D_{ij}) whose values correspond to the setup operations duration required to alter from a product at each line (of index $1, \dots, i$) to a product at each column (of index $1, \dots, j$).

4.1.5. Establishment of performance measures

It is essential to define measures that may evaluate the current state of the system regarding the approached problems, as well as differentiate the proposed solutions to those problems. Thus, the KPIs presented in Table 4.3 were defined, taking into consideration the problems addressed and the approach proposed.

Table 4.3. Listing of the Key Performance Indicators.

Tissue Factory	Nº of JRs produced
	Average Cycle time
	Nº of setups at the Tissue Machine
	Segmentation of production (internal and external)
	OEE of the Tissue Machine
Jumbo Roll Warehouse	Occupation rate
	Nº of expedited and received JRs
	Average lead time (time on inventory)
Converting Lines	Nº of pallets produced
	Average production rate
	Nº of Tissue paper backlogs
	Nº of JRs consumed
	Time on setup
	Average nº of JR waiting in line

4.2. Simulation model development

The simulation model was programmed using the SimPy python simulation package, which was aided by the open-source data visualization tool Streamlit. This subchapter contains a concise overview of the practical development of the model, following the conceptualization exposed in the previous section.

4.2.1. Simulation with SimPy

SimPy is a process-oriented simulation package in python first released in 2002. It consists of a set of python libraries that enables the access to a discrete event simulation environment. The process-based nature of the framework translates in the programming of each of the system's features as processes, which, in python, are created through modules, also known as functions (Matloff, 2008). Essentially, a simulation model can be built through the programming of the interactions between processes, established on the discrete event simulation environment.

This tool presents numerous advantages when comparing to other simulation software. For the context of this thesis, there is one particularly attractive: by being based on python programming, the integration of the simulation model with other development tools is highly facilitated (Moulton, 2011). Thus, the developed model may be object for further development of more elaborated decision support systems, such as optimization models or real-time control systems.

4.2.2. Simulation model programming

This subchapter serves as brief description of the objects present in the model, each related to specific features of the manufacturing system. Though this listing does not encompass every object in the simulation program, it summarizes the code structure developed. The model objects may be segmented in model initiation, production resources, information flow, and output visualization (*Streamlit*).

4.2.2.1. Model initiation

The first processes executed are related to the input modelling, described in section 4.1.4.1. Through this segment of code, each dataset is imported and pre-processed into a structure that is favorable for the intended operations. Furthermore, additional processes were formulated with the intention of approximating the model's initial conditions to those present in the day-to-day activity of the system. Since the working conditions of the *Tissue Machine*, *Rewinder* and *Converting Lines* do not vary over time, those elements were not considered in this initial step.

Regarding the *JR Warehouse*, on the contrary, the level of inventory is fluctuant and has a direct effect on the remaining elements performance. Thus, it was firstly developed the process $InitializeWarehouse$, which, having the annual forecast of JRs as a reference, creates JR entities and stores them in the $JumboRollWarehouse$ list. As input variable, the process assesses the initial occupation rate and stops creating entities when such rate is accomplished. With the advance of the simulation run, the resultant list, which represents the *JR Warehouse*, is manipulated by the remaining production elements, being them able to request or store JR entities there.

Further operations had to be accounted for a robust model initiation. Those are related to the outgoing flow of JRs from external clients or from *Factory 2*. These operations are executed by a cyclic process, $ExternalJRFlow$, which iterates along the external orders' due dates and extracts a previously established number of JR entities from the $JumboRollWarehouse$ when the due date is reached.

4.2.2.2. Production resources and material flow

As referred above, the *JR Warehouse* is represented by the list $JumboRollWarehouse$, which is accessed by each of the remaining elements of the system. As for the remaining production resources, they were grouped accordingly to the facility in which they are inserted. The *Tissue Machine* and *Rewinder* were grouped in a single object: the $TissueFactory$ class, which composes a group of modules, each representing an operation performed at the facility. Further on, each *Converting Line* was modelled by the same segment of code: the $Converting$ class, which, similarly to the *Tissue Factory*, contained every operation performed in that facility.

The following sub-processes were created at the $TissueFactory$ class: $RunTissueFactory$, $GenerateProductionPlan$, $GenerateDowntime$ and $GenerateSetup$. The first is the master process, which dictates the triggering of each of the other processes, while executing the main operation performed: the tissue paper production, where the *Tissue Machine* and the *Rewinder* production activity is inserted. The second is responsible for executing the production plan reformulation described in section 4.1.4.1. At last, the remaining processes determine when the state of the equipment should change (by generating failures or setup operations, respectively) and execute those modifications, restricting the productive capacity of both the *Tissue Machine* and $Rewinder$.

In order to start the tissue paper production, the $RunTissueFactory$ process is triggered, along with the $GenerateProductionPlan$. After the creation of the reformulated production plan, the master process generates entities of type $EntTissueProdOrder$ (TPO), accordingly to the production plan. By accessing the information from each TPO, the tissue paper type to produce, the quantity of rolls and its destination is recorded, being then started the tissue production. This is the main operation of the facility and is modelled by the processes $SrvTissueMachine$ and $SrvRewinder$. At the end of production of each JR, the $RunTissueFactory$ process generates an entity $EntJumboRoll$, adding it to the $JumboRollWarehouse$ list. Once the production order is completed, the $EntTissueProdOrder$ is deleted and replaced by the following order on the production plan.

Regarding the $Converting$ class, the operations considered resulted in the following modules: $RunConvertingLine$, $GenerateDowntime$, $GenerateSetup$ and $RequestJR$. The first three are executed and behave similarly to the equivalents from the $TissueFactory$ class. The last, however, is specific to the operations at *Converting Lines* and composes the process that ensures the availability of raw material (JR entities) when it is required.

When triggered, the $RunConvertingLine$ initiates the activity of one of the *Converting Lines*, which will be distinguished by the datasets imported (each of the referred in section 4.1.4). From there, the monthly production plan of the line is recorded, and it is generated a CPO entity, corresponding to the first order from the plan. At this point, the state-changing processes ($GenerateDowntime$ and $GenerateSetup$) are triggered, assessing the occurrence of equipment failures during the order execution and the requirement of setup operations between orders, respectively. At last, the production of finished product pallets is triggered; however, restricted to the condition of availability of raw material (JR entities). Hence, it was developed the process $RequestJR$, which, considering the tissue paper type required, the *Converting Line* from which the request comes, and the finished product reference being processed, searches and returns the position that the next JR entity occupies in the $JumboRollWarehouse$ and moves it to the $Converting$, initiating the production process.

As it may be deducible from the Figure 4.3, at *Converting Lines*, the advance of time is defined by either the consumption of JRs or the completion of production orders. Thus, each time the production operation occurs, it is calculated the expected time left to complete the batches of the current CPO entity, as well as the maximum duration of the raw materials (two JR entities), defined by its weights and consumption rate (specific for each type of converting reference). Then, the next event to occur will be the one with the minimum value of duration. At each of those events, the production throughput during the advanced time is calculated and appended to the overall throughput of the model.

