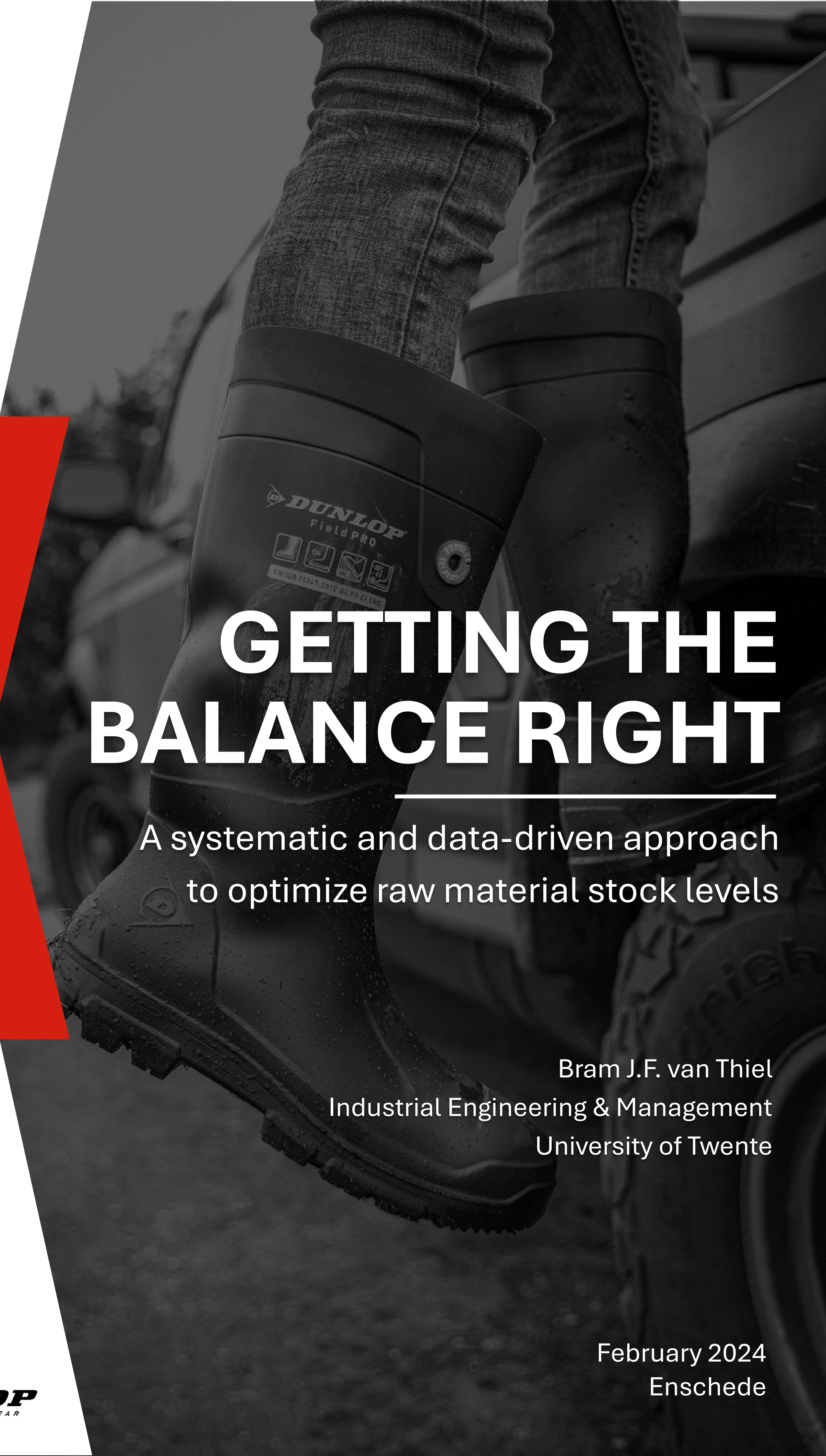

GETTING THE BALANCE RIGHT

A systematic and data-driven approach to optimize raw material stock levels

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Enschede

UNIVERSITY OF TWENTE.

DUNLOP PROTECTIVE FOOTWEAR

Getting The Balance Right

"A systematic and data-driven approach to optimize raw material stock levels"

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Note:
This version of the report is publicly available. Important company data is anonymized and numerical data is manipulated using several multiplication factors. These factors are known to the author.

Preface

Dear reader,

With a sense of joy, relief and gratitude, I am pleased to present my bachelor thesis: *“A systematic and data-driven approach to optimize raw material stock levels”.* This report acts as the final assignment for my bachelor in Industrial Engineering & Management, addressing a critical raw material inventory challenge at Dunlop Protective Footwear in Raalte.

This thesis marks my first experience in crafting an academic research. The process from start to end has been a challenging ride. It pushed me beyond my comfort zone and caused me to encounter multiple self-reflections. The journey introduced many new insights and discoveries about both myself and the industry.

I owe a significant debt of gratitude to the team at Dunlop, particularly Johan Faber. His generous support and willingness to involve me in crucial company processes have been instrumental in bridging the gap between theory and real-world application. The practical insights gained from his mentorship have greatly enriched my personal knowledge.

I am equally thankful to my academic supervisors at the university. The expertise and constructive feedback of Dr. Ir. L.L.M van der Wegen and Dr. M.C. van der Heijden elevated my thesis to a higher level. I am grateful for their encouragement which empowered me to delve deeper into the subject matter and broaden my understanding.

As I present this thesis, I hope that the findings of this thesis prove to be practically applicable and mark the beginning of a more systematic and data-driven approach to inventory management at Dunlop.

Bram J.F. van Thiel

Enschede, February 2024

Summary

In the field of inventory management, reducing costs has always been a major challenge for many companies. It remains a struggle to strike a balance between fulfilling demand and avoiding excess stock. This is also evident in the context of Dunlop Protective Footwear's raw material inventory.

In recent years, their raw material inventory levels surged to unsustainable heights. This resulted in high inventory costs that increasingly threaten the company's financial health. As a result, management decided it is necessary to make significant cost reductions. In the first place by selling dead stock, and in the second place, by improving current inventory processes.

This thesis focusses on the second part of this reduction effort. It aims to reduce the raw material inventory costs by suggesting a new control framework for better inventory management.

Current Situation

To initiate the development of this new control framework, the first step consists of gaining a comprehensive understanding of the current inventory situation.

The raw material inventory is currently divided into sixteen distinct item groups. These item groups are all related to different components of finished products and all have their own characteristics. When the items are prioritized on characteristics such as inventory value, criticality and inventory coverage, item group RM16 and RM52 stand out. These item groups show high values for all three factors. This is primarily the case for the three items in Table 1.1.

Item Group	Item ID	Value	Criticality	Coverage	Lead time
RM16	R6	€ 95,596	3	110 weeks	19 weeks
RM52	R7	€ 178,058	2	35 weeks	19 weeks
RM52	R8	€ 151,957	2	127 weeks	13 weeks

Table 1.1: The three raw materials with both a high inventory value (the average value in the last three periods in July 2023), high criticality grade (between 1-5, where 1 is the highest), high inventory coverage and high lead time.

The evaluation of the current ordering process revealed that demand for raw materials is known with certainty for four weeks. This demand follows from the frozen period. It means that demand after these four weeks is unknown and follows from forecasts. Since the lead times of most raw materials are higher than these four weeks (see Table 1.1), a large part of demand has a high degree of uncertainty.

To account for this uncertainty, the purchasing manager currently sets the re-order point equal to a somewhat arbitrary number. This level follows from past experience and intuition. When the inventory position comes close to this threshold he places an order with a pre-determined order size. This quantity also follows from past experiences and is a result of common sense.

Although this inventory system based on intuition and experience works in practice, it seems far from optimal. It offers substantial room for improvement.

Solution

In an effort to improve the current situation, this thesis proposes a new control framework. This new framework is primarily supported by the famous (R, s, Q) policy. With the review period (R) equal to one week, it suggests to check each week whether the inventory position is below the re-order point (s). Once this is the case, a new order with a pre-specified order quantity (Q) should be placed.

To increase the effectiveness of the policy, the input parameters of the (R, s, Q) policy need some minor adjustments. While the policy assumes stochastic demand, it is possible to manipulate the demand parameters such that it considers both known and unknown demand.

When these adjustments are in place, the framework provides clear methods to determine appropriate values for the re-order point (s) and order quantity (Q). Since the determination of the re-order point depends on the distribution of demand, the framework suggests to distinguish the items on their demand variability. Raw materials with a low variability ($CV \leq 0.5$) follow a normal distribution and with a high variability ($CV > 0.5$) follow a gamma distribution.

For items with substantial inter-arrival times ($\bar{T}$) between consecutive demand occurrences ($\bar{T} > 4\ weeks$), the demand is intermittent. In these cases the (R, s, Q) policy should be replaced by other approaches. These items are often slow-moving and allow for more precise ordering. Depending on the length of the lead time and review period a fully deterministic approach yields better results.

Implementation
To implement the new control framework, it comes with a policy tree and digital tool. The policy tree helps to select the proper method for a raw material. Once the proper method is selected, the digital tool helps to calculate the appropriate values for the re-order point (s) and order quantity (Q).

Additionally, the framework suggest to install a new module with nine important key performance indicators (KPIs) in the raw material dashboard. These KPIs help to monitor the inventory's performance and detect early problem cases. This ensures the framework's input parameters can be adjusted in time, to prevent shortages and excess inventory.

Achieved Benefits
When the new control framework is applied to the three problem cases, items R7 and R8 are controlled using the (R, s, Q) policy. This yields significant benefits (see Table 1.2):

Item ID	Old re-order point	New re-order point	Unit price	Released capital
R7	27.5 weeks	23.9 weeks	€1.41	€32,281
R8	27.5 weeks	20.7 weeks	€1.49	€20,247

Table 1.2: The old and new re-order points in weeks of demand, together with the unlocked capital.

The difference in volume between the old and new re-order point shows how much capital is released. For items R7 and R8 this means a combined capital of **€52,528**.

Not only this released capital is a major benefit, the costs of holding these larger quantities of stock are also decreased. Since the holding costs equal around 15% of the unit costs this means that around **€7,878** of holding costs are saved every year. Most importantly, the new control framework provides the purchasing manager with more control over the raw material inventory. It replaces his old intuition and experience-based method and allows him to precisely determine appropriate minimum stock levels and order quantities. .

Recommendation
The implementation of the new control framework is expected to streamline the raw material inventory and enhance overall cost-efficiency. The highlighted raw materials present practical cases that yield significant cost benefits. Once these are successfully implemented, the framework can be extended to other raw materials.

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1. Introduction

This first chapter serves as an introduction to the research project. It starts with providing background information about Dunlop (Section 1.1), explaining the problem context (Section 1.2) and identifying the core problem (Section 1.3). Related to this core problem, several stakeholders are described (Section 1.4) and the theoretical framework of inventory management is explained (Section 1.5). Additionally, the research design is discussed (Section 1.6) together with its deliverables (Section 1.7) and limitations (Section 1.8).

1.1 The Company

This bachelor thesis is conducted at Dunlop Protective Footwear. The company is active in the footwear industry and has a clear mission: *"to empower the world's creators and builders with the finest protective footwear."* It produces comfortable and protective boots across various sectors including agriculture, fisheries, food processing, and the oil, gas and mining industries. Additionally, it extends its commitment to safety into outdoor and leisure boots, reflecting a comprehensive dedication to safeguarding individuals in all aspects of life.

The company is an integral component of the longstanding *Dunlop®* brand. The brand originates from the invention of the first practical pneumatic tire for bicycles and was founded in 1888 by John Boyd Dunlop. His invention laid the foundation for the brand's expansion into an internationally recognized brand known for selling rubber-related products.

Under ownership of Hevea BV, the company independently sells protective boots made of their innovative *Purofort®*. Purofort® is a unique material that is exceptionally lightweight, thermally insulated, flexible and strong. The recipe for this material has always remained a secret and there are currently no other boots on the market that are as lightweight and strong as Dunlop's boots. This has given the company a strong market position.

1.2 The Problem Context

Currently, the company faces growing challenges to its robust market position. In recent years, the operational landscape changed drastically due to several events.

First of all, the outbreak of Covid-19 introduced more uncertainty to the market dynamics. This resulted in significant demand fluctuations and forced the company to expand their safety inventories. Secondly, the company replaced a substantial segment of their management team, while also implementing a new ERP-system and launching a new product line. Collectively, but to varying degrees, these developments led to an undesired increase in overall inventory levels, introducing high inventory costs.

As the economy is cooling down and demand is declining, these high inventory costs start to form a significant risk to the company's profitability and overall financial health. In particular the accumulation of excessive amounts of raw materials has become very expensive. As a result, management has set the goal to reduce the raw material inventory value from €3.2 million to €2.8 million before the end of 2023. Ideally, they prefer a reduction to €2.5 million.

Initial discussions have revealed that the company is already in the process of reducing inventory levels. They order less and try to sell unused raw materials. However, the general process of managing the raw material inventory remains unchanged. Management is afraid raw materials will accumulate again in future efforts. Therefore, they see opportunities to increase the efficiency of the general management process.

1.3 The Core Problem

The current raw material inventory levels are too high and too expensive. Additionally, there is a desire from management to decrease the raw material stock levels and prevent the levels from getting out of proportion again. The high inventory value is a clear indicator that something is not working properly in the process of managing the raw material inventory. As a result, a clear **action problem** can be identified:

"*The raw material inventory value of Dunlop is currently €3.2M while it should be below €2.5M.*"

With the high inventory value as a clear indicator, the action problem only shows the symptom of the underlying causes. Discussions with responsible staff members revealed some other, but related problems.

First of all, the staff responsible for purchasing the raw materials seems to be insufficiently trained on the topic of inventory management. Due to a different educational background they are not able to make efficient use of the data that is provided by the ERP-system. They lack important knowledge about essential inventory management principles.

Secondly, there is no working system or guideline that acts as a substitution for this missing knowledge and allows the staff to efficiently operate. As a result, the data from the ERP-system is barely used and the purchasing managers make the ordering decisions based on their intuition. As they tend to play it safe and because the sales forecasts are often on the high side, they tend to overestimate the necessary inventory levels. This overestimation results in high stock-to-revenue levels.

In addition, the lack of this ordering guideline causes the production department to act on the wrong targets. There is nothing telling production to focus on optimizing inventory costs. Instead, they focus on making the most efficient use of the available time and capacity of the machines. Therefore, they prefer high safety stocks to have a high degree of utilization on their machines, again resulting in high stock-to-revenue levels.

It is clear that one of the abovementioned problems stands out. In the various conversations with important stakeholders this problem kept coming back. It is at the root of all other problems and is considered as the ***core problem***. It is defined as follows:

"There is no guideline for determining raw material stock levels that optimize inventory costs"

The other problems that require solutions like finding suitable staff or extensively educating current staff can be very expensive and time intensive. Additionally, the bad forecasting problem requires improved sales forecasts. These are often difficult to make and existing inventory models are often able to compensate for bad forecasts. Therefore, solving the problem of having no ordering guideline is the problem with the most benefits compared to the effort of solving.

In the core problem, the variable 'inventory costs' can be measured with the following indicator:

- "The stock value of the raw material inventory".

1.4 The Stakeholders

It is important to clearly understand the various stakeholders that are involved in the inventory management problem. Therefore, Figure 1.1 provides an interest-power matrix that gives insight into their mutual relationships.. The stakeholders that have both a high level of power and a high level of interest should be managed closely while the stakeholders with a low level of power or interest only need to be monitored.

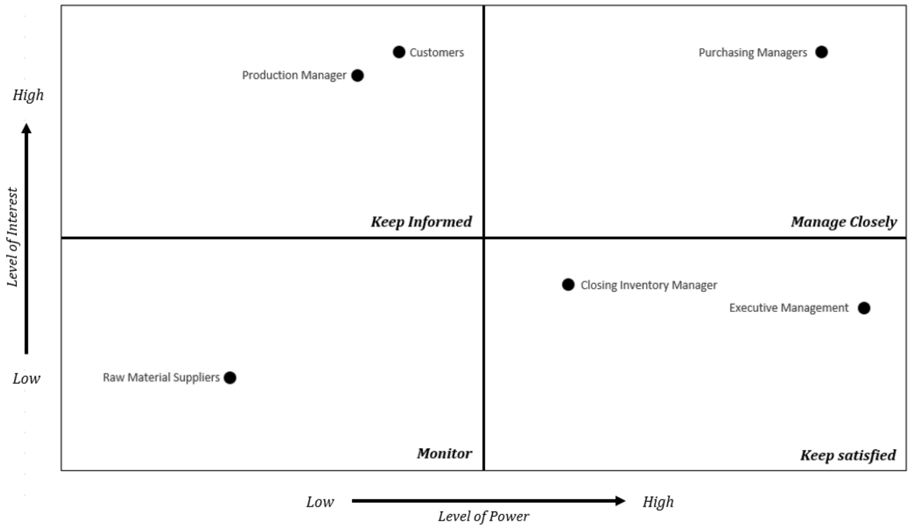

Figure 1.1: An interest-power matrix including the stakeholders involved in the inventory problem.

