Analysis of the performance of Demand Driven Material Requirements Planning on supply chain management: A multiple case study

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STATEMENT OF ORIGINALITY

I hereby declare that the research recorded in this thesis and the thesis itself, were developed entirely by myself at the Industrial Management Area, Mechanical and Manufacturing Department, at Mondragon Unibertsitatea.

I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

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Proiektu hau ezingo nuen burutu zuen laguntzarik gabe, beraz eskerrik asko guztioi!

LABURPENA

2011. urtean materialen eta informazioaren fluxua errazteko eta horrela banaketa eta ekoizpeneko enpresen abantaila lehiakorra sustatzeko helburuarekin, Demand-Driven Material Requirements Planning (DDMRP) metodologia garatu zen.

Hainbat ikerketa lanek simulatu eta aztertu dute DDMRP-aren jokaera. Halere, literaturaren errebisioan, enpresa erreal baten DDMRP-aren inplementazioa, ikertzen zuen lanik ez genuen aurkitu. Ikerketa lan honek, beraz, hiru enpresek MRP-tik DDMRP-ra migratzearen prozesua eta ondoren hiru enpresa hauek abantaila lehiakorraren ikuspuntutik izan zuten bilakaera aztertu du.

Kasuen azterketa zehatza burutu eta kasu bakoitzean izandako gertaerak identifikatu eta ulertzeko, ikerketa kualitatiboa gauzatu genuen. Datuak biltzeko, elkarrizketa erdi-egituratu, dokumentu eta fitxategien erregistroak erabili genituen. Behin datu guztiak izanik, enpresak DDMRP-aren inplementazioaren aurretik eta ondoren lortutako emaitzak aztertu eta alderatu genituen eta DDMRP-aren inplementazioak enpresaren errendimenduan izandako inpaktua aztertu genuen. Behin hiru kasuak aztertuta, hauen arteko azterketa gurutzatua burutu genuen beraien arteko parekotasunak eta ezberdintasunak identifikatzeko.

Lortutako emaitzen arabera, DDMRP-a inplementatu ostean, hiru enpresen hornidura kateko ikuspena nabarmen handitu zen, bullwhip efektua eta eskaera urgenteak gutxituz. Inbentarioan ere izan zuen eragina. Izan ere aztertutako hiru kasuetan materialen inbentarioak jaitsiera garrantzitsua jasan zuen hauen kontsumoa hazi zen bitartean. Guzti hau enpresak bezeroekin DDMRP-aren aurretik zuen ia 100% zerbitzu maila mantenduz.

RESUMEN

En el 2011 se desarrolló la metodología Demand-Driven Material Requirements Planning (DDMRP) con el objetivo de aumentar el flujo de materiales e información y así mejorar la ventaja competitiva de las empresas de fabricación y distribución.

Varios trabajos de investigación que simulan el comportamiento del DDMRP han sido realizados desde entonces. Sin embargo, en la revisión de la literatura no se han encontrado estudios que analicen la implementación del DDMRP en una empresa. El presente trabajo, por lo tanto, analiza la evolución que tres empresas han tenido tras migrar del MRP al DDMRP y el impacto de este proceso en la ventaja competitiva.

Para analizar y comprender en detalle los hechos de cada estudio de caso, se ha realizado una investigación cualitativa. Para la recogida de datos se han utilizado entrevistas semiestructuradas, documentos y registros de archivos. Tras recopilar todos los datos se han comparado los resultados de antes y después de cada implementación de DDMRP y se ha evaluado la evolución del desempeño de cada empresa. Finalmente, se ha realizado un estudio de casos cruzados.

Los resultados obtenidos, demuestran que con la metodología DDMRP las empresas aumentan la visibilidad en la cadena de suministro reduciendo considerablemente el efecto bullwhip y los pedidos urgentes. Cabe destacar también la evolución del inventario, ya que en los tres casos el inventario sufre una reducción importante mientras que el consumo de los materiales aumenta. Todo esto mientras que las empresas son capaces de mantener el nivel de servicio prácticamente en un 100%.

ABSTRACT

In 2011, the Demand-Driven Material Requirements Planning (DDMRP) methodology was published with the goal of increasing material and information flow to enhance the competitive advantage of manufacturing and distribution companies. Many research works have developed models to simulate the behavior of DDMRP. Nevertheless, there were no studies found in the literature that analyzed the implementation of DDMRP in a company. The present work therefore, analyzes the performance of three companies after converting from MRP to DDMRP, and the impact of this process on competitive advantage.

To achieve an in depth understanding of the case studies a qualitative approach was taken. Data was collected from semi-structured interviews, documents and archival records. The results from before and after the implementation of DDMRP were compared, and the evolution of the performance of each company was evaluated. Finally, a cross-case study was carried out.

The results clearly show that using DDMRP increases visibility in the supply chain by reducing considerably the bullwhip effect and rush orders. Importantly, the inventory level of the studied companies was reduced while material consumption was increased. At the same time, the companies were able to maintain nearly 100% service level.

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GLOSSARY OF ACRONYMS

ACRONYM	STAND FOR
ADU	Average Daily Use
BOM	Bill of Material
CL MRP	Close-Loop Material Requirements Planning
CRM	Customer Relationship Management
CRP	Capacity Requirements Planning
DBR	Drum-Buffer-Rope
DDMRP	Demand Driven Material Requirements Planning
DLT	Decoupled Lead Time
DOC	Desired Order Cycle
EOQ	Economic Order Quantity
ERP	Enterprise Resource Planning
ERP II	Extended Enterprise Resource Planning
FOQ	Fixed Order Quantity
I&CT	Information and Communication Technologies
JIT	Just in Time
MES	Manufacturing Execution Systems
MM	Min-Max
MOQ	Minimum Order Quantity
MPC	Manufacturing Planning and Control System
MPS	Master Production Schedule
MRP	Material Requirements Planning System
MRP II	Manufacturing Resource Planning
NB	Non-Buffered
NFP	Net Flow Position
OPT	Optimized Production Technology
PPM	Purchasing and Planning Manager
P&IM	Production and Inventory Management
ROP	Reorder Point
SCM	Supply Chain Management
SCOR	Supply Chain Operations Reference
SKU	Stock Keeping Units
SS	Safety Stock
TOC	Theory of Constraints
TOC-SCRS	Theory of Constraints Supply Chain Replenishment System
TOG	Top of Green
TOR	Top of Red
TOY	Top of Yellow
WIP	Work In Progress

GLOSARY

Average Daily Use	Average use of a part, component or good on a daily basis.
Agile	The ability to quickly plan, source, make, and deliver to adapt and respond to changes in the competitive environment. It is a Supply Chain Operations Reference (SCOR) performance attributes that includes product or service flexibility (speedy introduction of new products and services), mix flexibility (ability to quickly change products or services offered), volume flexibility (ability to service large order quantities), and delivery flexibility (ability to quickly change delivery dates to meet new requirements.
Bill of Material	A list of all the subassemblies, intermediates, parts, and raw materials that go into a parent assembly showing the quantity of each required to make an assembly.
Buffer status alert	Alerts that show the current and projected status of the decoupling point positions across the network of dependencies.
Bullwhip effect	An extreme change in the supply position upstream in a supply chain generated by a small change in demand downstream in the supply chain. Inventory can quickly move from being backordered to being excess. This is caused by the serial nature of communicating orders up the chain with the inherent transportation delays of moving product down the chain. The bullwhip effect can be eliminated by synchronizing the supply chain.
Decoupled explosion	The cessation of a bill of material explosion at any buffered or stocked position.
Decoupled lead time	A qualified cumulative lead time defined as the longest unprotected or unbuffered sequence in a bill of material.
Decoupling point	The location in the product structure or distribution network where inventory is placed to create independence between processes or entities. Selection of decoupling points is a strategic decision that determines customer lead times and inventory investment.
Demand driven manufacturing strategy	The strategy that supplies the company with flexibility and visibility of real requirements and manufacturing orders so as to adjust market requirements and make correct decisions in a simple way.
Demand Driven Material Requirements Planning	A method to model, plan, and manage supply chains to protect and promote the flow of relevant information and materials. DDMRP is the supply order generation and management engine of Demand Driven Operational Model.
Demand uncertainty	The uncertainty or variability in demand as measured by the standard deviation, mean absolute deviation or variance of forecast error.
Dependent demand	A demand that is directly related to or derived from the bill of material structure for other items or end products. Such demands are therefore calculated and should not be forecast.
Forecast	An estimate of future demand.
Independent demand	The demand that is unrelated to the demand for other items.

Lean	A philosophy of production that emphasizes the minimization of the amount of all the resources (including time) used in the various activities of the enterprise. It involves identifying and eliminating non-value-adding activities in design, production, supply chain management, and dealing with customers.
Manufacturing Planning and Control system	A closed-loop information system that includes the planning functions of production planning (sales and operations planning), master production scheduling, material requirements planning, and capacity requirements planning. Once the plan has been accepted as realistic, execution begins. The execution functions include input-output control, detailed scheduling, dispatching, anticipated delay reports (department and supplier), and supplier scheduling.
Material flow	Production planning, purchasing and inventory management and control.
Material Requirements Planning	A set of techniques that uses bill of material data, inventory data, and the master production schedule to calculate requirements for materials. Specifically, it makes recommendations to release replenishment orders for material.
Production and Inventory Management	A general term referring to the body of knowledge and activities concerned with planning and controlling rates of purchasing, production, distribution, and related capacity resources to achieve target levels of customer service, backlogs, operating costs, inventory investment, manufacturing efficiency, and ultimately, profit and return on investment.
Reorder Point system	Is the inventory method that places an order for a lot whenever the quantity on-hand is reduced to a predetermined level known as the order point.
Safety stock	A quantity of stock planned to be in inventory to protect against variations in demand or supply.
Stock coverage	The average number of days goods remain in inventory before being sold.
System nervousness	Is a characteristic of an MRP system and it happens when minor changes in higher level (e.g., level 0 or 1) records or the master production schedule cause significant timing or quantity changes in lower level (e.g., level 5 or 6) schedules and orders.
Theory of Constraints	A holistic management philosophy developed by Dr. Eliyahu M. Goldratt, based on the principle that complex systems exhibit inherent simplicity. Even a very complex system comprising thousands of people and pieces of equipment can have, at any given time, only a very, very small number of variables- perhaps only one, known as a constraint- that actually limit the ability to generate more of the system´s goal.
Uncertainty	Unknown future events that cannot be predicted quantitatively within useful limits.

Chapter 1

1. Introduction

1.1. Relevance of the subject of study

In the last century, many Manufacturing Planning and Control systems (MPC) have been developed according to industrial needs. These include, among others the Reorder Point (ROP) system, the Material Requirements Planning System (MRP), Just in Time (JIT) and the Theory of Constraints (TOC) philosophy, which are widely used in many companies (Rondeau and Litteral, 2001).

Between the 1960s and the 1980s, the markets trend and behavior underwent a drastic change (Rondeau and Litteral, 2001). Customers began to call for customized products with a shorter lead time. Companies went from competing locally to competing globally. Dealing with this new scenario became a challenging day-to-day for business.

MPC systems play an important role in addressing this new situation, due to the fact that they can manage material flow in an efficient manner so that companies can provide a good service level to their customers (Ptak and Smith, 2011). For the purposes of this thesis, materials flow refers to the planning and control of production, purchasing and inventory management.

In spite of this advance however, the abovementioned MPC systems were developed for the 1980s, and have certain drawbacks when managing material flow.

Into 2011, a new methodology – Demand Driven Material Requirements Planning (DDMRP) – was published. The goal of this methodology was to efficiently manage the flow of materials. According to Ptak and Smith (2011) DDMRP contributes to the following improvements:

- Positioning the inventory in a strategic way so the company is better prepared to face variability.
- Adjusting the inventory level, converting it into an asset for the company.
- Increasing the service level provided to the customer.
- Adjusting the inventory levels so that the company can best deal with market changes.
- Facilitating the work of planning material requirements.
- Increasing visibility in the internal management of the company.

Given these characteristics, DDMRP is well placed to better manage the material flow of companies supply chains.

Several companies have implemented this methodology obtaining very competitive results (Demand Driven Institute, 2017). In addition, several of the scientific works analyzed in this thesis support this fact (Lee and Jang, 2013, 2014; Rim et al., 2014; Ihme, 2015; Ihme and Stratton, 2015; Miclo et al., 2015; Miclo, 2016; Shofa and Widyarto, 2017; Miclo et al., 2018). Nevertheless, there were no studies found in the literature that analyzed the implementation of DDMRP in different companies and evaluated the evolution of their performance.

The purpose of this thesis is to analyze the performance of three companies after DDMRP implementation. The results from before and after each implementation of DDMRP were compared and the performance was evaluated. In addition, a cross-case analysis of the three case studies was carried out to compare the results and patterns in different environments.

1.2. Statement of the problem and purpose of this study

In the 1960s, the primary competitive thrust for companies was cost, therefore manufacturing strategy was based on high-volume production, cost minimization, and stable economic conditions. However, the market changed between 1960 and 1980, with quality becoming the driver competitiveness (Rondeau and Litteral, 2001). What mattered in the 1980s was the ability of the suppliers to create or adapt new products and services on a timely basis to meet specific customer needs (McKenna, 1990).

This new reality required a dynamic production environment where products, processes and production schedules could change frequently (Rondeau and Litteral, 2001). Thus, companies were under pressure to lower total costs in the entire supply chain, reduce manufacturing throughput times, drastically reduce inventories, expand product choice, provide more reliable delivery dates and better customer service level, and improve quality to achieve competitive advantage (Shankarnarayanan, 2000; Umble et al., 2003; Cox and Schleier, 2010; Rahmani et al., 2010; Olhager, 2013).

Barney and Clark (2007) defined competitive advantage as economic net value gained; either greater profits were obtained at the same cost in comparison to competitors, or profits were the same as those of the competitors but produced at lower cost. Many organizations have begun to recognize that supply chain management is the key to building sustainable competitive edge for their products and/or services in an increasingly crowded marketplace (Jones, 1998). Supply chain management is the integration of both information and material flows seamlessly across the supply chain and thus it functions as an effective competitive weapon (Childerhouse and Towill, 2003; Feldmann and Müller, 2003; Li et al., 2006).

In the contest of the supply chain, Bower and Hout (1988) and Christopher (2016) suggested that a reduction in the order cycle led to a major source of competitive advantage as it directly influenced the customer satisfaction level. Lutz et al. (2003) pointed out that customer satisfaction depends increasingly on the achievement of logistical success factors such as lead time, service level and delivery due-date reliability. Jones and Riley (1985) found that reducing the inventory level while keeping or improving customer service level led a positive differentiation from competitors. In the same line, Abuhilal et al. (2006) and Wu et al. (2013) concluded that the thorough management of inventories is essential in the achievement of competitive advantage.

Defining and adjusting the inventory level to manage the supply chain successfully is a challenging task however, due to the trade-off relationship between ensuring the availability of products to the end consumer while simultaneously reducing the inventory cost. This challenge is depicted in Figure 1.1 (Goldratt, 1994).

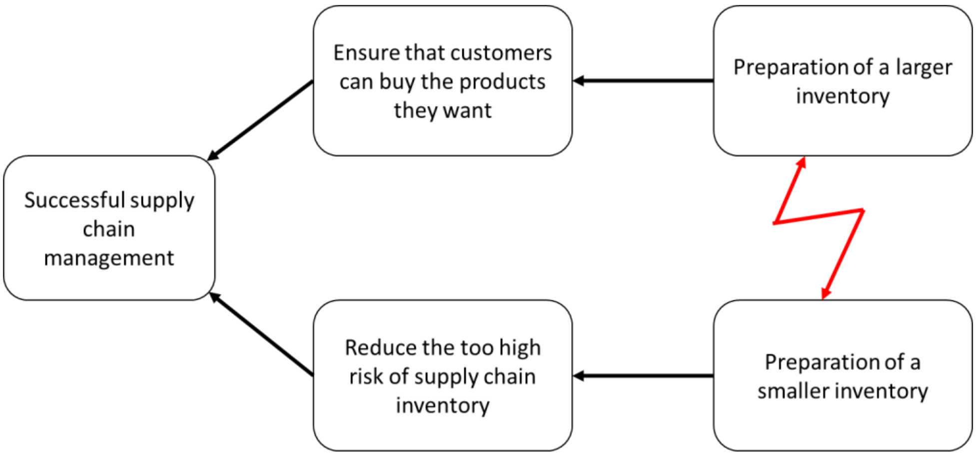


Figure 1.1: The conflict graph of supply chain management (Goldratt, 1994)

Visibility is another concept that many authors link to competitive advantage. Mora-Monge et al. (2010) measured it in terms of accuracy and speed of information flow. They stated that visibility was key in supply chain management because it improved operational efficiency preventing the effect of stockout and increasing resource productivity. Furthermore, visibility improved the effectiveness of the planning process, reducing inventory levels, increasing delivery performance and enabling a timely response to fluctuation in demand (Croom et al., 2000; Abuhilal et al., 2006). Hoyt and Huq (2000) and Barratt and Oke (2007) pointed out that visibility was required in the supply chain linkage to achieve sustained competitive advantage.

Assuming that logistic factors play a significant role in competitive advantage, the choice of the MPC system is considered to be crucial (Abuhilal et al., 2006). In the last century, many MPC systems were developed, the most widespread being the ROP, MRP, JIT and TOC.

Ptak and Smith (2011) analyzed these MPC systems and they concluded that they did not effectively perform in a dynamic production environment, since:

- MRP was constructed under a “push and promote” mentality where the market was more tolerant of longer lead time and shortages.
- JIT defines inventory as a waste. Companies that implement a JIT system, reduce their inventory level considerably, making the supply chain too brittle and less agile when the demand and supply are volatile.
- TOC does not consider the Bill of Material (BOM) explosion, hence it has difficulties dealing with complex BOM structures greater than two levels.

A further disadvantage of JIT and TOC is that although they are focused on efficient production they do not incorporate a planned approach to identifying real production and purchase requirements.

Ptak and Smith (2011) therefore, developed a new MPC known as DDMRP. This approach gathers concepts from Lean, TOC and MRP and incorporated new innovative features to manage the material flow. These authors found that using DDMRP, a company is better placed to face variability and adjust the inventory level while maintaining, or even increasing, the service level to the customer. In turn, this simplifies the job of planning material requirements and improves information flow and visibility.

Many authors agreed that DDMRP manages material efficiently (Lee and Jang, 2013, 2014; Rim et al., 2014; Ihme, 2015; Ihme and Stratton, 2015; Miclo et al., 2015; Miclo, 2016; Shofa and Widyarto, 2017; Miclo et al., 2018). Nevertheless, there were no studies found in the literature that analyzed the implementation of DDMRP in a company under real production conditions. The present work therefore, seeks to fill this gap and contributes three case studies that analyze a real world DDMRP implementation to determine the impact of DDMRP on material management.

1.3. Structure of the document

This thesis is divided into 12 chapters as set out in Table 1-1.

Table 1-1: Structure of the thesis

	DESCRIPTION
Chapter 1: Introduction.	The research project is introduced, analyzing the purpose of the study and its objectives.
Chapter 2: Manufacturing Planning and Control systems literature review.	Main Manufacturing Planning and Control policies are analyzed.
Chapter 3: Demand Driven Material Requirements Planning.	DDMRP methodology and its five components are explained.
Chapter 4: Critical study of the state of the art.	The literature review is presented and the gaps that constitute the research project are identified.
Chapter 5: Development of research framework, objective and propositions.	The research question, the main objective and the research propositions are defined.
Chapter 6: Research design and methodology.	Different research methodologies are analyzed to determine the methodology used to carry out this research work.
Chapter 7: Case study 1.	Case study 1 is reported and the results explained.
Chapter 8: Case study 2.	Case study 2 is reported and the results explained.
Chapter 9: Case study 3.	Case study 3 is reported and the results explained.
Chapter 10: Cross-case study.	A cross-case study is carried out and the main findings are used to support or deny the propositions.
Chapter 11: Conclusions and future lines.	The conclusions are presented and future lines are identified.
Chapter 12: References.	The references used are listed.
Chapter 13: Academic results	The academic results are listed.

Chapter 2

2. Manufacturing Planning and Control systems literature review

2.1. Introduction

Companies competing in a highly volatile and variable market are under increasing pressure to implement methodologies to increase their competitive edge. Production and Inventory Management (P&IM) has been identified as one of the key factors to achieve this goal (Abuhilal et al., 2006). P&IM is defined as:

> *"A general term referring to the body of knowledge and activities concerned with planning and controlling rates of purchasing, production, distribution, and related capacity resources to achieve target levels of customer service, backlogs, operating costs, inventory investment, manufacturing efficiency, and ultimately, profit and return on investment"* (APICS, 2016, p.143) [1].

Effective P&IM requires an MPC system to ensure that the right material is available at the right time and in the right quantity (Goddard, 1982; Jacobs et al., 2011). MPC is defined as:

> *"A closed-loop information system that includes the planning functions of production planning (sales and operations planning), master production scheduling, material requirements planning, and capacity requirements planning. Once the plan has been accepted as realistic, execution begins. The execution functions include input-output control, detailed scheduling, dispatching, anticipated delay reports (department and supplier), and supplier scheduling"* (APICS, 2016, p.106).

Jacobs et al. (2011) summarized MPC systems in three phases (Figure 2.1) and described them as follows:

- The front end phase establishes the overall company direction for manufacturing planning and control. It is composed of:
    - **Demand management:** Encompasses among others the forecasting customer/end product demand, order entry and spare parts requirements.
    - **Sales and operations planning:** Balances the sales/marketing plans with available production resources.
    - **Resources planning:** Determines the capacity necessary to produce the required products now and in the future.
    - **Master Production Schedule (MPS):** Defines which end items or product options manufacturing will build in the future.
- The engine phase encompasses the set of MPC systems for detailed material and capacity planning. It encompasses:

[1] As APICS is the premier professional association for supply chain and operations management, its dictionary is used to define the terms that are used in this research work.

  - **Detailed material planning:** Calculates the requirement of thousands of parts, and schedules machines and other work centers.
  - **Detailed capacity planning:** Defines labor or machine center capacity required to manufacture all the component parts.
  - **Material and capacity plans:** Considers the material and capacity planning and links both systems.
- The end phase depicts MPC execution systems and is composed of:
  - **Shop-floor systems:** Establish priorities for all shop orders at each work center so the orders can be properly scheduled.
  - **Supplier systems:** Provide detailed information to the company suppliers.

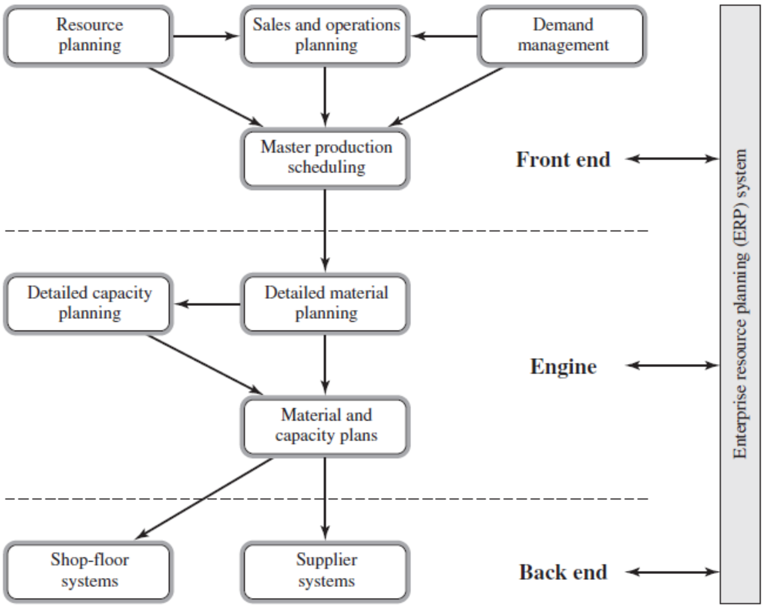


Figure 2.1: MPC system framework (Jacobs et al., 2011)

MPC systems have existed since the earliest days of the Industrial Revolution and have evolved incorporating the latest developments in Information and Communication Technologies (I&CT) to meet market requirements (Rondeau and Litteral, 2001). This evolution is set out in Figure 2.2.