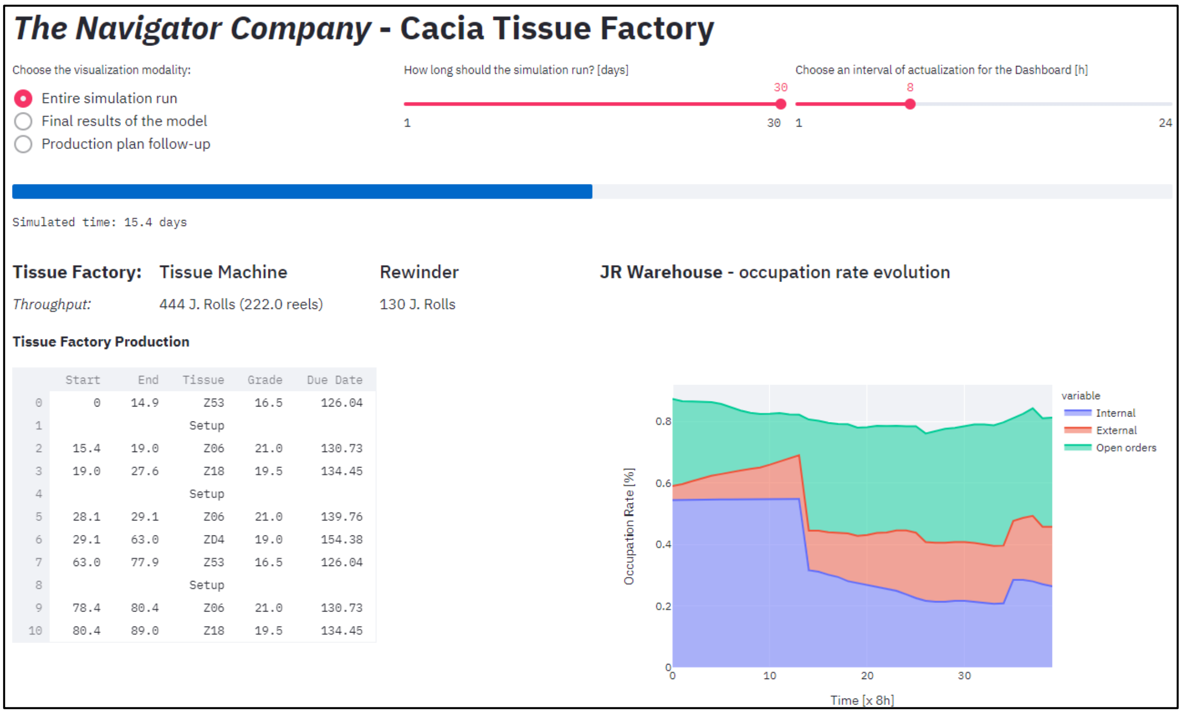
4.2.2.3. Information flow

Besides the model initiation and the productive resources, further activities alter the state of the *JR Warehouse*'s SKUs, even without any input or output flow. These activities are related to the last decoupling point stated at the section 3.2.3. Essentially, to assign JR entities to a specific CPO, it is analysed the forthcoming week of the production plan, assessing the predictable tissue necessity from each order (which then can be transposed in number of JRs required). Thus, two additional processes were modelled: $PlansNecessities$ and $OpenOrders$.

Both processes are cyclic, being executed on a weekly basis, and present a complementary behavior. From the execution of the $PlansNecessities$, the expected gross tissue paper requirements are obtained. Then, in the immediately next instant, the process $OpenOrders$ is executed, assessing the availability of such requirements on the warehouse and allocating the stored JR entities to the considered CPOs (as stated in section 3.2.3). The results from the allocation consist of a listing of the expected tissue paper net requirements and the decoupling of a parcel of the inventory, which may, from then, be successfully requested by each of the *Converting Lines*. At last, the resulting tissue paper net requirements are forwarded to the $GenerateProductionPlan$ module at the $TissueFactory$ class, which, by crossing those internal necessities with the external requirements, creates a new weekly production plan to be executed by the $TissueFactory$ class.

4.2.2.4. Output visualization

Ultimately, a data visualization dashboard was developed with Streamlit. Using this interface, the simulation run may be followed, aided by dynamic graphical objects, whose data is updated along the run. Through this approach, the utility of the simulation model was exponentiated, since not only this analysis tool is visually improved, but also the flexibility that it presents, in terms of visualization, may aid the decision making in a broad range of the company's sectors. Figure 4.9 displays a segment of the developed dashboard, during a simulation run.


The Navigator Company - Cacia Tissue Factory

Choose the visualization modality:
● Entire simulation run
○ Final results of the model
○ Production plan follow-up

How long should the simulation run? [days]: 30

Choose an interval of actualization for the Dashboard [h]: 8

`Simulated time: 15.4 days`

Tissue Factory: **Tissue Machine** **Rewinder**

Throughput: 444 J. Rolls (222.0 reels) 130 J. Rolls

Tissue Factory Production

	Start	End	Tissue	Grade	Due Date
0	0	14.9	Z53	16.5	126.04
1			Setup		
2	15.4	19.0	Z06	21.0	130.73
3	19.0	27.6	Z18	19.5	134.45
4			Setup		
5	28.1	29.1	Z06	21.0	139.76
6	29.1	63.0	ZD4	19.0	154.38
7	63.0	77.9	Z53	16.5	126.04
8			Setup		
9	78.4	80.4	Z06	21.0	130.73
10	80.4	89.0	Z18	19.5	134.45

JR Warehouse - occupation rate evolution

Figure 4.9. Screenshot of the developed dashboard.

4.3. Model verification and validation

In order to take advantage of this simulation framework tool, it is mandatory to ensure that the developed model presents an identical behaviour to the system. Then, each feature encompassed by the model scope was object of a validation process, where its representation and performance at the simulation model was compared to the correspondent features at the existing system.

This process was executed through two distinct steps. Firstly, an in-depth trace of the model entities' behaviour was performed, assuring that information and material flows presented in section 4.1.3 were correctly modelled. Posteriorly, the KPIs resultant from a one-month simulation run were compared with those obtained from a standard month of activity from the real system (monthly average values from a 5-month sample). The selection of the KPIs considered in this stage was based on the information gathered with the company, which could not provide data regarding the remaining indicators defined in Table 4.3. As it is displayed, the developed simulation model contains an accurate representation of the overall system productive capacity, being the absolute relative error in the KPIs available (between real system and model) not superior than 5.4%.

Table 4.4. Model validation through KPIs from 25 days of production.

		Real System	**Simulation Model**	**Relative Error**
Tissue Factory	Nº of JRs produced	650	652	**+ 0.3 %**
	Avg. Cycle time [h/reel]	1.29	1.22	**- 5.4 %**
	Tissue Machine OEE [%]	77.45	79.5	**+ 2.6 %**
Jumbo Roll Warehouse	Occupation rate [%]	85 to 90	81.6	**- 4.0 %**
Converting Lines	Nº of pallets produced	23917	24286	**+ 1.5 %**
	Average production rate [pal/h]	79.72	76.12	**- 4.5 %**

A relevant aspect regarding the validation process of this system is the occurrence of tissue paper backlogs at the *Converting Lines*, i.e. lack of JR entities to trigger the production process at the $Converting$ class. In the real system, these events trigger the reformulation of the production plan being executed. However, this reformulation activity is highly dependent on the deliberation based on the experience from the planners, which cannot be modelled in the simulation system. This issue was contoured by accounting the processing time of the production orders that enter in backlog. That means that, if a JR is not available at the beginning of the order, the production line will stop producing (initiating a downtime) until the scheduled time for the start of the next order. This way, the following orders of the plan will not be affected by the earliness that would result from the backlog. Even though the production capacity of the *Converting Lines* is reduced by this solution (an extension of the backlog period directly increases the time portion of non-value-added activities), the overall throughput capacity is accurately represented by the model, with an error of 1.5%, as we can verify at Table 4.4.

4.4. Final remarks

As previously stated, a simulation study is a time-consuming procedure that may require a considerable number of iterations until the obtention of a valid and robust model. As presented in section 3.4, the system's performance is highly influenced by the sources of variability inherent to its productive resources, such as the floating availability of the *Converting Lines* and the occurrence of web breaks at the *Tissue Machine*. Those features have enhanced the motivation for applying a simulation methodology, since these stochastic elements can be analyzed and inserted in the model in the form of probability distributions. However, the validation process of a stochastic model is complex and requires a thorough statistical analysis; therefore, the developed model that will be analyzed presents a deterministic nature, not encompassing this variability that is strongly present in the system.