1.4.1 Manage Closely and Keep Satisfied

The most important stakeholders are the *purchasing managers*. They are responsible for supplier selection, price agreements and determining order timing and volume. Their goal is to maintain a balance between keeping enough inventory and minimizing excess inventory to reduce carrying costs. Their main interest is to purchase raw materials as cheaply as possible, often by ordering large quantities to make use of economies of scale. Additionally, they aim to keep inventory costs as low as possible and therefore have a great interest in this project. They are also the stakeholder with the most power as they are the ones making decisions considering order quantities.

The *closing stock manager* takes care of the inventory of the finished products. This inventory is separated from and exists in addition to the inventory of raw materials. The closing stock manager is responsible for communicating the lead times to the customers and it is in his interest to keep the stock levels as close as possible to the predicted demand. It is important for the closing inventory manager that he knows what is happening with the raw material inventory as this inventory directly influences production and thereby indirectly his own inventory. Since he has the most contact with customers, he has quite some power to change inventory strategies according to customer wishes.

The *executive management* of Dunlop is responsible for the long-term success of the organization. As inventory problems can impact the overall performance and strategic direction of the company, it is in the management's interest that the inventory policies are in line with the overall strategy and direction of the company. It is the executive management that set the goal to reduce the inventory value to 1.6 million euros. For them it is important that a suitable solution is found, but the exact way in which this is done does not concern them. It is important management is satisfied with the solution and that they are involved when making important decisions, as they have a lot of power.

1.4.2 Keep Informed and Monitor

The *production manager* is responsible for the production process of the boots. He aims to produce as efficiently as possible, meaning he wants to optimally use the available machines and time to achieve its targets. It is in his interest to have as many raw materials available as possible so that he can always produce when any capacity is available. Despite the fact he has great interest in the inventory levels, he has relatively little power to determine how much is actually ordered.

The *customers* of Dunlop interact on a business-to-business basis. Almost all customers are retailers. The retailers adapt their orders to their own demand. They like to order as flexible as possible and they appreciate low lead times. As the inventory strategy of Dunlop influences their purchasing strategy it is important to keep them well informed.

All raw materials are delivered by *suppliers*. It is in their interest to sell as much as possible and to get a stable demand from Dunlop so they can adjust their production processes accordingly. High inventory levels can affect Dunlop's ability to order new stock from suppliers. This could damage relationships. Although the suppliers have relative little interest and power, it is important to monitor them since their decisions can still influence inventory strategies.

1.5 The Theoretical Framework

This bachelor thesis is based on the *inventory management* framework. The framework consists of various complicated and specific concepts. It is important to understand the concepts that are crucial for the continuation of the research.

1.5.1 Framework Definition

The term *inventory* refers to the accumulation of materials, customers or information as they move through processes or networks (Slack et al., 2019). The management of these accumulations is known as *inventory management*.

According to Stevenson (2018), inventory management is defined as a framework used by firms to control their interest in inventory. It involves recording and observing stock levels, estimating future requests, and deciding when and how to arrange inventory. Essentially, it aims to optimize inventory costs while achieving a certain satisfactory level of customer service.

1.5.2 Inventory Decisions

Within the framework of inventory management the operations managers are responsible for handling the daily tasks. In their role of overseeing the system, operations managers make three major types of decisions (Slack et al., 2019):

Timing decisions – The manager first needs to determine at what point in time he should place an order. This is often represented by a certain stock level known as the *minimum stock level*.

Volume decisions – Whenever a replenishment order is placed the manager needs to determine how large this order should be. This is known as the *order quantity*.

Control decisions – The manager is also responsible for determining what procedures or models should be used to make the abovementioned decisions. This could involve allocating priorities to different inventory items or selecting suitable control policies.

The research focuses on this last mentioned control decision. The goal is to select suitable procedures or models to make appropriate volume and timing decisions.

1.5.3 Inventory profiles

Inventory profiles are used as a visual representation that illustrates the fluctuation of inventory levels throughout a specific duration (Slack et al., 2019). Figure 1.2 shows a simplified version of such an inventory profile. The inventory profile is clarified with various important inventory concepts.

Order quantity – is the amount of items that are ordered every time an order is placed. This number is often represented by the variable Q.

Cycle inventory **–** represents the inventory that is consumed or depleted between orders. It exists because most businesses do not order inventory in small quantities every time they need it. Instead, they place larger orders at specific intervals to benefit from economies of scale.

Safety inventory **–** is an additional inventory buffer that helps to protect against the risk of stock-outs and to ensure customer demand is consistently met. It is determined by demand variability, supplier reliability and desired service levels. It is often defined by a *minimum stock level* that indicates the level below which actual stock items should not normally be allowed to fall.

Average inventory **–** refers to the average level of inventory held over a specific period of time. It is calculated by adding the beginning ($SS + Q$) and ending inventory level (SS) and dividing it by two ($= SS + Q/2$).

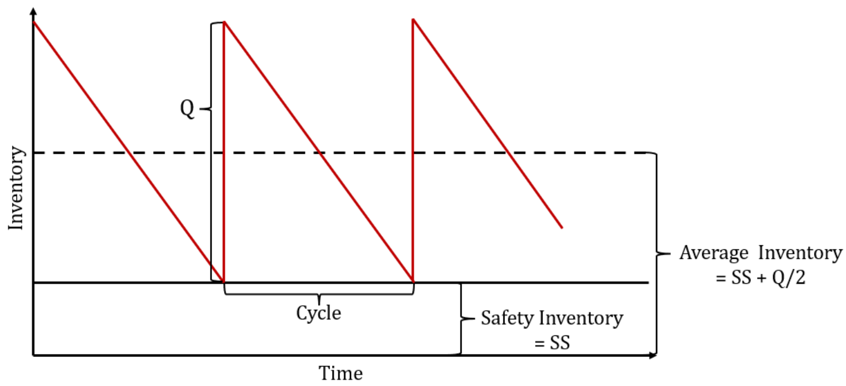

Figure 1.2: A simplified version of a typical inventory profile.

1.5.4 Monitoring Inventory

Besides inventory profiles, there are other methods to check the inventory's performance. Luther (2022) defines several key performance indicators (KPIs) in inventory management that help to monitor and make decisions about inventories.

Dead stock is inventory that is no longer in demand or has become obsolete, resulting in little or no sales activity. ***Inventory value*** refers to the aggregated monetary value of all goods that a company stores in its inventory at a given point in time. ***Lead time*** is the time it takes to receive a product after it is ordered. **S*ervice level*** addresses the percentage of how many times a supplier was able to deliver on time during a specific time period. ***Stock-outs*** refer to the event of not having enough inventory available to meet customer demand for a particular product.

The KPIs explained above help to better understand the analysis of the current situation in Chapter 2. The literature research in Chapter 3 elaborates on the important control measures that are available in literature.

1.5.5 Item Classification

To make monitoring and controlling inventories even more manageable, inventory items are often categorized based on certain attributes. Various ways to divide inventories into different categories exists. The most common and popular technique is the ABC-classification. It categorizes and prioritizes items based on their value (Liiv, 2006). The method is based on the Pareto Principle and states that approximately 80% of the effects in a business come from 20% of the causes, meaning that 20% of inventory items generate 80% of the income (Priniotakis & Argyropoulos, 2018).

As the name suggests, the ABC-classification divides inventory items into three groups: A (high priority), B (medium priority) and C (low priority). The classification is usually determined using the annual dollar usage ranking method, which ranks items based on their monetary value or demand volume (Liiv, 2006). Many different ratios are used, but to give an example, according to Huang et al., Group A items represent 10% of inventory but contribute to 70% of sales, Group C items account for 70% of inventory but contribute to 10% of sales and Group B contains the rest. Table 1.3 and Figure 1.3 visualize this division.

Classifying items into categories A, B and C enables companies to focus their attention on managing the items with the highest priority (Silver et al., 2017).

Class	Description
A	10% of inventory contributes for 70% of sales.
B	The remaining 20% of inventory contributing for 20% of sales.
C	70% of inventory contributes for 10% of sales.

Table 1.3: An example for dividing items in the A, B or C category.

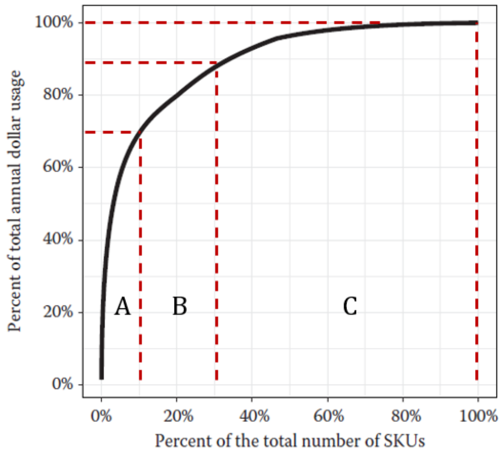

Figure 1.3: A visual representation of dividing items in the A, B, or C category depending on their value.

1.6 The Research Design

The research is guided by a main research question that aims to solve the management problem and thereby the core problem. This question is formulated as follows:

> *"How can the current inventory management process be improved to increase cost efficiency?"*

To answer this main research question, several sub questions are formulated. All questions relate to separate parts of the managerial problem solving method (MPSM) as described by Heerkens & Van Winden (2017).

1.6.1 Problem analysis

The first relevant phase of the MSPM-model is the problem analysis phase. In order to gain a proper understanding of how the problem currently exists, the current situation should be thoroughly analyzed. This led to the formulation of the first research question:

Question 1: How is the raw material inventory currently managed?

This research question can be divided into three sub questions. These help to make the analysis more precise:

a) *What kind of raw materials is the current inventory dealing with?*

The initial phase involves understanding the product landscape. It includes the examination of clients, agreements and the product portfolio. This explains the origins of the raw materials and helps to shape an initial understanding of the factors influencing specific raw material behavior. It results in an extensive list of raw materials that are involved in inventory.

b) *Which raw materials make the most impact in terms of costs?*

To narrow down the extensive list of raw materials, this second phase sorts the raw materials on their impact in terms of costs. It evaluates several characteristics including value, criticality, coverage and lead times. It prioritizes a small section of items that score high on all aspects.

c) *How are the raw materials currently ordered?*

The last step involves evaluating the current ordering process. It helps to understand how the prioritized raw materials are ordered and why this process currently functions inefficiently. Several stakeholders are interviewed to visually map the ordering process and get a thorough understanding of the involved considerations and actions.

1.6.2 Alternative solutions

The second relevant phase of the MSPM-model focusses on finding alternative solutions. This happens through a literature review on the topic of inventory management.

Question 2: *Which inventory management techniques are available in literature?*

Finding an answer to the question enables the research to benefit from the expertise of others. It saves time and ensures reliability. This part is divided into three separate knowledge questions:

a) *What are the basic principles of inventory management?*

Inventory management includes several important concepts that are important to understand before any complicated techniques or models can be identified. This first question creates an overview of these concepts.

b) *What inventory control models are appropriate?*

Since most demand of the raw materials is stochastic, the literature review delves into the stochastic control models that are available.

c) *What control measures are available to track inventory performance?*

To effectively manage the raw material inventory and to see whether chosen modeling strategies actually work, it is crucial to monitor the inventory performance. Therefore, this question helps to find relevant key performance indicators to supervise the raw material inventory.

1.6.3 Choosing a solution

Once the current situation is analyzed and the available techniques are understood, the insights of the first two questions are combined. This helps to choose a suitable solution for the last relevant phase of the MSPM-model.

Question 3: *What inventory control framework works best to decrease inventory costs?*

Choosing an appropriate solution is challenging. The current situation is complex and there are multiple solutions available. The question is therefore guided by the following sub questions:

a) *What methods should be included in the framework?*

The first step is to select the best techniques by considering the results from the current situation analysis and the literature review. The choice is substantiated with strong arguments.

b) *How does the new control framework decrease inventory costs?*

The choice is further substantiated by calculating the frameworks' potential cost-savings.

c) *How does the new control framework fit into the current inventory system?*

The new control framework should not only work in theory, it should also be functional in practice. Therefore, the wishes from management are collected and several solutions are suggested to support the implementation of the framework.

1.7 Deliverables

The final outcome of the research is a tailor-made solution that improves the cost-efficiency of managing the raw material inventory. The solution comes in the form of a clear guideline on how to manage the raw materials using appropriate control policies and how to monitor the inventory's performance. The control policies help to determine optimal timing and volume decisions.

This final outcome is a result of the following sub deliverables that followed from answering the above described research questions:

- An understanding of the raw materials and their characteristics.
- An extensive analysis on the raw materials with the most impact in terms of costs.
- A visualization and description of the current inventory management process.
- A comprehensive overview of available inventory techniques and models.
- An understanding of the requirements for the final solution.
- A selection of an appropriate control policy to tackle high impact items.
- An identification of suitable models for other types of items.

1.8 Limitations

The research for this bachelor thesis is conducted over a period of 10 weeks. This short period comes with some limitations and forces the scope of the research to be narrowed.

- As actions are already taken to reduce the inventory value by losing dead stock and ordering less, this research focusses on improving the cost-efficiency of the inventory management processes to prevent the costs from unnecessarily rising again.
- The research ignores the size levels for all raw materials. This decreases overall complexity and does not cause problems for the implementation of the solution. There are *size curves* available which distribute sizes according to demand. As the different sizes show similar behavior for similar items, the curves can be applied afterwards.
- To create more depth in the research, the final solution focuses on the raw materials that make the most cost related impact. The other raw materials receive a more superficial advise on what control methods are suitable.

2. Current Situation

The first step in solving the inventory problem is to gain a proper understanding of the current situation. Therefore, this chapter answers the first research question: *"How is the raw material inventory currently managed?"* It starts with explaining what kind of items the current inventory deals with (Section 2.1) and continuous with identifying the items that make most impact in terms of costs (Section 2.2). Once these are selected the ordering process is assessed and areas for improvement are identified (Section 2.3). Finally, the results of the sections are combined to answer the first research question (Section 2.4).

2.1 Product Landscape

This first section explains the product landscape and helps with understanding how the current situation is shaped. It answers the first sub-question: *"What kind of raw materials is the current inventory dealing with?"*. It lies the foundation for the raw material analysis in the next section. It explains what clients and agreements are involved (Section 2.1.1), what the final product offering consists of (Section 2.1.2) and what different types of raw materials are involved and how these are currently organized within the inventory (Section 2.1.3).

2.1.1 Clients and Agreements

The client base of Dunlop primarily consists of retailers. Almost all direct client interactions occur on a business-to-business basis. As a result, clients purchase in batches and have strong negotiating positions. This creates nuanced relationships that lead to varying production strategies, each associated with distinct customer order decoupling points (CODPs).

The majority of retailers engage in a straightforward transactional model. They purchase directly from the existing stock of finished boots. These clients are served using a made-to-stock (MTS) strategy. Items are produced in anticipation of demand and kept in inventory before customer orders are received. The CODP is positioned downstream as decoupling occurs after the products have been standardized and stocked. For this type of agreement, Dunlop commits to a lead time of 6.3 weeks, allowing for swift delivery and efficient inventory management. However, in practice, the actual customer order lead time is often lower. The stock of finished boots is large enough to process orders within a week or two.

Alternatively, a subset of clients embrace a finish-to-order (FTO) or made-to-order (MTO) agreement. Under this model, orders are finalized according to specific customer specifications, introducing a degree of customization into the manufacturing process. For example, some items get different labels or transfers for marketing purposes. As a result, the CODP lies more upstream and standardization ends before the ordered products are finished (FTO) or produced (MTO). For these clients, the trade-off is an extended lead time of 9.4 and 12.6 weeks, respectively.

Agreement	Customer order lead time	Description
Made-to-stock (MTS)	6.3 weeks	Delivered from finished products stock
Finish-to-order (FTO)	9.4 weeks	Made-to-stock + specialized packaging
Made-to-order (MTO)	12.6 weeks	Design + purchasing + production

Table 2.1: The three types of customer agreements with their agreed lead times perceived by the customer.

It is important to note that the varying positions of the CODP result in different degrees of demand uncertainty. This is crucial for both the production and inventory process. The earlier actual demand is known, the more accurately it can be forecasted what products to manufacture and what raw materials to order. While this varying degree of uncertainty creates opportunities for optimization (Section 4.1.2), it also increases overall ordering complexity.

2.1.2 Typical Product

Another factor that increases ordering complexity is the vast size of the product portfolio. It currently consists of sixteen different boots, each featuring unique designs and specializations. While it is not practical to show and explain every individual product, gaining an understanding of the common components among models is crucial.

Figure 2.1: The Purofort® Fieldpro Thermo+ as an example to show the main parts of a pair of boots.

Figure 2.1 illustrates the key elements of a typical pair of boots. It uses the *Purofort® Fieldpro Thermo+* as an example because it has clear distinctions between the different parts.