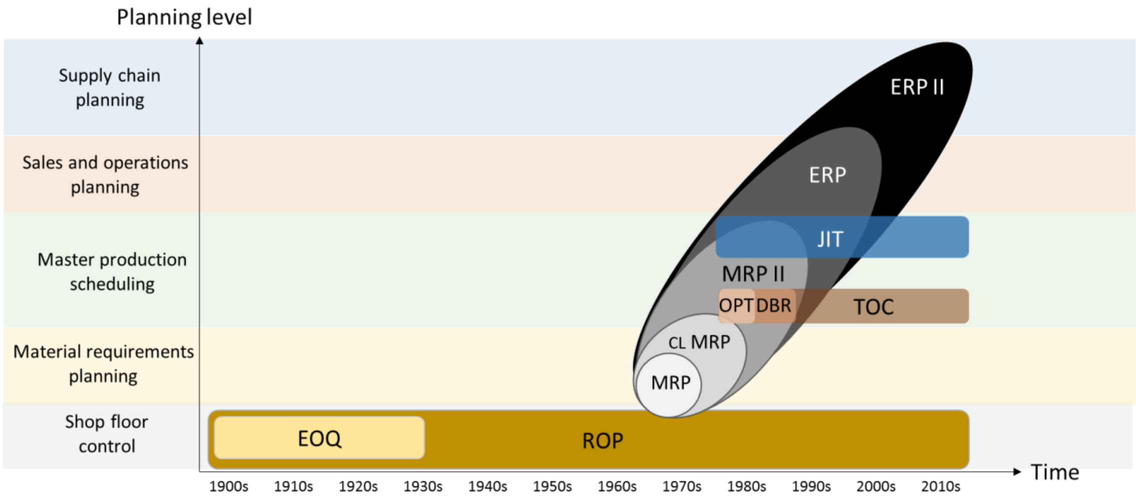


Figure 2.2: The evolution of the MPC systems

According to Olhager (2013) in In the early 1900s many companies began using the Economic Order Quantity (EOQ) model to make optimal purchasing and manufacturing decisions. In 1930s the EOQ evolved into the ROP system, which in addition to identify how much to purchase also provided a signal about when to purchase. This method helps to prevents stockouts and is still in use in many companies today. With the introduction of computers in 1960s, it became possible to automate ROP systems.

During 1970s, MRP was introduced and many companies migrated from ROP to MRP. Later evolutions of MRP included Capacity Requirements Planning (CRP), which in turn led to Closed-Loop MRP (CLMRP). In 1980s, more functionality was incorporated and this system became known as Manufacturing Resource Planning (MRP II).

At this point new systems such as JIT and Optimized Production Technology (OPT) emerged. The latter approach, with the incorporation of new functionalities became Drum-Buffer-Rope (DBR), which subsequently evolved into TOC.

The 1990s saw increased I&CT functionalities added to MRP II and the system was re-branded as the Enterprise Resource Planning system (ERP). Around the turn of the century, more and more companies realized that competitive advantage could not be achieved solely by increasing operational efficiency. Supply chain management was also critical as the nature of competition was changing from between companies to between supply chains (Christopher, 2016). To meet this demand ERP incorporated new functionalities such as a Supply Chain Planning system and e-business processes and evolved into Extended Enterprise Resource Planning (ERP II) (Pairat and Jungthirapanich, 2005).

These MPC systems are analyzed in depth below.

2.2. Reorder Point system

ROP is considered as an evolution of EOQ which is one of the oldest model in the inventory analysis literature (Olhager, 2013; Andriolo et al., 2014). In 1915 Ford Whitman Harris determined that EOQ=$\left[{}^{2AS}/_{CI}\right]^{1/2}$ where A is the annual quantity, S is the ordering cost, C is the item cost and I is the inventory holding cost. This equation considered that the demand rate was known and constant, shortages were not allowed, and replenishments were instantaneous (Erlenkotter, 1989). The aim of EOQ was to minimize the holding cost and the ordering cost (Figure 2.3) (Toomey, 2000).

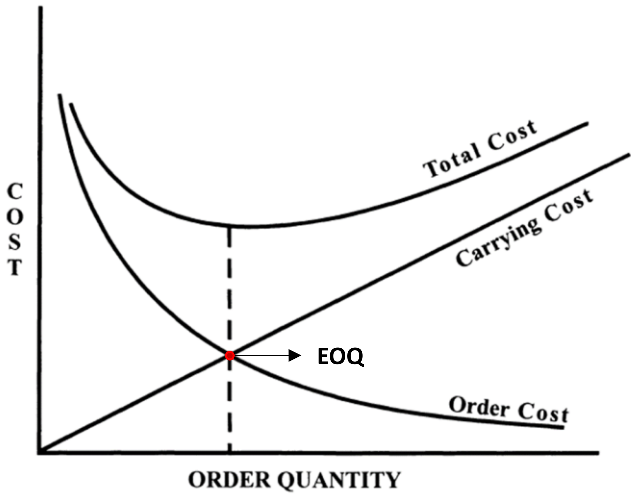


Figure 2.3: The relationship of ordering cost to carrying cost (Toomey, 2000)

In 1930s the ROP system was gradually introduced. "ROP is the inventory method that places an order for a lot whenever the quantity on-hand is reduced to a predetermined level known as the order point" (APICS, 2016, p.125). The amount ordered is known as Fixed Order Quantities (FOQ) and is usually calculated by the EOQ (Rondeau and Litteral, 2001). Figure 2.4 depicts the ROP system.

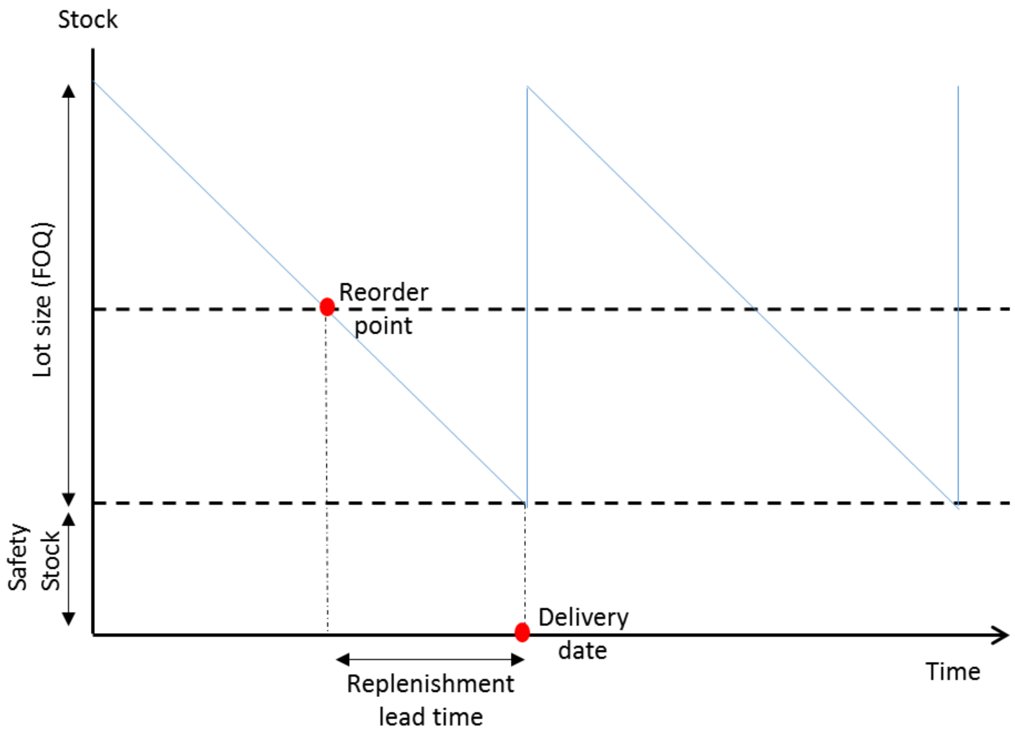


Figure 2.4: The ROP system

The reorder point is calculated taking into account the anticipated demand during lead time and Safety Stock (SS). The anticipated demand is forecast and assumed to be independent, continuous, and uniform (Toomey, 2000).

2.2.1. Forecast

Forecast is defined as “an estimate of future demand” (APICS, 2016, p.72). The ROP system considers demand as independent, or “the demand that is unrelated to the demand for other items” (APICS, 2016, p.85). This type of demand, must be forecast unless there is sufficient order backlog to cover the planning and execution lead times (McKenna, 1990).

Many advanced forecasting modules were developed to try to model demand and predict which product to manufacture or purchase, and in which quantities (Cox and Schleier, 2010). However, Ptak and Smith (2011) stated that forecasting works only if the past is an accurate indicator of the future. Otherwise, it generates uncertainty since:

- Forecasts are always in error.
- The more detailed the forecast, the greater the error.
- Long-range forecast are more susceptible to error.

To compensate for forecast error and to protect against fluctuations in demand and supply, companies use SS (Figure 2.4) (Chu and Hayya, 1988; Toomey, 2000).

2.2.2. Safety Stock

SS is defined as "a quantity of stock planned to be in inventory to protect against variations in demand or supply" (APICS, 2016, p.164).

In addition to demand and supply variations, companies also have to manage operational and self-imposed variability (Figure 2.5) (Ptak and Smith, 2011).

- **Supply variability:** The deviation from request dates and/or promised dates for supply order receipts.
- **Demand variability:** The fluctuation and deviations experienced in demand patterns and plans. On many occasions, this is driven by MRP system nervousness, which is explained in Section 2.3.
- **Operational variability ("Murphy´s Law"):** The normal and random variation exhibited by a system in steady state.
- **Self-Imposed variability:** A direct result of decisions made within the company.

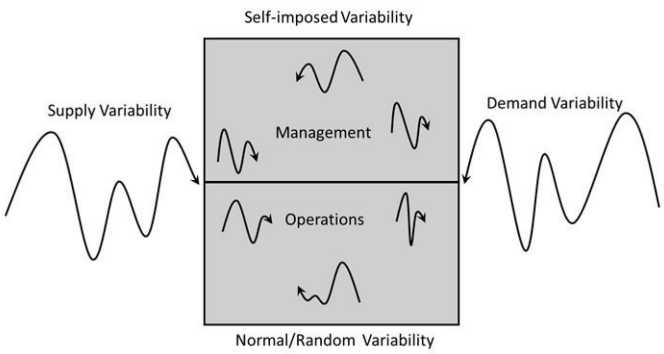


Figure 2.5: The 4 sources of variation (Ptak and Smith, 2011)

Variability requires careful management since it causes uncertainty (Ptak and Smith, 2011). This is defined as "unknown future events that cannot be predicted quantitatively within useful limits" (APICS, 2016, p.194).

Chu and Hayya (1988) identified three different mechanisms to deal with uncertainty:

- **Safety capacity:** Consists of overstating the work center capacity requirements for each period in the capacity requirements plan. However, this approach may become extra capacity and may lower the overall capacity utilization by imposing false requirements.

- **Safety lead times:** This approach brings parts into stock before the requirement indicates a planned need for them. These early releases may lead to unrealistic priorities.
- **SS:** Is the most popular method for protection against uncertainty. If demand occurs unexpectedly, the SS can protect against this risk of shortage. However, it is important to be aware that this extra inventory may involve waste.

Chu and Hayya (1988) stated that demand and supply uncertainty can be lowered by using a better forecasting technique. Nonetheless, many forecasts are estimations, therefore it may be difficult to match the actual demand.

2.2.3. Six Sigma

Bragg and Hahn (1989) identified that Six Sigma reduces the variability of a company. Six Sigma is defined as:

> *"A set of concepts and practices that focus on reducing variability in processes and reducing deficiencies in the product. Six Sigma is a business process that permits organizations to improve bottom-line performance, creating and monitoring business activities to reduce waste and resource requirements while increasing customer satisfaction"* (APICS, 2016, p.174).

Six Sigma methodology is divided into 5 steps (Kwak and Anbari, 2006):

- **Define:** Definition of the requirements and exceptions of the customer, project boundaries and process by mapping the business flow.
- **Measure:** Here the key characteristics of the process are measured and data is collected.
- **Analyze:** In this step the data collected in the measure step is analyzed. The aim of this is to convert the data into information that provides insights into the process.
- **Improve:** Here changes in the process are implemented to solve the problem. The result of the changes are measured so the company can judge if they are beneficial or if another change is necessary.
- **Control:** If the process is performing as desired and at a predictable level, it is put under control. In other words, the process is monitored to ensure that it is working as the company wants.

Six Sigma can improve business profitability and the effectiveness and efficiency of all operations to meet the needs of the customers. It reduces variability, however minimum variation will continue to exist in all processes (Antony and Coronado, 2001; Antony, 2004; Ptak and Smith, 2011).

Having described what forecasting is, and how to deal with the variability that forecast error generates, we return to describing the features of the ROP system.

Dependent demand is known as “a demand that is directly related to or derived from the BOM structure (defined in Section 2.3) for other items or end products. Such demands are therefore calculated and should not be forecast” (APICS, 2016, p.50). When managing this kind of demand, ROP techniques suffer from false assumptions about the demand environment, tend to misinterpret observed demand behavior, and lack the ability to determine the specific timing of future demand (Ptak and Smith, 2011).

Figure 2.6a shows that when the inventory level of the end product crosses the order point (indicated in red 1) it will draw from the inventory of the components in corresponding quantities (Figure 2.6b). This will deplete component inventories and at some time drive them below the order point (indicated in red 2). At this point, the Inventory Manager will reorder the components, taking out a large amount of raw materials to produce their order quantities (Figure 2.6c). In the example, it should be noted that this raw material was stored in the warehouse since January without considering when it was required. In other words, the ROP system launches a purchase or production order whenever the inventory level crosses the order point without questioning when this material will be required.

For dependent demand items, MRP offers considerable advantages over the ROP system by trying to insure that all the parts for the assembly of the product are available at the right time. Thus, it can reduce overall stockholding costs while improving the service that the stock is providing (Burcher, 2015).

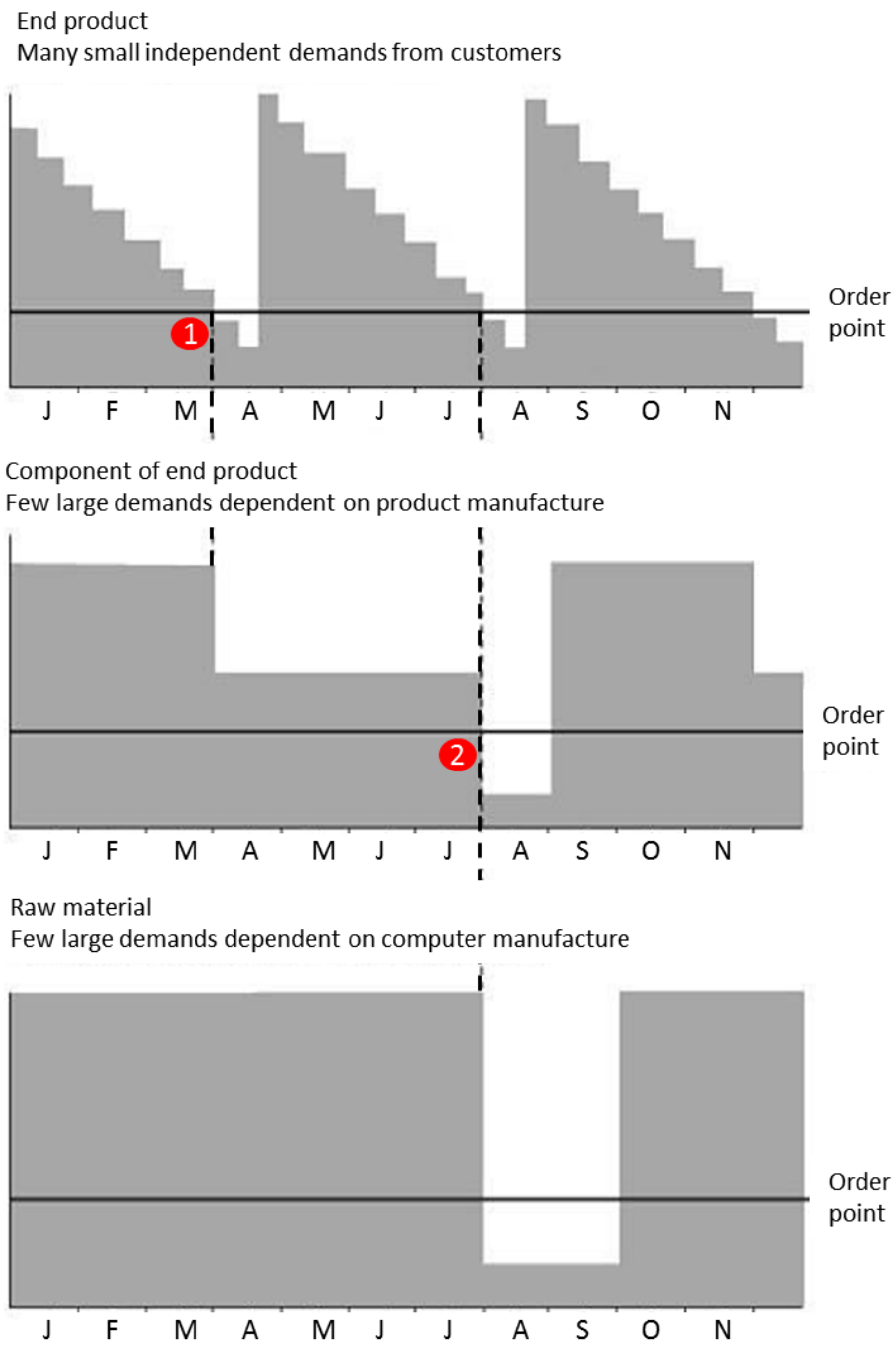


Figure 2.6: Inventory management of (a) end product (b) component of end product and (c) raw material using ROP system (Ptak and Smith, 2011)

ROP continues in use to the present day for the management of inexpensive parts when the cost of installing and operating a complex system such as MRP cannot be justified (Jacobs and Whybark, 1992). Moreover this approach is still widely accepted by many industries for its simplicity (Andriolo et al., 2014).

2.3. Material Requirements Planning

MRP is "a set of techniques that uses BOM data, inventory data, and the master production schedule to calculate material requirements. Specifically, it makes recommendations to release replenishment orders for material" (APICS, 2016, p.110). In essence, MRP was designed for a dependent demand environment with the objective of providing the right parts at the right times (Burcher, 2015).

MRP uses the MPS, BOM and the Inventory System as input data and proposes production and purchase orders (Figure 2.7).

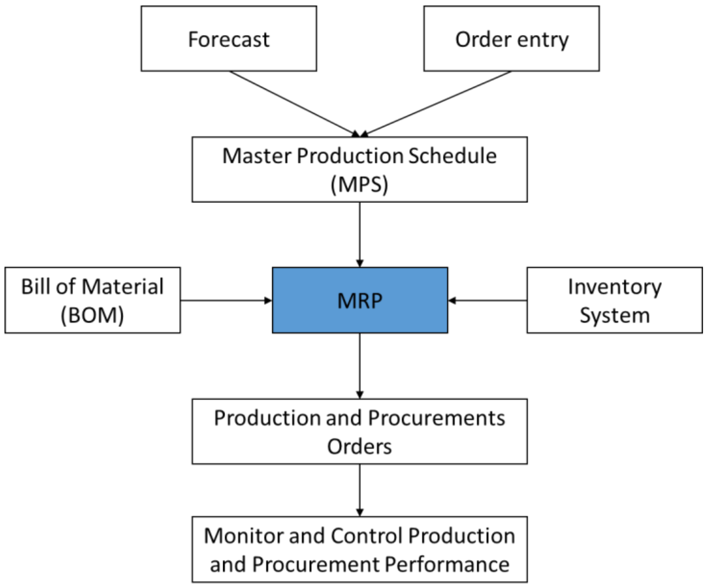


Figure 2.7: MRP structure adapted from (Anderson and Schroeder, 1984)

- **MPS:** is defined as:

"A line on the master schedule grid that reflects the anticipated build schedule for those items assigned to the master scheduler. The master scheduler maintains this schedule, and in turn, it becomes a set of planning numbers that drives material requirements planning. It represents what the company plans to produce expressed in specific configurations, quantities, and dates. The master production schedule is not a sales item forecast that represents a statement of demand. The master production schedule must take into account the forecast, the production plan, and other important considerations such as backlog, availability of material, availability of capacity, and management policies and goals" (APICS, 2016, p.108).

- **BOM:** is "a list of all the subassemblies, intermediates, parts, and raw materials that go into a parent assembly showing the quantity of each required to make an assembly" (APICS, 2016, p.16). This approach shows the complete structure of the product. As an example, Figure 2.8 shows the BOM of a shovel. This BOM is composed of 4 levels, with level 0 being the end product item "shovel complete" and level 3 being raw materials

"129 top handle bracket" and "1118 top handle coupling". This structure shows the link between different levels of the BOM. For instance, the "shovel complete" is composed of 4 "062 nails" generating the dependent demand between parts of the BOM.

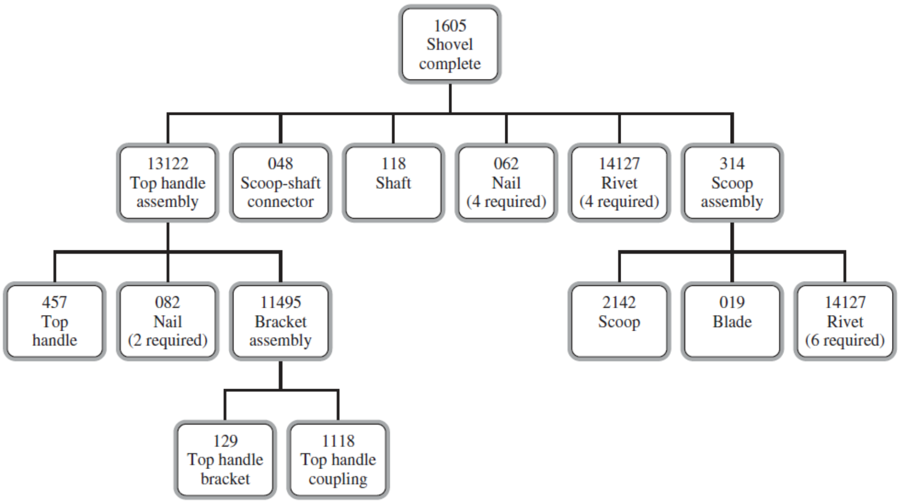


Figure 2.8: BOM of a shovel (Jacobs et al., 2011)

Consequently, MRP only forecasts the demand of the end product. Nevertheless, demand forecast error is also broadcast to the rest of the items, causing system nervousness (Chu and Hayya, 1988). This effect "is a characteristic of an MRP system and it happens when minor changes in higher level (e.g., level 0 or 1) records or the master production schedule cause significant timing or quantity changes in lower level (e.g., level 5 or 6) schedules and orders" (APICS, 2016, p.116).

- **Inventory System:** In order to know if there is enough raw material to carry out the plan, MRP checks the inventory level of each reference of the BOM to know if a supply requirement is necessary.