Even though one of the main advantages from the simulation approach could not be seized (analysis of stochastic systems), the complexity inherent to the manufacturing system’s productive processes, as well as the possibility of an integrated study of the entire production chain, maintains the interest and suitability of this methodology. In addition, the developed model may now be employed in a scenario analysis of the current system’s performance, allowing the obtention of its expected response to distinct operating conditions.

5. METHODOLOGY DEVELOPMENT AND ASSESSMENT

The fifth chapter of this dissertation discusses the results obtained from the implementation of the exposed methodology, as well as the presentation of measures that may improve the overall performance of the manufacturing system. Consequently, the first step consists of an analysis of the current system's performance, followed by establishing the control range, i.e. the set of parameters and procedures that may be manipulated during the exploitation of alternatives/solutions. Then, a new configuration for the production planning process is proposed. Each graphical object presented in this chapter is adapted from the data visualization dashboard developed in *Streamlit* (Figure 4.9).

5.1. Current system analysis

Being the model verified and validated, the next step of this study is to analyze the current situation of the system, which should bring insights to the development of alternative planning strategies. This sub-chapter intends to quantitatively display the impacts from the various issues regarding the system's performance, identified in section 3.4 above.

The starting point of the manufacturing system, the *Tissue Factory*, together with the incoming flows from *Factory 2*, is responsible for feeding not only the downstream stages of production, i.e. *Converting Lines*, but also the external demand. Hence, the development of efficient production plans for the *Tissue Machine* turns to be crucial to the overall performance of the company. Figure 5.1 presents a comparison between the production of JRs, at the *Tissue Factory* (stacked bars, segmented between internal and external orders) and the intermediate inventory keeping (stacked areas), similarly differentiated. Through this chart, the production campaigns executed by the *Tissue Factory* are observable. These campaigns are composed of several batches from various tissue paper orders with similar characteristics. During the production planning process, these long periods are defined to produce continuously to satisfy a parcel of either the internal or the external tissue paper requirements (demand for the case of external clients).

Considering the internal operations, this procedure results in large periods during which there is consumption at the *Converting Lines*, without (internal) production from the *Tissue Factory*. In the same manner, from the external environment point of view, there are long periods of demand where there is no coverage being performed by the *Tissue Factory*. Consequently, the intermediate inventory must continuously account for internal and external material requirements.

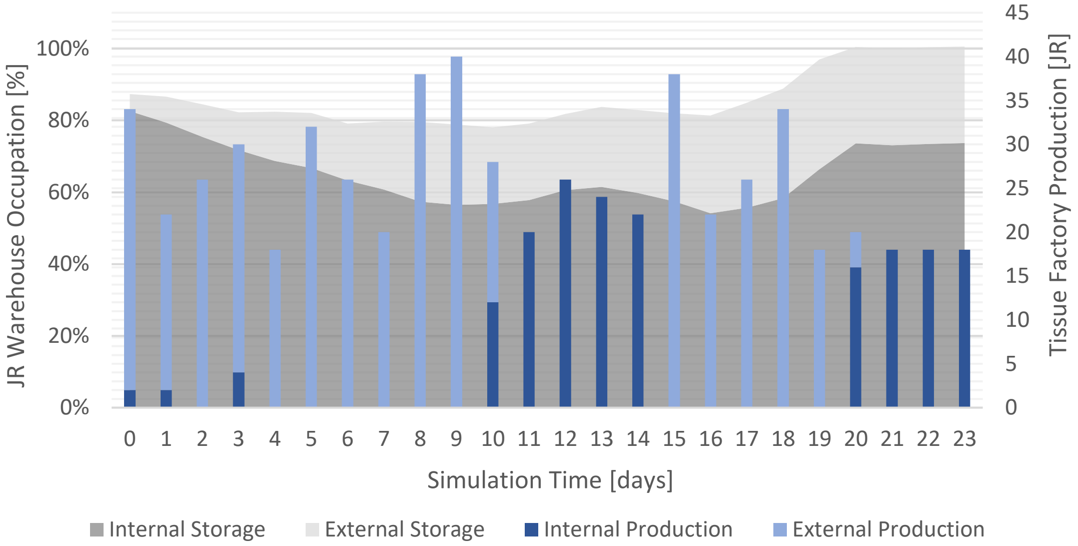


Figure 5.1. Combined chart of JR Warehouse occupation and tissue paper production.

This policy of operation serves as a mean of exploiting the capacity of the *Tissue Machine*, since these large sequences of production result in a reduction of the setup operations requirement, hence an increase of the productivity of the equipment. However, the production planning of such campaigns, for the cases of the tissue requirements from the *Converting Lines* may be problematic, since the estimation of the timing of arrival of those necessities is quite uncertain. Then, the longer the planning horizon, the more susceptible is the efficiency of the production plan to the uncertainty at the stations ahead. On the one hand, this uncertainty may lead to the increase of the time in inventory from the JRs that are supposed to be internally consumed. On the other hand, the requirement of tissue may occur sooner than the estimation considered when planning the production campaign, originating a tissue paper backlog.

By now, the plan reformulation process that is executed by the planners is justified, since these unproductive periods at the last transformation phase may cause a rupture of capacity at the intermediate storage unit, *JR Warehouse*. Analyzing Figure 5.2, it can be obtained a notion on when those reformulations should be performed. Considering the necessity for a continuous production on each of the lines, the interval between reformulations ranges from 1 to 7 days (distance between highlighted points - backlogs).

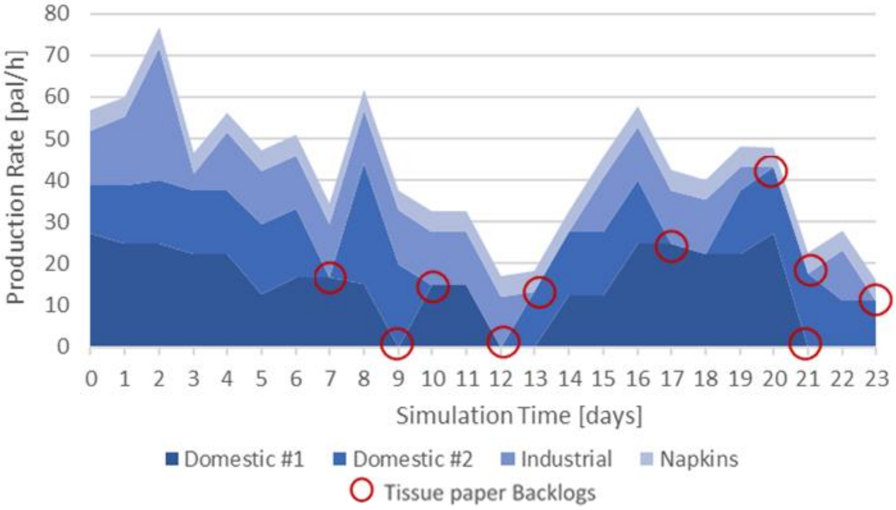


Figure 5.2. Evolution of the production rate of each Converting Line (stacked).

Being demonstrated the influence of the productivity of the *Converting Lines* in the intermediate storage unit, it is now time to address the opposite relation. By assessing the sources from the tissue paper consumed internally, a mapping of the resulting work and capacity loads along the system may be obtained. At the moment, almost half (46%) of the production of the converting facility is assured by the materials kept in the *JR Warehouse* (Figure 5.3). That means that only 54% of the inventory consumed during the simulated period was actually produced or received during that period. This implies that the inventory of the intermediate materials should be enough to cover for 46% of the internal tissue paper requirements.

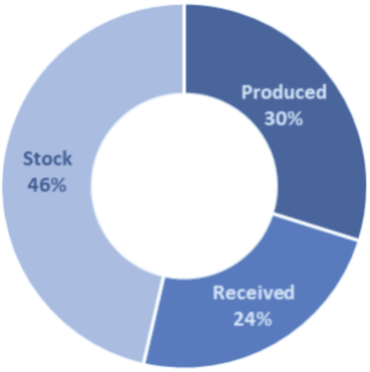


Figure 5.3. Segmentation of the sources from the converted JRs.