The first thing to notice is the boots' green exterior. It covers a substantial proportion of the outside of the boots and is considered as the main material. It consists of *Purofort®*, a unique type of plastic which is responsible for the flexible but strong character of the boots. The bottom of the boots contains outer soles that ensure traction and stability. They are accompanied by inner soles that provide comfort on the inside. This comfort is further enhanced by soft linings or socks that cover the interior and are attached to the inside of the *Purofort®* material. In some cases, boots contain protective parts such as steel toe caps. They provide additional protection for extra dangerous environments.

2.1.3 Raw Materials

While these parts from the previous section form the basis of a typical pair of boots, there are many different types of linings, soles and protective parts. In addition, a finished product requires more than just the boots. For instance, all boots are packaged in cardboard boxes with labels and stickers and sometimes specific materials such as hydraulic oil is needed for maintaining machinery. These items are all part of an extensive list of raw materials.

To keep an overview of this extensive list, it is currently divided into sixteen distinct item groups. These item groups are numbered with a code that consists of the letters R and M, followed by two digits. Table 2.2 shows all item groups in numerical order.

Group-ID	Group name	Group-ID	Group name
RM02		RM51	
RM03		RM52	
RM07		RM55	
RM08	*Protected Data*	RM56	*Protected Data*
RM16		RM58	
RM17		RM97	
RM18		RM98	
RM50		RM99	

Table 2.2: All item groups with their group-id and group names.

2.2 Raw Materials

Since the list of raw materials is still quite extensive and as the item groups have very different characteristics, this section focusses on narrowing down the list. It does so by answering the second sub-question: *"Which raw materials make the most impact in terms of costs?"*. It starts with identifying the most valuable raw materials (Section 2.2.1) and explaining their criticality to the production process (Section 2.2.2). It continuous assessing the inventory coverage (Section 2.2.3) and supplier lead times (Section 2.2.4). Subsequently, it combines the sections to conclude which items deserve most attention (Section 2.2.5).

2.2.1 Value classification

The most common method to assess the cost impact of raw materials is the ABC-classification. This classical method categorizes items based on their monetary value. It is based on the Pareto principle (Section 1.5.5) and divides inventory items into three groups: A (high priority), B (medium priority) and C (low priority). The method helps as a first step to identify which items deserve to be focused on. Table 2.5 shows how the sixteen item groups from Section 2.1.3 can best be divided for the specific case of Dunlop:

Category	ID	ItemGroup	Share	Description
A	RM02	*Protected Data*	15.6%	Only 25% of raw material item groups is responsible for over 69.1% of inventory value.
	RM03		19.8%	
	RM07		16.2%	
	RM52		15.6%	
B	RM08		12.4%	Additionally, another 25% of raw materials is responsible for 24.7% of inventory value.
	RM16		6.3%	
	RM17		3.6%	
	RM56		2.4%	
C	RM18		1.4%	50% of raw materials is together responsible for only 6.2% of inventory value.
	RM50		1.6%	
	RM51		0.5%	
	RM55		0.7%	
	RM58		1.4%	
	RM97		0.4%	
	RM98		0.1%	
	RM99		0.1%	

Table 2.5: The item groups classified into an A, B or C category depending on their share of total monetary inventory value.

The A-category consist of only four item groups, but is responsible for 69.1% of inventory value. The items within this group are clearly the most valuable. Decreasing the costs for these item groups will yield the biggest marginal gains and could potentially unlock significant amounts of capital. The same applies, to a lesser extent to the B-category. This category also consists of only four item groups and is still responsible for a significant 24.7% of inventory value. In contrast, the C-category consist of twice as many item groups, but is responsible for only 6.2% of total value.

Since the item groups are a combination of several individual items, it is important to check for outliers within. The important outliers occur mainly in the A- or B-category. Table 2.6 shows the eight most valuable individual inventory items. In the remainder of this thesis these individual items are sometimes referred to as SKUs (stock keeping units). They are defined as individual items of stock that are distinct in terms of function, style, size, color and often location (Van Kampen et al., 2012). As explained in Section 1.8 the SKUs in this thesis ignore size level.

Item ID	Group ID	Group Name	Inventory Value period 06-09 (euros)	Unit Price (euros)
R1	RM03	Protected Data	€ 303,927	€ 3.01
R2	RM03		€ 149,152	€ 2.68
R3	RM07		€ 188,631	€ 3.23
R4	RM07		€ 141,104	€ 3.23
R5	RM08		€ 170,494	€ 12.91
R6	RM16		€ 95,596	€ 20.25
R7	RM52		€ 178,058	€ 1.41
R8	RM52		€ 151,957	€ 1.49

Table 2.6: The 8 most valuable SKUs with their item group, average inventory value and related unit price. The red numbers indicate outliers. The data originates from the summer of 2023.

The individual items in Table 2.6 are together responsible for 55% of all SKUs within the A- and B-category. Their inventory value helps to get a better feeling for the composition of the raw material inventory and indicates suitable candidates for a shortened, impact focused, list of raw materials.

In addition to the inventory value, the table also shows the unit prices. They help to understand whether the high values are a result of high stock volume or high unit prices. Here, raw material *R5* and *R6* stand out. They show considerably higher unit prices than the other SKUs, meaning their high inventory value is primarily a result of their high purchasing costs. This does not make them less important, but improving their efficiency might yield lower results because a relative large portion of their costs lies inside their unit price, which is harder to influence. On the other hand, the high inventory values of *R1, R3* and *R7* are a result of high volumes, which are easier to influence as stock levels are often a result of internal processes.

Nevertheless, it is important to note that inventory value and their related volumes and unit prices are not the only characteristics that determine the cost impact of raw materials.

2.2.2 Criticality

Another important characteristic to assess the impact of raw materials is their criticality to production. While the shortage of one raw material would only cause an altered production schedule, the shortage of another raw material could be detrimental and immediately cause a production stop. These stops can become extremely expensive and as a result, raw material criticality is an important factor to predict cost impact.

Table 2.3 shows how Dunlop currently assesses the raw material criticality. It divides the item groups from Section 2.1.3 into five different criticality grades. The distinction follows from a risk assessment presentation that was made for management. It is slightly adjusted to better fit with the contents of this thesis. The item groups that only occur on an international scale are ignored.

Criticality	Item Groups	Description
1	RM02, RM07	Protected Data
2	RM03, RM51, RM52, RM56	
3	RM08, RM16, RM17, RM55, RM58	

4	RM18, RM50	*Protected Data*
5	RM97, RM98, RM99	

Table 2.3: The categorization of raw material item groups based on their criticality grades.

It is clear that the main parts of the boots (see Section 2.1.2) all have a criticality score below three. Without these parts it is impossible to finish a pair of boots. However, it strikes that RM51 and RM56 have a higher criticality score than for example RM08, RM16 or RM17. Their score description leads to the conclusion that these last three raw materials are only needed for non-standard items. This means that these materials do not occur in standard boots and therefore belong to boots that are more flexible in the production schedule, thus decreasing their criticality. On the other hand, the RM51 and RM56 are needed to finish every pair of boots, including the standard boots. This makes them more critical than the raw materials only needed for special types of boots.

When combining the raw material criticality with the value classification from the previous section, it becomes clear there is an important similarity. None of the items with a criticality of four or five occur within the A- or B-group. These items do clearly not yield a significant impact in terms of costs. Therefore, to narrow down the list of raw materials, the item groups with a low criticality ($criticality \geq 4$) are excluded in the remainder of this thesis. Additionally, RM55 and RM58 are excluded as well. Although they have a criticality of 3, they are part of the C-group and their criticality is not significant enough to make them relevant.

2.2.3 Inventory Coverage

While the previous sections focus more on where most raw materials costs are located, the inventory coverage will indicate where most costs can be saved. This inventory metric shows for what time items on average stay in inventory. In the ERP-system of Dunlop this metric is denoted as *"weeks-on-hand"*. Table 2.7 shows this metric as the average weeks-on-hand for the left over item groups.

Group ID	Group Name	Average weeks-on-hand
RM02	*Protected Data*	15.9
RM03		54.5
RM07		109.9
RM08		63.6
RM16		65.9
RM17		26.7
RM52		128.7
RM56		18.8

Table 2.7: The item groups with their average weeks-on-hand metric. The red (severe) and orange (moderate) color indicate important outliers.

The inventory coverage is significantly higher for the RM07 and the RM52. The items within these item groups are stored for a relative long period of time and therefore have a low inventory turnover. This indicates these items are not managed efficiently. The same applies, to a lesser extent, to the RM03, RM08 and RM16.

2.2.4 Supplier Lead Times

Something that is closely related to the inventory coverage are the lead times from suppliers. A high inventory coverage is often a result of high lead times. However, the RM07 are an important outlier to this relationship. This is shown in Table 2.8 by sorting the item groups on their average weeks-on-hand.

Group ID	Average weeks-on-hand	Average lead time (days)
RM02	15.9	55
RM56	18.8	66
RM17	26.7	88
RM03	54.5	50
RM08	63.6	88
RM16	65.9	132
RM07	109.9	57
RM52	128.7	121

Table 2.8: The average lead times of suppliers together with the average weeks-on-hand per item group. The red color shows the important outlier.

Conversations with the purchasing manager have revealed that the relative high inventory coverage for the RM07 is a result of a rescue operation to keep their RM07 supplier, who only produces for Dunlop, alive. The conversations also revealed that these standard linings together with the RM03 and the RM08 already receive a lot of attention when it comes to improving efficiency and lowering stock levels. As a result, the RM52 and the RM16 are the item groups that yield the most potential for improvements.

2.2.5 Item Selection

The RM52 and RM16 do not only yield the most improvement potential when it comes to inventory coverage, but also when it comes to the other discussed characteristics. As a result of narrowing the list step by step, these item groups also have a relative high inventory value and raw material criticality. Since these characteristics all strongly influence the raw material impact in terms of costs, be it where the costs are located or where most savings can be made, the RM16 and RM52 are the perfect item groups to focus on when improving efficiency.

Zooming into the individual stock keeping units shows that especially items *R6*, *R7* and *R8,* which are within the two item groups, have high inventory values that offer room for improvement. Table 2.9 gives an overview of the characteristics of these three items.

Item Group	Item ID	Average value period 06-09 (euros)	Criticality (grade)	Coverage (weeks)	Lead time (days)
RM16	R6	€ 95,596	3	110	132
RM52	R7	€ 178,058	2	35	132
RM52	R8	€ 151,957	2	127	88

Table 2.9: The three raw materials with both a high inventory value (the average value in the last three periods in July 2023), high criticality grade (between 1-5, where 1 is the highest), high inventory coverage and high lead time.

In addition, to the high inventory value, criticality and inventory coverage the items also all have a relative high lead time. This characteristic becomes helpful when searching proper methods to improve the current ordering processes (Section 2.4). However, before these methods can be selected it is important to get a proper understanding of these current ordering processes.

2.3 Order Process Evaluation

Now that the raw materials that make most impact are selected, it is important to understand how these materials are ordered. Therefore, this section answers the third sub-question: *"How are the raw materials currently ordered?".* It explains the managing process in three different steps: checking the current status (Section 2.3.1), determining when and how much to order (Section 2.3.2) and monitoring the delivery process (Section 2.3.3). Eventually, the three different steps are brought together and their limitations are discussed (Section 2.3.4).

2.3.1 Checking The Current Status (1)

The ordering process of the raw materials starts when the purchasing manager opens the ERP-system. Using a periodical review strategy, the purchasing manager checks the status of all raw materials on a weekly basis. The initial phase of the ordering process is illustrated in Figure 2.7.

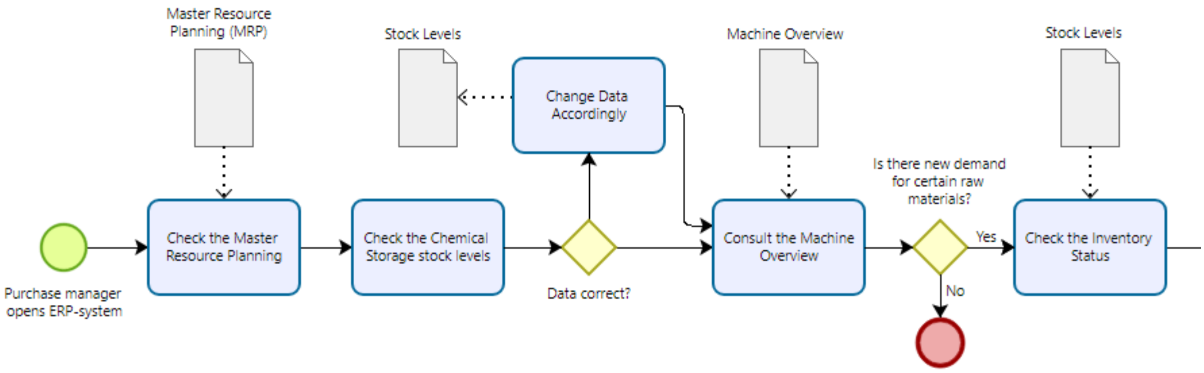

Figure 2.7: The first part of the raw material ordering process, focused on checking the current status.

The purchase manager starts by checking the Master Resource Planning (MRP). This ERP-module advises on what to order based on existing orders, minimum stock levels, current stock levels and production orders. In principle, these production orders are entered four weeks prior to their planned execution. This is what is referred to as the frozen period, a period in which no changes should be made to the production schedule. These four weeks are available for ordering the raw materials.

In reality, alterations to the production schedule within the frozen period are not completely rare. Based on the real production numbers, the planning is often slightly shifted backwards as a little more is planned than can actually be made. On top of that, the lead times of most raw materials exceed the four week frozen period. For these raw materials there is still quite some uncertainty on actual demand. As a result, the MRP-module serves as a first indication to understand what minimum action is needed.

After the purchase manager has gained a first idea of the raw materials status, he visits the physical chemical storage to check whether the administrative stock levels match with the actual stock levels. If he finds a mismatch, he updates the administrative data accordingly.

To expand his knowledge on the expected demand, the purchase manager continues the process by consulting the machine overview. This overview is compiled by the logistics manager and is discussed during the S&OP meeting. In this meeting, marked as a crucial input for the process, the Chief Commercial Officer (CCO) and the customer service desk manager (among others) check whether the planning is in line with the sales forecasts and other information they have.

The machine overview shows the machine planning for the upcoming twelve weeks. It is updated every four weeks where an additional four weeks are added to the end of the planning. The first four weeks are fixed and represent the production schedule and thus the frozen period. The remaining weeks in the overview contain a lot more uncertainty than these first four weeks and changes occur often. It is mainly used to see whether and when 'special' raw materials are needed. Those are raw materials that only occur in a selected group of end products. Furthermore, it provides a general estimation of future demand. This estimation gives a rough idea of the raw materials that will be needed in the upcoming periods.

With the MRP and machine overview in mind, the purchase manager checks the current stock levels. This information is needed for the next part of the ordering process.

2.3.2 Determining Order Volume and Timing (2)

Depending on the characteristics of the raw materials, the purchase manager uses different strategies to determine when and how much he needs to (re-)order. Figure 2.8 shows this second part of the process where he determines the so-called "volume" and "timing" decisions.

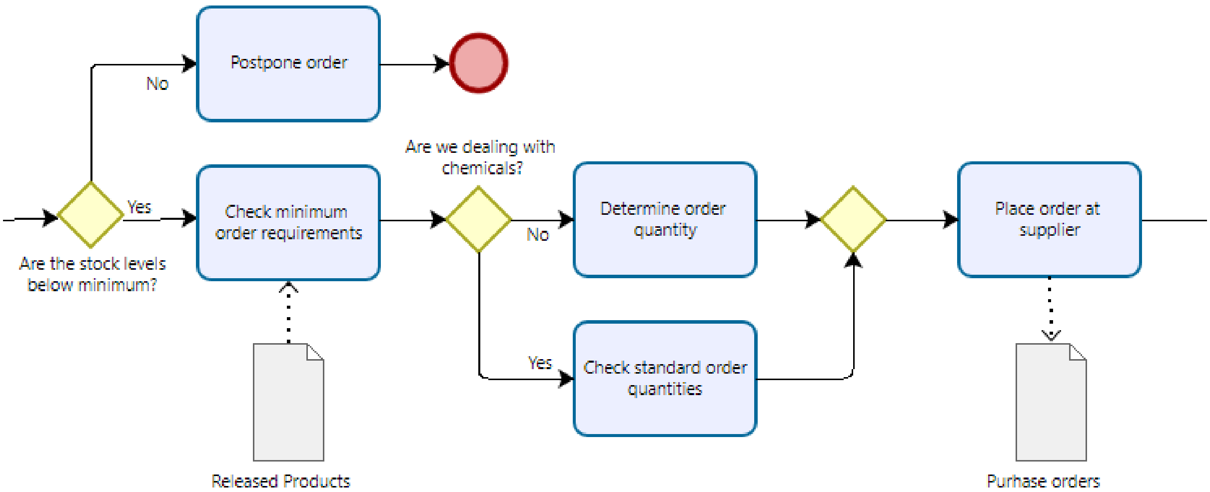

Figure 2.8: The second part of the ordering process, focused on determining the volume and timing decisions.