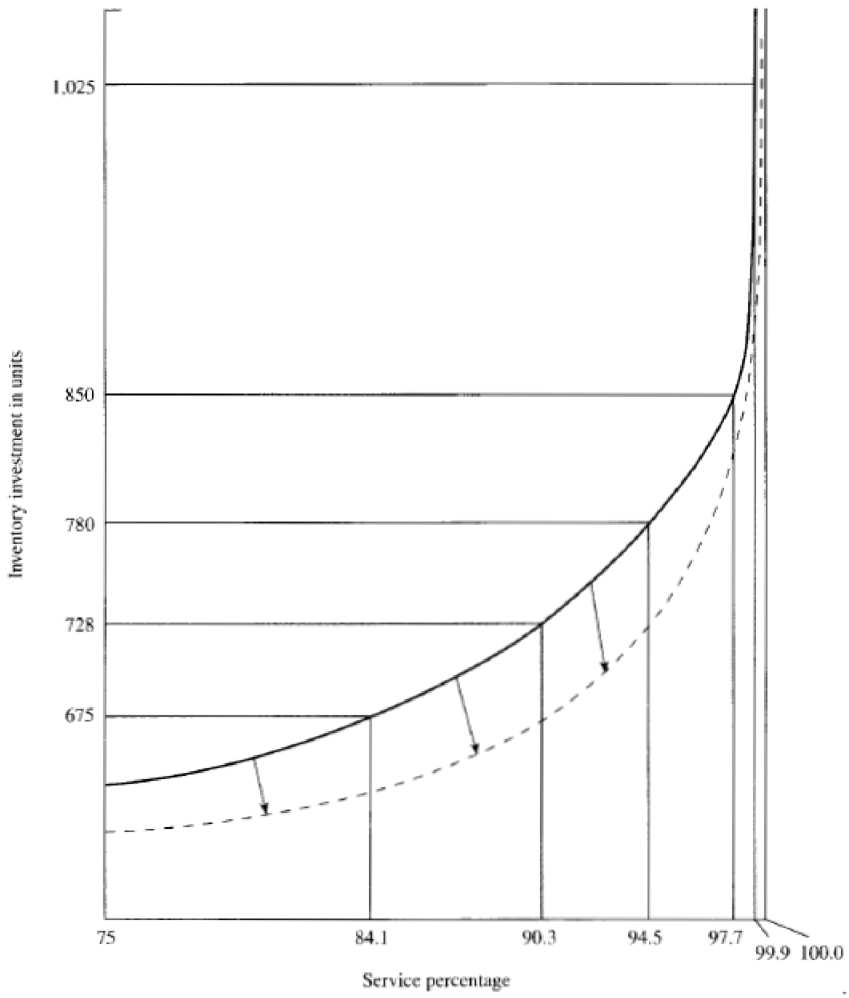
Many firms have changed from ROP to MRP reducing inventory holding cost, improving customer service and reducing rush orders (Bregman, 1994). MRP can provide significant benefits such as improved customer service, better production scheduling and reduced manufacturing costs (Stevenson et al., 2005).

However, many authors have analyzed the MRP system and concluded that it is not the best MPC for a volatile and variable world. For instance MRP was the most widely used concept in Finland, but many companies were not satisfied with it because of material shortages and continuous need for replanning (Matsuura et al., 1995). The study that Anderson and Schroeder (1984) conducted, indicated that less than 10% of the companies surveyed were receiving the full benefits from MRP, another 30% were receiving good benefits but not full results, and more than half were getting modest or no benefits. Moreover, these authors noted that an analyzed large job shop decided to abandon MRP since the information reported by the system was highly inaccurate, the discipline was too confining, and the system was generally a liability rather than an asset to management.

The rapidly changing environment of global manufacturing and the global supply chain is worsening the effects of MRP shortcomings and putting increased pressure on MRP systems and planning personnel (Ptak and Smith, 2011). Cox and Schleier (2010), highlighted these shortcomings as follows:

- **Unacceptable inventory performance:** Having too much of the wrong material, too little of the right material, high obsolescence, and/or low inventory turnover.
- **Unacceptable service level performance:** Customers continue to put pressure on the company, which quickly exposes poor on-time delivery, low fill rates, and poor customer satisfaction.
- **High shipping-related expenses and waste:** Managers commit to payment premiums and additional freight charges or increase overtime to fulfil promises.

MRP forecasts future demand, which causes uncertainty, as, explained in Section 2.2.1. As a result of this uncertainty, MRP does not generate the appropriate signals to effectively realize material planning. This leads to high Work in Progress (WIP) and long cycle times increasing costs (Stevenson et al., 2005). In other words, when demand uncertainty increases, more capacity and inventory is required to maintain the same service level. This is depicted in Graph 2.1 (Lambert et al., 1998; Guide Jr and Srivastava, 2000; Bollapragada et al., 2004).



Graph 2.1: Relationship between inventory investment and customer service level (Lambert et al., 1998)

As a result of this uncertainty many supply chains suffer from the bullwhip effect (Chen et al., 2000) which is defined as:

> *"An extreme change in the supply position upstream in a supply chain generated by a small change in demand downstream in the supply chain. Inventory can quickly move from being backordered to being excess. This is caused by the serial nature of communicating orders up the chain with the inherent transportation delays of moving product down the chain. The bullwhip effect can be eliminated by synchronizing the supply chain"* (APICS, 2016, p.20).

Many authors underlined the importance of information sharing and coordination in the supply chain in order to avoid bullwhip effect. Lee et al. (1997) emphasized the relevance of the information flow which is passed along the supply chain since it has a direct impact on production scheduling, inventory control and delivery plans of individual links in the supply chain. Chen et al. (2000) stated that providing each stage of the supply chain with complete access to customer demand information can significantly reduce uncertainty. However, they noted that the bullwhip effect will exist even when demand information is shared by all links.

An important feature of MRP is its reporting function, however this frequently does not satisfy the information requirements of the company. For these reason many companies resort to using other kinds of documents and customized data manipulation tools, such as Excel spreadsheets to have the key information to hand (Cox and Schleier, 2010). These spreadsheets are usually developed by the planner of the company and the calculations are based on personal knowledge and intuition. In such cases, the company is required to trust that these calculations are the correct ones. Moreover, this kind of document must be updated, otherwise, the planner will be taking decisions with the incorrect information. According to Smith (2014), 95% of companies use Excel spreadsheets for planning, and he defines this practice as “Excel Hell” for these reasons:

- The use of Excel spreadsheets can involve significant risk because the company depends completely on the person that has developed these documents. If someday this person decides to leave, the knowledge will also go with them.
- The company must believe that they are correctly developed and there is no error.
- When a spreadsheet is developed, it is usually standalone and not connected to other documents. As a result, the company has to spend a lot of time reviewing other spreadsheets to be able to work with the current one.
- The upgrade of these spreadsheets is costly and therefore many companies work with stale data, which, in turn, leads to erroneous decisions.

In summary, MRP is one of the most widely used systems for production planning and control (Guide Jr and Srivastava, 2000). Nevertheless it does not respond to the demand driven manufacturing strategies that are required for companies to be fast, lean, and flexible in today’s hypercompetitive environment (Cox and Schleier, 2010).

2.3.1. Manufacturing Resource Planning

MRP works on the bases that the production capacity of a company is infinite. Hence, a company runs into problems because many times what MRP plans is not feasible. For this reason, capacity requirements were added to MRP, converting it into CLMRP. This new approach is defined as:

> *“A system built around material requirements planning that includes the additional planning processes of production planning (sales and operations planning), master production scheduling, and capacity requirements planning. Once this planning phase is complete and the plans have been accepted as realistic and attainable, the execution processes come into play. These processes include the manufacturing control processes of input-output (capacity) measurement, detailed scheduling and dispatching, as well as anticipated delay reports from both the plant and suppliers, supplier scheduling, and so on. The term closed loop implies*

not only that each of these processes is included in the overall system, but also that feedback is provided by the execution processes so that the planning can be kept valid at all times” (APICS, 2016, p.29).

This represented significant improvement for the MRP system since it closed the loop between the shop floor and the MPS. As a result, required capacity is brought into line with the available capacity when scheduling materials (marked in red in Figure 2.9) (Anderson and Schroeder, 1984). Hence firms are able to more efficiently schedule and monitor the execution of production plans (Rondeau and Litteral, 2001).

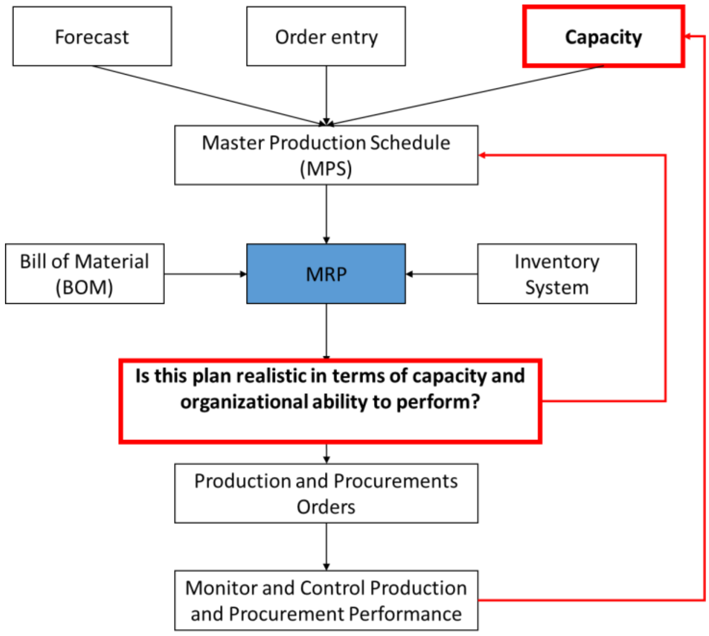


Figure 2.9: CLMRP structure adapted from Anderson and Schroeder (1984)

In the 1980s, more approaches were added to CLMRP converting it into MRP II. This new approach is defined as:

“A method for the effective planning of all resources of a manufacturing company. Ideally, it addresses operational planning in units, financial planning in dollars, and has a simulation capability to answer what-if questions. It is made up of a variety of processes, each linked together: business planning, production planning (sales and operations planning), master production scheduling, material requirements planning, capacity requirements planning, and the execution support systems for capacity and material. Output from these systems is integrated with financial reports such as the business plan, purchase commitment report, shipping budget, and inventory projections in dollars” (APICS, 2016, p.106).

MRP II includes information of different areas of the company, not only the production system (marked in red in Figure 2.10) (Anderson and Schroeder, 1984).

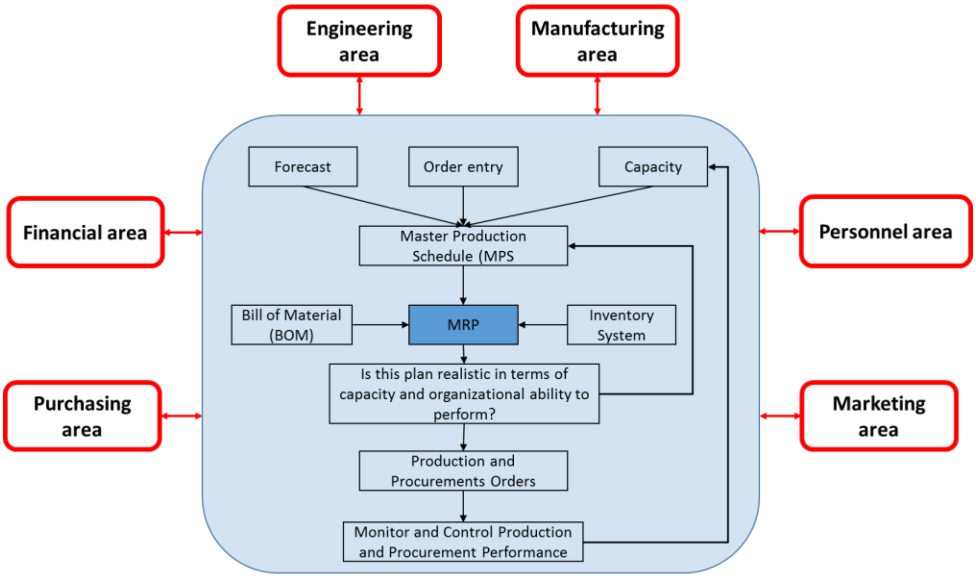


Figure 2.10: MRP II structure adapted from Anderson and Schroeder (1984)

Through an iterative trial and error process MRP II overcame many shortcomings of the MRP system (Ptak, 1991). However, the new system requires a high degree of human intervention in making the proper adjustments to schedule and in determining the optimal sequence of manufacturing orders that best accommodate the dynamic and often volatile environment of the shop floor. Although the added functionalities of MRP II provide valuable additional feedback in reporting the status of shop floor activities, it does not provide information about how to better manage the execution of these activities (Rondeau and Litteral, 2001). Moreover, despite these additional features, the basic mechanism of MRP and MRP II, remains the same (Benton and Shin, 1998).

2.3.2. Enterprise Resource Planning

In the 1990s many firms and professional organizations like APICS reached the conclusion that an MPC system more advanced than MRP II, capable of real-time manufacturing planning and execution control, was needed (Rondeau and Litteral, 2001). Therefore, Manufacturing Execution Systems (MES) were developed as an interface between MRP II and the shop floor control system. MES is defined as “programs and systems that participate in shop floor control, including programmed logic controllers and process computers for direct and supervisory control of manufacturing equipment” (APICS, 2016, p.105).

MES serves these 6 general functions (Rondeau and Litteral, 2001):

- The management of machine resource availability.
- Prioritization of production schedules.
- Control of the flow of production units between machines.

- Management of available labor.
- Automated document control.
- Provision of quality, process and maintenance management support

By the late 1990s many companies had to reinvent their products and services including their organizational structure and operational controls to cope with increasing global competition and changing markets. Companies needed an approach to align themselves with the requirements of the customer, namely customer centered supply chain management (Rondeau and Litteral, 2001). Traditional MRP and MRP II applications were not able to rise to the challenge presented in this new environment since they are focused on the planning and scheduling of internal resources. ERP, therefore, evolved from its predecessors to play an integrated supporting role in the creation of a value chain (Chen, 2001).

ERP is "a framework for organizing, defining, and standardizing the business processes necessary to effectively plan and control an organization so the organization can use its internal knowledge to seek external advantage" (APICS, 2016, p.60-61). This system usually includes a set of mature business applications and tools for financial and cost accounting, sales and distribution, materials management, human resource, production planning and computer integrated manufacturing, supply chain, and customer information (Figure 2.11) (Shehab et al., 2004).

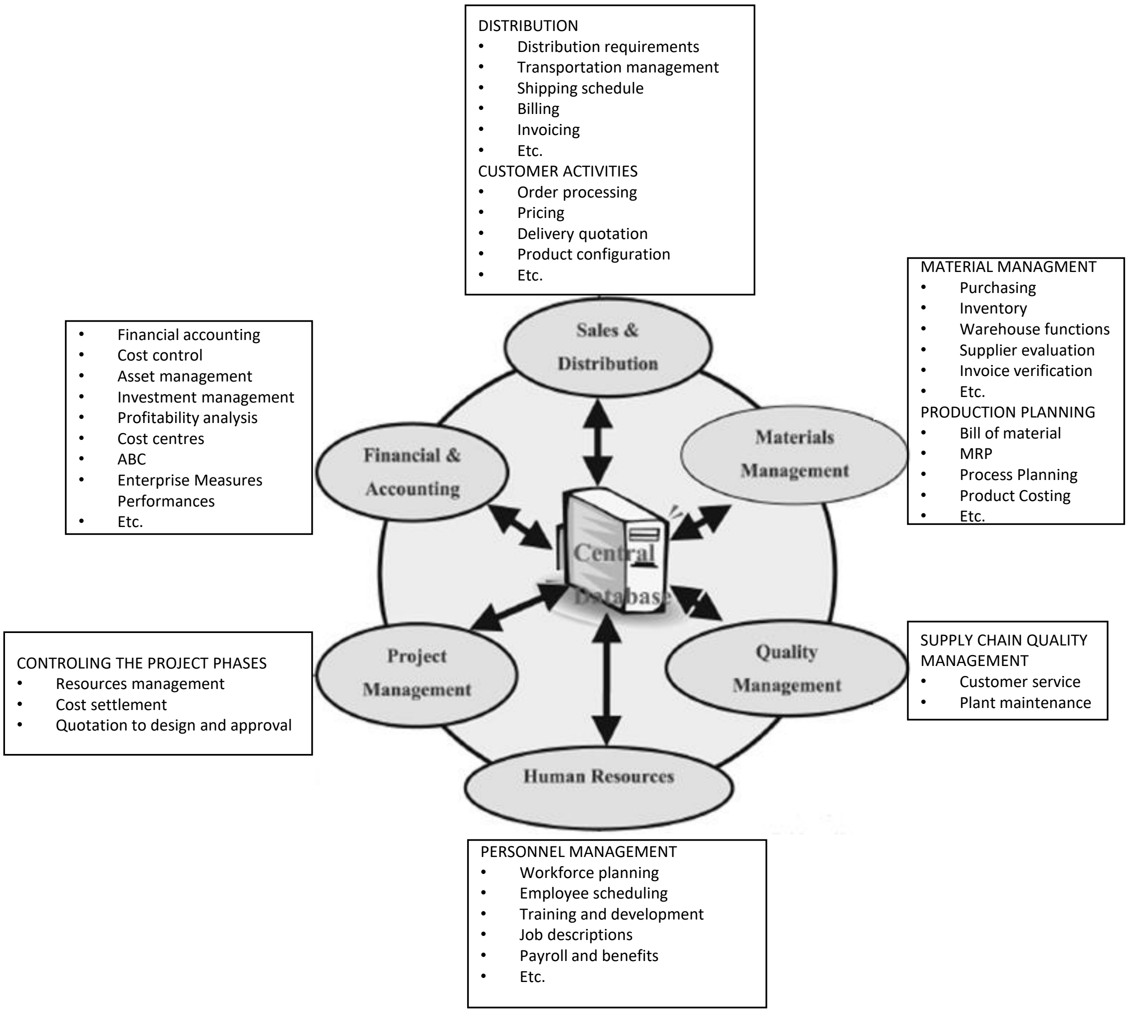


Figure 2.11: ERP structure (Shehab et al., 2004)

Fui-Hoon Nah et al. (2001) highlighted the abilities of ERP to:

- Automate and integrate business processes of an organization.
- Enable implementation of all variations of best business practices with a view towards enhancing productivity.
- Share common data and practices across the entire enterprise.
- Produce and access information in a real-time environment.

Many authors analyzed the ERP system and outlined the benefits of this system. Rao Siriginidi (2000) found that a company that implemented ERP could reduce lead time, cycle time and WIP, had on-time shipments and increased business and inventory turnover. It was therefore the opinion of this author that ERP would provide better customer satisfaction, improved vendor performance, increased flexibility, reduced quality costs, improved resource utility, information accuracy and decision making capability. According to Themistocleous et al. (2001) ERP provides solutions to the problems of legacy systems, reduced development risk, increased global competitiveness and business efficiency. However, this study identified many drawbacks such as: implementation complexity, integration problems, customization problems and over-budget and late projects among others.

Moreover, ERP traces its roots to MRP and MRP II (Chen, 2001). Although technology has evolved and market requirements have changed, the basic engine used to drive information systems in ERP is still the traditional MRP system with all its inherent inflexibility (Guide Jr and Srivastava, 2000; Hwa Chung and Snyder, 2000; Ptak and Smith, 2011).

2.3.3. Extended Enterprise Resource Planning

The 1990 saw the addition of different e-business solutions such as Customer Relationship Management (CRM) and Supply Chain Management (SCM) to the ERP system giving rise to ERP II (Figure 2.12) (Weston Jr, 2003). ERP II became an e-business backbone for organizations doing on-line business transactions over the Internet. The aim of this system was to improve customer satisfaction, increase marketing and sales opportunities, expand distribution channels and provide more cost-effective billing and payment methods (Rashid et al., 2002).

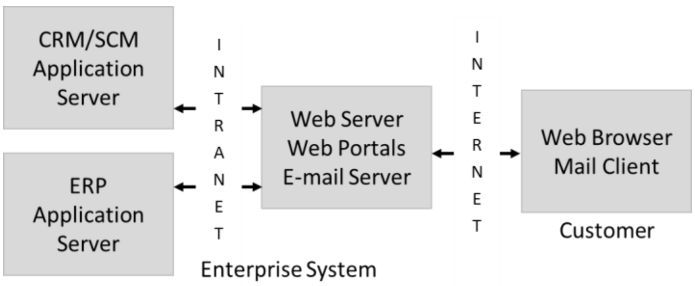


Figure 2.12: Web-enabled ERP II system (Rashid et al., 2002)

CRM is an integration of several tools such as Data Warehouses, Data Mining, Web sites, Intranet, Extranet, Phone support systems. Data Warehouse and Data Mining applications can help companies to decrease costs or increase differentiation. Organizations disseminate information regarding their products through the Internet, in a more customized and personalized way. Extranets can provide customers with the option of self service by including product configurations to customize products (Dave, 2014).

SCM has sub-modules to procure materials, transform the materials into products and distribute these products to customers. Successful SCM allows an enterprise to anticipate demand and deliver the right product to the right place at the right time at the lowest possible cost. Significant savings can be achieved in inventory reduction, transportation costs and reduced spoilage, by matching supply with actual demand (Rashid et al., 2002).

In the digital age, having access to reliable data is of paramount importance. This data needs to be up to date and accurate, and independent of language, location, and currency (Weston Jr, 2003). ERP II makes managing and moving data through the supply chain easier, as it is the information link for a company (Addo-Tenkorang and Helo, 2011). When SCM and CRM applications are integrated with ERP through the Internet, there are further benefits that can be achieved. For instance, suppliers and manufacturers can communicate with each other in more cost efficient ways, thus decreasing costs. Furthermore, the Internet captures customer information that allows organizations to customize existing products according to need (Dave, 2014).

Notwithstanding the above advantages, it is important to bear in mind that MRP still reminds the basic engine that drives the majority of ERP II production control software packages which are commercially available (Burcher, 2015).

2.4. Lean

The lean operating principle grew out of manufacturing environments and is known by a variety of synonyms such as Lean Manufacturing, Lean Production, Toyota Production System and JIT production (Kilpatrick, 2003). It is defined as “a philosophy of production that emphasizes the minimization of the amount of all the resources (including time) used in the various activities of the enterprise. It involves identifying and eliminating non-value-adding activities in design, production, supply chain management, and dealing with customers” (APICS, 2016, p.97).
Kilpatrick (2003) defined non-value adding activities as:

- **Overproduction:** Producing more than customer demands. Anything produced beyond customer orders (SS, WIP, inventories, etc.) ties up valuable labor and material resources that might otherwise be used to respond to customer demand.
- **Waiting:** This includes waiting for material, information, equipment, tools, etc. All resources must be on a JIT basis, namely neither too soon, nor too late.
- **Transportation:** Material should be delivered to its point of use, instead of raw materials being shipped from the vendor to a receiving location, processed, moved into a warehouse, and then transported to the assembly line.
- **Non-value-added-processing:** The product should be made correctly the first time.
- **Excess inventory:** If the inventory level is beyond the level which is needed to meet customer demands, it will negatively impact on cash flow and will use valuable floor space.

- **Defects:** Production defects and service errors waste resources in 4 ways: materials are consumed, labor used to produce the part the first time cannot be recovered, labor is required to rework the product and labor is required to address any forthcoming customer complaints.
- **Excess motion:** Unnecessary motion is caused by poor workflow, poor layout, housekeeping, and inconsistent or undocumented work methods.
- **Underutilized people:** This includes underutilization of mental, creative, and physical skills and abilities.

Therefore, JIT production implies a broad philosophy of pursuing a journey towards perfection. That is, 0 defects, 0 inventory, 0 disturbance and total standardization. To succeed in this production system uniform plant load, low setup times, minimum WIP, preventive maintenance, supplier participation and continuous improvement of activities are necessary (Figure 2.13) (Huq and Huq, 1994; Benton and Shin, 1998).