Consequently, the last transformation phase is highly dependent on the availability of each tissue reference at the *JR Warehouse*, hence reinforcing the need for high inventory levels, resulting in long lead times and low inventory rotation rate.

In order to establish a starting point, indicative of the overall performance of each element of the current system, the values of the KPIs obtained from the simulation run are listed in Table 5.1. These values will enable the assessment of the quality and suitability of the experiments performed ahead.

Table 5.1. Overall KPIs from the system.

Tissue Factory	Nº of JRs produced	Internal consumption	**216**
		External orders	**436**
		Average Cycle time [h/reel]	**1.22**
		Nº of setups at the Tissue Machine	**10**
		Tissue Machine OEE [%]	**79.5**
Jumbo Roll Warehouse		Average occupation rate [%]	**81.6**
		Average lead time* [days]	**12.4**
		Nº of JRs received from Factory 2	**172**
	Nº of expedited JRs	to Converting Lines	**724**
		to clients and Factory 2	**348**
Converting Lines		Throughput [pal]	**24 286**
		Production Rate [pal/h]	**38.06**
		Nº of Backlogs	**24**
		Time on setup [%]	**19.9**
		JRs waiting in the lines (surplus)	**10.4**

*The JR lead time indicator does not characterize the system modelled. In the real system, the inventory kept has a considerably low inventory rotation rate, reaching lead times of months and even years. However, the obtention of approximated values required a deep historical data that was not available, related to the specification of the references kept in inventory and the lead times of such references. Thus, this indicator will ultimately serve as a comparison between the values obtained in the current model and the experiments performed ahead.

5.2. Control environment

Previously to the exploitation of solutions to the existing issues, it is important to establish the range of control in which these alternatives may act. This step consists of analyzing the operating procedures and conditions of the system and defining which parameters and dynamics of the model may not be manipulated in the process of experimentation. Furthermore, the assumptions performed during the design of experiments are exposed.

The *Tissue Factory* production planning process, once again, is founded on the internal and external requirements of tissue paper. Regarding the external parcel of production orders, those are planned on a long-term, encompassing due dates accorded with clients, as well as expected monthly tissue requirements from *Factory 2*. Due to the lack of information regarding such requirements, it was assumed that the delivery of those orders had to be done until the end of the month, not considering specific due dates over that period.

For the case of the converting production planning, however, the process is more complex, being dealt with more clients, thus more due dates agreements. As a result, the search for an alternative to the production planning at that stage would require an enormous amount of information regarding flexibility agreements with each client, which is protected by the company's privacy policies. Hence, this production planning procedure was discarded from the control range of the study.

5.3. Experiments

After analyzing the trade-offs that are inherent to the production system and establishing the range of influence of the study, the seek for alternative strategies was initiated.

In section 5.1, various issues were identified as potentially harmful for the production capacity of the manufacturing system. According to the analysis performed, the actual production planning of campaigns of several batches may worsen the reporting of material needs from *Converting Lines* to the *Tissue Factory*. Meanwhile, on the other end of the manufacturing system, the feeding of the *Converting Lines* turns out to be considerably dependent on the high levels of inventory that characterize the system.

These two issues are strongly connected. By presenting an inefficient production planning at the *Tissue Machine*, the availability of the materials required by the *Converting Lines* is highly sensitive. To maintain the desired levels of production at the downstream element, the satisfaction of the tissue necessities relies mainly on the intermediate storage unit, forcing the need for large inventory levels. Thus, the solution developed for the current state of the system focused on increasing the material fluidity between the tissue production and consumption, relieving the reliance of the system’s productivity on the intermediate inventory.

5.3.1. Re-design of the production and inventory planning process

Currently, the production planning process at the *Tissue Machine* is based on the reporting of the weekly tissue net requirements from the *Converting Lines* and on the forecast of the external demand of JRs (Figure 3.5). However, as it has been noticed, this procedure is inefficient, resulting in an increase of the inventory level and in the necessity of recurrent plan reformulation of the stations ahead. Then, a new planning methodology was developed, based on the previously performed analysis. This new framework is oriented to the improvement of the fluidity between *Tissue Factory* and *Converting Lines*, aiming at enhancing the capacity of the *Converting Lines*, disinhibiting the excess of intermediate inventory.

One of the major modifications, comparing to the current configuration of the system, is related to the frequency of the tissue requirements reporting to the *Tissue Factory*. Ideally, this activity should be performed in real-time in order to null the impact of disparities between the expected necessity report and the actual occurrence of necessity. However, each update of such requirements leads to a reformulation of the *Tissue Factory* production plan, which, if too recurrent, may be unfeasible and even harmful to the visibility of the periods of production ahead. Nevertheless, with an appropriate frequency of review (higher than the current), the benefits may surpass the drawbaks. Thus, the first analyzed proposal was the reduction of the granularity of the production planning at the *Tissue Factory*. The dimension of this reduction will be addressed ahead.

Through this higher frequency of planning, it is expected that the *Tissue Factory* is able to satisfy a larger parcel of the internal demand of tissue paper, coming from the *Converting Lines*. Then, it is proposed an adjustment regarding the inventory management, more concretely the material allocation process. In the current system, the *JR Warehouse* attenuates the consequences from uncertainty regarding the availability, thus productivity, of both the *Converting Lines* and *Tissue Factory*. By reducing the time between plan updates, the impact of this uncertainty is reduced, being decreased the need for such high levels of inventory. Hence, it may be beneficial to manipulate the inventory decoupling that is executed during the production planning process. It is proposed that the allocation of materials (decoupling point) be simplified into the differentiation of the JRs destination: exportation and internal consumption.

Not having a specific CPO or external client assigned to each JR allows for a reformulation of the role of the *JR Warehouse*. It was demonstrated that, by having a more direct flow between the two productive stages, the necessity for high levels of inventory may be dissipated. Then, it is proposed that, in this new configuration, the inventory acts as a storage of the surplus of the converting stage production, being the remaining capacity used to buffer the uncertainty from the entire productive system. Furthermore, some of the storage capacity should be used to satisfy the external demand.

5.3.2. Development of planning heuristics

The development of this methodology took into consideration the industry's previous struggles in adapting to purely analytical solutions, such as mathematical formulations (Malik and Qiu, 2008). It was then important to deliver a framework that was oriented for the concrete context where it is applied, easing the understanding of such by the planners of the system. Then, two heuristics have been developed: one for the reporting of material requirements at the new system configuration and another for the production scheduling. This set of heuristics functions in cycle and has the main objective of taking full advantage of the *Tissue Factory* capacity, by improving the accuracy of its production planning.

Both heuristics are subject to a set of parameters which were object of a sensitivity analysis, with the aim of reaching satisfactory values for each of them. Those parameters are:

- Δt - interval between successive updates of material requirements, which will be the same as the granularity of the production planning process at the *Tissue Factory*.
- D - maximum number of setup operations at the *Tissue Machine* for the interval considered, which will dictate the maximum available capacity for that interval. The minimum value of this parameter is established at 2, in order to allow for the cyclic nature of the heuristics (explained ahead).

- e - Maximum parcel of the productive capacity of the *Tissue Factory* assigned to external orders, which serves as a control parameter for the allocation of capacity to internal or external production orders.

5.3.2.1. Material requirements reporting

This first heuristic is responsible for reporting the production necessities to the *Tissue Factory*. The basis of the heuristic is similar to the procedure of a standard Material Requirement Planning (MRP), identically to what is performed in the current system. Through the parameters Δt and D, along with the rate of availability of the *Tissue Machine*, the total production capacity of the *Tissue Factory* (Maximum Workload - MWL) for the period considered is defined:

$$MWL = 6 * round\ up\left(\Delta t - \frac{D}{2}\right) * Availability_{TM} \tag{5.1}$$

Equation 5.1 relates the minimum batch size (6 tons, with a production time of 1 hour) with the available time of production: the interval considered minus the maximum time on setup (each occurrence last half an hour), multiplied by the availability of the *Tissue Machine* (which do not account for stoppages for setup operations). Then, the available capacity to be assigned to the satisfaction of internal requirements (Internal Workload - IWL) is obtained by multiplying the MWL by $1 - e$.