The purchase manager checks whether the current stock levels have fallen below the minimum stock levels. This minimum stock level is mostly a result of "what feels safe". As a rule of thumb the purchasing manager sets the re-order point of items R7 and R8 equal to 6 months' worth of demand. In cases where demand is intermittent he holds 1 production run (1 week) of safety stock (item R6), so he can always start production when asked for. This intermittent case seems to work well. He then continues the process to determine the order quantities. When the stock levels are still safe, he postpones the order and checks again next week.

For the raw materials that need replenishment, the purchase manager first checks the minimum requirements. This includes minimum order quantities and default order settings like box and pallet sizes. Then he determines how much he wants to order. If he is dealing with chemicals, he uses standard order quantities that account for consumption, available space in inventory and lead times. If he deals with non-chemical materials, he determines a suitable order quantity based on his experience and intuition. This means considering available truck/container space, production capacity of a supplier or combination prices where some items become cheaper when buying it in combination with other materials. He sometimes orders materials that are not directly needed, but become useful in the short or medium term. After the order quantity is determined he places the order in the system and at the supplier.

2.3.3 Monitoring The Delivery (3)

The last step of the ordering process is all about keeping an eye on the delivery. When lead times are delayed or there are other problems with the raw materials, the purchasing manager should inform the logistic and production manager.

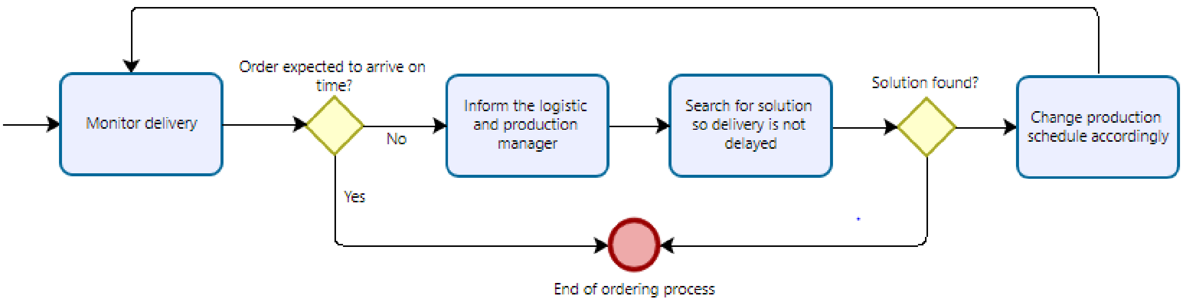

Figure 2.9: The third and last part of the ordering process, focused on monitoring the delivery process.

Once the related managers are informed they start looking for a solution to make sure the delivery can still be on time. This includes looking for alternative suppliers or making use of an urgent courier. If no suitable solution is found, the production planning is altered to account for the changes in raw material availability. Of course, Dunlop tries to avoid alterations as much as possible. Changing the production schedule will lengthen lead times of the end products and could ultimately lead to dissatisfied customers and harm the company's reputation. After the schedule is changed, the delivery process should still be monitored until the raw materials have arrived. Once they have arrived, the ordering process ends.

2.3.4 Process Evaluation

Although the current ordering process is working and the occurrence of shortages are very rare, the process is far from optimal. Some aspects seem to work really well, while others seem to bound the overall efficiency of the system and therefore create room for improvements.

Considering the limited time and widespread workload of the purchasing manager, the periodic review approach makes sense. The comprehensive checks on a diverse range of sources influencing demand showcase a thorough understanding of factors impacting the ordering process. Additionally, the use of minimum stock levels as triggers for orders reflects a strategic approach to inventory maintenance and preventing shortages. This is in line with the proactive determination of the chemical order quantities and the fact that cost optimization efforts are made through exploiting quantity discounts.

However, notable inefficiencies deserve attention. The broad range of sources influencing demand is not fully harnessed, suggesting untapped potential for improving the system's overall efficiency. The absence of a mathematical method for determining minimum stock levels introduces inefficiencies that could be addressed through a systematic, data-driven approach. Furthermore, the lack of a clear and efficient method for determining "economic" order quantities for other raw materials highlights a crucial area where optimization efforts can create significant cost-savings.

2.4 Conclusion

The existing inventory management system shows important strengths but also reveals opportunities for refinement. The major weakness of the current system lies in the determination of inefficient order quantities and minimum stock levels. Currently, these values are determined by meeting their minimum requirements and applying some common sense and intuition to decide which quantities seem somewhat optimal.

A systematic, mathematical and data-driven approach to determine economic order quantities and optimized minimum stock levels could increase the systems efficiency and result in significant cost-savings. This new approach should leverage the positive aspects of the current system by further exploiting the various demand influencing factors like the different client agreements and machine overview. Meanwhile it should improve the system's weaknesses by optimizing the process of determining the volume and timing decision.

The raw material analysis showed that the lack of efficiency is mainly reflected in the high item coverage of the RM52 and RM16 item groups. These item groups stand out, not only for their high item coverage, but also due to their high monetary values and high degrees of criticality. This makes them the most impactful raw materials and should therefore be the focus when designing a new inventory management approach. Especially, the three items in Table 2.9 stand out.

Item Group	Item ID	Average value period 06-09 (euros)	Criticality (grade)	Coverage (weeks)	Lead time (weeks)
RM16	R6	€ 95,596	3	110	132
RM52	R7	€ 178,058	2	35	132
RM52	R8	€ 151,957	2	127	88

Table 2.9: The three raw materials with both a high inventory value (the average value in the last three periods in July 2023), high criticality grade (between 1-5, where 1 is the highest), high inventory coverage and high lead time.

It strikes that the selected item groups mainly consist of items with high lead times ($L > 4$). This characteristic means that demand is not certain before the raw materials arrive in inventory and therefore they demonstrate stochastic behavior. As a result, the next chapter focusses on the available literature related to stochastic inventory policies that are suitable for the periodic review system of Dunlop.

3. Literature Review

As the areas for improvement are now identified, this chapter explains the related literature to inventory management with a special focus on stochastic review policies. It answers the second research question: *"Which inventory management techniques are available in literature?"*. It starts with explaining important basic inventory principles (Section 3.1) and then narrows down to the stochastic review models (Section 3.2). Additionally, to later monitor the effectiveness of the models, it discusses several relevant key performance indicators (Section 3.3). Finally, the separate sections are brought together in the conclusion (Section 3.4).

3.1 Inventory Principles

Before any complicated models can be suggested, it is important to understand the basic inventory principles. This section answers the first sub-question: *"What are the basic principles of inventory management?"*. It starts with explaining the basic concepts and terms of inventory management (Section 3.1.1). It pays special attention to the concept of service levels (Section 3.1.2) and explains different kinds of inventory costs (Section 3.1.3). Eventually, different types of inventory control policies are explored (Section 3.1.4).

3.1.1 Terminology

There are several important terms to describe different metrics of an inventory. These terms are crucial to correctly asses inventory status. According to Silver et al. (2017), it is useful to categorize inventories using the following concepts:

On-Hand Stock (OH) **–** This is stock that is physically available in inventory: it can never have a negative level. It is relevant to determine whether a particular demand is satisfied directly from the shelf.

Net Stock (NS) – In contrast to the on-hand stock, this quantity can become negative if there are backorders. It is defined by the following equation:

Net stock = (On-Hand) – (Backorders)

Inventory Position (IP) **–** This quantity indicates the actual position of the inventory. It is an important metric that is crucial in many control policies (Section 3.1.4). It accounts for stock on-hand, stock on-order, backorders and committed inventory. It is defined by the following equation:

Inventory position = (On-Hand) + (On-Order) – (Backorders) – (Committed)

The on-hand stock is clear. The on-order stock is stock that is ordered but is not yet physically received. The backorders represent orders from clients that still need to be fulfilled. The committed stock is stock that is already assigned to customers and can therefore not be used for other purposes anymore.

Safety Stock (SS) – This is the average level of the net stock just before a replenishment arrives. A positive safety stock provides a buffer against larger-than-average demand while waiting for a replenishment.

The appropriate value for safety stock depends on what happens to demand when stockouts occur. There are two extreme cases when a customer cannot be satisfied:

1. *Complete backordering* – when demand cannot be fulfilled it is backordered and filled as soon as an adequate-size replenishment arrives. It commonly occurs in government organizations or for example with exclusive car dealers.
2. *Complete lost sales* – when demand cannot be fulfilled it is completely lost. The customer goes elsewhere to satisfy their need. It is most common for retailers directly dealing with consumers.

Most inventory models choose either a backordering or a lost sales system. In practice, it is often a combination of both extremes. Nevertheless, the models serve as suitable and sufficient approximations for costs that occur in reality.

3.1.2 Inventory Related Costs

Where the stock terminology helps to categorize inventories, Silver et al. (2017) also define important cost factors that are related to inventory. These costs form a crucial basis for the control models that are discussed in Section 3.2. The cost factors below use more obvious notation than is used by Silver et al. (2017), but the definitions remain the same:

Unit Costs (C): the unit costs of an item are expressed in euros per unit. In its simplest form, it is the price paid per unit to a supplier. This price can depend, via quantity discounts, on the size of on order. However, in addition to the price paid to the supplier, the value of an item should ideally measure the actual amount of money (variable cost) spend on the SKU to make it available for usage. This actual value should also include order and transportation costs, and warehouse handling costs. These costs can sometimes be hard to accurately define, but fortunately, as will be shown (section 3.2.4), most inventory models are relatively robust to errors in cost estimation. Most importantly, the unit costs form the basis for holding cost calculations.

Holding Costs (H): the holding costs are the costs of having physical goods in storage over a period of time. It is one of the most difficult costs to accurately define and can be split up into three major components: storage, capital costs and risk. Storage costs may include facilities, equipment, personnel or software systems. It is usually related to unit value as an approximation with a percentage in the range 3-6%. Capital costs can be estimated by the interest of a company's bank loan (i.e. 6%) or opportunity costs like the highest return for alternative investment (i.e. 15%). It is often a percentage of the unit value in the range 10-18%. Risk costs may include item obsolescence, price erosion, insurances or taxes. They vary considerably between SKUs and from business to business. It lies in the range of 2-30% of unit value. In general, the total holding costs are in the range of 20-40% of the unit value.

Setup Costs (S): the setup costs include various expenses incurred during the process of placing an order. It includes determining the required quantity, preparing invoices, transportation costs or handling equipment to move items to the storage area. The setup costs are typically a fixed amount per order, regardless of the order size.

While the costs above can be quite specific and are relatively clearly defined, there is also another more important cost associated with inventories that should not be neglected:

Shortage Costs are the result of lost sales due to insufficient inventory. They arise when demand exceeds the available inventory. It includes various expenses such as the cost of lost profits, lost customers and damage to customer relationships. In case a shortage occurs for items that are used internally, the cost of lost production or downtime is considered a shortage costs. In general, measuring the shortage costs is challenging and often requires subjective estimations.

3.1.3 Shortage Costs and Service Levels

The shortage costs are especially relevant when dealing with uncertain demand or uncertain delivery capabilities. In these cases there is a risk of not being able to satisfy demand directly out of stock or of having too much if demand is lower than expected. Both situations are not ideal and require balanced safety stock levels. There are two common approaches to determine optimal levels of safety stock (Silver et al., 2017):

A common method is the ***cost-minimization*** approach. It involves assigning costs to shortages and finding the overall lowest costs. For example, using air freight to meet demand may be more expensive but decreases the probability of having shortages. On the other hand, keeping more inventory decreases this probability as well, but increases holding costs. This approach considers the trade-off between holding more inventory and the cost of shortages.

The difficulty in determining the cost of shortages introduces another method that makes use of a control parameter known as ***service-level***. This control parameter exists in different forms. One common approach is the *cycle service-level (CSL)* which represents the percentage of stock cycles in which no shortage occurs (e.g. 95%). Another common method is the *fill-rate* which represents the fraction of customer demand that is met routinely from stock without backorders or lost sales.

In essence, both the cost and service-level approaches balance between the costs associated with shortages and costs associated with holding excess inventory. The shortage costs approach directly addresses the financial implications of running out of stock, while the service level approach addresses the customer service aspect by determining appropriate level of stock to meet demand consistently. Organizations must find the right equilibrium that aligns with their specific goals.

3.1.4 Control Models

The approaches to quantify optimal levels of safety stocks become very useful in inventory control models. These models help with the timing and volume decisions. They are divided into two types, based on their demand type. Demand can either follow a deterministic model, or a stochastic model. These models are distinguished by the amount of uncertainty that is involved.

The ***deterministic model*** assumes stable conditions with relatively little or no uncertainty in the level of demand. It is a reasonable approximation of reality for many situations. For most cases it is suitable to use the relatively simple EOQ approach (Section 3.2.5). When expected (certain) demand depletes inventory a new order of size EOQ is placed. In other cases the Silver-Meal heuristic yields better results. This method calculates for how many periods it is optimal to order demand in advance. However, as most demand for raw materials is stochastic, the deterministic approaches are not further explored in this thesis.

The **stochastic model,** on the other hand, assumes the demand rate to vary with time. It considers uncertainty and randomness in various factors such as demand, lead time and supply. It is suitable when demand and lead times show reasonable variability. Since the raw materials with the greatest impact all have considerable high lead times (Section 2.4), and since the lead times of these raw materials are higher than the frozen period of four weeks (Section 2.3), this causes the demand pattern to involve a degree of uncertainty. As a result, the appropriate inventory methods to use are stochastic models.

3.2 Stochastic Models

Now that the basic principles of inventory management are explained, this section answers the second sub-question: *"What inventory control models are appropriate?"*. It starts with arguing why periodic models are most applicable (Section 3.2.1) and which different types of periodic models are commonly used (Section 3.2.2). It then explains how the different variables of the models can be quantified by assessing the re-order point (Section 3.2.3) and the economic order quantity (Section 3.2.4). All theory in this section follows from Silver et al. (2017).

3.2.1 Review Type

Inventory models for items with a stochastic demand type further divide the demand type based on the way the demand and inventory position are reviewed. It is either continuously tracked and a **continuous** review policy is used, or it is checked at regular periodic intervals and a **periodic** review policy is used.

Since Dunlop currently uses a periodic system (Section 2.3.1), a periodic review policy makes sense above a continuous review policy. This policy is often simpler to implement and is more straightforward to administer compared to continuous monitoring. Additionally, it limits any additional pressure on the available time of the purchasing manager and most importantly, it offers opportunities to coordinate the replenishment of related items. For example, items that are ordered overseas are often combined to fill a shipping container so shipping costs remain under control. Since Dunlop has multiple items they order overseas, this extra coordination could yield significant cost savings.

3.2.2 Periodic Review Policies

There are two common periodic control systems that help with managing inventories. These systems follow from Silver et al. (2017):

The (R, S) system is the most basic one. In this system, every R units of time an order is placed which raises the *inventory position* to the order-up-to-level (S). Because it is a periodic review model, the system offers a regular opportunity to adjust S so it can be more in line with new demand patterns. The system is in common use, particularly in companies without sophisticated computer control or companies that order from the same supplier. A typical behavior of this system is shown in Figure 3.1.

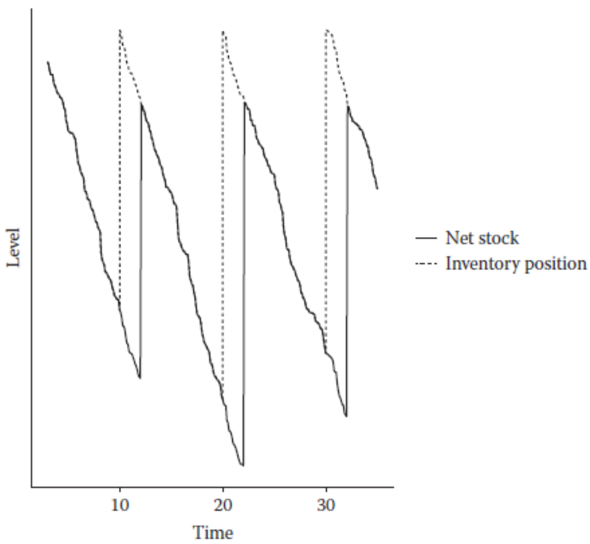

Figure 3.1: The (R, S) system, orders every 10 periods, with lead times of 2 periods (Silver et al., 2017).

When this model is extended it becomes a (R, s, S) system. In this system, every R units of time the *inventory position* (Section 3.1.1) is checked and if it is at or below the reorder point s, enough is ordered to raise it to the order-up-to-level S. Above the reorder point s nothing is done until the next review. In general, this method is the one that produces the lowest total amount of costs compared to any other system. According to Silver et al. (2017), under quite general conditions, the models in the (R, s, S) family minimize the total of review, replenishment, carrying and shortage costs.

In the (R, s, S) system, the S could also be replaced by a fixed order quantity Q. It then becomes an (R, s, Q) or related (R, s, nQ) system. Here, an order of (optimal) size Q, or an multiple nQ, is placed once the inventory position is below the reorder point s. This system is similar to the (R, s, S) system and is suitable for situations where fixed order quantities are preferred, for example when it is efficient to order a full container.