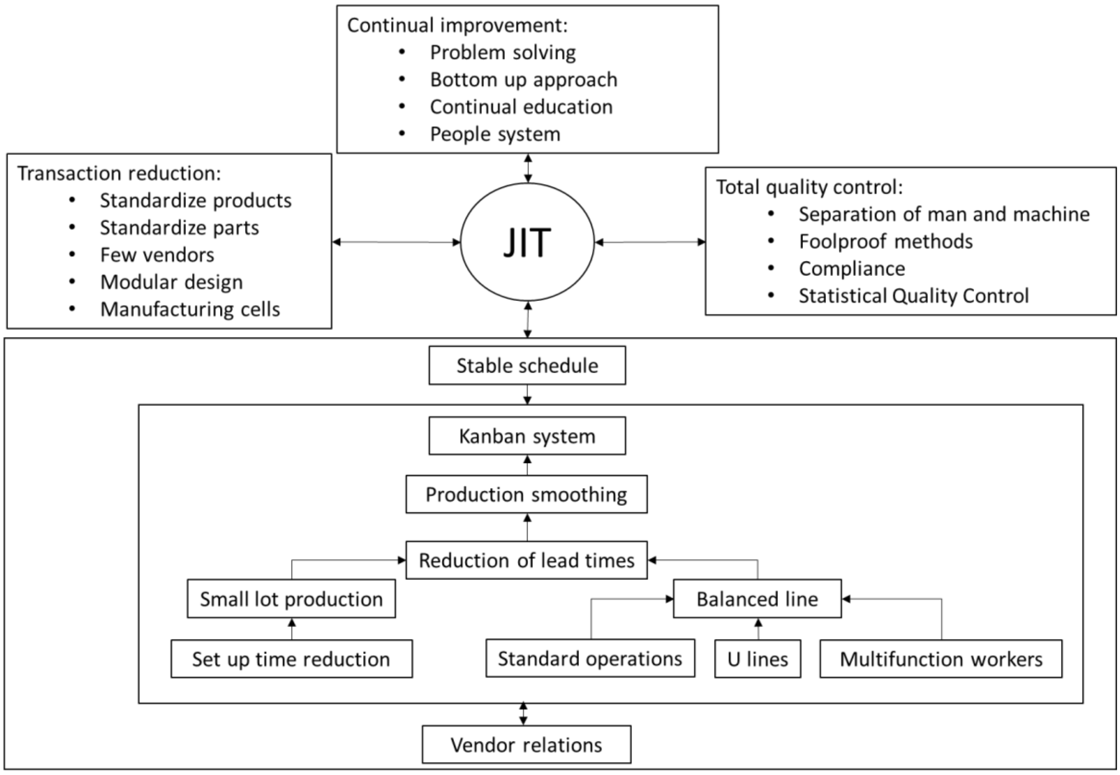


Figure 2.13: Steps to achieve JIT production (Huq and Huq, 1994)

The National Institute of Standards and Technology Manufacturing Extension Partnership undertook a survey of 40 clients who had implemented JIT production. They found that lead time was reduced by 90%, the WIP inventory by 80% and space utilization by 75%. In addition, productivity increased by 50% and quality was improved by 80% (Kilpatrick, 2003).

In order to control inventory levels, the raw material and the proper quantity and time of production, and supply requirements JIT production uses Kanban (Lage and Godinho, 2010).

Kanban is defined as: “a method of JIT production that uses standard containers or batch sizes with a single card attached to each. It is a pull system in which work centers signal with a card that they wish to withdraw parts from feeding operations or suppliers” (APICS, 2016, p.94). It is important to note that due to the pull system, material is not issued until a signal comes from the user.

Many authors studied the advantages of using the Kanban. For instance Benton and Shin (1998) reported that Kanban provides visual information of material flow that helps the Field Managers to identify bottlenecks on the shop floor. According to Ptak and Smith (2011), Kanban is very easy to establish and begin to use. Nonetheless, they also stated that when the company grows to any significant size, the overhead to manage Kanban can quickly become overwhelming.

If Kanban is applied in an environment with large batch sizes and setup times it does not produce the advantages associated with such a system (Krajewski et al., 1987). In the same line Lage and Godinho (2010) stated that Kanban is not adequate in situations with unstable demand, processing time instability, non-standardized operations, long setup time, great variety of items, and raw material supply uncertainty.

Therefore, the JIT production system appears most suitable for the repetitive manufacturing environment (Huq and Huq, 1994; Benton and Shin, 1998). Since, this system defines inventory as waste, many companies have carried out a reduction of the inventory in their process. The disadvantage of this however, is that their supply chain becomes too brittle and less agile (Steele et al., 1995; Ptak and Smith, 2011).

Implementing a JIT production system also requires the main features of conventional MPC systems such as MPS and MRP in order to be effective and cope with variability (Benton and Shin, 1998). Hence JIT production is directly applicable to only a small proportion of manufacturers but most companies must carefully judge which lean practices can be used immediately in their companies and which need to be adapted (Jina et al., 1997).

2.5. Theory of Constraints

In the 1980s, a new philosophy was developed by Eli Goldratt. This philosophy evolved from the OPT and by 1987, the overall concept became known as the TOC, which the author viewed as "*an overall theory for running an organization*" (Goldratt, 1988).

The essence of TOC can be summarized thus:

1. Every system has at least one constraint which is defined as anything that limits a system from achieving higher performance versus its goal (Goldratt, 1990).
2. The existence of constraints represents opportunities for improvement. Contrary to conventional thinking, TOC views constraints as an opportunity to improve the performance of the system (Rahman, 1998).

The working principles of the TOC production environment consist of 5 focusing steps, which are explained below. Before implementing the steps of the TOC, Goldratt (1990) stated that the company must define the global goal of the system and the measurements that will enable the company to judge the impact of any subsystem and any local decision, on this global goal.

1. **Identify the constraints of the system:** This also means to prioritize them according to their impact on the goal.
2. **Decide how to exploit the constraints of the system:** Once the constraint is identified, the company must be sure that it does not waste the little that it has, making the constraint as effective as possible.
3. **Subordinate everything else to the above decision:** The company must manage the non-constraint resources so that everything that the constraints are going to consume will be supplied by the non-constraints.
4. **Elevate the constraints of the system:** there must be a way to reduce the limiting impact of the constraints. Hence, the company must carry out rigorous improvement efforts on these constraints in order to reduce their limiting impact.
5. **If in any of the previous steps a constraint is broken, go back to step 1:** Once the company has elevated the constraint of the system, this resource might not limit the system any more. Nevertheless, removing the system limitations does not necessary mean there is no other constraint on the system. Thus, it will be necessary to return step 1 to identify the new constraint.

Rigorous academic testing has revealed that manufacturing systems employing TOC techniques exceed the performance of those using MRP and JIT. The results of these studies have indicated that TOC systems produce greater levels of output while reducing inventory, manufacturing lead time, and the standard deviation of cycle time (Watson et al., 2007). Mabin and Balderstone (1999) drew the same conclusion. After conducting a survey of over 100 published case studies in various industries they found that using TOC, inventories were reduced on average by 49%; production times (measured in terms of lead times, cycle times or due date performance) improved by over 60%; and financial performance by 60%. However, in the conditions of make-to-order manufacturing with a high variability of work and a long lead time, buffer management based on classic TOC tools was difficult and ineffective because the system does not accurately plan material requirements (Hadaś and Cyplik, 2010).

Therefore, to manage distribution and supply chain, the Theory of Constraints Supply Chain Replenishment System (TOC-SCRS) emerged. The goal of TOC-SCRS is to solve the conflict problem in the inventory management in the supply chain, so that a win–win strategy can be devised to maintain a lower inventory level and prompt delivery to satisfy customer needs. (Wu et al., 2014). This method is composed of 6 steps explained below (Cox and Schleier, 2010):

1. **Aggregate stock at the highest level in the supply chain:** keep large buffer stocks at the divergent point and use a pull replenishment mechanism triggered by sales at the end of the chain, the consumption point. This method guarantees keeping the lowest stock level possible to support the demand of the various consumption points.
2. **Determine stock buffer sizes for all chain locations based on demand, supply and replenishment lead time**: the stock buffer size is the maximum amount of inventory of an item held at a location in the supply chain to protect throughput. The aim is to set the right stock levels to ensure that every potential customer finds the desired products available for purchase.
3. **Increase the frequency of replenishment:** The traditional purchasing practice for managing within a supply chain encourages purchasing in large quantities due to volume discounts, the minimum transportation volume and extra cost of managing small quantities. By making the frequency of delivery higher, a better availability of material is created whereas the cost of shipment increases. By making the frequency lower, the company will have to pay with either lower availability or with much higher inventory levels kept at the consumption points in order to cover for variations in demand.
4. **Manage the flow of inventories using buffer and buffer penetration:** TOC-SCRS divides the buffer into three zones: green when the inventory at the consumption point is high,

providing more than enough protection for now; yellow when the inventory at the consumption point is adequate, so there is a need to order more units from the upstream supply chain; and red when the inventory at the consumption point is at risk of stocking out. Units in transport/manufacturing should be considered. There is another zone known as black, which is when the stock has run out at the consumption point. Therefore, every hour that passes at this stage means lost sales opportunities.

5. **Use dynamic buffer management:** Variations exist in reality, so Goldratt provided a mechanism to manage buffers in a dynamic environment, eliminating the need for these complex forecasting models. Monitoring the Stock Keeping Units (SKU) buffer penetration identifies whether the buffer size that it is set is correct. In this way, the real stock buffer level required to cover for the demand is easily reached. Using pull distribution and dynamic buffer management is very effective therefore, in eliminating lost sales and overstocking.
6. **Set manufacturing priorities according to urgency in the stock buffers:** TOC prioritizes the production orders based on their due dates. Nevertheless, another source of demand has to be dealt with, so the best priority mechanism is to take the buffer penetration for the item as the priority for the replenishment manufacturing order, since the stock status reflects the consumption from all downstream locations and thus the total status of this item in the supply chain, eliminating the need for forecast.

The performance reported by companies that implemented TOC-SCRS includes reduction of inventory level, lead time and transportation costs and customer service levels. In addition advantages also included a reduction in expired products (or reduction in the out rate), and more rapid reaction in terms of market changes (Wu et al., 2013; Wu et al., 2014).

2.6. Comparison between ROP, MRP, JIT and TOC

In the course of this literature review, many research works that compared MRP, JIT and TOC approaches were found. However, very few research works included the ROP system in their comparisons. This thesis presents a comparison between all four systems and the main findings are summarized below.

The first, and perhaps the main difference of these systems is the goal of each one. The aim of ROP is to control storage level, to which end it generates a replenishment order with a set batch size when the stock reaches or falls below the order point (Toomey, 2000). The main objective of MRP, on the other hand, is to determine net requirements of the parts and components

(Gupta and Snyder, 2009). The reduction of waste is the main objective of JIT (Miltenburg, 1997), while the main goal of TOC is to control and improve bottlenecks as they determine the throughput of the plant (Goldratt, 1990).

Depending on the fix or dynamic behavior, an MPC system can be classified as active or passive. For instance, MRP is considered as a passive approach since it plans and controls a production system assuming that it is fixed. Namely, setup times, breakdown rates, repair times and processing times among others are fixed. However, JIT and TOC are considered as active approaches. JIT is constantly improving the production system by reducing setup times, move and queue times, scrap rates and so on. TOC is also considered an active approach as its goal is to maximize the output which it achieves by identifying and exploiting the bottleneck resource (Huq and Huq, 1994; Miltenburg, 1997).

Another differentiation to underscore is the input data that each system uses to perform. In the case of ROP, requirements for components are forecast from the previous requirements of each component; whereas in MRP requirements for components are derived from production orders placed at successor stages, namely demand is considered as dependent through the BOM (Bregman, 1994). The JIT system is a pull system and thus is not based on forecast. As for TOC, before the constraint is considered as a pull system and after as a push system, hence it only requires data accuracy at the constraint (Swann, 1986; Bolander and Taylor, 2000; Gupta and Snyder, 2009).

With regards to data management, it is worth noting that MRP needs to manage a large amount of data to work properly, and sometimes companies have problems keeping all this data updated. In contrast, JIT and TOC need little data to achieve their aim (Gupta and Snyder, 2009).

As for demand variability JIT performs better than TOC when seasonal variability is low (Chakravorty and Brian Atwater, 1996). However, when the demand variability increases or when there are many engineering changes and many product options, MRP is more appropriate (Abuhilal et al., 2006). According to Olhager (2013), markets with high-volume, standardized products, few variants, and short lead times should be planned and controlled with a JIT approach, whereas markets with low-volume, highly customized products, wide product range, and long lead times should be planned and controlled using MRP-type approaches.

Concerning the inventory, the JIT approach limits the amount of inventory between stations and allows a station to work only to replace inventory withdrawn from its storage area. Hence, it attempts to eliminate dependence between work stations. However, TOC is focused on improving the constraint resource and only restricts the total amount of inventory in the system, not the flow of inventory between stations. Therefore, TOC is more suitable for job shop environments and is more widely applicable. As for the MRP system, as it is focused on increasing efficiencies at individual work stations, it creates a large amount of inventory in the system (Chakravorty and Brian Atwater, 1996; Gupta and Snyder, 2009).

According to Ptak and Smith (2011), there are three key steps in supply chain management that companies must take into account to ensure material flow:

- **Planning**: Assigning numbers to future events to create plans.
- **Execution:** Converting plans to reality.
- **Control**: Tracking execution, comparing execution to plans, measuring deviations, sorting the significant from the trivial, and instituting corrective actions in either the plans or the execution.

Nevertheless, not all MPC systems contemplate all these steps. For instance, MRP was designed to plan material replenishment and can also produce prioritized schedules via the MPS and BOM (Swann, 1986). However, according to Benton and Shin (1998), MRP is not concerned with managing operational performance on the shop floor.

As for JIT, it is focused on executing and controlling open orders. Consequently, as JIT does not contemplate planning steps, the company will release many requirements to the internal or external suppliers with too little notice (Ptak and Smith, 2011). Hence, the supplier may be unable to respond in time, and the whole line can be disrupted or stopped until the supplier is able to provide the requested part.

To get more performance at the bottleneck, TOC just plans the tasks to be done at this resource and subordinates the rest of the resources to this plan. However this approach does not consider a long-term vision in executive decision-making (Watson et al., 2007).

Considering that each system has interesting features and can contribute and work in the step it belongs to, many authors have considered the option of generation hybrid manufacturing systems. In this way, the company could carry out the planning, execution and control of the material flow using the most appropriate system for each stage in the supply chain management.

2.7. Hybrid manufacturing system

All MPC systems have their own advantages and disadvantages. Various authors have tried to identify which of MRP, JIT or TOC is superior, however there is a consensus that the three fundamental systems are complementary and their successful integration would result in an efficient hybrid manufacturing system (Rahmani et al., 2010). This system is defined as "a production planning method that combines the aspects of both the chase and level production planning methods" (APICS, 2016, p.82).

Benton and Shin (1998) analyzed combining MRP and JIT and noted that there are three important factors that have contributed to the evolution of the hybrid manufacturing environment: (1) accumulated operating problems in implementing JIT manufacturing techniques, (2) the compatibility between MRP as a planning system and JIT production system as a shop floor control device and (3) the flexibility of MRP in long term capacity planning and the agility of JIT in daily production control.

This combination of MRP and JIT systems can provide many advantages. For instance, Ghrayeb et al. (2009) stated that when both systems are being integrated, in most cases, the disadvantages are eliminated and the advantages of each system are strengthened respectively. Golhar and Stamm (1991) found that the integration of MRP and Kanban would allow firms to improve productivity and customer service level. Along similar lines, Flapper et al. (1991) provided a framework for embedding JIT into an MRP system, where JIT production system controls material flow within the MRP hierarchy. Matsuura et al. (1995) stated that some Japanese companies intend to integrate MRP with a JIT production system to exploit the strength of MRP and JIT production. However, they also stated that there are some interface problems. Pun et al. (1998) analyzed a company that integrated JIT into an MRP, achieving the following improvements:

- Inventory levels were reduced by 20% in WIP and by 25% in end product.
- Obsolete scrap per month was reduced by 38%.
- Setup and changeover times were reduced by 33% to 70% in various items.
- Throughput time was reduced by 43%.

According to Benton and Shin (1998) MRP/JIT integration can be considered a natural evolutionary progress toward and idealistic hybrid manufacturing environment. They also noted however that MRP/JIT integration is easy in theory, but challenging in practice since the JIT production system requires reduced batch size and setup time and unique facility layout.

Adjusting those requirements to the MRP controlling mechanism is not easy. Along similar lines, Sillince and Sykes (1993), found that MRP and JIT hybrid systems have problems dealing with priorities owing to the fact that the BOM is flat for JIT. Therefore, priority ordering is not implicit.

MRP and TOC integration have also been studied. For instance, Reimer (1991) analyzed the case study of Valmont company, which decided to incorporate TOC in their MRP. Specifically, Valmont used MRP as an information system and TOC as the scheduling and shop floor control system. In this case study, two weeks after the implementation, the company depleted the all finished goods inventory. WIP was also reduced and machines, which worked overtime on many occasions, became idle, and scrap and reject parts dropped from 15% to around 2%. Moreover, on-time shipments improved.

Hadaś and Cyplik (2010) defined a hybrid model that consisted of three basic levels: strategic, planning and operational (Figure 2.14). The strategic level was concerned with make strategic decisions about the development directions of an enterprise. The planning level was dominated by MRP II logic. As for the operational level, it was managed by TOC. The authors of this model stated that the model combined the effectiveness of aggregated planning with the effective flow subordinate to critical resources. However, they asserted that developing and implementing a complex hybrid system of planning and the shop floor control was not an easy task, due to the fact that there are no universal MRP, JIT or TOC models. Therefore, there is no single universal method of combining them.

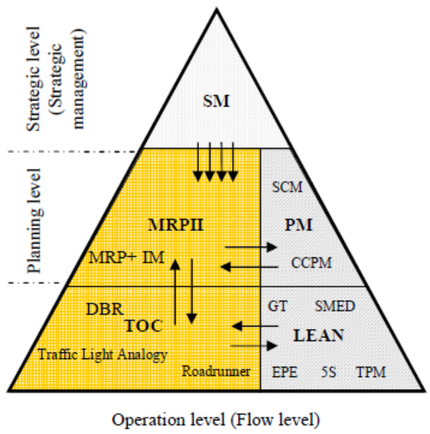


Figure 2.14: A system of planning and shop floor control in the conditions of make-to-order manufacturing (Hadaś and Cyplik, 2010)

In summary, many authors agree that a hybrid system integrating the best of JIT, MRP and TOC appears to be the solution, albeit not a very easy solution to implement (Gelders and Van Wassenhove, 1985; Ptak, 1991; Chakravorty and Brian Atwater, 1996; Rahmani et al., 2010).

In 2011 a new methodolgy called DDMRP was published, incorporating features of MRP, TOC, Lean, Six Sigma and innovative concepts. DDMRP can thus be considered as a hybrid manufactuing system and is explained in greater depth in Chapter 3 (Ptak and Smith, 2011).

2.8. Summary

In this chapter different systems to manage the material flow in a company have been presented.

The first MPC system presented in this thesis is the ROP system. Its aim is to control storage level, to which end it generates a replenishment order with a set batch size when the stock reaches or falls below the order point. This system forecasts the future demand but, forecast causes uncertainty. To manage this uncertainty SS is used.

In the 1960s, the ROP system was replaced by MRP. The aim of this system is to determine net requirements of parts and components. To achieve this, MRP represents the structure of the articles through the BOM and takes into account dependent demand of the parts of the BOM. In addition, it is a push-based system that forecasts the demand of the end-part. The uncertainty that this forecast causes is solved using SS.

MRP nowadays is one of the most widely used MPC system. When there is bulk demand, variability and uncertainty, it manages material requirements more effectively than other systems. Nevertheless, to provide a good service level to customers in changeable environments this system usually needs a large amount of inventory.

Lean philosophy is another system, which is also widely used. Its aim is to reduce waste. Lean is usually used to execute and control production, for which it uses the Kanban tool. This system performs well when the demand is stable and there is no variability. However, in uncertain environments, MRP performs more effectively than Lean.

Finally, TOC is the last MPC analyzed, the aim of which is to control and improve bottlenecks as these determine the throughput of a company. To manage bottlenecks TOC employs a five-step approach whereas supply chain management is handled by the TOC-SCRS methodology.

Each system offers advantages and disadvantages, and sometimes it is difficult to choose a single system. For this reason many authors have analyzed the possibility of integrating more than one MPC into a single manufacturing system to achieve better results. Nevertheless, it appears that while theoretically this is a suitable solution, in practice, it is not an easy task.

In the rapidly changing world of global manufacturing, companies need to mark a point of difference from the competition and offer complete solutions that fully satisfy customer demand. In this context, efficient supply chain management focused on customer demand is required to prevent constant production stoppages, rush orders or excess inventory to cover all eventualities. Nevertheless, an analysis of the literature reveals that MPC systems are not demand-driven and have not evolved to meet customer necessities.

DDMRP was developed with the objective of managing the supply chain efficiently, allowing companies to achieve a demand-driven manufacturing strategy. This methodology integrates features from different MPC systems so that can be considered as a hybrid manufacturing system. DDMRP is explained in detail in Chapter 3.

Chapter 3

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3. Demand Driven Material Requirements Planning

Considering today's highly volatile and variable manufacturing environment where planning scenarios are more complex than ever, a demand-driven manufacturing strategy is necessary. The goal of this strategy is to compress lead times and align efforts to market demands. This includes careful synchronization of planning, scheduling and execution with material consumption. This strategy encourages companies to centralize the demand instead of the inventory. Thus they are able to sense and adapt to market changes becoming more agile (Ptak and Smith, 2011).

> *"Agile means the ability to quickly plan, source, make, and deliver to adapt and respond to changes in the competitive environment. It is a Supply Chain Operations Reference (SCOR) performance attribute that includes product or service flexibility (speedy introduction of new products and services), mix flexibility (ability to quickly change products or services offered), volume flexibility (ability to service large order quantities), and delivery flexibility (ability to quickly change delivery dates to meet new requirements)"* (APICS, 2016, p.6).

The MPC systems analyzed in Chapter 2 lack functionalities to carry out a demand-driven manufacturing strategy. Traditional push approach MRP may have some shortcomings to deal with environments with unpredictable demands. At the same time, the limited set of materials planning and inventory control tools in pull-based philosophies such as TOC and JIT are also inadequate to implement a demand-driven manufacturing strategy (Ptak and Smith, 2011).

Taking into account this dilemma and the needs of a MPC that addresses a demand-driven manufacturing strategy, the DDMRP methodology was developed. DDMRP is a formal multi-echelon planning and execution method to protect and promote the flow of relevant information and materials through the establishment and management of strategically placed decoupling points (Ptak and Smith, 2016).

Becoming DDMRP does not mean "make to order everything" or "put inventory everywhere" or "forecast better". Becoming Demand Driven requires a fundamental shift from the centrality of supply- and cost-based operational methods (commonly referred to as "position and promote") to a centrality of actual demand- and flow-based methods (commonly referred to as "position, protect, and pull") (Ptak and Smith, 2016).

This new methodology was developed and published by Ptak and Smith (2011). These authors published a new book in 2016, where the latest developments of DDMRP were described (Ptak and Smith, 2016). These two works are consider to be the bible of the DDMRP field, and are the basis for the description of DDMRP in this research work.

DDMRP incorporates features of MRP, Distribution Requirements Planning (DRP), Lean, TOC, Six Sigma and Innovative concepts (Figure 3.1). Hence, it can be considered as a hybrid MPC system.