Below is presented a listing for the variables, and its explanation, the procedure of the heuristic and the description of its stoppage conditions and constraints.

Variables

- t – Time at which the iteration of the heuristic is triggered;
- EGR_{i,T_j} – Set of the Expected Gross Requirements for the interval considered. These are obtained by crossing the forthcoming converting orders with the BOM of each reference. The result is a list of tissue paper requirements for each CPO, containing the tissue paper weight needed for the completion of each order i, for both tissues T_j, with $j \in \{1, 2\}$ that must be fed to the *Converting Lines*. For the cases where the tissue type is the same, the procedure is identical, then, no distinction was performed for the case where $T_1 = T_2$;

- TWL – Total workload, which registers the state of the *Tissue Factory* workload that has been allocated along the heuristic process;
- IWL – Internal workload. This variable consists of the *Tissue Factory* workload that is available to be assigned to internal production orders.
- ST_i and ET_i – Expected start and end time of converting order i from the EGR list, respectively;
- $MinOrder_{i,T_j}$ and $Order_{i,T_j}$– Minimum size of the ordered batch of each tissue T_j to complete the converting order i and actual size of the ordered batch (next multiple of 6), respectively;
- $Surplus_{T_j}$– Amount of tissue T_j in inventory available to be allocated. In order to ease the dependency of the system on the inventory levels, the material allocation process is performed considering solely the surplus inventory (that has been produced in previous iterations of the heuristic);
- $\Delta Consumption_{i,T_j}$ – Expected consumption of tissue T_j at order i until the instant $t + \Delta t$. This is only applied in the cases where $ET > t + \Delta t$, i.e. last orders encompassed by the interval Δt, since for the remaining orders, this value will be the represented as $MinOrder_{i,T_j}$. Here, this variable is calculated by considering the expected consumption rate Q_{i,T_j} of tissue T_j from each order i, and the time left until $t + \Delta t$;
- $CoveredConsumption_{i,T_j}$ – Actual consumption covered, based on the minimum requirement $\Delta Consumption_{i,T_j}$ and the satisfaction of the *Tissue Machine* batch size. This value is later used to update the tissue requirement from the converting orders ahead;
- $ReleasedOrders$ – List of all the internal production orders to be processed by the *Tissue Factory*.

Procedure

A graphical representation of the procedure bellow is presented in Appendix A – Material requirement reporting heuristic.

1. For each *Converting Line*, list the orders i where $ST_i \in [t, t + \Delta t]$ and group them in a single list, ordered ascending by ST_i;

2. Calculate EGR_{i,T_j} of each order through the BOM explosion;

3. For each requirement i on EGR and for both tissue $T_j, j \in \{1, 2\}$:

3.1. If $TWL = IWL$:

STOP

3.2. If $ET_i \leq t + \Delta t$ or $EGR_{i,T_j} \leq 6$:

$$MinOrder_{i,T_j} = EGR_{i,T_j} - Surplus_{T_j} \tag{5.2}$$

$$Order_{i,T_j} = round\ up \left(\frac{MinOrder_{i,T_j}}{6} \right) * 6 \tag{5.3}$$

3.3. If $ET_i > t + \Delta t$:

$$\Delta Consumption_{i,T_j} = Q_{i,T_j} * (\Delta t - ST_i + t) \tag{5.4}$$

$$Order_{i,T_j} = round\ up \left(\frac{\Delta Consumption_{i,T_j}}{6} \right) * 6 \tag{5.5}$$

$$CoveredConsumption_{i,T_j} = Order_{i,T_j} + Surplus_{T_j} \tag{5.6}$$

$$EGR_{i,T_j} = EGR_{i,T_j} - CoveredConsumption \tag{5.7}$$

3.4. Update the variable:

$$TWL = TWL + Order_{i,T_j} \tag{5.8}$$

3.5. If $Order_{i,T_j} > 0$, add it to $ReleasedOrders$

Stoppage conditions

Through this algorithm, internal production orders will be released until the occurrence of one of the two scenarios:

1. **Every requirement from converting is satisfied**. When this scenario occurs, the unallocated capacity of the *Tissue Factory* ($MWL - TWL$) will be assigned to external production orders (in the next heuristic).
2. **The released production orders fill the available capacity** at *Tissue Factory* assigned to the satisfaction of internal requirements ($TWL = IWL$). On these occasions, the remaining portion of the internal requirements must be fulfilled by the inventory available.

Establishing these stopping conditions ensures that there is no overlapping of order releases between two iterations of the heuristic. Another constrain inserted in the framework was the minimum batch size of the *Tissue Machine*, which is fixed in 6 ton (1 reel – 2 JRs). This restriction leads to the release of production orders whose total weight is a multiple of 6. A relevant recapitulation in relation to the material consumption at *Converting Lines*: for the execution of production orders, there is the need for 2 JRs of one or two specific tissue paper types. Then, each requirement from each order is composed of two tissue necessities, represented as $T_j, j \in \{1, 2\}$. Note that this nomenclature does not make any reference to the tissue type. Instead, it simply serves as an indicator of the two material requirements of each converting order.

This segment of the proposed methodology delivers an updated strategy that, although not being much different from the actual material requirement reporting process, suits the reconfiguration of the system that was presented. The main result from this process is the obtention of internal *Tissue Factory* production orders, $ReleasedOrders$, that already consider the production capacity of the *Tissue Factory* that is assigned to the satisfaction of the internal demand (IWL). This way, capacity overloads of the *Tissue Factory* are avoided, and it is created a smoother flow to the *Converting Lines*. The next step consists in concretizing the upstream information flow, by generating production plans for the *Tissue Factory*.

5.3.2.2. Production scheduling

This second heuristic is triggered at the end of the process presented above. In the development of this second set of rules, it was assumed that the previous is accurate, then no production orders are overlaid between successive iterations. The planning methodology consists of developing an initial schedule for the $ReleasedOrders$ and, considering the limitation imposed by the MWL and number of setups (D), insert production orders to satisfy a parcel of the external demand into that schedule. Then, the additional data considered in this second heuristic is the set of external requirements, monthly established.

Assuming that the incoming of external orders is frequent, it was not considered a stoppage condition of filling every external requirement. Instead, the only stoppage condition established was the allocation of the totality of the *Tissue Factory* maximum workload, i.e. when $TWL = MWL$.

Variables

- $ProdSchedule$ – Production schedule where production orders will be planned.
- $ReleasedOrders$ – Set of the i internal production orders, obtained from the iteration k of the first heuristic;
- $ExternalOrders$ – List of the m external orders to deliver, by the end of the month;
- $ProdOrder_{x,y}$ – Production order for destination internal or external, with $x \in \{i, m\}$ scheduled in the position y of the production schedule;
- W_m – Quantity of tissue (weight) required to satisfy external order m;
- T_n – Tissue paper of type n, with n ranging from 1 to the number of distinct types of tissue paper processed;
- G_{T_n}- Grade of the tissues of type n, which will define the occurrence of setups of a specific schedule (going from an inferior to a superior grade requires a setup operation);
- ST_i – Start time of the internal order i. This value returns the timing of the material requirement, at which the material should be available;
- d – Number of setups on *Tissue Machine* resultant from the current production schedule.

Procedure

A graphical representation of the heuristic below is presented in Appendix B – Production scheduling.