3.2.3 Economic Order Quantity (EOQ)

Both the (R, s, S) and (R, s, Q) models use the economic order quantity (EOQ) to determine an appropriate window or exact value for the actual order size. It plays a crucial role in the *volume* decision (Section 1.5.2) and advises the purchasing manager on an appropriate order size.

The economic order quantity aims to minimize the total inventory related costs. It makes a trade-off between order costs and inventory holding costs. It assumes a new order is placed every time the inventory reaches a level of zero. Additionally, it makes several assumptions that are important to keep in mind while using the model in practice:

- *D items per unit of time* – constant demand rate.
- *Q items to order* – order quantity to be determined.
- *C costs per unit* – average price paid per unit purchased.
- *S costs for setup* – fixed costs incurred every time the warehouse places an order.
- *H costs for holding inventory* – incurred per unit per day that the unit is held
- H is calculated by *h* × *C*, where *h* is a percentage of the price per unit.
- *Lead time = 0*
- *Initial inventory = 0*

As the model aims to minimize the total inventory related costs, the total cost (TC) per year follow from the following equation:

$$TC(Q) = CD + \frac{SD}{Q} + \frac{hCQ}{2}$$

The total costs for a certain order quantity ($TC(Q)$) result from the sum of the material costs (CD), order costs ($S \times \frac{D}{Q}$) and cycle stock costs ($\frac{h \times C \times Q}{2}$). By rewriting the equation, the optimal order quantity ($Q*$) follows from the economic order quantity equation:

$$Q* = \sqrt{\frac{2SD}{hC}}$$

With the optimal order quantity (Q^*) it is rather simple to calculate the related optimal order frequency (n^*):

$$n^* = \frac{D}{Q^*} = \sqrt{\frac{DhC}{2S}}$$

One of the most important aspects of the EOQ-model is that the total relevant costs are rather insensitive to deviations from the optimal lot size provided by the EOQ. As can be seen in Figure 3.2, the total cost curve is quite flat near the EOQ. This

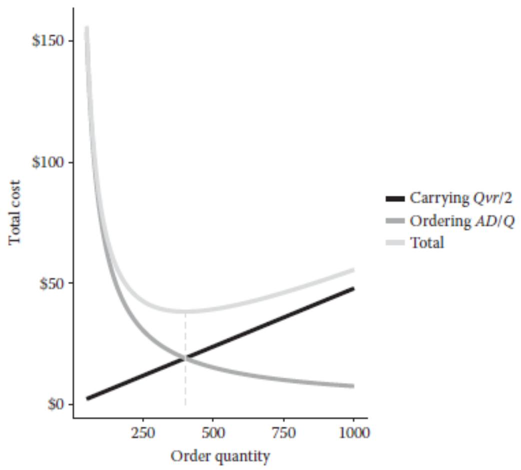

Figure 3.2: Cost as functions of the replenishment quantity (Silver et al., 2017)

means that any reasonable deviations will have little impact on the total cost incurred. Without this flexible characteristic of the EOQ, implementable decisions systems would be difficult to design.

To make the model more implementable, several extensions to the EOQ-model exists. These are important because the basic EOQ-model is often too simple in nature and uses several assumptions which ignore aspects or opportunities that occur in reality. Extensions include the exploitation of quantity discounts or multi-item ordering opportunities. However, due to time constraints these extensions are not considered in this thesis.

3.2.4 Re-order point (s)

Within the members of the (R, s, S) family, the re-order point (s) is a crucial and recurring variable. While the economic order quantity helps to determine the order *volume,* the re-order point helps to determine the order *timing*. It assesses *when* a new order of a predetermined quantity should be placed. Its value should be high enough to protect against demand during the lead time and review period. Depending on the demand distribution, there are different methods to determine the appropriate re-order point.

In the case that demand is normally distributed, the re-order point (s) can be determined with the equation below:

$$s = \bar{x}_{L+R} + k\sigma_{L+R}$$

The first part of the re-order point equation represents the average demand during the lead time and review period ($\bar{x}_{L+R}$). It follows from adding the average demand during lead time ($\bar{x}_L$) with the average demand during the review period ($\bar{x}_R$):

$$\bar{x}_{L+R} = \bar{x}_L + \bar{x}_R$$

When the average demand ($\bar{x_D}$) is known, the average demand during the lead time ($\bar{x}_L$) and the average demand during the review period ($\bar{x}_R$) follow from the equations below:

$$\bar{x}_L = \bar{x_D} \times E[L]$$

$$\bar{x}_R = \bar{x_D} \times R$$

The average demand ($\bar{x}_D$) is multiplied by the expected length of the lead time ($E[L]$) and the length of the review period (R), respectively. These lengths should be in the same unit as the unit of the average demand ($\bar{x}_D$), for example in weeks.

The second part of the re-order point equation ($k\sigma_{L+R}$) consists of two separate parts: the safety factor (k) and the standard deviation of demand during the lead time and review period (σ_{L+R}). This last part follows from the equation below. It is reasonable to assume the variance of the lead time and review period are independent:

$$\sigma_{L+R} = \sqrt{\sigma_L^2 + \sigma_R^2}$$

The variance of the demand during lead time (σ_L^2) results from the equation below. It accounts for the standard deviation of demand (σ_D) and the standard deviation of the lead time (s_L):

$$\sigma_L = \sqrt{E[L]\sigma_D^2 + \bar{x_D}^2 s_L^2}$$

The standard deviation of the review period (σ_R) follows from the equation below:

$$\sigma_R = \sqrt{R}\sigma_D$$

To calculate the safety factor (k), it is important to first check how demand is distributed using the coefficient of variation (CV). This works by dividing the standard deviation of demand during the lead time and review period with the average of demand during this same period:

$$CV = \frac{\sigma_{L+R}}{\bar{x}_{L+R}}$$

When the coefficient of variation is low ($CV \leq 0.5$), it is reasonable to assume the demand follows a normal distribution. In this case, the safety-factor (k) can be derived using the equation for the expected units short per cycle ($ESPRC$):

$$ESPRC = \frac{\sigma_R^2 + J_u(k)}{2\bar{x}_R} = (1 - P_2) \times \left(S - s + \frac{\sigma_R^2 + \bar{x}_R^2}{2\bar{x}_R}\right)$$

The part between brackets represents the expected order size. This is where the economic order quantity plays a role (Section 3.2.6). The safety factor (k) is then derived by Silver et al. (2017) with the equation below. It calculates $J_u(k)$, a function of the unit normal distribution:

$$J_u(k) = \frac{2(1 - P_2)\bar{x}_R\left(S - s + \frac{\sigma_R^2 + \bar{x}_R^2}{2\bar{x}_R}\right)}{\sigma_{L+R}^2}$$

With a pre-specified fill rate (P_2) the equation gives the value of $J_u(k)$. By using the table of $J_u(k)$ versus k in Appendix B, the value for the safety factor (k) can be derived.

When the coefficient variation is high ($CV > 0.5$), a gamma distribution provides better results. In this case, the re-order point (s) follows from the probability density function:

$$s = f(P_1; \alpha, \beta)$$

The probability density function ($f(P_1; \alpha, \beta)$) provides an appropriate re-order point using a pre-specified cycle service level (P_1), the shape parameter ($\alpha = \bar{x}_{L+R}^2/\sigma_{L+R}^2$) and the scale parameter ($\beta = \sigma_{L+R}^2/\bar{x}_{L+R}$).

It is important to note that the equation used for the case of a gamma-distribution uses a cycle service level (P_1) instead of the fill rate (P_2). However, to make the general approach more convenient, the related fill rate (P_2) can be derived using the gamma distribution ($F(s; \alpha, \beta)$) with the two equations below:

$$ESPRC = \alpha\beta[1 - F(s; \alpha + 1, \beta)] - s[1 - F(s; \alpha, \beta)]$$

$$P_2 = 1 - \frac{ESPRC}{Q}$$

When the separate approaches for calculating the re-order point are applied in practice, it is rather simple to use the fill-rate in both cases. Using a trial and error method, the cycle service level (P_1) can be adjusted until it matches the desired fill rate (P_2). This is further explored in the final solution (Section 4.1.3). The next section will explain how the order quantity (Q) is related to the re-order point (s).

3.2.5 Actual Order Quantity (Q)

Within the (R, s, S) family the related order quantities play a different role. In the case of the normal (R, s, S) policy, the order quantity $(S - s)$ can be determined using the economic order quantity:

$$S - s = EOQ - E[Z]$$

The difference between the order-up-to-level (S) and the re-order point (s) should equal the economic order quantity (EOQ) minus an expected undershoot $(E[Z])$. This undershoot accounts for fluctuations during the review period. It is based on the demand during the review period (D_R):

$$E[Z] = \frac{E[D_R^2]}{2E[D_R]} = \frac{\sigma_R^2 + \bar{x}_R^2}{2\bar{x}_R}$$

The expected order size then approximately equals the economic order quantity. As mentioned in Section 3.2.3 small derivations of the economic order quantity have little effects on the costs. The expected order size is equal to the equation below:

$$E[order\ size] = S - s + \frac{\sigma_R^2 + \bar{x}_R^2}{2\bar{x}_R}$$

In the case of the (R, s, Q) policy the variable order size is replaced by a fixed order of size Q. In the formula to derive the safety factor (k) the expected order size is replaced with the fixed order quantity (Q):

$$J_u(k) = \frac{2(1 - P_2)\bar{x}_R \times Q}{\sigma_{L+R}^2}$$

It is important to note that in many real-life scenarios demand is non-stationary. Seasonal effects or trends change the mean and standard deviation over time. These changes can have a significant impact on the required safety-inventory and re-order point. This influences both the (R, s, S) and (R, s, Q) policy. It is therefore extremely important that the input demand parameters of the control policies are regularly reviewed and updated. Additionally, by representing the re-order point in the number of weeks of demand, the value automatically adjusts when the average demand increases or decreases.

3.3 Key Performance Indicators

To effectively manage the raw material inventory and to see whether chosen classification and modeling strategies actually work, it is crucial to monitor the inventory performance. This section answers the third sub-question: *"What control measures are available to track inventory performance?".* It explains seven key performance indicators (KPIs) identified by Luther (2022) which help to show how the current inventory management strategies are performing.

3.3.1 Strategic Metrics

There are three major indicators which emphasize the strategic and long-term aspect of inventory management. These metrics have a significant impact on business strategy and performance:

Inventory Value – The most common measure for inventory performance is the monetary value of the current stock. It is often calculated by taking the on-hand volume in numbers of items and multiplying it by the value or purchasing costs of the item. However, although it is a great measure for the investment in stock, it gives no indication of how large the investment is in comparison to the company's throughput. For these relative indications, other measures are needed.

Lead time – The lead time indicates the time it takes to receive a product after it is ordered. Short lead times are often preferred as they make a supply chain more flexible to fluctuations in demand. In the case of raw materials, it can be important to track the lead time and deviations in lead time to determine supplier reliability or to define different strategies for items with different lead times.

Service Level – The service level is a metric to measure how well a business is meeting customer demand while maintaining an optimal level of inventory. It is used to balance excess inventory costs and stock-out costs that result from having too much or too little inventory to fulfill orders. A supplier that is known to be reliable often has a high service level.

3.3.2 Operational Metrics

The operational metrics focus more on the day-to-day operational aspects of inventory management. It provides insights into the efficiency and effectiveness of inventory processes:

Inventory Coverage – The inventory coverage shows the amount of time an inventory would last under a normal demand rate without the stock being replenished. It is often indicated in weeks, but sometimes also in days, months or years. It is calculated by dividing the average stock level of an item by the consumption rate (demand) of this item.

Inventory Turnover Ratio – The inventory turnover ratio is the reciprocal of the inventory cover. This measure shows how often the stock is used up in a period, usually a year. It is used to compare stock levels with sales. It measures how well a company makes sales from its inventory.

Stock-outs – Stock-outs refer to the event of not having enough inventory available to meet customer demand for a particular product. In the case of the raw material this metric measures the frequency of stock-outs or instances where you run out of a particular raw material. It is calculated by dividing the number of stock-outs by the number of stock-out opportunities.

Raw Material Age – The age of raw materials tracks for how long each raw materials has been in your inventory. This metric helps to identify slow-moving or obsolete items. When items are no longer in demand and become obsolete, they are referred to as dead stock. This represents products that are sitting idle in storage without generating revenue. It ties up valuable resources, such as warehouse space and capital.

3.4 Conclusion

The examination of available literature on the topic of inventory management uncovered a range of strategies to enhance the current situation. In the first place, the exploration of important inventory terminology and related inventory costs helps to gain a better understanding of crucial inventory principles. Additionally, the control models discussed afterwards provide clear guidelines for a new inventory policy. Here, the stochastic and periodic control models stand out. These are particularly applicable to raw materials with high lead times and uncertain demand.

Within these control models, the (R, s, S) and $(\mathrm{R}, s, \mathrm{Q})$ policy emerge as potential candidates for improving the raw material inventory system. The policies suggest clear methods for determining effective order quantities (the volume decision) and appropriate re-order points (the timing decision). They show significant potential for increasing the level of control on raw material inventory and have enough room to adjust the input values so that they better fit with the demand behavior and opportunities of Dunlop, such as the part of demand that is deterministic.

To account for non-stationary demand patterns, it is important to regularly review and update the input values used to calculate the order quantity and re-order point. Representing this re-order point (s) in weeks of demand, rather than in the number of units, automatically adjusts for variations in the average demand.

Additional preventive measures involve implementing specific key performance indicators (KPIs), as highlighted in the literature review. These KPIs serve as valuable metrics for assessing the system's performance, monitoring over- and understocking risks and facilitating the identification of necessary adjustments and actions. They can be implemented into current monitoring dashboards.

When combined with the insights from the analysis of the current situation (Chapter 2), the explored control policies and KPIs lay a robust foundation for the development of an effective inventory management system tailored to the specific needs of the raw material inventory. The next chapter will utilize these identified methods and techniques to construct a new control framework.

4. Final Solution

This chapter combines the insights from the current situation analysis (Chapter 2) with the technical knowledge from the literature review (Chapter 3). It answers the third research question: *"What inventory control framework works best to decrease inventory costs?"*. First, it explains which methods should be included as basis (Section 4.1). Subsequently, it shows how these methods yield significant savings for the items selected in the raw material analysis (Section 4.2). Additionally, it shows how the policy fits within the requirements and wishes of management (Section 4.3). The overall results are considered in the conclusion (Section 4.4).

4.1 Control Framework

The final solution for the raw material inventory consists of a new framework for its control. This section answers the first sub-question *"What methods should be included in the framework?"*. The section starts with motivating the choice for a (R, s, Q) policy (Section 4.1.1). It then explains how the models underlying the (R, s, Q) policy should be adjusted to improve its practicality and effectiveness (Section 4.1.2). Additionally, it considers a special case for items with intermittent demand (Section 4.1.3).

4.1.1 Policy Motivation

For most items, the stochastic and periodic (R, s, Q) policy is the most effective method to tackle the cost-efficiency problem of Dunlop. This control policy yields significant cost savings (Section 4.2) and is rather simple to implement (Section 4.3).

The raw material analysis (Section 2.2) showed that item groups with a high inventory value, high criticality and high inventory coverage are most impactful when it comes to cost-efficiency. It also showed that these item groups have high lead times and therefore show a high degree of demand uncertainty. This explains the need for a stochastic approach.

The periodic nature of the model is in line with the current ordering process and available time and resources of the purchasing manager. In contrast to a continuous system where items are constantly monitored, the purchasing manager is able to check once a week whether action is needed. Therefore, with $R = 1$, the policy can be implemented smoothly.

Additionally, the order process evaluation showed how the purchasing manager primarily struggles with determining appropriate minimum stock levels and optimal order quantities (Section 2.3). The (R, s, Q) model focusses on both aspects. The re-order point (s) serves as minimum stock level and the economic order quantity helps to determine an optimal order quantity (Q).

4.1.2 Input Adjustments

To make the (R, s, Q) policy practical and to increase its effectiveness, the demand parameters require some minor adjustments. These adjustments account for the deterministic part of demand. This part is known with a high degree of certainty since it follows from the production orders. These orders are entered four weeks prior to actual production. Incorporating this extra degree of certainty makes the calculation of the re-order point more accurate.

The adjustments consist of changing the mean demand per week $(\bar{x}_D)$ and standard deviation per week (σ_D) of the input of the (R, s, Q) policy (see Section 3.2.4). These values should be adjusted such that there is a distinction between the demand in the known weeks $(x_n \; with \, n = week \; number)$ and mean demand per week following from demand forecasts $(\bar{x}_F)$ with the standard deviation per week of this forecasted demand (σ_F). Table 4.1 shows how these adjustments are realized when the sum of the lead time and review period is low ($L + R \leq 4$) and Table 4.2 shows the adjustments when this value is high ($L + R > 4$). It assumes the lead time (L) and review period (R) are integer values and represent the number of weeks (which makes sense for Dunlop). For convenience, the expected lead time ($E[L]$) and the lead time as indicated by the supplier (L) are equal.