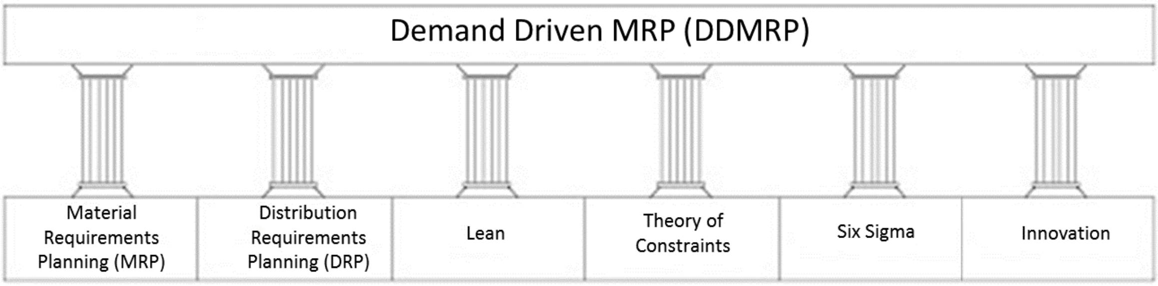

Figure 3.1: The methodological foundation of DDMRP (Ptak and Smith, 2016)

DDMRP is composed of five components. The first three components define the initial and evolving configuration of the DDMRP model. The fourth and fifth define the actual operational aspects of the DDMRP system, which are planning and execution.

Each of these components are explained in greater depth in the following subsections.

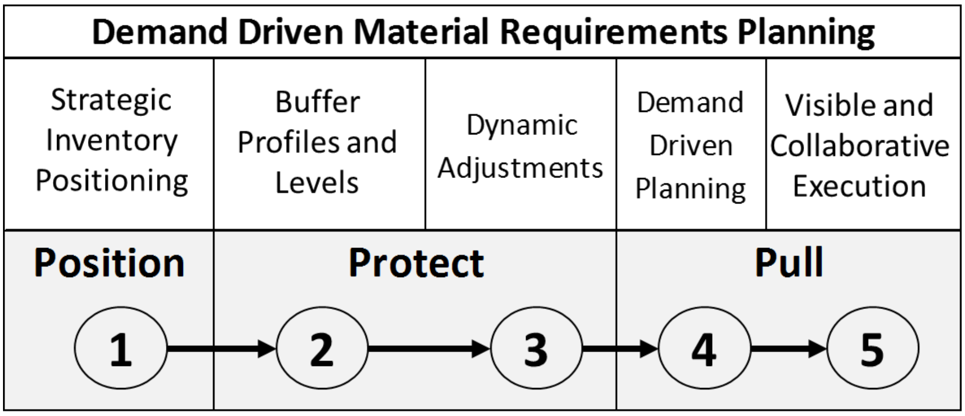

Figure 3.2: The 5 primary components of DDMRP (Ptak and Smith, 2016)

3.1. Strategic Inventory Positioning

This first component of DDMRP defines where to place the inventory to function as decoupling points. Decoupling points are “the location in the product structure or distribution network where inventory is placed to create independence between processes or entities. Selection of decoupling points is a strategic decision that determines customer lead times and inventory investment” (APICS, 2016, p.46).

Putting inventory everywhere is an enormous waste of company resources. Nonetheless, eliminating inventory everywhere puts the company and supply chain at significant risk. Considering that supply and demand variability are the enemy of flow, inventory is positioned in the BOM to become a breaking wall that breaks the wave of variability and compresses lead times (Figure 3.3). DDMRP proposed 6 positioning factors to position the inventory (Ptak and Smith, 2016).

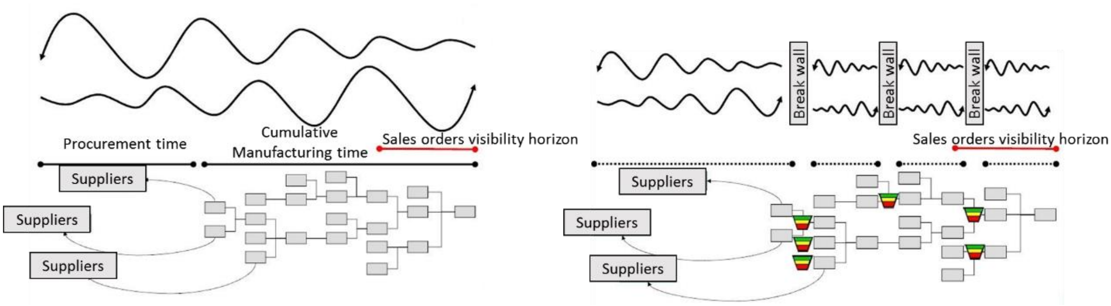

Figure 3.3: Supply chain (a) without stock and (b) with decoupling points (Ptak and Smith, 2011)

The allocation of decoupling points in the BOM creates a new lead time named Decoupled Lead Time (DLT) which is defined as "the longest cumulative coupled lead time chain in the product structure of a manufactured item. It is a form of cumulative lead time but is limited and defined by the placement of decoupling points within a product structure" (Ptak and Smith, 2016, p.69).

Figure 3.4. shows the DLT of an example end product FDP. The DLT of FDP is 7 days which is composed of the manufacturing lead time of FDP, 210 and 310 (red line). Manufacturing lead time of 410P and 412P are not considered since these parts have a stock-buffer.

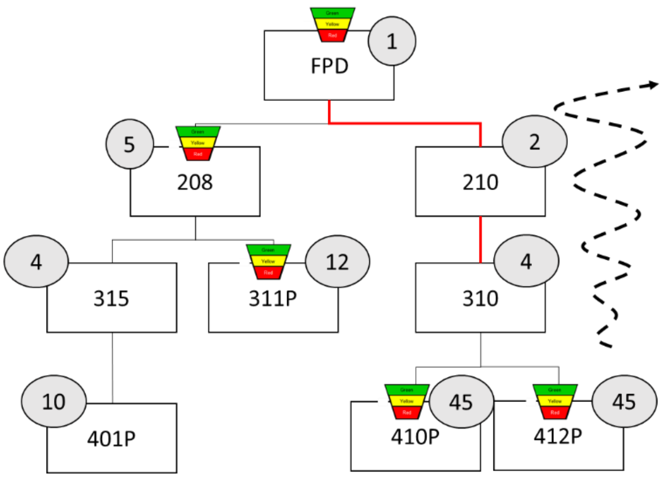

Figure 3.4: FPD product structure, lead times and stock-buffers (Ptak and Smith, 2016)

As a first step in the implementation of the DDMRP, the company needs to analyze its environment carefully and then position strategically the inventory in the supply chain.

3.2. Buffer profiles and level determination

The second step of DDMRP is to determine the amount of protection at the decoupling points. Too much inventory involves excess cash, capacity, materials and extra space to store this inventory. In addition, obsolescence risks are higher. On the other hand, when a company has too little inventory, frequent shortages prevail that can trigger missed sales opportunities and costly rush orders (Ptak and Smith, 2016).

Ptak and Smith (2016) argued that the correct inventory level of a part must be positioned between points A and B (Figure 3.5). Thus, inventory is considered an asset. Outside these two points, the inventory is considered as liability and triggers the aforementioned shortcomings.

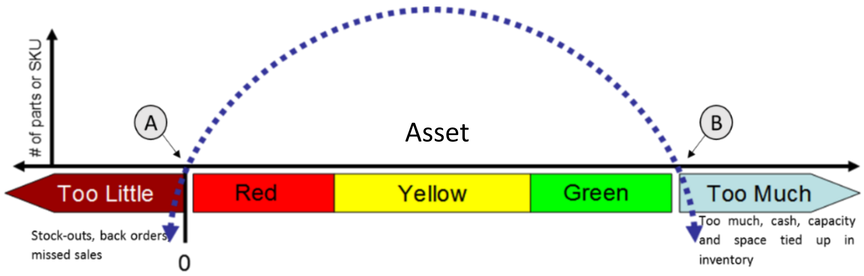

Figure 3.5: Inventory asset liability curve with buffer zones (Ptak and Smith, 2011)

Before dimensioning the inventory, in those parts that has been decided to position the inventory in the previous component, it must be defined the part designation to be used in order to manage each reference. DDMRP defines five different part designation (Figure 3.6) (Ptak and Smith, 2016).

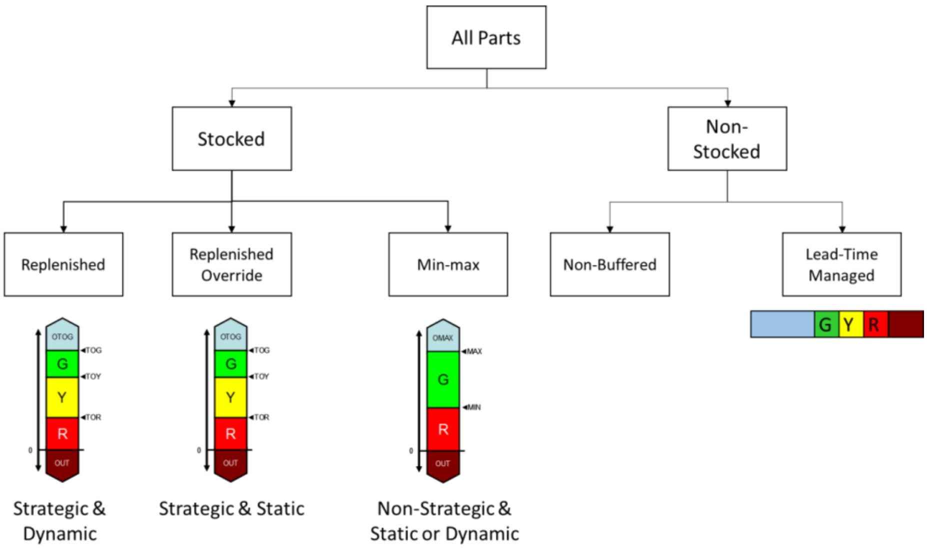

Figure 3.6: DDMRP part designation (Ptak and Smith, 2016)

- **Replenished parts:** These parts are strategically chosen parts that have several open orders within a lead time. These parts are managed by a color-coded buffer system for planning and execution where each zone has its function (Figure 3.7).

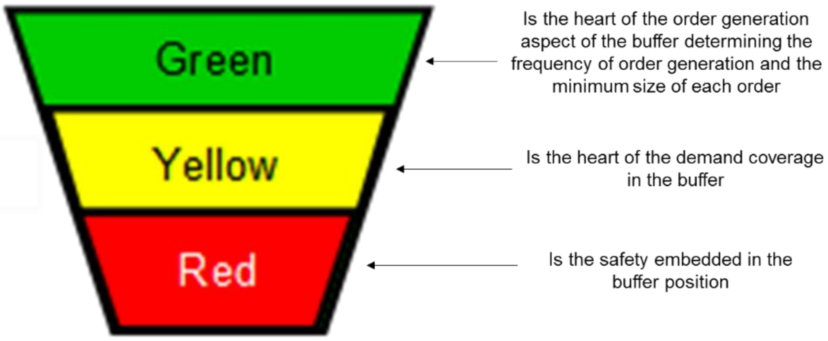

Figure 3.7: Zones of the buffer (Ptak and Smith, 2016)

To size each zone a combination of a grouping assignment (called buffer profiles) and individual part attributes are considered. The Buffer profile is a grouping of parts that have similar characteristics and thus can be managed with the same set of rules. The factors to be considered to define buffer profiles are explained below. Table 3-1 summarizes the main buffer profiles:

- **Item type:** Determines if the item is manufactured (M), purchased (P), distributed (D) or intermediate (I).
- **Lead time:** This can be segmented into three categories: short, medium or long.
- **Variability:** This can be divided into three segments: high, medium or low.

Table 3-1: Basic buffer profile combinations (Ptak and Smith, 2016)

	Purchased	Manufactured	Distributed	Intermediate		
Short	PSL	MSL	DSL	ISL	Low	Variability Category
	PSM	MSM	DSM	ISM	Medium	
	PSH	MSH	DSH	ISH	High	
Medium	PML	MML	DML	IML	Low	
	PMM	MMM	DMM	IMM	Medium	
	PMH	MMH	DMH	IMH	High	
Long	PLL	MLL	DLL	ILL	Low	
	PLM	MLM	DLM	ILM	Medium	
	PLH	MLH	DLH	ILH	High	

As for individual part attributes, DDMRP considers the following to size the buffer (Ptak and Smith, 2016):

- **Part Average Daily Use (ADU):** This rate is dynamic and is updated frequently. If the ADU significantly changes it will yield a significant change in the buffer size.
- **Part Lead Time:** For manufactured or intermediate item, this lead time should be the DLT of the part. For purchased parts, the purchase lead time and for distributed parts, the transportation lead time.

- **Part Minimum Order Quantity (MOQ):** This can affect buffer levels when they are large in relation to the rate of use. These are known as "significant" MOQ and will have a direct impact on the sizing of green zone of the buffer.
- **Part Location:** This attribute is unique to distributed part types. Each part that is distributed through the network has a separate ADU and Lead time for each distribution point.

Depending on the buffer profile and a few critical individual part attributes, each zone of the buffer is sized as explained below:

- **Green zone:**
  - **Option 1:** An imposed or Desired minimum Order Cycle (DOC) x ADU. This method is used when there is an imposed factor through the use of a product scheduling wheel or there is a desired average number of days between orders.
  - **Option 2:** Lead time factor x ADU. Lead time factor is a factor expressed in percentage of usage within a full lead time of the part.
  - **Option 3:** MOQ. If the buffered part has an MOQ the green zone should never be less than the MOQ. If the MOQ yields the largest value as a green zone (compared to option 1 and 2), then that MOQ is considered as significant.
- **Yellow zone:** ADU x DLT.
- **Red Zone:** This zone is divided in two subzones. Hence, the total size of red zone is the sum of both subzones.
  - **Red base:** Lead time factor x ADU x DLT.
  - **Red Safety:** Red base x variability factor. Like lead time factor, variability factor rate is a percentage that has a value depending on whether the part experiences high, medium or low variability.

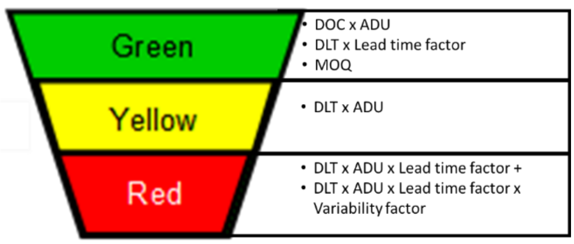

Figure 3.8: The buffer equation summary (Ptak and Smith, 2016)

- **Replenished override parts:** These items are like replenished parts but buffer zone levels are static. This system is used when there are space limits, for instance vending machines.
- **Min-Max (MM) parts:** This designation is for less strategic and readily available stock parts that do not have a stable consumption and do not work properly with the color-coded buffer. In addition, these parts do not have multiple open orders within a lead time. This buffer has defined a minimum quantity that works as an order point. If the stock level is below the minimum quantity, an order is recommended up to the maximum level.

  The following example describes how this buffer works: There is a reference X that on average is ordered once per month with 60 units. Considering that a month has 20 working days, the ADU of this reference is 6 units. Once the system is running, when an order of 60 units is launched, the net flow position (this concept is explained in Section 3.4) reaches the red zone, consuming the green, yellow and half of the red zone (Figure 3.9a).

  This is not the normal behavior of color-coded buffers since net flow equation usually flip-flops between the green and yellow zones. However, in this example whenever there is a request, the net flow equation will arrive at the red zone, not performing its function.

  If X reference is managed by an MM buffer, the red zone would be the amount of the spike (60 units in this example) and the green zone would be sized as the green zone of the color-coded buffer (15 units in this example).

  When a 60 unit order is launched, the net flow position crosses the reorder point generating a new order until the TOG zone (Figure 3.9b).

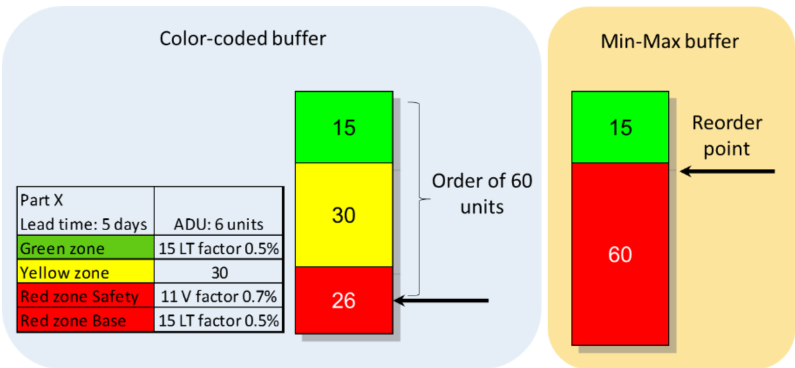

Figure 3.9: Example managed by (a) color-coded buffer and (b) MM buffer

- **Non-Buffered (NB) parts:** These parts are not stocked. They are transferred, made, or purchased to order or actual demand.

- **Lead Time Managed:** These parts are not buffered. But when there is a requirement for them, an alert is set to avoid synchronization problems. To this end, the lead time of the part is divided into three parts and the last third is divided into three zones: green, yellow and red. This last zone will be the lead time managed alert. Hence, when the part enters a zone, the planner will receive an alert notifying them of this fact.

By the end of this step, the company has defined and sizes each decoupling point, taking into consideration the buffer profile and the particular attributes of each reference.

3.3. Dynamic adjustments

Supply chains must be ready to adapt to volatile markets and provide the best service to the customer. This requires the use of dynamic buffers to be able to adjust to new requirements. For this purpose, DDMRP provides dynamic adjustments that define buffer level fluctuations based on operating parameters, market changes, and planned or known future events. The dynamic adjustments that DDMRP proposes are set out below (Ptak and Smith, 2016):

- **Recalculated adjustment:** Adjust buffer level based on changes to individual part attributes or buffer profile adjustments. The most dynamic part attribute is the ADU, hence it is consistently being recalculated and updated. DLT and MOQ may also change. These three attributes are involved in buffer zone determination, thus updating these attributes also updates the buffer zones.
- **Planned adjustments:** Are based on strategic, historical and business intelligence factors. These adjustments manipulate the buffer equation that affects inventory positioning by raising or lowering buffer levels and their corresponding zones at certain points in time. These adjustments are frequently used in seasonal parts, when introducing a new part or when a product is deleted.

At this point the company is already configured in a DDMRP environment.

3.4. Demand driven planning

Demand driven planning is the process by which supply orders (purchase orders, manufacturing orders, and stock transfer orders) are generated (Ptak and Smith, 2016). DDMRP proposes a Net Flow Equation that provides the supply order generation recommendation signal (timing and quantity) for buffer replenishment. This equation provides the Net Flow Position (NFP) of each buffer and should be performed daily in all decoupled points.

NFP is calculated as On-Hand + On-Order - Qualified Sales Order Demand. Where On-Hand is the physical stock, On-Order the quantity of stock that has been ordered but not received, and Qualified Sales Order Demand is the sum of sales orders past due, sales orders due today and qualified spikes.

An order is qualified as a spike if the order is within the future time window called Order Spike Horizon and the order quantity of a particular day surpasses the Order Spike Threshold (Figure 3.15).

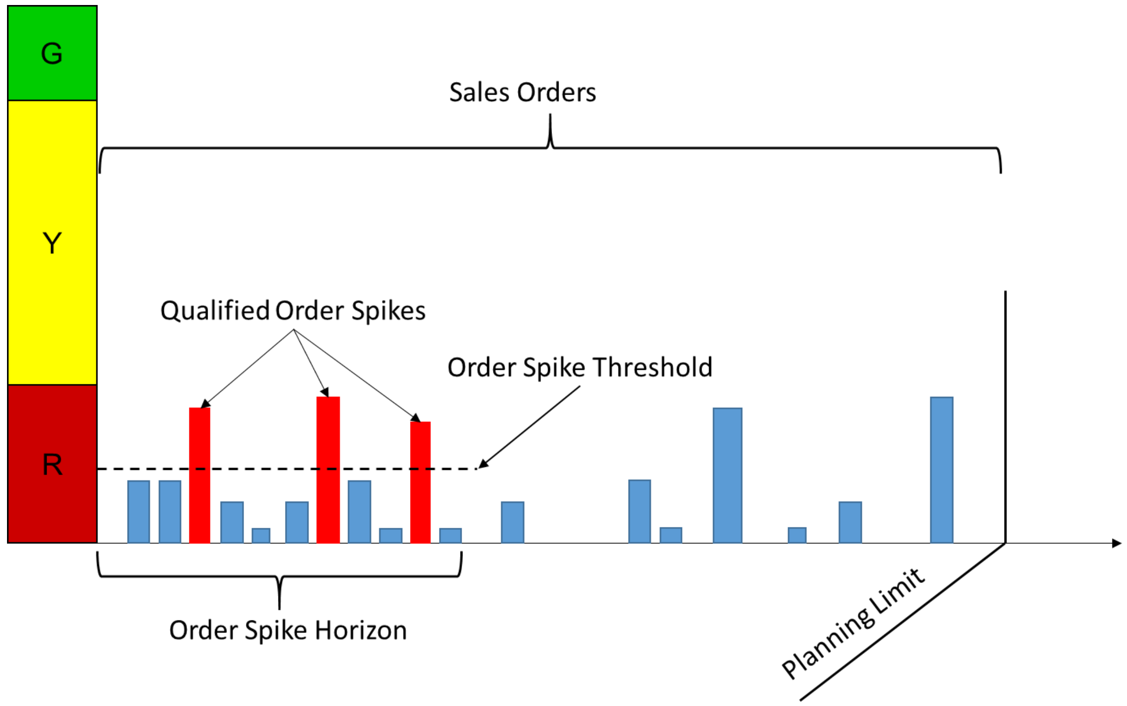

Figure 3.10: Order Spike Qualification (Ptak and Smith, 2011)

DDMRP generates a supply order generation based on NFP. Therefore, when the NFP is below the Top of Yellow (TOY), a supply order is recommended for a quantity that is the difference between the NFP and the Top of Green (TOG).

Decoupling points together with the planning process explained above allow decoupled explosions in the BOM. In other words, when a supply order is generated at a higher level, decoupling stops the explosion of the BOM at decoupling points placed at a lower level. The explosion stops since the decoupling point is buffered. Thus, the NFP is independently calculated at that point. The explosion will only continue if the NFP of that position is below TOY. Figure 3.11 shows an example of a decoupled explosion. When part FPA has its NFP below TOY explosion begins and stops when a decoupling point is found. ICB and SAD parts will explode independently when their NFP reaches the TOY. Finally, when the NFP of part SAB reaches its TOY, it will independently explode.