1. Create the $ProdSchedule$ by ordering the $ReleasedOrders$ by ST_i (ascending)
2. While $d > D - 2$:
    2.1. Search position (a) of the order where the first setup occurs: $ProdOrder_{i,a}$
    2.2. Search for the first position (b) where $G_{T_n,b} \geq G_{T_n,a}$
    2.3. Relocate $ProdOrder_{i,a}$ to the position $b + 1$
3. While $TWL < MWL$:
    3.1. Record the next external order to produce: $ExternalOrders_1$

```
        3.2. If the $W_1 \leq MWL - TWL$:
        Insert $ExternalOrders_1$ in the last position of the $ProdSchedule$
        Delete $ExternalOrders_1$
        3.3. If the $W_1 > MWL - TWL$:
        Insert order of weight $MWL - TWL$ from tissue of $ExternalOrders_1$
        Update the variable:
            $W_1 = W_1 - MWL + TWL$    (5.9)
    4. Order the inserted external orders by $G_{T_n}$ (descending)
```

Through this second heuristic, the *Tissue Factory* production schedule for each interval Δt is developed. At the first half of the procedure (steps 1 and 2), an initial schedule is obtained, considering solely the internal orders, resultant from the first heuristic. During step 2, it is established that besides the setups from that initial schedule, there will only occur 2 additional setup operations. Since the external orders are then ranked by grade, it is assured that no setups will occur during that period. Then, the 2 additional setups will occur: 1) during the passage from internal to external production and 2) between iterations of the heuristics (if necessary). In the case where there is no need for either of those two setups, the surplus production capacity ($MWL - TWL$) will be assigned to the order that is produced in last, resulting in production for inventory or in additional amortization of the last external order requirement.

5.3.3. Design of experiments

A parametric analysis was conducted for each input variable of the method, exploiting its values towards a better performance of the system. After reaching the most appropriate parameters for the heuristics, the performance of the resulting production planning method was compared to the one of the current system.

Regarding the parameters Δt and D, its definition is interdependent. In reality, the width of the interval selected to the granularity of the production planning is the most important factor to determine how many setup operations should be allowed. Consequently, the first analysis was oriented to reach an empirical description of the most beneficial ratio between these two measures.

Considering the current configuration of the system, where the plan updates are performed weekly, and the number of setups is relatively low (as a consequence of the production campaign planning), the limits for the parametrization of these variables were established. The values of Δt were restricted to durations between 1 and 4 days, while the maximum number of setups (D) was delimited between 2 and 8. In relation to the remaining parameter, e, it was analysed a range between 10 and 30%.

An additional indicator was considered to develop this parameterization of the heuristics developed: the initial occupation rate of the *JR Warehouse*. As it was previously referred, the inventory of this new version of the system will serve to: store the surplus from production, compensate the possible lack of production capacity from the *Tissue Factory* for both internal and external orders, and mitigate the impact from uncertainty at the downstream stage of production. The value assigned for this indicator was 60%, which comprises a significant reduction when comparing to the actual conditions of the manufacturing system.

5.3.4. Results of the experiments

Having been restricted the values of the parameters to be defined, production runs were executed, in order to assess the performance of the framework and compare it to the current system. Regarding the parameterization of the algorithm, sensitivity analyses indicated that the most appropriate set of values to consider was: $\Delta t = 4$ days, $D = 4$ and $e = 15\%$.

5.3.4.1. Analysis of the proposed solution

From the parameterization process, it was noticed that, by applying the methodology to the proposed configuration of the system, the inventory keeping drastically reduces (around 20%) along the simulated month. This comes as a result from the more efficient production planning at the *Tissue Factory*, which enabled the inhibition of the material flow through the *Converting Lines*. Figure 5.4 presents a comparison between the *as-is* model, i.e., current system configuration, and the *to-be* model, i.e., the proposed system configuration. The chart crosses the evolution of the occupation rate, on both scenarios, with the difference in productivity of *Converting Lines* (subtraction of production rate at each instant on the new system by the one on the current system) caused by the methodology developed. Here, it is verified that this continuous decline of the inventory is mainly caused by the increased productivity of the *Converting Lines*. This is inferable because, at the moments where, at the *as-is* model, the level of inventory grew, at the *to-be* model that inventory increase was replaced by an increase of productivity in the production stages ahead.

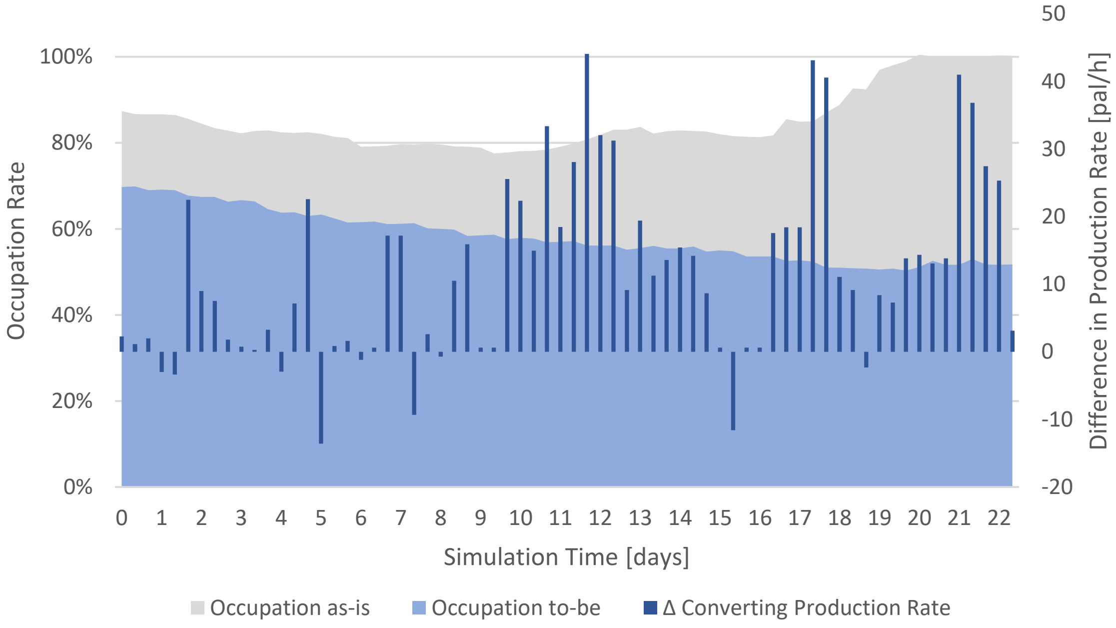


Figure 5.4. Comparison of inventory level and converting productivity between the *as-is* and the *to-be* models.

Nevertheless, this inventory decline turns the solution unfeasible since, in the long run, the levels of inventory will not be enough to maintain this feeding rate of both *Converting Lines* and external orders. At this point, it is clear that the incoming rate of JRs, from *Tissue Factory* and *Factory 2*, is not enough to sustain the set of internal and external demand of materials. Then, it was analyzed a proposal for the balance for these input and output rates at the intermediate *JR Warehouse*.

Considering the nature of the products on both production stages, the last ones present a superior value-added to the company, since more steps of transformation are performed. Consequently, it was established that, in order to stabilize the flow of materials of the system (increasing the throughput capacity of finished products), a parcel of the external demand of intermediate materials (JRs) would be excluded from the set of requirements that the system must accomplish. Here is exposed a trade-off, that may be later addressed by the company, between the satisfaction of external orders and productivity of the *Converting Lines*. Posteriorly, this issue may lead to a reformulation regarding the capacity planning of the company's supply chain, aiming at reallocating a parcel of the external demand to distinct facilities.

To the dimensioning of the external demand portion which should be excluded from the production planning, a new sensitivity analysis was performed to the performance of the methodology developed (Figure 5.5). Having as a reference the gradient of the inventory decline, the value of this portion was limited to a minimum of 30%.