In the first case ($L + R \leq 4$), average demand per week ($\bar{x}_D$) results completely from the average known demand ($\bar{x}_k$). It depends on the length of the lead time and review period for how many weeks this known demand is considered. The known demand is calculated by summing the demand in the relevant known weeks (x_n) and dividing it by the number of weeks demand is considered ($L + R$). In this case, since demand is known with certainty, the standard deviation can equal zero. In the re-order point equation, safety stock follows only from lead time deviations. The calculations are shown in Table 4.1 below.

Case 1: ($L + R \leq 4$)

Variables	Equation
$\bar{x}_k$	$\bar{x}_k = \frac{1}{L+R}\sum_{n=1}^{L+R} x_n$
$\bar{x}_D$	$\bar{x}_D = \bar{x}_k$
σ_D	$\sigma_D = 0$

Table 4.1: The equations to adjust the demand variables of the (R, s, Q) policy in the case the lead time is low.

In the second case ($L + R > 4$), average demand per week ($\bar{x}_D$) consists for four weeks of known demand per week ($\bar{x}_k$) and for the lead time and review period minus four weeks of unknown forecasted demand per week ($\bar{x}_F$). This forecasted demand is thus considered for the remaining period of $L + R$ for which demand is unknown. The standard deviation per week (σ_D) is then only considered for the unknown forecasted demand per week (σ_F). The calculations are shown in Table 4.2 below.

Case 2: ($L + R > 4$)

Variables	Equation
$\bar{x}_k$	$\bar{x}_k = \frac{1}{4}\sum_{n=1}^{4} x_n$
$\bar{x}_D$	$\bar{x}_D = \frac{4}{L+R}\bar{x}_k + \frac{L+R-4}{L+R}\bar{x}_F$
σ_D	$\sigma_D = \sigma_F$

Table 4.2: The equations to adjust the demand variables of the (R, s, Q) policy in the case the lead time is high.

By incorporating the deterministic part of demand in this manner, the average demand per week ($\bar{x}_D$) and its standard deviation (σ_D) are manipulated and can be used for calculating the re-order point in both the case of normal and gamma distributed demand. The remaining calculations where $\bar{x}_D$ and σ_D are used to find the re-order point are the same as in Section 3.2.4.

Although this adjusted (R, s, Q) policy works for the most important raw materials, there are cases where this model is not effective. These special cases of intermittent demand are discussed in the next section.

4.1.3 Intermittent Demand

The stochastic (R, s, Q) policy works well for raw materials with a continuous demand pattern. This is the case for most high impact raw materials. These high impact raw materials have high demand, are frequently used in production and are therefore considered as fast-moving. However, for raw materials that have a more intermittent demand pattern the (R, s, Q) policy might not be effective. In these cases other approaches are more appropriate.

The demand pattern of a raw material can be considered as intermittent when the average inter-arrival time ($\bar{T}$) between consecutive production occurrences is high ($\bar{T} > 4\ weeks$). These raw materials are often only produced during a limited number of weeks per year. The demand for these items is low and the items are considered slow-moving.

Since the intermittent items are slow-moving and there are only a limited number of these items, the methods for optimizing these raw materials lie outside the scope of this research. The current approach of keeping one production run of safety stock is sufficient in these cases.

However, it is important to acknowledge there are important opportunities here which could be explored in future research (Section 5.3). When the period of the lead time and review period of such an intermittent raw material is low ($L + R \leq 4$), it is possible to apply a full deterministic approach. In these cases the average demand per week ($\bar{x}_D$) follows completely from known demand and uncertainty is mainly caused by small deviations in the lead time. For such cases, there are several deterministic methods that optimize costs. In cases where the period of the lead time and review period of a raw material with intermittent demand is high ($L + R > 4$) it is harder to use these deterministic approaches. Here the focus in future research should lie on improving forecasting methods to increase demand certainty. These forecasting methods lie outside the scope of the research as well.

On the other hand, the case with continuous demand, which has the most impact on costs and where the adjusted (R, s, Q) policy is recommended, is considered in the next section.

4.2 Achieved Benefits

To show how the (R, s, Q) policy is effective in decreasing the inventory related costs, this section answers the second sub-question: *"How does the new control framework decrease inventory costs?"*. It uses the selected items from Section 2.2 as an example. It starts with determining the demand characteristics (Section 4.2.1) and the order quantities (Section 4.2.2). It then uses this information in the equations for calculating the re-order point (Section 4.2.3) and showing the achieved benefits (Section 4.2.4). The section finishes with a sensitivity-analysis for the re-order point method (Section 4.2.5).

4.2.1 Demand Characteristics

The first step in applying the new control framework is to analyze the demand characteristics and to determine the correct approach. This is demonstrated by using the three individual items identified earlier (Section 2.2). These items have a high value, high criticality and high inventory coverage. They make the most impact in terms of costs and therefore have the most potential to yield significant cost-savings.

Table 4.3 shows the average inter-arrival time between consecutive demand occurrences ($\bar{T}$) over the year 2023. The length of all periods in which no production occurs are summed and divided by the number of periods for which this is the case. When the average inter-arrival time is low ($\bar{T} \leq 4\ weeks$), the demand is considered continuous. When the value is high ($\bar{T} > 4\ weeks$), the demand is considered intermittent. As explained in the previous section a different approach is appropriate.

Item ID	Average inter-arrival time	Continuity	Approach
R6	8.4 weeks	Intermittent	Current
R7	1 week	Continuous	(R,s,Q)
R8	3.1 weeks	Continuous	(R,s,Q)

Table 4.3: The demand continuity of the three selected raw materials with their appropriate approach.

In the case of item R6 the demand pattern is intermittent and the current approach of keeping one production run as safety stock is appropriate. Here, the economic order quantity can help to save costs (Section 4.2.2). In the case of items R7 and R8 the (R, s, Q) policy can be applied. This approach is further explained below and starts with determining the demand distribution.

The coefficients of variation of these items show which distribution and equations should be used. In Table 4.4 these coefficients are calculated using the mean ($\bar{x_F}$) and standard deviation (σ_F) of forecasted demand. In this example, these values follow from weekly demand in 2023. Later these values could be adjusted to follow from actual forecasts. According to Silver et al. (2017), depending on the coefficient of variation, the normal-distribution ($CV \leq 0.5$) or gamma-distribution ($CV > 0.5$) is appropriate.

Item ID	$\bar{x_F}$ (mean per week)	σ_F (st. dev per week)	$CV\ (\sigma/\bar{x}\ )$	Distribution
R7	13796	5924	0.43	Normal-distribution
R8	4839	4438	0.91	Gamma-distribution

Table 4.4: The two items following (R,s,Q) approach with their corresponding distributions based on past weekly demand.

As shown in Section 4.2.2, the lead time of the corresponding items tells which equations should be used to manipulate the demand input. Table 4.5 shows the average demand ($\bar{x}_D$) and standard deviation of demand (σ_D) together with the additional variables needed to calculate them. The example assumes the standard deviation of the lead time is half a week ($s_L = 0.5$). The known demand during the first four weeks ($x_n\ with\ n = 1,2,3,4$) follows a fictional demand pattern which is in line with actual demand patterns and their mean and standard deviation.

Item ID	Lead time	$\bar{x_1}$	$\bar{x_2}$	$\bar{x_3}$	$\bar{x_4}$	$\bar{x_k}$	$\bar{x_D}$	σ_D
R7	12 weeks	10990	15700	14130	9420	12560	13416	5924
R8	8 weeks	11775	0	3140	5495	5103	5021	4438

Table 4.5: The three selected raw materials with their mean demand and standard deviation following from the known and unknown demand equations in Section 4.2.2.

With the adjusted values for the mean and standard deviation of demand, it is possible to calculate the other demand values that are used in the (R, s, Q) policy. Table 4.6 shows these values that follow from the equations in Section 3.2.4.

Item ID	$\bar{x_L}$	σ_L	$\bar{x_R}$	σ_R	$\bar{x}_{L+R}$	σ_{L+R}
R7	160985	21589	13416	5924	174400	22811
R8	40172	12802	5021	4438	45192	13549

Table 4.6: The three selected raw materials with all demand parameters as shown in Section 3.2.4.

4.2.2 Order Quantity

The second step in applying the new control framework involves determining the order quantity (Q). It is one of the key variables within the (R, s, Q) policy and is extensively researched in literature. It differs per raw material how simple the optimal value for the order quantity can be derived. It depends on how well the associated costs are available and understood.

Since the exact order costs for items R7 and R8 are not immediately available, this example uses their current (fixed) order quantities. These order quantities relate to the size of a full container. The example assumes these quantities are already optimal as it is often cheaper to order a full container load (FCL) instead of a less than container load (LCL). When comparing the old situation with the new situation (Section 4.1.5) the order quantity is the same in both situations. These order quantities therefore have little effect on the achieved savings. However, they are important to mention as they are a crucial variable in the (R, s, Q) policy and have significant potential for improvement. A further research attempt could recalculate the fixed order quantities for R7 and R8 by carefully investigating the related costs and applying the economic order quantity equation (Section 3.2.3).

In the case of item R6 the demand is intermittent and the methods are deterministic. In these cases the (R, s, Q) policy is not appropriate. Although these deterministic methods are not further explored in this thesis, the determination of the order quantity plays an important role in them. Therefore, to provide an example and to create a starting point for these deterministic cases, the equation for the economic order quantity for item R6 is considered.

Since supplier takes care of all shipping costs and charges no direct setup costs to Dunlop. The order quantity (Q) can therefore be determined with the economic order quantity (EOQ) equation.

Item R6	Costs	Notes
Unit costs $(\boldsymbol{C})$	€20.72	*Protected Data*
Setup costs $(\boldsymbol{S})$	€550	
Holding costs $(\boldsymbol{h})$	15%	

Table 4.7: The costs associated with ordering and holding item R6 in inventory.

Together with the annual demand $(D = 22{,}179)$ the formula for the economic order quantity (EOQ) provides the optimal order quantity (Q^*):

$$Q^* = \sqrt{\frac{2 \times 550 \times 22179}{0.234 \times 20.72}} = 2243 \; units$$

When ordering 2243 units per order, the purchasing manager has to order around 6 times per year. These values become useful when the deterministic methods are further explored in future research.

In Table 4.8 below, the order quantities for items R7 and R8 are summarized. They are used in the remainder of the section to calculate the related re-order points.

Item ID	Order Quantity (Q)	Order Frequency (n)	Notes
R7	126699	8.9 times per year	Fixed by purchasing manager.
R8	65940	3.8 times per year	Fixed by purchasing manager.

Table 4.8: The order quantity (Q) and order frequency (n) for the three selected raw materials.

4.1.3 Re-order Point

With the pre-defined order quantity (Q) it is possible to determine the re-order point (s). Depending on the demand distribution (Table 4.4), a different approach is required.

In the case of demand with a normal-distribution (item R7), the re-order point is determined with the safety factor (k) which follows from the equation for $J_u(k)$ (Section 3.2.4) using the fill-rate ($P_2 = 99\%$). The fill-rate of 99% is used as it is a common value used for raw materials and fits with the example purposes. The value could later be adjusted based on experience. The results for item R7 are shown in Table 4.9.

Item ID	$J_u(k)$	k	s
R7	0.07212	1.37186	23.9 weeks of demand

Table 4.9: The re-order point (s) of item R7, calculated with the equation for normal-distributed demand.

In the case of demand with a gamma-distribution (item R8), the re-order point is determined by the shape parameter (α), the scale parameter (β) and the cycle service-level ($P_1 = 70\%$). Using trial and error it is made sure the cycle service level equals the earlier used fill-rate ($P_2 = 99\%$). The results are shown in Table 4.10.

Item ID	α	β	P_1	P_2	s
R8	11.1	2587.6	92%	99%	20.7 weeks of demand

Table 4.10: The re-order points (s) of item R6 and R8, calculated with the equation for gamma-distributed demand.

4.1.5 Achieved benefits

The new re-order points yield significant benefits and savings compared to the old re-order points. To quantify these savings the re-order points in the old and new situation are compared in Table 4.11.

As a rule of thumb, the purchasing manager currently sets the re-order point for items R7 and R8 at 6 months' worth of demand (Section 2.3). This approximates to around 17.5 weeks of demand. The new re-order points are significantly lower.

Item ID	Old Re-order Point	New Re-order Point	Unit Price	Released Capital
R7	27.5 weeks	23.9 weeks	€1.41	€32,281
R8	27.5 weeks	20.7 weeks	€1.49	€20,247

Table 4.11: The old and new re-order points of item R7 and R8 together with their unlocked capital.

The difference in volume between the old and new re-order point shows how much capital is released. For items R7 and R8 this means they together release a capital of **€52,528**.

Not only this released capital is a major benefit, the costs of holding these larger quantities of stock are also decreased. Since the holding costs equal around 15% of the unit costs this means that around **€7,878** of holding costs are saved every year.

Even more important than the direct savings, the new control framework provides the purchasing manager with more control over the raw material inventory. It allows him to precisely determine appropriate minimum stock levels and order quantities. This solves the research problem of having no clear guideline for this essential process. It replaces the old intuition and experience-based method and thereby lowers the re-order points.

4.1.6 Sensitivity Analysis

To show the sensitivity of the re-order point model, this sensitivity analysis shows how different values for important input variables change the output. First the output is shown with values as used in the example above (Table 4.12)

Item ID	*Re-order point*
R7	23.9 weeks
R8	20.7 weeks

Table 4.12: The re-order points in weeks of demand in the normal situation.

When changing the input variables of gamma-distributed items (R8), the cycle-service-level (P_1) always needs to be adjusted such that the fill rate (P_2) remains at the desired level. This becomes clear when decreasing the fill rate from 99% in the original scenario to 95% in this new alternative scenario.

Item ID	*New Value*	*Re-order point*	*Change*
R7	95%	19.6 weeks	-16.1%
R8	95% (P1=68%)	16.0 weeks	-22.7%

Table 4.13: The re-order points in weeks of demand when changing the fill-rate from 99% to 95%.

As expected, the re-order point is lower when the fill rate is lower. A lower fill rate means that a lower safety-factor is needed. Therefore, it makes sense the re-order point is lower as well.

Item ID	*New Value*	*Re-order point*	*Change*
R7	Q*2	21.7 weeks	-7.4%
R8	Q*2 (P1=86%)	19.0 weeks	-8.3%

Table 4.14: The re-order points in weeks of demand when multiplying the order quantity with a factor two.

When increasing the order quantity with a factor two, the re-order point decreases depending on the initial size of the order quantity. Since a higher order quantity decreases the order frequency, there is less uncertainty due to lead time variations and thus a lower re-order point is needed.

Item ID	*New Value*	*Re-order point*	*Change*
R7	R*2	25.3 weeks	+8.1%
R8	R*2 (P1=93%)	22.9 weeks	+10.6%

Table 4.15: The re-order points when multiplying the review period with a factor two.

When increasing the review period with a factor two, the re-order point increases. This makes sense since there is less certainty on the actual inventory position.

In general, it strikes that in the cases where demand is gamma-distributed (item R8), the cycle service level (P_1) shows significant changes when other variables are adjusted. Although this was expected, it emphasizes the importance of adjusting the cycle service level (P_1) such that the fill rate (P_2) remains at the desired level in all cases.

4.3 Implementation

For a smooth implementation, this section considers the wishes of management. It answers the third sub-question: *"How does the new control framework fit into the current inventory system?"*. It starts with listing the wishes of management (Section 4.3.1). Subsequently, it provides an answer to the wishes by discussing a policy tree (Section 4.3.2), a digital policy tool (Section 4.3.3) and a guideline for monitoring the inventory performance (Section 4.3.4).

4.3.1 Requirements of Management

In order to make the new control policy practical, management expressed a short list of wishes for the final solution. These wishes follow from interviewing the closely involved purchasing- and quality manager.

1) A clear guideline for controlling the raw material inventory system.
2) A digital tool to determine optimal order quantities and re-order points.
3) A selection of key performance indicators to monitor the inventory's performance.

The next sections discuss the wishes one by one. They represent practical solutions for a smooth implementation of the new control framework into the current ordering system. With these solutions the framework is extended to serve a wider range of raw materials.

4.3.2 Policy Tree

The first wish of management is realized in the form of a policy tree (Figure 4.1). This policy tree shows which method should be applied for which type of raw material. It summarizes the control framework as explained in Section 4.1.

The policy tree starts at the green circle where it distinguishes raw materials on the continuity of their demand pattern. When this pattern is continuous ($\bar{T} \leq 4\ weeks$), the tree distinguishes between the variability of demand. Items with a low variability ($CV \leq 0.5$) should be controlled with a (R, s, Q) policy that assumes normal distributed demand and items with a high variability ($CV > 0.5$) should be controlled with a (R, s, Q) policy that assumes gamma distributed demand.

On the other hand, when the demand pattern is intermittent ($\bar{T} > 4\ weeks$), other approaches yield better results. This side of the policy tree is displayed in a gray color as it lies outside the scope of the research. However, the policy tree shows how the items can be further divided based on the length of the lead time and review period. When the length of the lead time and review period is low ($L + R \leq 4$) a full deterministic approach is appropriate. Here approaches such as lot-for-lot, economic order quantity or the Silver-Meal heuristic become interesting. When the length of the lead time and review period is high ($L + R > 4$) this deterministic approach is only viable when demand forecasts are improved. Although the impact of this raw material group is relatively low and the ordering process remains unchanged compared to the current situation, the branches and approaches are displayed to serve as starting point for future research.