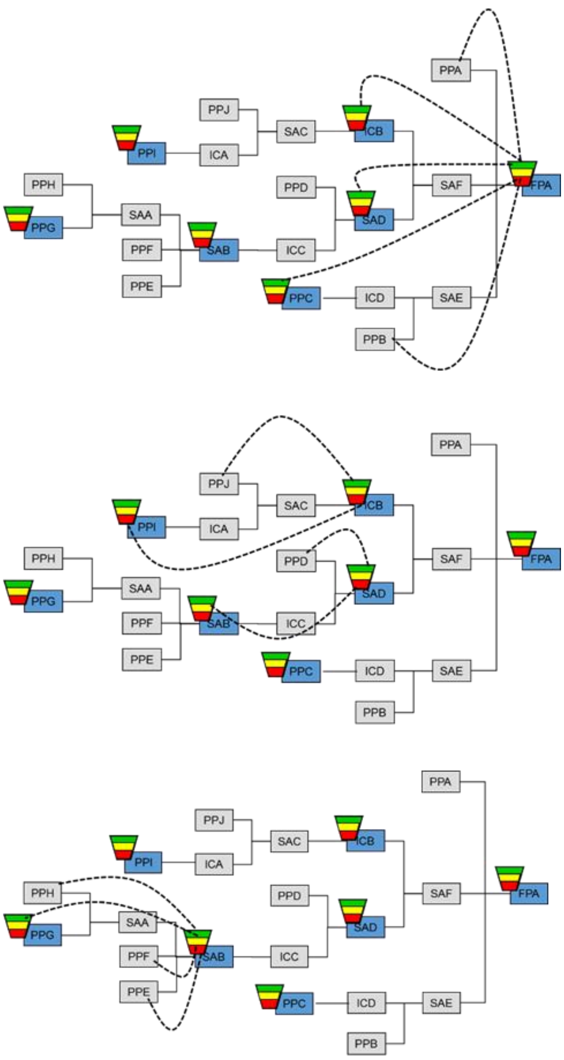

Figure 3.11: Decoupled explosion (Ptak and Smith, 2011)

With this approach, planning becomes much simpler as planners can see buffer status quickly and react appropriately before they get into trouble. In addition, the direct connection between forecast demand and supply order generation means that supply orders are being generated with signals that are known to be wrong. This ties up cash, capacity space, resulting in irrelevant materials and forces additional effort to obtain the relevant materials. DDMRP in contrast, avoids such pitfalls as it is based on real demand (Ptak and Smith, 2016).

3.5. Highly visible and collaborative execution

DDMRP distinguishes between planning and execution. Planning is the process of generating supply order requirements using NFP, and ends once the recommendations are approved and become open supply orders.

As for execution, this is the management of these open supply orders in order to protect and promote flow. For this reason DDMRP defines four alerts in two categories (Figure 3.12) (Ptak and Smith, 2011):

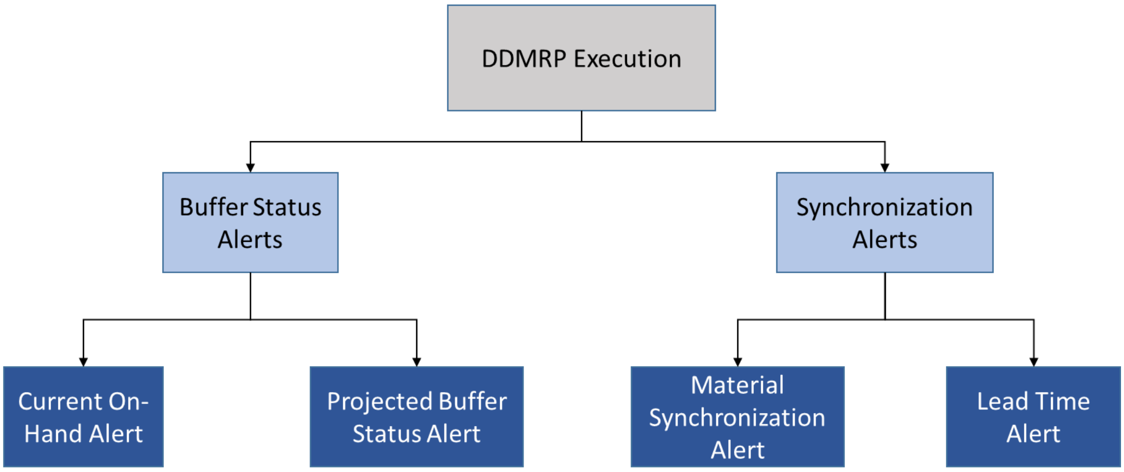

Figure 3.12: DDMRP basic execution alerts (Ptak and Smith, 2011)

- **Buffer Status Alerts:** Most supply chain personal use due dates to prioritize supply orders. Thus, when a supply is closer to being due it is considered a priority, and if it is past due it is more important than all other open orders.

  DDMRP on the other hand, uses the buffer status to prioritize the open orders since this shows real requirements and priorities. Buffer status is calculated considering only the on-hand percentage of the buffer. Thus, from an execution perspective, when on-hand is above Top of Red (TOR), the buffer status alert will display green. Yellow and red are determined by the severity of the on-hand situation in relation to the total red zone value. The most common way to determine the on-hand level is to set 50 percent of the red zone. Therefore, above this value the buffer status alert will display yellow and below red (Figure 3.13).

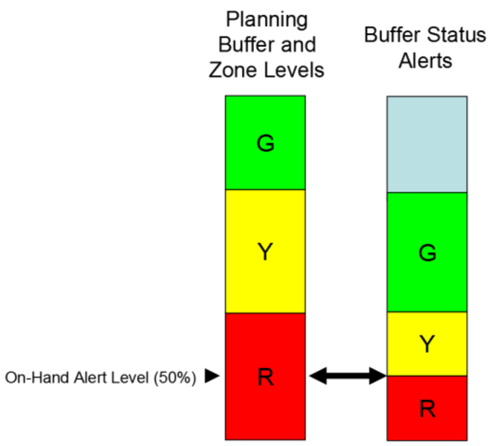

Figure 3.13: Buffer status alert zones (Ptak and Smith, 2011)

Table 3-2 shows an example of open supply orders with due date and buffer status information. If only the due date information was considered, orders PO 280-89, PO 279-84 and PO276-54 would have priority. However, analyzing the on-hand buffer status, supply orders PO 275-44, PO281-21 and PO276-54 show the on-hand value in red. Moreover, PO 275-44 is critically low with only three percent of the on-hand. Although its due date is later than the rest, in a DDMRP system this open supply order will have the highest priority, since its buffer is almost empty.

Table 3-2: Example of orders prioritized by buffer status (Ptak and Smith, 2011)

Order	Due date	Customer	On-hand buffer status
PO 280-89	12/5	Super Tech	54% (yellow)
PO 279-84	12/5	Super Tech	47% (yellow)
PO 276-54	12/5	Super Tech	27% (red)
PO 281-21	14/5	Super Tech	17% (red)
PO 275-44	16/5	Super Tech	3% (red)

- **Synchronization Alerts:** These are designed to highlight problems with dependencies between decoupling points. When synchronization problems have greater visibility less variability is transferred between buffers and to the customer.

Alerts provide relevant information and visibility about which order should take precedence. Using them, the company increases its visibility since it realizes quickly when an anomaly happens. Moreover, attention is focused only on those references that require management instead of wasting time checking references that are in good supply. Therefore, with the correct management of alerts the company gains agility and reacts on time avoiding shortages (Ptak and Smith, 2011).

Chapter 4

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4. Critical study of the state of the art

Since the 1980s companies have been forced to compete in an increasingly volatile market, delivering more complex and customized products, with shorter lead times. Many businesses however, continue to struggle with inaccurate forecasts, complex material synchronization and long lead times of multiple offshore suppliers, forcing them to maintain large stocks to provide a good service level.

This thesis has analyzed the most widely used MPC systems, as the systems play an important role in the company planning the requirements of materials and executing orders to meet customer demand. Nevertheless, an analysis of the literature reveals that although market requirements have changed and technology has evolved considerably, MPC systems have not evolved in the same manner hindering the agility of the company to respond to demand. In the following lines, the main features of each system are summarized.

The ROP system is the first known MPC. When it emerged, after the Industrial Revolution, it represented an important approach, managing inventory when companies began producing in bulk. In the 1960s, it was replaced by the more complete MRP system. Nowadays ROP is used in companies because it is a cheap alternative to managing inexpensive parts when an implementation of a more costly MRP cannot be justified (Jacobs and Whybark, 1992).

Among other benefits, MRP developed the BOM, reduced inventory holding cost and improved customer service level. Nonetheless, MRP has some weaknesses. It is based on a push system which means that supply requirements are driven by forecast, thereby generating uncertainty. As MRP produces a dependent binding between parts of the BOM, the variability generated by the forecasting transmits nervousness through the BOM. Moreover, MRP considers that everything goes exactly according to plan to obtain the predicted result. Therefore, it is not able to execute and control open orders when things do not go exactly as planned. Thus, companies are overwhelmed by rush orders resulting in the maintenance of high stock levels to be able to meet customer demand.

Another widely used MPC is the JIT system, the aim of which is to reduce costs by eliminating waste from the manufacturing process. The JIT system is based on a pull system and uses the Kanban tool as a signal to know what to produce, managing each part independently. JIT reduces the batch size by shortening the setup time, eliminating process inventory and standardizing jobs (Huq and Huq, 1994; Benton and Shin, 1998). Nonetheless, it only achieves its goal in repetitive manufacturing environments. In other words, as JIT does not consider the planning process, when there is uncertainty or long lead time references are present, the system shows shortcomings, requiring higher stock levels to meet customer requirements. Therefore, in dynamic environments, MRP performs better than the JIT system (Huq and Huq, 1994; Benton and Shin, 1998; Lage and Godinho, 2010).

As regards TOC, its aim is to manage bottlenecks to increase the throughput of the company. This MPC is composed of 5 steps (Goldratt, 1990). According to Mabin and Balderstone (1999) and Watson et al. (2007) this MPC performs better than MRP and JIT. It shortcoming however, lies in the fact that it does not make material requirements planning and thus does not identify the real material necessities.

Considering that supply and demand variability is the enemy of flow, DDMRP was developed to protect and promote the flow of relevant information and materials through the business. It dampens, if not eliminates, the unnecessary nervousness of traditional MRP systems and the resulting bullwhip effect in complex and challenging environments. This MPC supplies the company with flexibility and visibility of real requirements and manufacturing orders, so as to adjust to market requirements and make appropriate decisions aligning the company to the demand driven manufacturing strategy (Ptak and Smith, 2011). The analysis of the literature undertaken in this thesis shows that traditional MPC systems struggle to achieve this goal.

Using a traditional MPC system, the stock level shape of a company shows a bimodal distribution that can be described as "too much of the wrong and too little of the right at any point in time and too much in total over time" (Ptak and Smith, 2016, p.11). Bimodal distribution is as set out in Figure 4.1 Stage 1, where the inventory level flip-flops back and forth between too much and too little inventory entailing high cost and low service level. Nevertheless when a part begins to be managed by DDMRP outlying events are reduced and a single uniform distribution is achieved (Figure 4.1 Stage 2). Before long, this part shows a tighter uniform distribution with even smaller amounts of outlying occurrences (Figure 4.1 Stage 3) (Ptak and Smith, 2016).

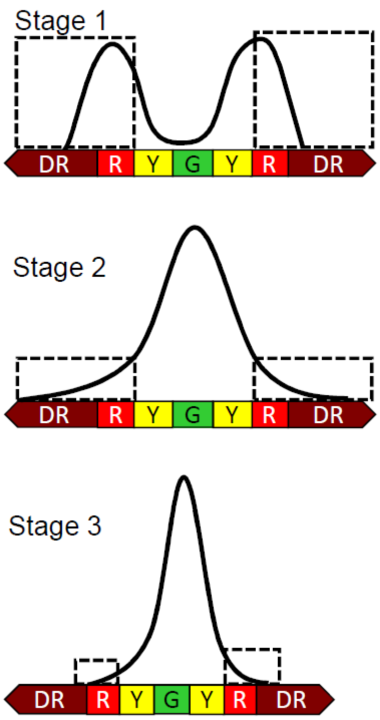


Figure 4.1: The progression of a company through DDMRP (Ptak and Smith, 2016)

Bearing in mind the advantages that DDMRP provides, the logical next step is to analyze DDMRP implementation. For that purpose DDMRP scientific works were analyzed and are summarized below:

- Ptak and Smith (2011) explained the implementation of DDMRP in two different companies:
  - Oregon Freeze Dry is the largest diversified food freeze dryer in the world. This company used traditional MRP before DDMRP implementation. They implemented DDMRP in 2012 with the following results: sales increased by 20%, customer fill rate increased from 79% to 99.6% and inventory was reduced by 60% at their Mountain House division. In the Industrial ingredient division, lead time was reduced by 60% in make to order orders, they achieved 100% on-time delivery and inventory was reduced by 20%. Raw material also was reduced by $2.5 million and did not have any stockouts.
  - Le Tourneau Technologies Inc. is a manufacturing company specialized in large scale and high load bearing equipment for a number of industrial applications including oil and gas, steel, mining and forestry products. This company has two sister facilities: Longview and Houston. They were both similar in size, making similar products, with similar capabilities, equally strong management, both using exactly the same ERP system. In 2004 the company found itself with a set

of recurrent problems that was hampering its ability to capitalize on the predicted upswing in its market. To underline: too long cycle times, too high WIP, too high obsolete inventory, too low inventory turns, too low on-time delivery, too high overtime and expediting and too low Return on Average Capital Employed.

Considering the situation, Le Tourneau engaged Constraint Management Group for a strategic planning session where many synchronization opportunities between various market segments were found:

- The company implemented DDMRP on strategic parts to ensure pull based production and project systems would not suffer from shortages.
- They implemented DBR to redefine the manufacturing scheduling and execution strategy.
- To redefine the project control and execution strategy Critical Chain Project Management was implemented.
- Finally a new set of rules and metrics to support the above implementation strategy were applied.

The improvement model strategy defined above was implemented primarily in the Longview facility. The Houston facility stayed with a more traditional MRP driven system.

After the implementation, the Longview facility was able to dramatically control inventory, and expenses while maintaining excellent service level.

In 2005 there was rampant growth. In this period the revenue of Longview tripled (over $400 million) while inventory rose only by $80 million. However, in Houston inventory ended up growing at nearly the same rate as revenue.

In 2008 the markets began to cool off. Thus, in Longview DDMRP adjusted inventory levels to the situation while maintaining service levels. However, by this period Houston had a large amount of inventory. Furthermore, due to the nature of forecasting there was a risk that the inventory grew beyond revenue in the short run. Ptak and Smith (2011) stated that this is a classic effect of traditional MRP driven environments.

- Ptak and Smith (2016) described a case study where DDMRP was implemented in Maquila Internacional de Confecciones (MIC) which is a manufacturer and supplier of children´s clothes in stores of Colombia, Venezuela, Dominican Republic and Curaçao.
  The main reasons the company decided to implement DDMRP are listed below.

  - The company had unsatisfactory service level since it was suffering from constant stockouts in finished goods and raw materials.
  - MIC had long lead times to market.
  - Purchasing, production and distribution decisions were based on forecast.
  - The company intended to minimize unit costs, causing an excessive amount of WIP throughout the plan to maximize local production efficiencies.
  - MIC had constant "scarcity sensation" in stores despite having excess inventory
  - The cash flow of the company was negative.

  After the implementation of DDMRP the Operation Manager of MIC reported these results: 60% increase in revenues, 40% decreased inventory in the retail chain, longer product life cycles requiring less renewal of the product portfolio and reducing the complexity in the supply chain. They also noted that sales of high movers were 9 times higher during the high season (Christmas) compared with those of the same period before implementing DDMRP. In summary, in less than 18 months, MIC transformed from being in deep crisis to be granted with the distinction as "Best Supplier of the Year" by the largest retailer of Colombia.

- The Demand Driven Institute organized different DDMRP International world conferences where companies explained their experience with DDMRP. Some example experiences are summarized below:
  - Avigilon designs and manufactures high-definition surveillance solutions. They provide products to airports, casinos, heath care, stadiums and city surveillance among others. In 2010 this company had rampant growth. However they were having some operational problems since stocking locations were unplanned, priorities were not clear, overtime and rush orders were frequent and the backlog was growing but the offered service was eroding. Thus in 2013 Avigilon engaged Constraint Management Group and implemented DDMRP. As a result, Avigilon highlighted that the offered service level to the customers increased to greater than 99% and without any backlog. This was a great improvement since in 2013 it had $5 million backlog. Moreover overtime and expedited freight costs dramatically reduced. The company began planning the horizon from "what do we need to build now to fill orders" to "which stock buffer needs to be replenished". Furthermore, production volume increased significantly and plant performance increased with less stress and no heroics (Gelhorn, 2014).
  - British Telecom delivers home broadband equipment, set top boxes and mobile phones to about 25,000 customers every day. This company also provides

engineering consumables to over 28,000 engineers fulfilling around 15,000 orders every day. Before DDMRP, British Telecom had several proposals underway to improve the performance of the supply chain. For instance, statistical and business intelligence approach were used to forecast the demand. Distribution Resource Planning was used to place purchase orders against planned demand. Inventory optimization was used to calculate the optimal inventory level and SS to cope with forecast error. Sales and Operations Planning was used to balance supply and demand and achieve forecast accuracy. However, planning activities were still reactive and the inventory performance was below expectation. British Telecom wanted to improve forecast accuracy but did not know how to achieve it.

In 2016 the company decided to trial DDMRP by running a simulation. This allowed the company to compare the simulated DDMRP results to the existing systems in operation, drawing these conclusions:

- Stock was in balance and total inventory was halved
- DDMRP was not dependent on forecast so there was a chance to decouple from forecast error
- There were no service issues
- Inventory reduction
- Stable load in the factory

Finally the company implemented DDMRP obtaining the following results: 32% reduction in finished goods inventory, 43% reduction in SKUs over TOG, the company was not ordering product that they did not need, no reduction in service, availability above 99% and expedites and schedule breaks were reduced to almost 0 (Dooley, 2017).

- Michelin manufactures tires for different vehicles and equipment. Before DDMRP, Michelin recorded a high service level carrying heavy costs and considerable management workload due to changes in plan, overtime and shipments. With the aim of improving the performance of the company, Michelin implemented DDMRP in Valladolid (Spain), and as a result of the implementation supply crises were significantly reduced and risks and anomalies were efficiently identified in real time. Due to these improvements, the company decided to expand the implementation to the rest of the plants worldwide (d'Herouville, 2017).

In addition to the case studies presented by the developers of DDMRP, a number of researchers have analyzed the performance of this methodology in different simulated environments.

- Lee and Jang (2013) studied current inventory level of three companies and simulated the reasonable inventory on-hand level that the company would have based on DDMRP replenishment buffer management.
- Lee and Jang (2014) developed a thesis whose purpose was to prove that DDMRP was more robust than MRP in terms of some critical areas of performance. The work involved simulations with a system dynamic technique.
- Rim et al. (2014) carried out a study where a model was developed to determine the optimal position and quantity of WIP inventory for a given BOM using the actively synchronized replenishment lead time.
- Ihme and Stratton (2015) simulated how a real company that was using MRP would manage its material with DDMRP and compared the real results using MRP with those achieved in the simulation.
- Ihme (2015) evaluated DDMRP in the context of improving the performance of a printing ink manufacturing company. This evaluation involved simulation that showed the merits of DDMRP in the area of standardization of production-relevant decision-making and stock adjustment. Availability was improved as indicated by roughly 45% reduction of inventory alerts and a 95% reduction of stockouts over the period in focus.
- Miclo et al. (2015) wrote a case study to compare objectively and quantitatively MRP and DDMRP using Discrete-Event Simulation. The results showed that DDMRP obtained improved output indicators compared to MRP II with less working capital and WIP. Moreover, DDMRP adapted more rapidly to real demand. However, in this case study DDMRP had less satisfactory on-time delivery.
- Miclo (2016) simulated two case studies of MRP II, Kanban and DDMRP and compare the results. The first case was based on the Kanban game ""Jeu du Kanban©" scenario while the second one was based on a real company. Once the scenarios were modeled and simulations run, the author adjusted some DDMRP parameters using optimization algorithms.
- Miclo et al. (2018) explored DDMRP and evaluated its effectiveness relative to two other widely accepted approaches – MRP II and Kanban/Lean production – through a series of structured computer simulation experiments.

- Shofa and Widyarto (2017) compared and evaluated the performance of DDMRP and MRP in terms of level of effective inventory in an automotive company in Indonesia. Based on the simulation, DDMRP gave better results than MRP in terms of lead time and inventory level. DDMRP compressed the lead time part from 52 to 3 days (94% reduction) and overall, the inventory level was in an effective condition, which suggested that DDMRP was more effective for controlling the production-inventory.

The studies presented thus far, indicated that DDMRP manages material efficiently. However, Ihme (2015); Shofa and Widyarto (2017) stated that few studies have scientifically proven the performance of DDMRP. Miclo (2016) also pointed out the need for further research to uncover more aspects of DDMRP in terms of its value to manufacturing organizations. In addition, Lee and Jang (2014) highlighted the lack of studies of a real implementation of DDMRP in a company, to demonstrate that it achieves the theoretical results.

The present work therefore, analyzes three DDMRP implementation case studies in three real companies to determine the impact of DDMRP on competitive advantage.

Chapter 5

5. Development of research framework, objective and propositions

In this chapter we develop the research framework for the present study. To this end, in Section 5.1, we define the research framework and delimit the research question. In Section 5.2, the objective of this study is outlined and, in Section 5.3, we develop the propositions.

5.1. The research framework

Companies nowadays are competing in a global market whose uncertainty is growing. At the same time, the profile of the customer is becoming even more demanding and less tolerant of mistakes or delays.

Several authors claim that efficient material flow management can position the company to improve competitive advantage. Logistical factors such as service level, inventory level and visibility within the supply chain are considered key to achieving this goal. For this reason, traditional MPC systems were analyzed in the literature review, emphasizing the advantages and disadvantages of each in dealing with current market requirements.

The DDMRP methodology was also analyzed to fully understand its philosophy and characteristics. Studies undertaken to date, suggest that this methodology can efficiently manage material flow of a company facing dynamic market requirements. However, all the works found in the literature have analyzed DDMRP in a simulated environment, and to the best of our knowledge there are no cases which study the implementation of this system in a real scenario.

This research work thus defines the following research question: **How does the material flow of a company perform in terms of service level, inventory and the number of unplanned rush orders after implementing DDMRP?**

5.2. Objective of this research study

Considering the research framework and the research question, the goal of this work is to analyze DDMRP implementations in real companies so as to evaluate the performance of material flow management.

Specifically this work analyzes in detail the changes that a company underwent after the implementation of DDMRP in terms of the planning and execution of purchasing and manufacturing orders. In the analysis, special emphasis was placed on the visibility that the Planning Manager requires to perform these tasks correctly. A quantitative analysis of the evolution of the inventory vs. material consumption and the stock coverage was also carried out. Visibility in the supply chain and the level of inventory vs material consumption are considered key to efficient supply chain management and can provide competitive advantage to the company (Jones and Riley, 1985; Hoyt and Huq, 2000; Barratt and Oke, 2007).

5.3. Research propositions development

The following propositions underpin the present work:

- **Proposition 1: A company that manages its materials with DDMRP increases the visibility of the flow of materials in the supply chain, reducing the number of unplanned rush orders.**

MRP was developed for planning supply order requirements. However, it does not provide tools that alert or help management when planned orders undergo deviations (Section 2.3). The JIT system was developed to execute and control open supply requirements but this system does not plan material requirements. Hence, supply chains with important variability tend to suffer from stockouts. In addition, this MPC does not alert when shortages are going to happen (Section 2.4). As for TOC, it is focused on the bottleneck, however in complex BOM or with references with long lead times, a tool like MRP to carry out the plan is lacking.

In summary, it seems that traditional MPCs do not provide visibility through the supply chain to react on-time in light of possible deviations. These types of situations are thus managed by launching unplanned rush orders.

In contrast, one of the main objectives of DDMRP is to increase the visibility of the supply chain. For that purpose, it incorporates different alerts which aim is to show in real time the status of the materials. In case of any deviation, the company can manage the situation avoiding shortages and reducing rush orders (Ptak and Smith, 2011). Proposition 1 allows us to test this fact in the analyzed case studies.

- **Proposition 2: A company that manages its materials with DDMRP is able to offer the same or even higher service level with less inventory level.**

Managing materials with traditional MPC systems makes the relationship between service level and inventory exponential (Graph 2.1). In contrast, Ptak and Smith (2011) found that by managing materials with DDMRP, companies adjust their inventory level to the real demand and this adjustment usually translates into a reduction in the inventory level maintaining or even increasing the provided service level. Proposition 2 allows us to test this fact in the analyzed case studies.