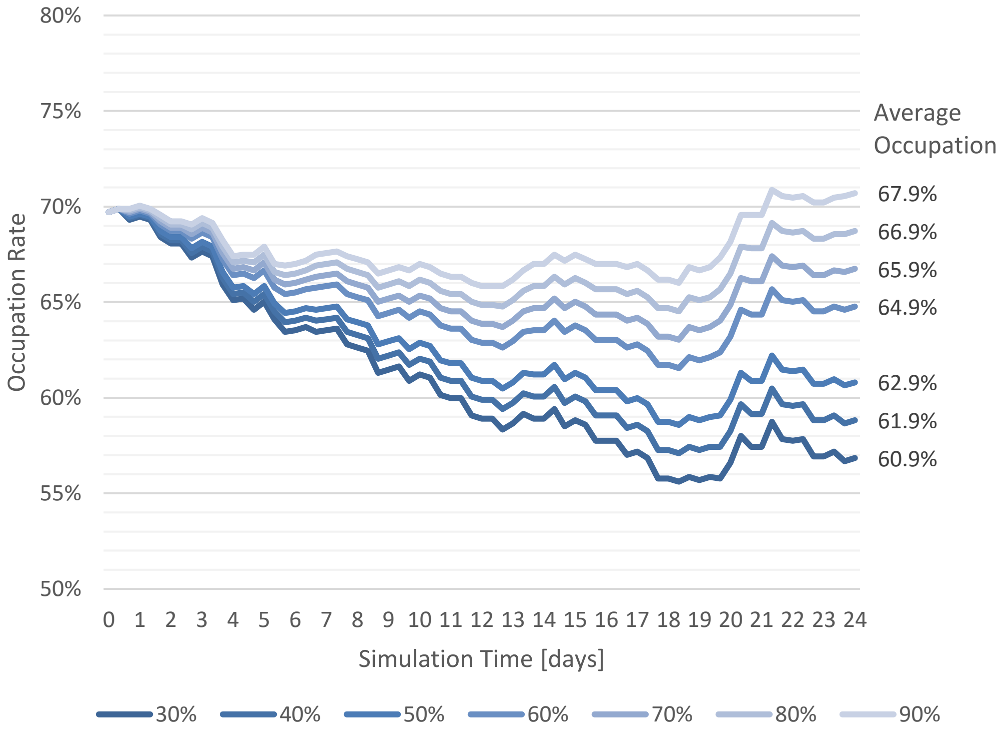


Figure 5.5. Effect of external demand on the inventory level.

As expected, by reducing the outgoing flow of JRs, the storage level tends to stabilize, approximating the system to a balance between input and output rates of the *JR Warehouse*. During the simulation run, this variable has no influence on the productivity of both *Tissue Factory* and *Converting Lines*, since the initial level of inventory considered is enough to keep up with the output flow of JRs for the period studied. Then, this parameter serves as a demonstration of the feasibility of the methodology for a distinct profile of demand assigned to the system. For the context of the following analysis, it was defined a reduction on the external demand of 80%.

5.3.4.2. Assessment of improvements

After completing the set of experiments that concluded the development of the methodology and described the limitations and benefits of the proposed solution, a final analysis was executed to quantitatively assess the improvements obtained. With the developed set of heuristics, the proposed configuration of the system is focused on the improvement of the synchronization between the upstream and downstream stages to the storage unit. It was proved that allocating a larger portion of the *Tissue Factory*'s production capacity to the feeding of the *Converting Lines* leads to an inventory level reduction. By balancing the internal consumption and the internal production, the reliance on the stock from the productivity of the *Converting Lines* was lowered, as shown in Figure 5.6.

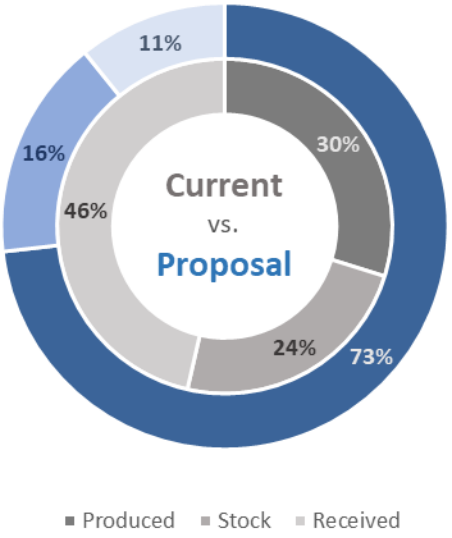


Figure 5.6. Segmentation of the sources of converted JRs.

As a matter of fact, this adjustment causes a considerable increase in the productivity at the converting stations. However, this improvement comes at the cost of releasing some of the production capacity of the *Tissue Factory* that is assigned to the satisfaction of external demand. Considering a reallocation of 80% of the external demand, the levels of the inventory were reduced and presented a lower range of variation along the simulated period (Figure 5.7), when comparing to the current state of the system.

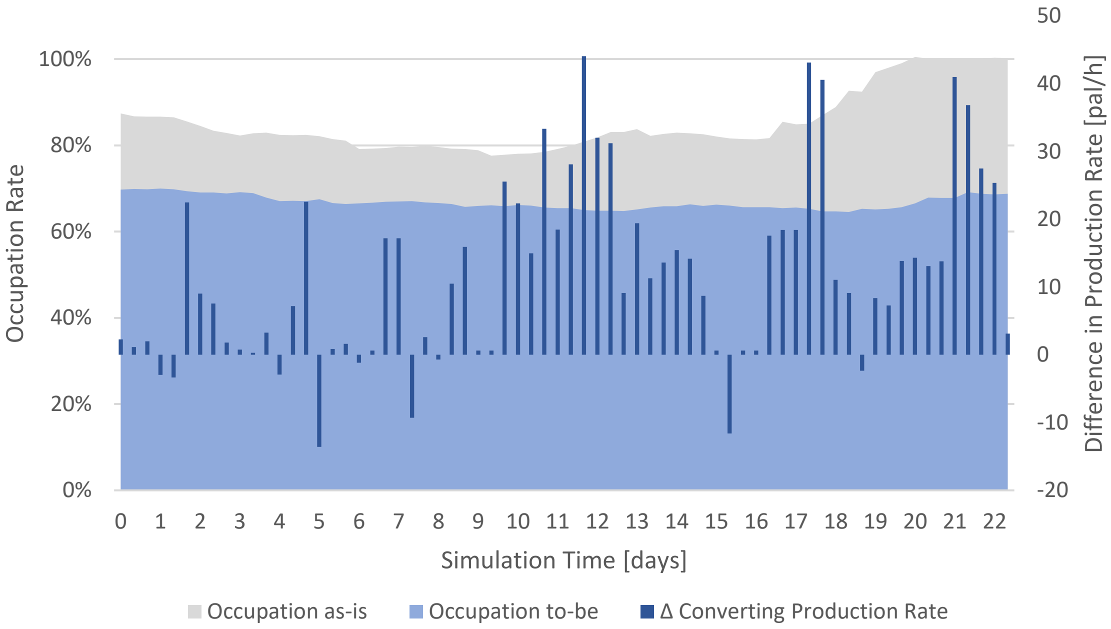


Figure 5.7. Comparison of inventory level and converting productivity between *as-is* and *to-be* models, for a reduced external demand

In conclusion, the developed framework presents an alternative to the first stage production planning currently applied at the company. The overall results from the implementation of the proposed methodology are summarized in Table 5.2. Through this new configuration, the total throughput of finished products was increased by 28.1%. In addition, the necessity for converting plan reformulation was almost entirely dissipated, having occurred only one tissue paper backlog. This improvement plays an important role in the overall system, since the visibility of the production plans is increased, easing the process of resource planning (such as subsidiaries and human work).

This downstream performance improvement has originated a significant reduction in the inventory levels (14.7%) as well as a reduction in the average time on inventory of 36.3%. However, this increased fluidity comes at the cost of lowering the rate of satisfaction of the external demand, which in the final analysis was shortened by 80%. Nevertheless, this system configuration effectively improved the major issues addressed by the company, presenting a valid alternative to its current operational strategies.