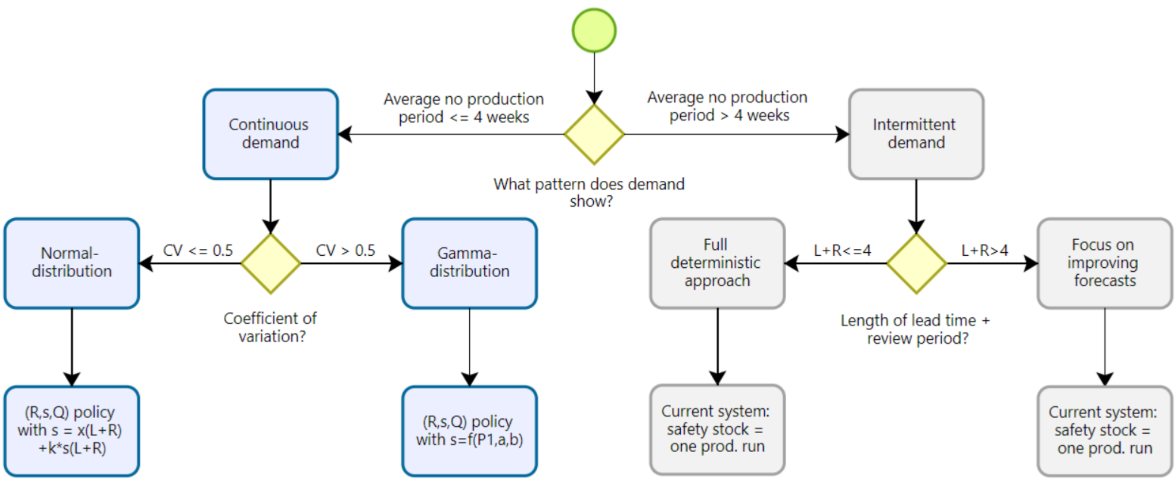

Figure 4.1: The policy tree to select the proper method for determining the timing decision.

The policy tree is suitable for item groups that fall into the A- and B-category, with exception of the PU chemicals. The process of the chemicals has already been optimized and is so different that the decision tree cannot be applied. The policy tree will be especially effective for item group RM16 and RM52, but can also significantly improve efficiency for RM03, RM07, RM08, RM17 and RM56. For remaining items that fall into the C-category it is not worth the effort to apply the policy tree and perform the extensive optimization calculations. These items have relatively little impact on inventory costs.

With this policy tree, the purchasing manager has a simple overview to determine the correct method for calculating appropriate re-order points. The most important items will fall into the two most left options where a (R, s, Q) policy is recommended. These options are extensively discussed in the previous two sections. Only a small proportion should be treated as intermittent demand. However, this approach and its methods are not further explored in this thesis. This group of items is too small and therefore lies outside the scope of the research (Section 1.8).

4.3.3 Digital Tool

To ensure the largest proportion of items are properly controlled, the policy tree is accompanied by a digital policy tool. This tool is developed in *Excel* and includes modules to calculate the economic order quantity and most importantly, appropriate re-order points.

With the tool, an user is able to change important input variables and adjust the relevant control policy to work for different raw materials. These input variables include all demand parameters (Section 4.2.1) and the variables necessary to calculate the economic order quantity (Section 4.2.2) and re-order point (Section 4.2.3).

The Excel tool consists of four sheets. It includes a sheet to calculate the economic order quantity (Sheet 1), two sheets to calculate the re-order point in the case of normal-distributed demand (Sheet 2) and in the case of gamma-distributed demand (Sheet 3), and a sheet that calculates the corresponding safety factor (k) for the value of $J_u(k)$, utilizing formulas provided by Silver et al. (2017).

The tool automatically calculates the optimal order quantity (Q^*) with the corresponding order frequency per year (n). Additionally, it calculates the re-order point (s) which functions as minimum stock level. The different result boxes of the tool are shown in the figures below. Its input variables and exact functionalities are explained in Appendix A.

Results

Name	*Symbol*	*Explanation*	*Value*
Order quantity	EOQ	*The economic order quantity that optimizes costs.*	900
Order frequency	n	*The average number of times to order per year.*	3,7

Figure 4.2: The results table of the order quantity (EOQ) module in the digital policy tool.

Results

Name	*Symbol*	*Explanation*	*Value*
Re-order point	s	*Place an order of size Q when inventory position reaches s*	115034

Figure 4.3: The results table of the re-order point (ROP) module in the digital policy tool.

4.3.4 Dashboard

To fulfill the third wish of management, this section discusses the current raw material dashboard. This current dashboard shows per period the average on-hand inventory level, the number of items purchased, consumed and the weeks inventory is on-hand considering production orders. It shows these KPIs both in volume (units) and value (euros). Additionally, it includes a line chart which shows the on-hand volume and value over time and there is an option to show a bar chart for the relative volume and value proportions of each item group.

Although this dashboard already functions to monitor the raw material inventory performance, there are important opportunities to increase its effectiveness. In the first place, the values of the current KPIs are displayed in a cluttered manner and are not used to their full potential. In the second place, the number of KPIs the dashboard shows is quite low and it misses some crucial measures that would significantly increase its usability.

The *inventory value* KPI illustrates the first opportunity. The current dashboard shows the inventory value and informs how much money is locked up in inventory. However, it shows these values on size level, instead of per item. Although specific data on size level is ignored in the thesis (see Section 1.8), it is important to mention that the raw material dashboard should also try to ignore this size level. This size level currently lowers the clarity of the dashboard as there is a vast number of sizes and therefore multiple items cannot be compared at a glance. For the same reason that the size levels are ignored in the thesis (sizes follow a fixed distribution), it is more efficient to detect problem cases on item level instead of size level. Adding the *purchase prices* to this overview helps to better understand the origin of extreme values.

Another important KPI related to the first opportunity is the *inventory coverage*. This metric is currently available as number of weeks-on-hand. It shows how long a raw material is available in inventory considering forecasted demand and the on-hand stock level. This KPI is very valuable as it indicates which raw materials accumulate too much inventory. However, there are significant opportunities to improve its effectiveness. The weeks-on-hand only shows the inventory coverage for what is currently on hand. It does not account for orders in transit, backorders or committed orders. It would be beneficial to add an additional metric that tracks the inventory coverage considering the *inventory position*. This provides a more realistic number for what is actually available. This *inventory position* is crucial for the dashboard. It is strongly linked to the re-order point and it is the value on which decisions need to based.

To specifically address the second opportunity, the dashboard should add KPIs that account for *near misses*. This helps to show whether re-order points are functioning properly. It shows the distance of the on-hand stock level to the safety inventory. A negative distance (red) indicates the safety stock is touched and a positive (green) distance means the safety stock is not touched. Here, it makes sense to use the on-hand stock above the inventory position. The installed safety measures are visible in the on-hand stock level. This level should at least equal the installed safety inventory. When the on-hand stock level regularly falls below this level it indicates the demand parameters have significantly changed and should be adjusted. This safety distance (SDIS) KPI can be accompanied by a related KPI to keep track of the frequency of these near misses (NMISS).

Table 4.16 shows how the KPIs can be displayed in the dashboard. It uses the same items as in Section 4.2. The inventory position, on-hand stock level and related variables are made up to serve the example. The raw materials are shown on item group and item level.

Dash-board	Stock (units)	Position (units)	Demand (units)	Price (euros)	Value (euros)	WOH (wks.)	WOP (wks.)	SDIS (units)	NMISS (freq.)
RM16	**6673**	**8086**	**440**	**€20.25**	**€86,075**	-	-	-	-
R6	6673	8086	440	€20.25	86,075	23.9	28.9	821	6
RM52	**141300**	**343830**	**18634**	**€2.90**	**€129,093**	-	-	-	-
R7	102835	239425	13796	€1.41	92,552	11.8	27.3	84182	2
R8	38465	104405	4839	€1.49	36,542	12.4	33.9	-6271	14

Table 4.16: Example that shows how to display key performance indicators in the dashboard.

The item group level shows the sum of its individual item members. The *stock* represents the on-hand inventory, the *position* shows the inventory position, the demand represents the forecasted demand average, the *WOH* represents the weeks-on-hand, the *WOP* represents the weeks-on-position which is related to the inventory position, the *SDIS* represents the safety distance and the *NMISS* represents the near misses.

Additionally, it is effective to translate the variables into graphs. This visual representation makes it even more simple to detect problem cases. Here the existing line and bar charts are sufficient. However, it is beneficial to extend these charts to more KPIs than only inventory value. This way the trends can be tracked and item groups can easily be compared.

Although incorporating the dashboard lies outside the scope of the research, including the abovementioned KPIs and visuals will improve the effectiveness of the raw material dashboard. It creates a general overview and enables earlier detection of problem cases.

4.4 Conclusion

The (R, s, Q) policy, characterized by its stochastic and periodic nature, stands out as the optimal control strategy for addressing the cost-efficiency problem. This approach not only delivers substantial cost benefits but is also simple to implement. Most importantly, the new control framework empowers the purchasing manager with more control over the raw material inventory, enabling precise determination of minimum stock levels and order quantities.

To increase the effectiveness of the (R, s, Q) policy, the demand input parameters should be adjusted to incorporating deterministic demand. Depending on the coefficient of variation the appropriate distribution (normal or gamma) can be selected to calculate the re-order point. However, for situations where demand is intermittent, alternative models are more appropriate. In cases where the lead time and review period are low $(L + R \leq 4)$, it is possible to apply a deterministic approach. In instances of longer period $(L + R > 4)$, improvements can be realized through enhanced forecasting methods.

An overview of this new control framework is created with the policy tree. This tree helps to apply the correct policy to the relevant raw material. It is accompanied by a digital policy tool which helps to automatically calculate the economic order quantities and appropriate re-order points. Once these values are installed, their performance can be monitored with an improved raw material dashboard that includes several new key performance indicators.

When the new control framework is applied to the high-impact raw materials of Section 2.2, it unlocks **€52,528** of capital and saves around **€7,878** per year in holding costs. However, most importantly, it provides the purchasing manager with more control over its raw material inventory.

5. Conclusions

This last chapter concludes the research. It answers the thesis' main research question: *"How can the current inventory management process be improved to increase cost efficiency?"*. It starts with the conclusion where it answers all research questions to answer the main research question (Section 5.1). Once the research question is answered it states several recommendations to improve the raw material inventory management (Section 5.2). Finally, the solution's limitations are discussed and future research is suggested (Section 5.3).

5.1 Conclusions

The bachelor thesis was guided by three important sub-questions that help to answer the main research question. This section answers these questions to provide a well-reasoned answer to the main research question.

Question 1: How can the raw material inventory system be improved?
The current raw material inventory is divided into sixteen distinct item groups. These item groups correspond to the main components of the finished products. It is possible to prioritize the item groups on their characteristics. The item groups that both have a high value, high criticality and high inventory coverage are most crucial when it comes to cost-efficiency. It turned out these item groups also have the highest lead times. This is especially the case for item group RM16 and RM52 which show a more extreme combination of high inventory coverage and high lead times. These items are therefore selected as the most impact full in terms of costs.

The process of managing these raw materials shows important strengths but also reveals clear opportunities for refinement. The purchasing manager struggles with determining efficient minimum stock levels and order quantities. They are currently managed by meeting the minimum requirements and simply applying common sense and intuition. A systematic and data-driven framework to determine optimal order quantities and minimum stock levels, focused on raw materials with high lead times, could increase the systems efficiency and result in significant cost-savings.

Question 2: Which inventory management techniques are available in literature?
The exploration of available literature on the topic of inventory management revealed several options for improving the current situation. In particular, the stochastic and periodic control models stand out. They are suitable for the raw materials with long lead times and uncertain demand. The (R, s, S) and (R, s, Q) policies mainly emerge as potential candidates for improving the raw material inventory problem. They provide clear methods for determining optimal order quantities using the economic order quantity equation, and for determining minimum stock level using the calculation of an appropriate re-order point.

Other methods that help to prevent practices of over- and understocking involve installing specific key performance indicators (KPIs). The literature review highlighted several KPIs that would be suitable for such risks. Together, the insights from the current situation analysis, the reviewed control policies and these KPIs create a foundation for developing a systematic and data-driven control framework to manage the raw material inventory.

Question 3: What inventory control framework fits best with the current situation?
The stochastic and periodic (R, s, Q) policy is clearly the most effective control policy for the current raw material inventory. With a minor adjustment to the demand parameters the control

policy can incorporate a lower degree of demand uncertainty by considering the production orders in the frozen period.

The suggested policy tree and digital policy tool increase the usability of the policy by ensuring a smoother implementation of the new control framework. This new framework is suitable for most important raw materials, except for the raw materials with intermittent demand. For these raw materials it is more appropriate to use other methods. In cases where the lead time and review period of such a raw material are low ($L + R \leq 4$), it is possible to apply a full deterministic approach. In methods where the length of this period is high ($L + R > 4$), the focus should lie on improving forecasting methods. In any case, for all raw materials, it is important to regularly monitor their performance. Key performance indicators such as the inventory coverage, inventory value and a metric to track near misses help to detect any problems, deviations or trend changes.

Together, the policies in the policy tree, the digital policy tool and the key performance indicators form a new control framework. This new control framework improves the current raw material inventory situation, decreases the overall inventory costs and provides the purchasing manager with more control over the raw material inventory.

Main research question: How can the current inventory management process be improved to increase cost efficiency?
The new control framework functions as a clear guideline for managing the raw material inventory. It forms a systematic and data-driven approach to determine the inventory's volume and timing decisions.

The suggested policy tree helps to select appropriate methods for calculating the optimal order quantities and minimum stock levels. Once the correct method is selected the digital policy tool guides the calculation of the economic order quantity and re-order point. These values can then be used within the classic (R, s, Q) policy. This policy suggests to check the inventory position once every week. As soon as the inventory position drops below the re-order point (s) a new order needs to be placed with the earlier determined order quantity (Q). This value should raise the inventory position above the re-order point. When the used order quantity is not sufficient a multiple (nQ) should be ordered.

It is important to weekly check the inventory performance. By installing key performance indicators such as the inventory value, inventory coverage and near misses it is simple to detect possible problem cases in an early stage. It allows for a quick reaction where the input parameters of the control policy can be adjusted before stock levels escalate.

5.2 Recommendations

The implementation of the new control framework is expected to streamline the management process of the raw material inventory, resulting in an enhanced cost-efficiency. Besides the recommendation to implement the new control framework into the current situation, it is important to consider some additional recommendations.

This thesis showed how the new control framework can be implemented for the three problem cases, in particular the cases with continuous demand. In the actual implementation, it is recommend to first start with these problem cases. These items yield the most cost benefits compared to the effort of implementation. Once the new control framework is sufficiently installed for these cases, it can be implemented for other raw materials one by one.

Additionally, the input parameters of any policy within the control framework should be checked regularly (Section 3.2.4). Seasonal effects or trend changes occur on regular basis and seriously affect demand patterns. Additionally, changes in lead times and costs are not uncommon. These changes could significantly impact the optimal order quantity and re-order point. Therefore, it is recommended to check at least once per month, or when there is a suspicion or a clear sign of change, whether the input parameters are still up to date.

The installation of the nine suggested key performance indicators (Section 4.3.4) will help to monitor the inventory's performance. When the re-order point is used as a threshold to decide whether action is necessary, it is crucial to use the *inventory position* rather than the on-hand stock to check the current inventory level. This position accounts for stock on-hand, stock on-order, backorders and committed demand (Section 3.1.1).

5.3 Discussion

In general, the new control framework provides a new guideline for managing the raw material inventory. It can serve as the starting point of applying a systematic and data-driven approach to control the inventory levels. However, it is important to acknowledge the control framework comes with some limitations.

First of all, the new control framework suggest to use a fill-rate of 99%. This is a common value in literature and provides suitable results. However, practice will show whether this value is actually optimal or should be adjusted to be more in line with strategic considerations.

Secondly, although the new control framework suggests to calculate optimal order quantities with the economic order quantity equation, it only provides a basic version of the equation. This basic version is not able to exploit opportunities such as quantity discounts or multi-item ordering. For many raw materials there will be cases where these opportunities yield significant cost-savings. Future research into these extensions could broaden the functionalities of the digital policy tool.

Additionally, the policy tree in the control framework suggests to apply a full deterministic approach for intermittent items with low lead times. Since there is only a limited amount of cases where this approach will apply, the underlying methods are not elaborated in the report. However, these cases could still provide a significant contribution to decreasing the inventory costs and should therefore be considered in future research.

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Appendix

Appendix A: Digital Policy Tool

The new control framework is accompanied by a digital policy tool. This tool is developed in Excel and can automatically calculate the relevant economic order quantities and re-order points. This appendix describes the functionality of this tool in more detail and explains its layout and its input and output variables.