Chapter 6

6. Research design and methodology

In this chapter, we describe the design and methodology followed in the research project. Specifically, in Section 6.1, we present the research design; in Section 6.2 the research strategy is defined; in Section 6.3, we explain the research tactics; and, in Section 6.4, the research design and methodology of this thesis is summarized.

6.1. Research design

Many authors have different opinions about what a research design includes (Robson, 2002; Yin, 2009; Hernández Sampieri et al., 2010), but all agree that a research design is a guideline of how to obtain the goal of the research statement. Robson (2002) defined two general principles and the aspects that must be followed for research design development (Table 6-1):

1. **Strategy:** The general broad orientation taken in addressing research questions.
2. **Tactics:** The specific methods of investigation.

Table 6-1: Research methodology aspects (Robson, 2002)

Research Strategy	Identification of the research purpose. Selection of the research strategy. Unit of analysis.
Research Tactics	Data collection methods. Analysis of data and evaluation.

6.2. Research strategy

Following the aspects depicted in Table 6-1, in Section 6.2.1 we explain the research purpose; in Section 6.2.2 we select the research strategy and type; and, in Section 6.2.3, the unit of analysis of this work is defined.

6.2.1. Identification of the research purpose

Every research method can be used for all three purposes: exploratory, descriptive and explanatory. A research has an exploratory purpose when the aim is to understand how a new phenomenon takes place, identifying key issues and key variables. In other words, it is an attempt to lay the groundwork that will lead to future studies. As a result, exploratory research lays the initial groundwork for future research (Robson, 2002).

As to descriptive purpose, its aim is to convince someone that a phenomenon is relevant (Gummesson, 2000; De Massis and Kotlar, 2014). This is used when the study provides an accurate description of observations of a phenomena. In other words, studies that explore and explain while providing additional information about a topic have a descriptive research purpose (Robson, 2002).

The final research purpose is the explanatory one and its aim is to understand why an event takes place analyzing the cause and effect relationship between variables. Specifically, explanatory research looks at how things come together and interact. This research does not occur until there is enough understanding to begin to predict what will come next with some accuracy (Robson, 2002).

In Table 6-2 we highlight the main characteristics of each purpose.

Table 6-2: Main characteristics of research types (Robson, 2002)

TYPE	CHARACTERISTICS
Exploratory	To find out what is happening. To seek new insights. To ask questions. To assess phenomena in a new light. Usually, but not necessarily, qualitative.
Descriptive	To portray an accurate profile of persons, events or situations. Requires extensive previous knowledge of the situation etc. to be researched or described, so that you know appropriate aspects in which to gather information. May be qualitative and/or quantitative.
Explanatory	Seeks an explanation of a situation or problem, usually in the form of causal relationships. May be qualitative and/or quantitative.

To the best of our knowledge, only a few scientific works analyze DDMRP in a simulated environment but there are none which analyze how a real company manages material flow using DDMRP. Moreover, different authors that have researched DDMRP pointed out the need for this type of study. Hence, the present work aims to analyze how the material flow of a company performs in terms of service level, inventory and the number of unplanned rush orders after implementing DDMRP.

We thus consider that the research purpose of this study is exploratory as we have studied a new methodology of which there have been few studies carried out so far. In addition, the work has a descriptive purpose, describing the operations of the analyzed companies before, during and after DDMRP implementation to assess the changes.

The explanatory purpose has been discarded as this study did not aim to analyze the causal links between the variables involved in the methodology. This is a possible future line of work.

6.2.2. Selection of the research strategy and research type

Research strategy can be designed as quantitative or qualitative. Quantitative research is based on mathematical or numerical data, statistical or computational techniques to determine patterns of behavior or test theories (Robson, 2002). Qualitative research, on the other hand, is when the design evolves during the data collection and when participants are asked broad questions and word data is collected (Robson, 2002).

This work follows a qualitative research strategy since, to answer the research question it is necessary to examine in depth material and production management of the company before, during and after DDMRP implementation. Hence, to carry out this work, no mathematical or statistical calculation is required, as the aim is not to analyze any pattern of behavior between variables. Thus, quantitative strategy is discarded.

As to the research type, Yin (2009) proposed 5 different methods of research (Table 6-3).

Table 6-3: Relevant situations for different research methods (Yin, 2009)

METHOD	FORM OF RESEARCH QUESTION	REQUIRES CONTROL OF BEHAVIORAL EVENTS?	FOCUSES ON CONTEMPORARY EVENTS?
Experiment	How, why?	yes	yes
Survey	Who, what, where, how many, how much?	no	yes
Archival Analysis	Who, what, where. How many, how much?	no	yes/no
History	How, why?	no	no
Case Study	How, why?	no	yes

To determine the best research methodology, the following three factors should be taken into account (Rowley, 2002; Yin, 2009):

- **The types of questions to be answered:** The research question of this work is to know how the material flow of a company perform in terms of service level, inventory and the number of unplanned rush orders after implementing DDMRP. Hence, the how questions type are answered.
- **The extent of control over behavior events:** In the examined case studies, the implementation of DDMRP was finished before the analysis commenced. Hence, we had no control over the behavior of the events.
- **The degree of focus on contemporary as opposed to historical events:** As DDMRP was published in 2011, it can be considered as a contemporary event.

Case studies are useful when how and why questions are being asked about a contemporary set of events over which there is little or no control (Table 6-3) (Yin, 2009). Therefore, to develop this research, the case study methodology was chosen.

To make sure that the chosen methodology was appropriate a bibliographic search of similar studies was carried out. According to Eisenhardt (1989), among qualitative methods, case studies present one of the most adopted qualitative methods in organizational and management studies since they encourage "understanding the dynamic present within single settings". Many other authors asserted that case studies are recognized as a standpoint to generate and test theory that has provided the management field with ground-breaking insights (Pettigrew and Pettigrew, 1973; Burgelman, 1983; De Massis and Kotlar, 2014). Along the same lines, case studies are defined as a method that is ideally suited to generating relevant knowledge (Leonard-Barton, 1990; Amabile et al., 2001). Moreover, case studies help to explore and describe the data in real-life environments, as well as to explain the complexities of real-life situations which may not be captured through experimental or survey research (Guide Jr and Srivastava, 2000; De Massis and Kotlar, 2014).

6.2.3. Unit of analysis

Regarding the unit of analysis, Yin (2009) defined 4 different designs (Figure 6.1). Single-case study projects are most useful at the outset of theory generation and late in theory testing. On the other hand, multiple-case designs are desirable when the intent of the research is description, theory building or theory testing (Benbasat et al., 1987). In addition, there is another classification depending on the unit of analysis: holistic is composed of a single unit of analysis whereas embedded is composed of multiple units of analysis.

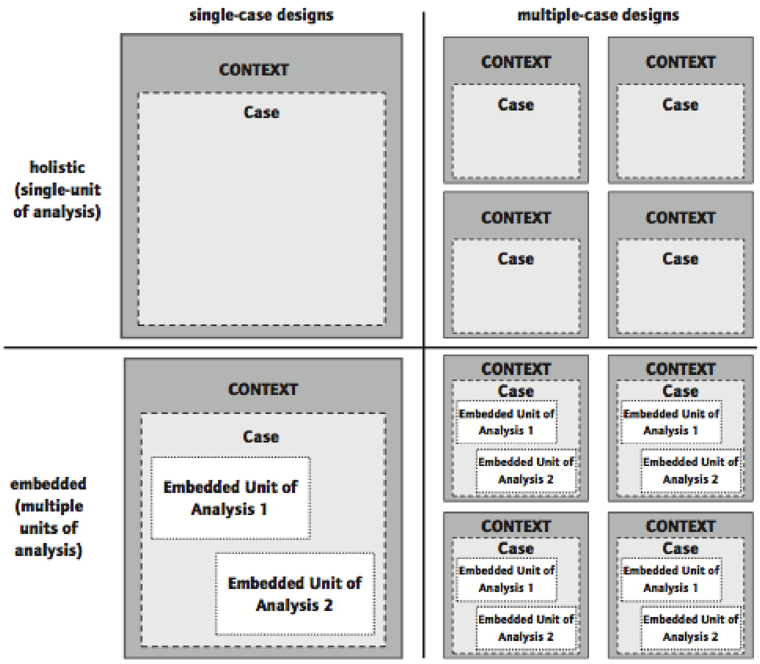


Figure 6.1: Basic types of design for case studies (Yin, 2009)

In the selection of the cases to be examined, it is important to bear in mind that the selected cases should be particularly suitable for visualizing a phenomenon and for extending relationships among variables (Eisenhardt, 1989; Graebner and Eisenhardt, 2004).

We chose three companies in different sectors so as to analyze the performance of DDMRP in different environments. In addition, in each of these three cases DDMRP was implemented in different links of the supply chain, allowing analysis of the performance of the system in each link.

For the first case study an implementation of DDMRP in CS1 Company was selected. This company buys and distributes goods without transforming them. In this case study, we analyzed the management of the material flow between suppliers and external customers (Figure 6.2).

For the second case study, CS2 Company was selected. This company buys raw material from different suppliers, transforms the raw material and offers a wide catalog of finished products to external customers. However, CS2 decided to only implement DDMRP in the purchasing area. Firstly, this case study allowed us to replicate the first case study since CS2 managed the flow of materials between suppliers and CS2 using DDMRP. In addition, it allowed us to analyze how DDMRP managed the needs of the internal customer, namely, the production. It is worth mentioning that as a result of the decision to limit DDMRP implementation to the purchasing area, production was managed with a different tool (Figure 6.2).

For the last case study, CS3 Company was selected. CS3 implemented DDMRP throughout the supply chain, allowing us to replicate the previous two cases. As in case studies 1 and 2, the flow of materials between the suppliers and the company was managed by DDMRP. Furthermore, in the same way as CS2, the needs of production were met by DDMRP. The novelty of this case was that it allowed us to analyze the production management using DDMRP (Figure 6.2).

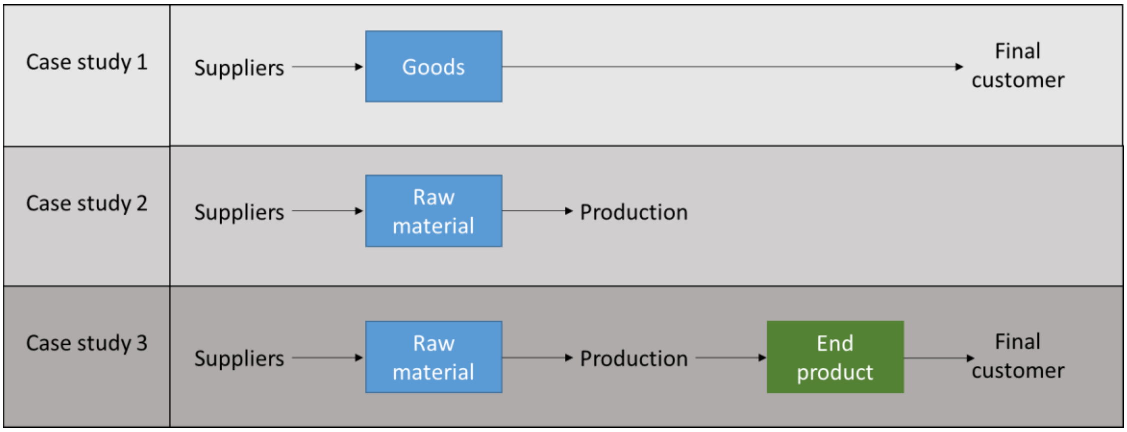


Figure 6.2: Summary of the case studies of this research work

As for the unit of analysis, in all cases it was the company itself. Therefore, the selected design of this research work was the holistic multiple-case study.

The case studies were analyzed following the methodology developed by Yin (2009) as set out in Figure 6.3:

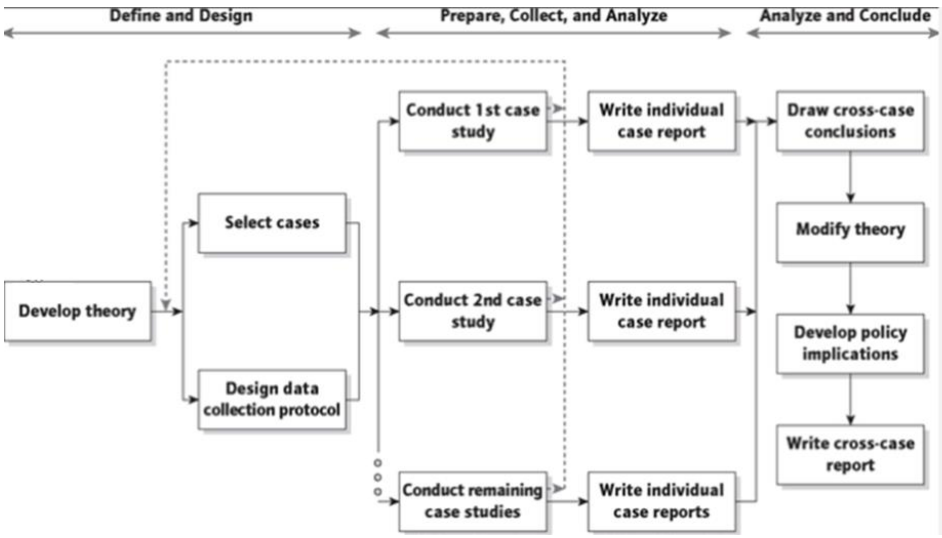


Figure 6.3: Case study methodology (Yin, 2009)

6.3. Research tactics

In this section we describe the research tactics of this study. Specifically, in Section 6.3.1, we explain the methods used to collect the data; in Section 6.3.2, we describe the research instruments used during the interviews; and, finally, in Section 6.3.3, we define how we analyzed and evaluated the data collected during the case studies.

6.3.1. Data collection methods

Depending on the kind of the research, there are different ways to collect data. The main methods to collect the data in qualitative research are summarized below (Table 6-4) (Yin, 2009).

Table 6-4: Summary of the different ways to collect data for qualitative research (Yin, 2009)

SOURCE OF EVIDENCES	STRENGTHS
Documentation	Letters, e-mail correspondence, administrative documents, etc. Helpful in verifying the correct spelling and titles or names of organizations that might have been mentioned in an interview. Can provide other specific details to corroborate information from other sources. Inferences can be made, but it is important to treat them as clues worthy of further investigation.
Archival records	Computer files and records such as service records, organizational records, maps, survey data, etc. In some case studies, records can become the object of extensive retrieval. In others, they may be only of passing relevance.
Interviews	One of the most important sources of case study information. Are guided conversations rather than structured queries.
Direct Observation	To see the natural setting of the case that is going to be analyzed.
Participant-observation	A type of observation where the viewer takes part in the case study by participating in the events.
Physical Artefacts	A technological device, a work of art or some other physical evidence.

Among data collection methods, interviews are often the primary data source in case studies (Eisenhardt and Graebner, 2007; De Massis and Kotlar, 2014). Interviews provide a direct contact with the main actors of the implementation, providing the opportunity to know the case thoroughly. For this reason, we used interviews as our main information source. Moreover, interviewing different profiles in the company provided different perspective of the same topic.

In addition to interviews, we also used archival records and documents to gather specific data about different indicators. We also used these documents as evidence to show the information collected in interviews.

We used triangulation to enhance data credibility (Patton, 1990; De Massis and Kotlar, 2014). In other words, the use of multiple data sources offered the chance to observe the same phenomenon from different angles, making findings more convincing and accurate (Jick, 1979; Pettigrew, 1990; Yin, 2009; Tracy, 2010; Stake, 2013; De Massis and Kotlar, 2014).

6.3.2. Research instrument

According to Robson (2002) there are three different types of interview: structured, semi-structured and unstructured, as illustrated in Table 6-5.

Table 6-5: Summary of the types of interview (Robson, 2002)

INTERVIEW TYPE	DESCRIPTION
Structured interview	Is a questionnaire with fixed questions in a predetermined order and standardized application, whereby responses to most of the questions have to be selected from a small list of alternatives.
Semi-structured interview	Has predetermined questions, but the order can be modified based upon the perception of interviewer of what appears most appropriate. Question wording can be changed and explanations given; particular questions, which seem inappropriate with a particular interviewee can be omitted, or additional ones included.
Unstructured interviews	The interviewer has a general area of interest and concern, but lets the conversation develop within this area. It can be completely informal.

To collect the data in this research we decided to use semi-structured interviews. This kind of interview proposes a certain set of questions while, at a given moment, offering the opportunity to add more questions for further information. They provide flexibility, allow the interviewer to go into more depth or clear up any misunderstandings and encourage co-operation and rapport (Robson, 2002).

To design the questions of these interviews the role of the interviewee was taken into account. To identify which roles should be interviewed and the questions to ask to each role, a modified Delphi study was made. This study consisted of validating the roles and questions with DDMRP experts that were Certified Demand Driven Planners and took part in the case studies. The following steps were undertaken:

1. Identify the implementation to analyze.
2. Identify the experts on DDMRP that had implemented DDMRP in the analyzed companies.
3. Identify the profiles that should be interviewed to obtain the key information of each case and define the questions to ask to each of them.
4. Validate both the profiles to be interviewed and the questions asked in each interview with the DDMRP experts identified in step 2.
5. Receive feedback and make corresponding changes considering their suggestion.

In order to gather as much information as possible, we recorded the interviews. The tape provides a permanent record and allows us to concentrate on the interview (Robson, 2002). These recordings were considered confidential and were not included in this research work.

6.3.3. Analysis of data and evaluation

Once the interviews were done and the data collected, the data was processed. The 4 steps followed to carry out the data processing are defined below (Miles, 1994; Tesch, 2013; De Massis and Kotlar, 2014):

1. **Data reduction:** Select, focus, condense and simplify the collected data to be ready for the analysis.
2. **Data display:** Create an organized system to keep the data in order to facilitate identification and extract the information.
3. **Data categorization:** Create different categories of information to enable comparisons and distinctions.
4. **Data contextualization:** Gather the collected data and the external contribution while identifying links and connections.

To carry out data analysis and evaluation, Yin (2009) suggested 4 different techniques: relying on theoretical propositions; developing a case description; using both qualitative and quantitative data; and examining rival explanations. He stated that the theoretical propositions strategy is preferred. Therefore, this thesis sets out a comparison between the theoretical propositions defined in Section 5.3 and the outcomes of the three case studies.

In addition, once the data analysis was finished, an overall assessment was made to determine if the data across the cases provided sufficient evidence to support the initial theory (Johnston et al., 1999). This cross-case analysis is set out in Chapter 10.

Case study research has been criticized as lacking objectivity and methodological rigor. For this reason Hirschman (1986) and Johnston et al. (1999) proposed 4 aspects to avoid a subjective interpretation of the evidence and data, ensuring theory-based, systemic and rigorous findings:

- **External validity:** Also known as replicating the study. The authors propose analyzing the same phenomenon in different contexts to see if the obtained results drew the same conclusion. Therefore, to carry out the external validity in this thesis three case studies where DDMRP was implemented were selected. This allowed us to identify how DDMRP managed the flow of materials between the links of different supply chains.

- **Internal validity:** To determine the credibility of a particular interpretation, the authors propose submitting the interpretation to the scrutiny of those individuals upon whom it is based, and seek their responses as to its authenticity. In this study, the report of each case study was supervised and validated by the analyzed company as well as the implementers who participated in the implementation of DDMRP. In this way, we ensured that the information gathered in the interviews was correctly reported in each case study.
- **Reliability:** This examines the temporal stability and internal consistency of measurements taken on a variable. To achieve this aspect, the authors propose first carrying out internal validity and then triangulating using multiple sources. These two tasks were undertaken in the present study. The cases were internally validated and to collect data a triangulation between semi-structured data, archival records and document sources was done (Section 6.3.1).
- **Objectivity:** This ensures that the interpretation of the outcomes of the case studies are based on observable phenomena and uninfluenced by personal prejudices. To carry out this aspect the authors propose subjecting all study findings to an external auditor to evaluate whether the findings appear to be logical and free from prejudice. To this end, the case studies as well as the cross case study of this research work were examined and evaluated by an expert in DDMRP who did not participate in, and did not know the analyzed case studies.

6.4. Summary

The research design and methodology followed in ths thesis is depicted in Figure 6.4. The research purpose of this work was exploratory and descriptive. As to the research strategy, we followed a holistic multiple case study. To collect the data, semi-structured interviews, documents and archival records were used. The analysis and evaluation of the data was carried out with theoretical propositions. Finally, to ensure objectivity in the interpretation of data internal and external validation, triangulation and an external audit was done.

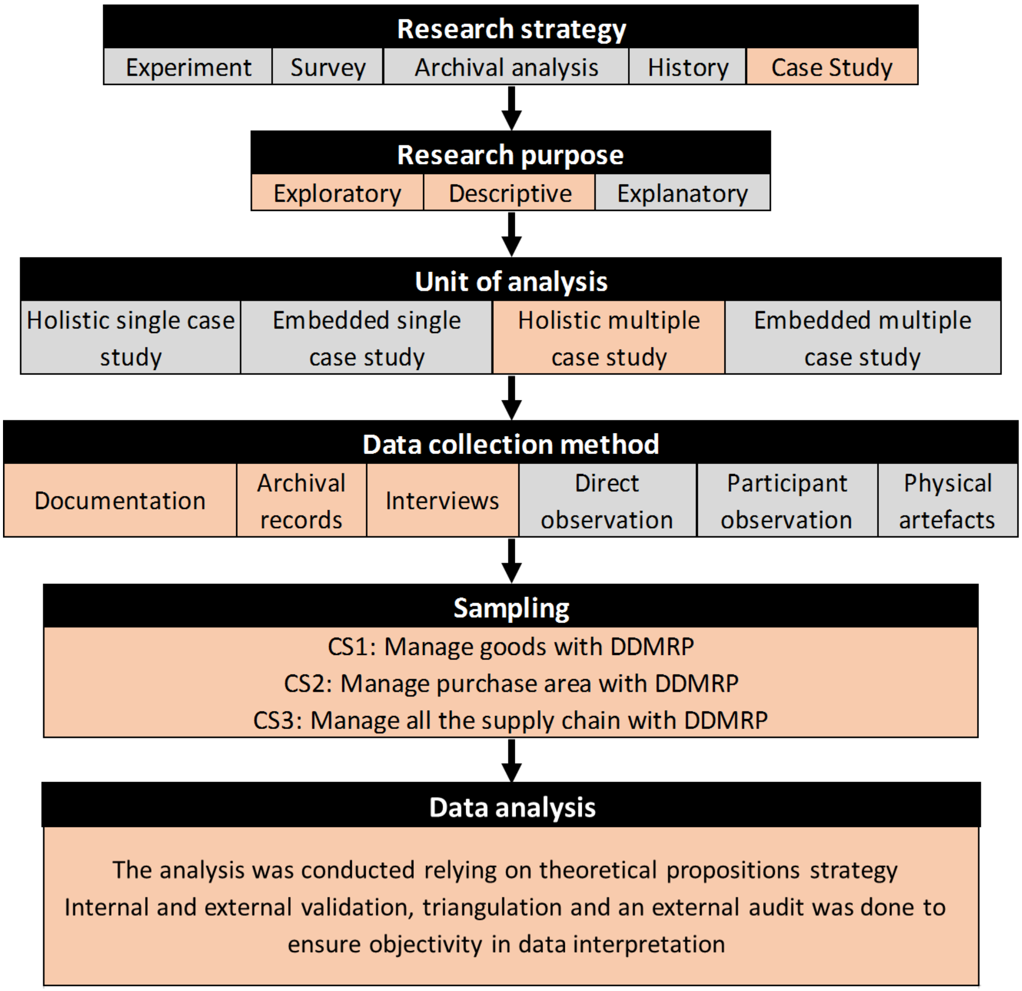


Figure 6.4: Summary of the research design and methodology

Chapter 7

7. Case study 1

In this chapter the company where DDMRP was implemented is introduced, and the reasons for implementation are explained. Then, critical points that prevented material and information flow are set out. After that, the DDMRP implementation is summarized and finally the qualitative and quantitative results and main findings are presented.