Table 5.2. Comparison of the overall values of KPIs.

			Current System	***Proposed Model***	***Var. (%)***
Tissue Factory	Nº of produced JRs		652	694	**+ 6.4**
	Nº of setups at the Tissue Machine		10	6	**- 40**
	Tissue Machine OEE [%]		79.5	80.1	**+ 0.8**
Jumbo Roll Warehouse	Average occupation rate [%]		81.6	66.9	**- 14.7**
	Average lead time [days]		12.4	7.9	**- 36.3**
	Nº of JRs received from Factory 2		172	89	**- 48.3**
	Nº of JRs expedited	to Converting Lines	724	824	**+ 13.8**
		to clients and Factory 2	348	75	**- 78.4**
Converting Lines	Throughput [pal]		24 286	31 118	**+ 28.1**
	Production Rate [pal/h]		38.06	52.18	**+ 36.8**
	Nº of Backlogs		24	1	**- 96.8**
	JRs waiting in the lines (surplus)		10.4	12.2	**+ 17.3**

6. CONCLUSION

Pulp and paper manufacturing systems have shown several difficulties in implementing efficient operational strategies. Strategies of vertical integration are a recurrent solution for the mitigation of costs in transportation. Thus, the operations of most paper manufacturers are organized along a multi-stage and multi-product chain of production. Here, the operations management is hindered by a significant uncertainty from the equipment availability, generated by the production of large product mixes using technology that is oriented for high-volume production. Hence, in such systems, it is required flexible and integrated approaches to support the processes of production planning and inventory management.

This study was motivated by the real case of an integrated tissue paper mill, which has been struggling to accomplish an adequate and efficient production planning methodology. This issue is currently reflected in the low productivity of the last production stage and on significant intermediate inventory levels.

The main goal of this work was to, through simulation modelling, assess the trade-offs inherent to the performance of each element from the tissue paper mill, in order to develop an effective production planning framework. One of the main obstacles during the development of this study was the obtention of a valid and robust simulation model. This type of approach is usually time-consuming and requires an iterative process towards the final model. The complexity of the system comprised the major factor for this barrier, since intricate dynamics had to be clearly understood, and a considerable amount of data had to be collected.

By developing a simulation model of the manufacturing system, it was possible to understand the behavior and relations between the integrated parts, then applied to the development of two complementary production planning heuristics. The low productivity in the last stage of production was identified as the main factor for the high levels of intermediate inventory. Furthermore, a substantial unbalance was noticed between the number of batches produced to internal consumption and actual consumed intermediate materials. This unbalance suggested that the productivity at the downstream stage was considerably dependent on the intermediate references available in inventory. Thus, the planning methodology presented focused on relieving that interdependence by increasing the number of batches produced for internal consumption.

The performance analysis of the new configuration of the system indicated that the solution proposed is not feasible for the current profile of external demand of intermediate products allocated to the system. Nevertheless, the study of a distinct scenario, where a parcel of such demand is reallocated to a distinct facility, showed that the production planning methodology is suitable to the characteristics of the system. The results obtained denote a significant increase in the throughput capacity of finished products (28.1%) and a reduction of the average intermediate inventory level of 14.7%. In addition, the necessity of plan reformulation, which is common in the current state of the system, was practically dissipated, increasing the visibility over the production plans developed.

One of the main results of the conducted study is the quantitative definition of the trade-off between the accomplishment of external orders and the levels of productivity and inventory. Through this information, further analysis may be led by the company, in order to obtain a satisfactory trade-off, by reformulating capacity planning of its supply chain.

The present work showed the suitability of a simulation approach to the assessment and improvement of production planning strategies. For the cases where flexible methodologies are required, such as the process industries, this may be a valuable tool to adapt existing methods to the system being studied.

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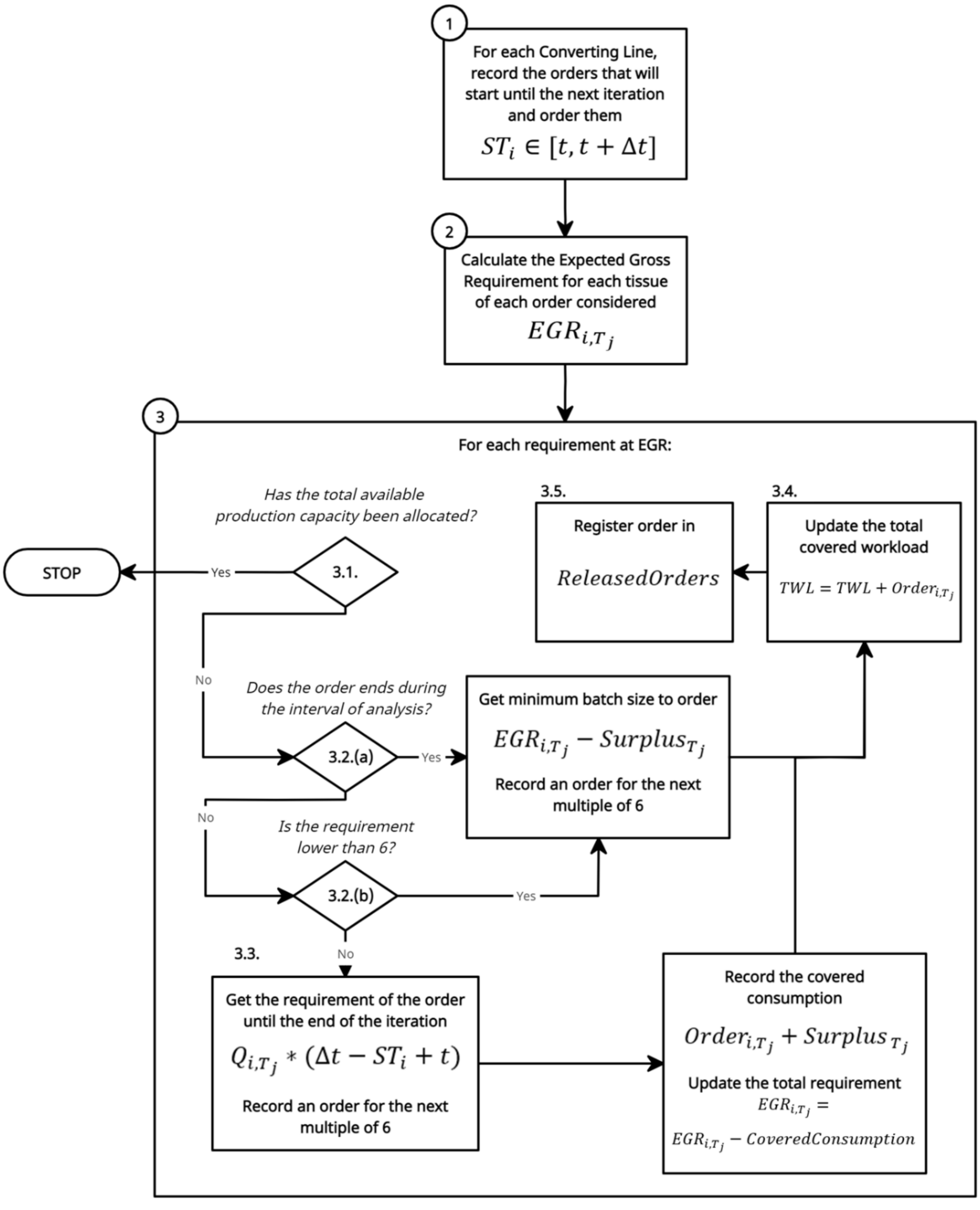
APPENDIX A – MATERIAL REQUIREMENT REPORTING HEURISTIC

For an understanding of the presented nomenclature, visit the *Variables* listing in section 5.3.2.1.



APPENDIX B – PRODUCTION SCHEDULING HEURISTIC

For an understanding of the presented nomenclature, visit the *Variables* listing in section 5.3.2.2.