A.1 Layout

The tool consists of four sheets. The first three sheets contain input and output tables and the fourth sheet contains variables and formula's to calculate the relevant values for $J_u(k)$ and safety factor k. At the bottom of the sheets Excel provides an overview of these four options (Figure A.1).

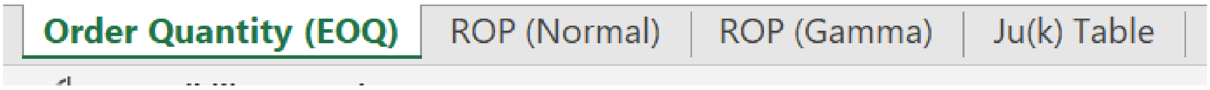

Figure A.1: Overview of the available sheets in the digital policy tool.

Sheet 1: "Order Quantity (EOQ)" contains input and output tables to calculate the economic order quantity (EOQ). By changing the associated costs and demand parameters, the output value (the EOQ) can be adjusted to a specific raw material. This quantity can then be used as input for the next two sheets.

Sheet 2: "ROP (Normal)" contains input and output tables to calculate the re-order point in the case of normal distributed demand. By changing the input variables the re-order point can be adjusted to a specific raw material. This re-order point can function as a minimum stock level.

Sheet 3: "ROP (Gamma)" contains input and output tables to calculate the re-order point in the case of gamma distributed demand. By changing the input variables the re-order point can be adjusted to a specific raw material. This re-order point can function as a minimum stock level.

Sheet 4: "Ju(k) Table" should not be used. Its values are used in the calculations of sheet 2 and sheet 3.

A.2 Input

The input variables for the economic order quantity consists of different costs and a demand parameter (Figure A.2). For the re-order point the input variables are more diverse. The input for the re-order point with normal distributed demand is shown in Figure A.3 and the input for gamma distributed demand is shown in Figure A.4. The input variables are explained inside the tool.

Basic EOQ			
Name	*Symbol*	*Explanation*	*Value*
Average demand	D	*Average annual (forecasted) demand.*	3360
Unit costs	U	*Total costs paid per unit.*	13,2
Setup costs	S	*Total fixed costs paid per order.*	350
Holding costs	h	*Percentage of storage, capital and risk costs*	22%

Figure A.2: The economic order quantity (EOQ) input table with explanation of the variables in the tool.

The difference between normal and gamma distributed demand in the input is the service-level measure. In the case of normal distributed demand the fill-rate (P_2) is used, and in the case of gamma distributed demand the cycle service level is used (P_1).

Input			
Name	*Symbol*	*Explanation*	*Value*
Demand			
Known:			
Demand week 1	x_1	*Week 1 of known demand from production planning.*	7000
Demand week 2	x_2	*Week 2 of known demand from production planning.*	10000
Demand week 3	x_3	*Week 3 of known demand from production planning.*	9000
Demand week 4	x_4	*Week 4 of known demand from production planning.*	6000
Unknown:			
Forecast average	x_F	*The average demand per week from forecasts*	8787
Forecast st. dev	σ_F	*The standard deviation of demand per week from forecasts.*	3773
Setup:			
Review period	R	*The review period in weeks.*	1
Fill rate	P_2	*The fill-rate in percentages.*	99%
Lead time	L	*The lead time in weeks.*	12
St. dev lead time	s_L	*The standard deviation of the lead time in weeks.*	0,5
Order quantity	Q	*The applied order quantity (could be from Sheet 1).*	161400

Figure A.3: The re-order point with normal distributed demand input table with explanation of the variables in the tool.

Input			
Name	*Symbol*	*Explanation*	*Value*
Demand			
Known:			
Demand week 1	x_1	*Week 1 of known demand from production planning.*	0
Demand week 2	x_2	*Week 2 of known demand from production planning.*	1200
Demand week 3	x_3	*Week 3 of known demand from production planning.*	0
Demand week 4	x_4	*Week 4 of known demand from production planning.*	0
Unknown:			
Forecast average	x_F	*The average demand per week from forecasts*	280
Forecast st. dev	σ_F	*The standard deviation of demand per week from forecasts.*	699
Setup:			
Review period	R	*The review period in weeks.*	2
Cycle Service Level	P_1	*Change this value until fill-rate equals wanted level.*	98%
Lead time	L	*The lead time in weeks.*	12
St. dev lead time	s_L	*The standard deviation of the lead time in weeks.*	0,5
Order quantity	Q	*The applied order quantity (could be from Sheet 1).*	900

Figure A.4: The re-order point with gamma distributed demand input table with explanation of the variables in the tool.

A.3 Output

The output variables of the economic order quantity consist of the EOQ itself and the related order frequency. This frequency indicates how many times an order should be placed per year when the economic order quantity is applied. This output is shown and explained in Figure A.5.

Results			
Name	*Symbol*	*Explanation*	*Value*
Order quantity	EOQ	*The economic order quantity that optimizes costs.*	900
Order frequency	n	*The average number of times to order per year.*	3,7

Figure A.5: The output table of the order quantity (EOQ) sheet with the order quantity and order frequency as output.

The output variables of the re-order point contains intermediate variables that help to calculate the final output: the re-order point itself. The output is shown and explained in Figure A.6.

Output			
Name	*Symbol*	*Explanation*	*Value*
Demand			
Known demand	$\bar{x}_K$	*Average demand during the known weeks.*	8000
Unknown demand	$\bar{x}_U$	*Average demand during the unknown weeks.*	8787
Mean demand	$\bar{x}_D$	*Average demand considering known and unknown demand.*	8524,667
St. Dev. demand	σ_D	*Accompanying standard deviation of average demand above.*	3080,642
Demand during lead time	$\bar{x}_L$	*Average demand during lenght of lead time*	102296
St. Dev. during lead time	σ_L	*Standard deviation of demand during lenght of lead time.*	11491,38
Demand during review period	$\bar{x}_R$	*Average demand during lenght of review period.*	8524,667
St. Dev. during review period	σ_R	*Standard deviation of demand during lenght of review period.*	3080,642
Demand during L+R	$\bar{x}_{L+R}$	*Average demand during lead time and review period.*	110820,7
St. Dev. during L+R	σ_{L+R}	*Standard deviation during lead time and review period.*	11897
Safety			
Ju(k)	$J_u(k)$	*Variable to find the correct safety factor k in Ju(k) table.*	0,200218
safety factor (k)	k	*The safety factor k retrieved from the Ju(k) table.*	0,354185

Results			
Name	*Symbol*	*Explanation*	*Value*
Re-order point	s	*Place an order of size Q when inventory position reaches*	115034

Figure A.6: The output table of the re-order point sheet with normal distributed demand.

The output table of gamma distributed demand is similar and replace Ju(k) and k with the shape and scale parameters. Additionally, it shows which value for the fill-rate is achieved using the input values. All output results from the theory and accompanying equations described in Section 3.2. The output for gamma distributed demand is shown in Figure A.7.

Output			
Name	*Symbol*	*Explanation*	*Value*
Demand			
Known demand	$\bar{x}_K$	*Average demand during the known weeks.*	300
Unknown demand	$\bar{x}_U$	*Average demand during the unknown weeks.*	280
Mean demand	$\bar{x}_D$	*Average demand considering known and unknown demand.*	286,6667
St. Dev. demand	σ_D	*Accompanying standard deviation of average demand above.*	570,7311
Demand during lead time	$\bar{x}_L$	*Average demand during lenght of lead time*	3440
St. Dev. during lead time	σ_L	*Standard deviation of demand during lenght of lead time.*	1982,259
Demand during review period	$\bar{x}_R$	*Average demand during lenght of review period.*	573,3333
St. Dev. during review period	σ_R	*Standard deviation of demand during lenght of review period.*	807,1357
Demand during L+R	$\bar{x}_{L+R}$	*Average demand during lead time and review period.*	4013,333
St. Dev. during L+R	σ_{L+R}	*Standard deviation during lead time and review period.*	990
Safety			
Shape parameter	α	*The shape parameter needed for the gamma distribution.*	16,4
Scale parameter	β	*The scale parameter needed for the gamma distribution.*	244,2
Fill rate	P_2	*The fill-rate that results from used input values.*	98,863%

Results			
Name	*Symbol*	*Explanation*	*Value*
Re-order point	s	*Place an order of size Q when inventory position reaches s*	6298

Figure A.7: The output table of the re-order point sheet with gamma distributed demand.

Appendix B: Functions of the Unit Normal Distribution

The figure below shows some functions of the unit normal distribution. Especially the Ju(k) and Ju(-k) are relevant for the thesis. The table comes from the book of Silver et al. (2017).

k	$f_u(k)$	$p_{u\geq}(k)$	$G_u(k)$	$J_u(k)$	$G_u(-k)$	$J_u(-k)$	k
0.00	0.3989	0.5000	0.3989	0.5000	0.3989	0.5000	0.00
0.01	0.3989	0.4960	0.3940	0.4921	0.4040	0.5080	0.01
0.02	0.3989	0.4920	0.3890	0.4842	0.4090	0.5162	0.02
0.03	0.3988	0.4880	0.3841	0.4765	0.4141	0.5244	0.03
0.04	0.3986	0.4840	0.3793	0.4689	0.4193	0.5327	0.04
0.05	0.3984	0.4801	0.3744	0.4613	0.4244	0.5412	0.05
0.06	0.3982	0.4761	0.3697	0.4539	0.4297	0.5497	0.06
0.07	0.3980	0.4721	0.3649	0.4466	0.4349	0.5583	0.07
0.08	0.3977	0.4681	0.3602	0.4393	0.4402	0.5671	0.08
0.09	0.3973	0.4641	0.3556	0.4321	0.4456	0.5760	0.09
0.10	0.3970	0.4602	0.3509	0.4251	0.4509	0.5849	0.10
0.11	0.3965	0.4562	0.3464	0.4181	0.4564	0.5940	0.11
0.12	0.3961	0.4522	0.3418	0.4112	0.4618	0.6032	0.12
0.13	0.3956	0.4483	0.3373	0.4044	0.4673	0.6125	0.13
0.14	0.3951	0.4443	0.3328	0.3977	0.4728	0.6219	0.14
0.15	0.3945	0.4404	0.3284	0.3911	0.4784	0.6314	0.15
0.16	0.3939	0.4364	0.3240	0.3846	0.4840	0.6410	0.16
0.17	0.3932	0.4325	0.3197	0.3782	0.4897	0.6507	0.17
0.18	0.3925	0.4286	0.3154	0.3718	0.4954	0.6606	0.18
0.19	0.3918	0.4247	0.3111	0.3655	0.5011	0.6706	0.19
0.20	0.3910	0.4207	0.3069	0.3594	0.5069	0.6806	0.20
0.21	0.3902	0.4168	0.3027	0.3533	0.5127	0.6908	0.21
0.22	0.3894	0.4129	0.2986	0.3473	0.5186	0.7011	0.22
0.23	0.3885	0.4090	0.2944	0.3413	0.5244	0.7116	0.23
0.24	0.3876	0.4052	0.2904	0.3355	0.5304	0.7221	0.24
0.25	0.3867	0.4013	0.2863	0.3297	0.5363	0.7328	0.25
0.26	0.3857	0.3974	0.2824	0.3240	0.5424	0.7436	0.26
0.27	0.3847	0.3936	0.2784	0.3184	0.5484	0.7545	0.27
0.28	0.3836	0.3897	0.2745	0.3129	0.5545	0.7655	0.28

(Continued)

k	$f_u(k)$	$p_{u\geq}(k)$	$G_u(k)$	$J_u(k)$	$G_u(-k)$	$J_u(-k)$	k
0.29	0.3825	0.3859	0.2706	0.3074	0.5606	0.7767	0.29
0.30	0.3814	0.3821	0.2668	0.3021	0.5668	0.7879	0.30
0.31	0.3802	0.3783	0.2630	0.2968	0.5730	0.7993	0.31
0.32	0.3790	0.3745	0.2592	0.2915	0.5792	0.8109	0.32
0.33	0.3778	0.3707	0.2555	0.2864	0.5855	0.8225	0.33
0.34	0.3765	0.3669	0.2518	0.2813	0.5918	0.8343	0.34
0.35	0.3752	0.3632	0.2481	0.2763	0.5981	0.8462	0.35
0.36	0.3739	0.3594	0.2445	0.2714	0.6045	0.8582	0.36
0.37	0.3725	0.3557	0.2409	0.2665	0.6109	0.8704	0.37
0.38	0.3712	0.3520	0.2374	0.2618	0.6174	0.8826	0.38
0.39	0.3697	0.3483	0.2339	0.2570	0.6239	0.8951	0.39
0.40	0.3683	0.3446	0.2304	0.2524	0.6304	0.9076	0.40
0.41	0.3668	0.3409	0.2270	0.2478	0.6370	0.9203	0.41
0.42	0.3653	0.3372	0.2236	0.2433	0.6436	0.9331	0.42
0.43	0.3637	0.3336	0.2203	0.2389	0.6503	0.9460	0.43
0.44	0.3621	0.3300	0.2169	0.2345	0.6569	0.9591	0.44
0.45	0.3605	0.3264	0.2137	0.2302	0.6637	0.9723	0.45
0.46	0.3589	0.3228	0.2104	0.2260	0.6704	0.9856	0.46
0.47	0.3572	0.3192	0.2072	0.2218	0.6772	0.9991	0.47
0.48	0.3555	0.3156	0.2040	0.2177	0.6840	1.0127	0.48
0.49	0.3538	0.3121	0.2009	0.2136	0.6909	1.0265	0.49
0.50	0.3521	0.3085	0.1978	0.2096	0.6978	1.0404	0.50
0.51	0.3503	0.3050	0.1947	0.2057	0.7047	1.0544	0.51
0.52	0.3485	0.3015	0.1917	0.2018	0.7117	1.0686	0.52
0.53	0.3467	0.2981	0.1887	0.1980	0.7187	1.0829	0.53
0.54	0.3448	0.2946	0.1857	0.1943	0.7257	1.0973	0.54
0.55	0.3429	0.2912	0.1828	0.1906	0.7328	1.1119	0.55
0.56	0.3410	0.2877	0.1799	0.1870	0.7399	1.1266	0.56
0.57	0.3391	0.2843	0.1771	0.1834	0.7471	1.1415	0.57

(Continued)

k	$f_u(k)$	$p_{u\geq}(k)$	$G_u(k)$	$J_u(k)$	$G_u(-k)$	$J_u(-k)$	k
0.58	0.3372	0.2810	0.1742	0.1799	0.7542	1.1565	0.58
0.59	0.3352	0.2776	0.1714	0.1765	0.7614	1.1716	0.59
0.60	0.3332	0.2743	0.1687	0.1730	0.7687	1.1870	0.60
0.61	0.3312	0.2709	0.1659	0.1697	0.7759	1.2024	0.61
0.62	0.3292	0.2676	0.1633	0.1664	0.7833	1.2180	0.62
0.63	0.3271	0.2643	0.1606	0.1632	0.7906	1.2337	0.63
0.64	0.3251	0.2611	0.1580	0.1600	0.7980	1.2496	0.64
0.65	0.3230	0.2578	0.1554	0.1569	0.8054	1.2656	0.65
0.66	0.3209	0.2546	0.1528	0.1538	0.8128	1.2818	0.66
0.67	0.3187	0.2514	0.1503	0.1507	0.8203	1.2982	0.67
0.68	0.3166	0.2483	0.1478	0.1478	0.8278	1.3146	0.68
0.69	0.3144	0.2451	0.1453	0.1448	0.8353	1.3313	0.69
0.70	0.3123	0.2420	0.1429	0.1419	0.8429	1.3481	0.70
0.71	0.3101	0.2389	0.1405	0.1391	0.8505	1.3650	0.71
0.72	0.3079	0.2358	0.1381	0.1363	0.8581	1.3821	0.72
0.73	0.3056	0.2327	0.1358	0.1336	0.8658	1.3993	0.73
0.74	0.3034	0.2297	0.1334	0.1311	0.8734	1.4165	0.74
0.75	0.3011	0.2266	0.1312	0.1283	0.8812	1.4342	0.75
0.76	0.2989	0.2236	0.1289	0.1257	0.8889	1.4519	0.76
0.77	0.2966	0.2206	0.1267	0.1231	0.8967	1.4698	0.77
0.78	0.2943	0.2177	0.1245	0.1206	0.9045	1.4878	0.78
0.79	0.2920	0.2148	0.1223	0.1181	0.9123	1.5060	0.79
0.80	0.2897	0.2119	0.1202	0.1157	0.9202	1.5243	0.80
0.81	0.2874	0.2090	0.1181	0.1133	0.9281	1.5428	0.81
0.82	0.2850	0.2061	0.1160	0.1110	0.9360	1.5614	0.82
0.83	0.2827	0.2033	0.1140	0.1087	0.9440	1.5802	0.83
0.84	0.2803	0.2005	0.1120	0.1064	0.9520	1.5992	0.84
0.85	0.2780	0.1977	0.1100	0.1042	0.9600	1.6183	0.85
0.86	0.2756	0.1949	0.1080	0.1020	0.9680	1.6376	0.86