7.1. Introduction to the company

This case study is based on a company that was established in 1948. They started business as a padlock manufacturer and the growing reputation of the brand, encouraged the company to widen its product range. Today, this company is leader in the Spanish locksmith market and provides sales coverage throughout Spain and more than 50 countries worldwide. Approximately 85% of total sales are national customers while the rest are international. To preserve the anonymity of the company, in this thesis it is called CS1.

Most suppliers of CS1 were located in China. Materials were transported in containers by boat due to the heavy weight of the goods, the low market price of the end products and the high cost of transportation. This resulted in considerable purchase lead times, on average 3.5 months. Figure 7.1 sets out the supply chain of CS1.

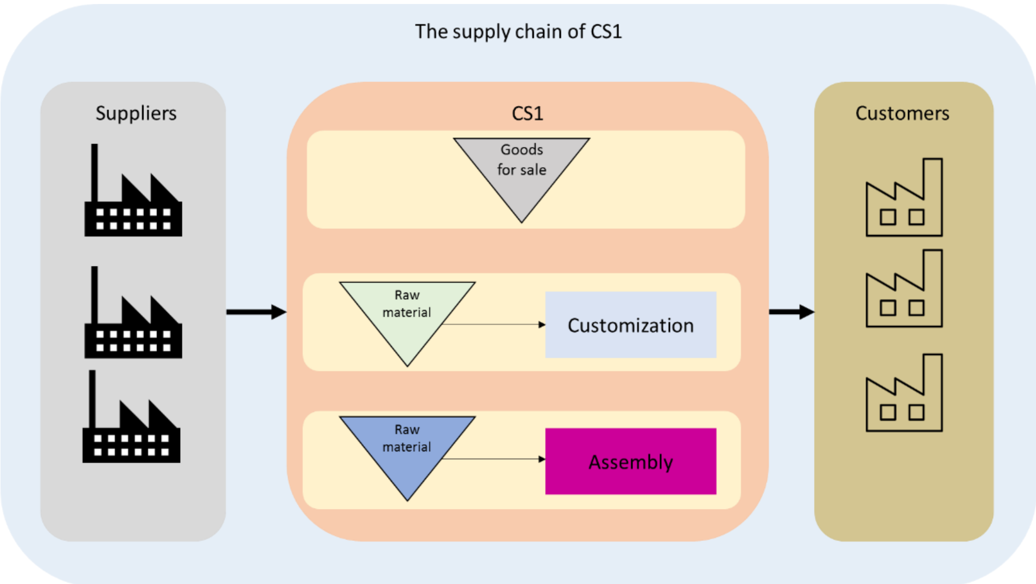


Figure 7.1: The supply chain of CS1

7.1.1. Reasons to implement DDMRP

Before DDMRP implementation, CS1 had an MRP tool. To plan new purchase orders, the Purchasing and Planning Manager (PPM) had to take into account several factors: the material requirements provided by the MRP, the information that he had about the status of the launched orders that were on the way, and instinct resulting from several years of experience. It is important to note that this task consumed a lot of time and effort on the part of the PPM.

The planning process was 100% dependent on the PPM since he was the only one that managed the required information to carry out material management. Hence, CS1 was unable to carry out any material planning without the involvement of this one individual, as only he knew the status of the on-order and on-hand material.

Before DDMRP, implementation CS1 reported almost 100% of service level. This came at a cost, however, as meeting and servicing customer orders in 24-48 hours required extremely high on-hand stock levels according to the General Manager of the company. Therefore, CS1 wanted to analyze the on-hand inventory level and adjust it to the real requirements whilst maintaining the service level.

With the aim of addressing this inefficiency, the General Manager of CS1 attended a DDMRP seminar organized by Mondragon Unibertsitatea where different companies explained their experience managing materials with DDMRP. Based on the information presented in the seminar, the General Manager saw opportunities for improvements in CS1 and in May 2016 they began implementing DDMRP. The implementation period lasted 5 months.

The end products of CS1 are classified into three clusters depending on the production process as set out in Figure 7.2:

1. **Goods:** CS1 purchased goods from China and sold them to customers without any processing. These goods were managed by make to stock strategy and represented 60% of the total sales.
2. **Raw material + customization:** CS1 purchased goods from suppliers and these were customized according to customer specifications. These products were managed by make to order strategy and accounted for 25% of the total sales.
3. **Raw material + assembly:** CS1 purchased raw material from suppliers and the end products were assembled in the company. These end products were managed by make to order strategy and made up the remaining 15% of the total sales.

As the abovementioned material management inefficiencies mostly occurred in goods management and in addition, this cluster represented a large percentage of the sales, CS1 decided to manage the Goods cluster (Cluster 1) with DDMRP. Thus, the analysis of this case study is focused on goods management (Figure 7.2 marked in red).

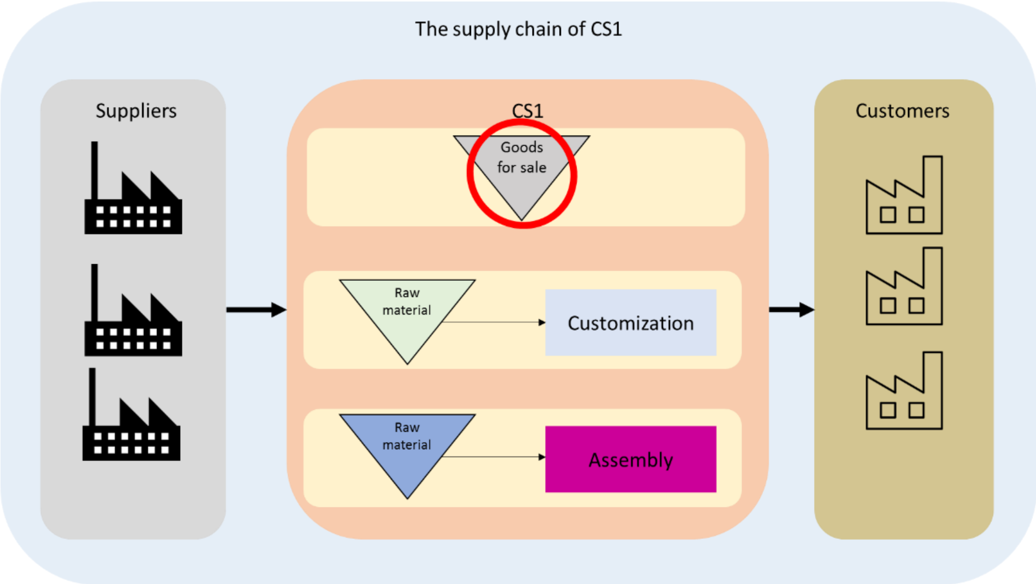


Figure 7.2: Link of the supply chain of CS1 where DDMRP was implemented

7.1.2. The Goods cluster of CS1

To observe the fluctuation of the on-hand goods inventory 579 references between June 2016 and April 2017 were analyzed. It is important to note that the purchase lead time of all these goods was on average 3.5 months.

For the purposes of clarity and to focus exclusively on the analyzed references (Goods cluster), hereinafter the supply chain of CS1 is represented only including the Goods cluster references (Figure 7.3).

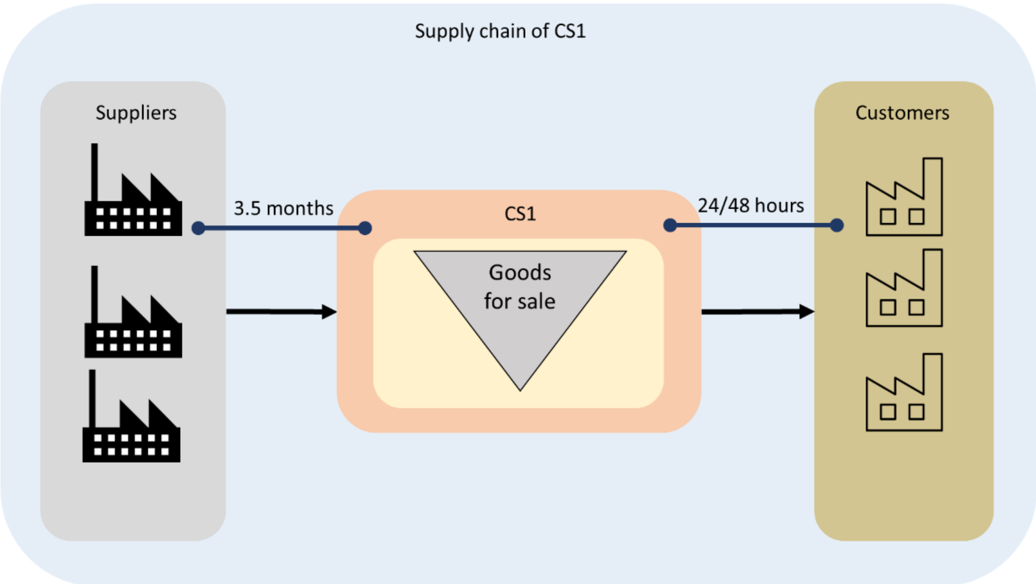


Figure 7.3: Supply chain of CS1 considered for the analysis

7.2. Critical points that reduced the flow of materials and information in the supply chain

When consultants in collaboration with Mondragon Unbertsitatea began analyzing data to implement DDMRP in the company, they found operational situations that were directly affecting the flow of materials and information. These situations are set out below.

7.2.1. High on-hand inventory level

The suppliers of CS1 were from China. Due to the weight and final price of the end products, CS1 transported the goods in containers by boat. Moreover, to optimize the transport cost, the company purchased in large batches. A final important point to note is that CS1 purchased material before the required date to deal with supply variability.

To plan purchase orders, the PPM used demand forecast. However, this forecast was seldom met. To manage this uncertainty CS1 required high SS level so as not to suffer from a stockout and to maintain a high service level.

CS1 could not launch rush orders as their suppliers did not have the capacity to meet them in the short-term. On the rare occasion suppliers could satisfy rush orders, the high cost of transportation by plane made supply financially unviable. Hence, high SS was the only way the company could manage demand uncertainty.

All these factors resulted in a high on-hand inventory level, skewing the bimodal distribution to the right and thus raising the inventory holding cost.

7.2.2. Planning purchase orders once per month

CS1 planned material purchases once a month for a period of 1 month. With an average purchasing lead time of 3.5 months, the PPM planned the material requirements of a month, 3.5 months in advance.

The main reason why CS1 planned once a month was due to the work involved. To identify material requirements, the PPM had to feed a manually programmed spreadsheet through the ERP. Then he had to interpret the data obtained to finally be able to launch the purchase orders. This consumed a lot of time and effort and it was therefore considered unfeasible to increase the frequency of this task.

This fact greatly reduced the visibility of the status of goods of CS1 as the PPM would not review it until the following month. In the same way, unforeseen references were also not identified until the next order was launched, loosing reaction capacity.

This lack of visibility had the potential to lead to stockouts, an outcome the company covered by holding a high SS once again resulting in a skewed bimodal distribution.

7.2.3. Lack of visibility to manage the references of the same family

CS1 purchased goods from many suppliers with certain providers supplying more than one type of good. These suppliers defined a common MOQ that had to be filled by the total amount of references belonging to the same family. In other words, the purchased quantity of different references of the same family needed to be greater than the common MOQ.

The ERP used by the company did not have the capacity to identify and visualize material status by families and therefore, could not determine the optimal joint purchase order for the established common MOQ of a family. CS1 had no choice but to set this MOQ to each reference individually, thereby buying more units than required, significantly increasing the on-hand inventory level and consequently diverting the inventory level towards the right side of the bimodal distribution.

7.2.4. Fully dependent purchasing process

Only one person was dedicated to the task of planning material requirements, the PPM, and only this person had required information and knowledge to carry out this task. The rest of the staff of the company had no knowledge of the process, the criteria to plan orders or the status of the on-order materials, since this information was not easily available in the ERP.

CS1 therefore, depended entirely on the PPM to plan the purchase orders. If at any time this person was absent from work, the company was unable to perform this task.

7.3. DDMRP implementation in CS1

The implementation of the five components of DDMRP in CS1 is set out below.

7.3.1. Strategic inventory positioning

Considering the supply chain of CS1, the strategic position of the inventory was positioned in the inventory of goods (Figure 7.4). Thus, CS1 decoupled customer demand and supplier supply. It is worth mentioning that CS1 already had inventory in this position. Therefore, in this phase the correct position of the inventory was validated.

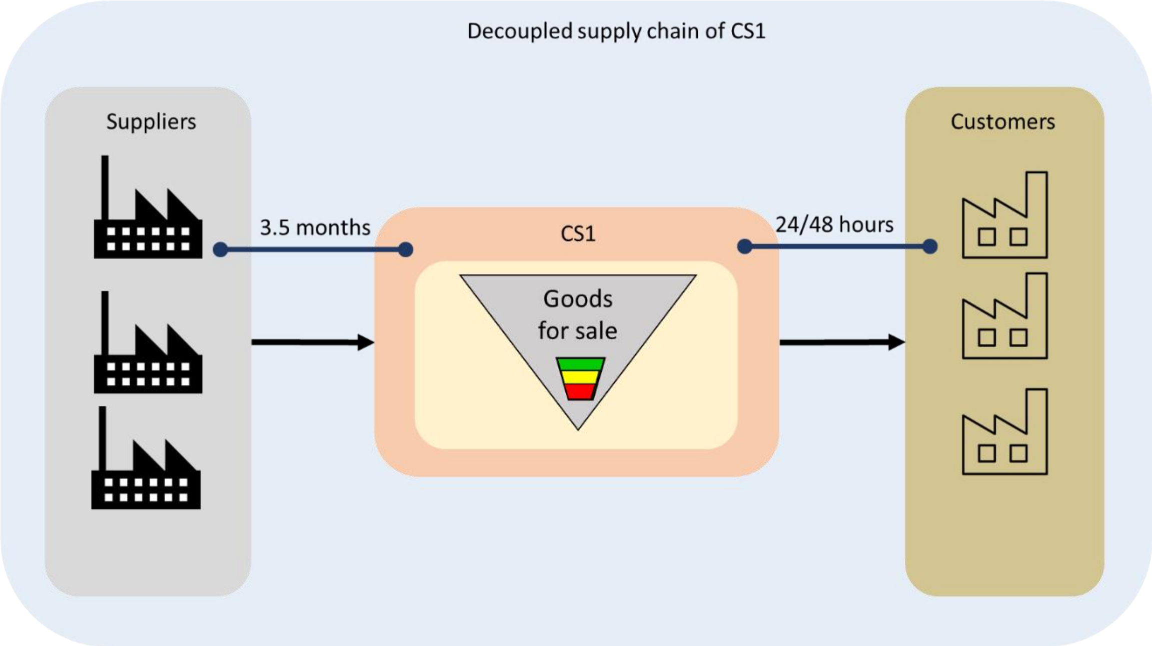


Figure 7.4: Decoupled supply chain of CS1

7.3.2. Buffer profiles and level determination

In this component, part designation was first defined (explained in Chapter 3 Figure 3.6), then, the inventory level of each part was determined.

To define part designation, the references to be stored were listed. These references were then plotted in a double Pareto chart and classified as A, B or C depending on their consumption and the consumption multiplied by the material cost. The results of both Pareto charts were correlated differentiating strategic references from non-strategic ones. In this first round strategic references were designed as replenished parts and managed by a color-coded buffer while the rest were designed as MM parts and managed by a MM buffer.

To double-check this classification the consumption pattern of each reference was studied to see if references had smooth or irregular consumption. In the case that a reference was classified as strategic with a color-coded buffer, but had irregular or chaotic consumption, part designation was changed to an MM-buffer. Color-coded buffers are not defined to manage highly irregular consumption references as explained in Section 3.2. Finally all part designations were corroborated by CS1.

In this step, the family code to which each reference belonged was also defined. In this way, references belonging to the same family could be filtered out and thus made visible when a joint purchase was carried out.

With the aim of centralizing all this information new fields were developed in the ERP of the company to record extra information such as ADU, part designation, red, yellow and green levels of the buffers and the family code of each reference.

7.3.3. Dynamic buffers

In this component the recalculated adjustment was scheduled, so that the buffers were adjusted based on changes to individual part attributes or buffer profile adjustments.

Planned adjustments were also configured to manage Chinese New Year as most CS1 suppliers were from China. This country celebrates the New Year at the beginning of February and the majority of companies close during this period. This fact affected the supply of materials of CS1, as from February to late March they did not receive material from Chinese suppliers. To continue serving customer orders over this period, CS1 had to bring forward to January the purchase orders to be consumed between February and March.

For that purpose, CS1 planned an adjustment considering factors such as material consumption between February and March, the lead time of the references whose supply would be interrupted and the time that Chinese suppliers would not serve the orders. With this data CS1 calculated an adjustment factor and resized the buffers. This adjustment resulted in an increase of the purchase orders so that in November they received 20% extra material, in December 40% and in January 75%. Thus, this extra inventory enabled the company to serve customer orders between February and March in spite of the fact that Chinese suppliers did not supply material until the end of March.

Once this festive period ended and the Chinese suppliers resumed normal business hours, the supply returned to normality, and buffers were adjusted to the new environment.

To better explain the planned adjustment a real example is set out in Figure 7.5. At the beginning of November, after implementing a planned adjustment factor, the buffer of the analyzed reference increased its size (point 1 in red) and CS1 ordered a greater amount of material increasing the NFP in (purple line, point 2 in red). This order arrived at the company in January increasing its on-hand inventory (point 3 in red). From this 3rd point forward the on-hand inventory (black line) as well as the NFP decreased equally which means that CS1 was serving customer orders and was not supplied by new material.

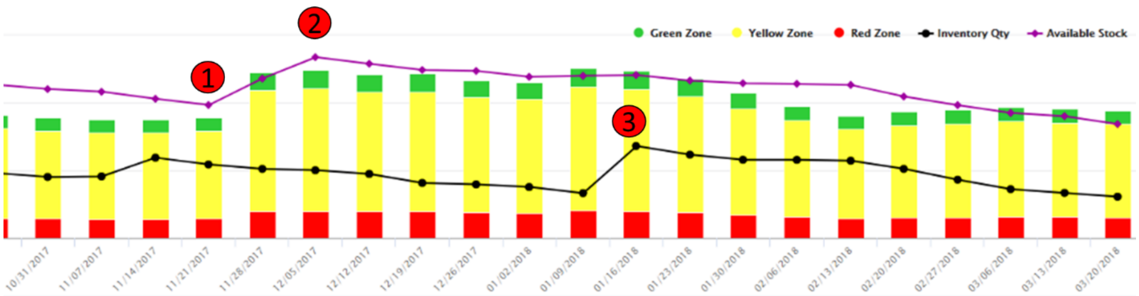


Figure 7.5: Real buffer evolution implementing a planned adjustment

7.3.4. Demand driven planning

After configuring the supply chain in a DDMRP environment, CS1 began planning using DDMRP. The information required to plan supply orders such as the demand of each reference within a lead time, the ADU, the lead time, the MOQ, the on-hand inventory, open supply orders, and the red, yellow and green zones of each references was exported daily from the ERP into software that managed DDMRP (R+).

R+, calculated the NFP of each reference and showed it using a color-coded alert. References in red were in a critical situation and needed to be analyzed carefully to understand what happened. Moreover, a supply order had to be launched in order to avoid stockouts. The references that were in yellow, were in the replenishment zone, and hence, also needed to be ordered. Finally, the references that were in green did not require any action.

Due to the family code defined for each reference (Section 7.3.2), the PPM was able to filter these references as set out in Figure 7.6. Thus, CS1 was able to check the status of the rest of the references belonging to the same family, launching purchase orders of those references whose NFP was closest to the replenishment zone, and filling the common MOQ defined by the supplier. This approach allowed the optimization of purchase batches, avoiding the purchase of large and unnecessary batches of the same reference.

Planner Tools › Workbench

1 | 80 items per page | 1 - 20 of 20 items

Nota	Agrupacion	Part Nu...	Average Daily...	On Hand	Available Stock	Reorder Qty	Due Date	MoQ
	k30	013000W	0.00	720	720			240
	k30	013025	3.41	457	697			240
	k30	013017n31030	5.81	964	1,204			240
	k30	013011	5.78	232	940			120
	k30	469044	3.60	796	796			240
	k30	013017n31130	1.13	573	813			240
	k30	469037	10.54	1,331	1,811			240
	k30	013001	4.25	287	743			120
	k30	013003	0.10	144	144			120
	k30	013005	8.84	1,480	1,720			240
	k30	013007n31030	2.81	502	742			240
	k30	469051	14.30	1,468	2,188			240
	k30	013007n31130	7.79	1,206	1,146			240
	k30	013000	23.03	2,493	3,885			720
	k30	013010W	0.00	360	360			240
	k30	013027n31230	0.33	298	298			240
	k30	013021	4.10	190	652			120
	k30	013020	12.18	845	2,025			240
	k30	013010	21.37	1,378	3,022			480
	k30	013015	16.67	976	2,176			240

Figure 7.6: Display of references of a specific family

In summary, this planning system allowed the PPM to plan material requirements daily in a quick and intuitive way.

7.3.5. Highly visible and collaborative execution

This component manages the tracking of the orders launched in the previous component to ensure supply within the expected dates and avoid stockouts due to unexpected delays.

When a launched order was delayed and did not meet the expected dates, the PPM was notified by an execution alert. Hence, he could contact the supplier of that particular reference and take the necessary measures to avoid a stockout.

Figure 7.7 shows the alert dashboard used to check the status of launched orders. The visibility provided in this dashboard, facilitated making decisions to expedite the delivery of launched orders whose buffer status was critical, avoiding an imminent stockout.

Information > Alerts > MSA > High

40 items per page — 1 - 7 of 7 items

Order Notes	MSA Status	Part Number	On Hand	Issued Qty	Supply Orders	Demand Allo...	Part Type
	10/19/2017	072501M	360	0.00	1,200.00	0.00	Buy
	10/19/2017	646080	1,233	0.00	20,000.00	42.00	Buy
	10/19/2017	044766	143	0.00	100.00	0.00	Buy
	10/19/2017	085005	77	0.00	364.00	6.00	Buy
	10/19/2017	072511M	191	0.00	480.00	0.00	Buy
	10/19/2017	028210	43	0.00	361.00	0.00	Buy
	10/17/2017	469380	284	0.00	1,020.00	0.00	Buy

Figure 7.7: Alert dashboard of possible stockouts

7.4. Results achieved after DDMRP implementation

The implementation of DDMRP in CS1 involved a change in material management. These changes brought qualitative and quantitative results that are explained in Sections 7.4.1 and 7.4.2.

7.4.1. Qualitative results

Prior to DDMRP implementation, CS1 relied on forecasts to launch purchase orders. However, forecast demand and real demand did not match and the company used SS to cover this mismatch and thus, maintain a high service level.

Using DDMRP criteria to manage inventory and plan material requirements brought about changes. The most important of which was that CS1 planned material requirements based on real consumption instead of forecast. Therefore, the uncertainty generated by forecast reduced considerably as shown in Figure 7.8. The inventory allocated in Goods also absorbed supply variability. These factors enabled the company to maintain the same level of service but with a lower on-hand inventory level (quantitative results are set out in Section 7.4.2).

It is important to note that before DDMRP, CS1 already had inventory positioned in Goods, but this was not managed based on DDMRP criteria. Thus, the company could not reduce the inventory level without compromising service level.

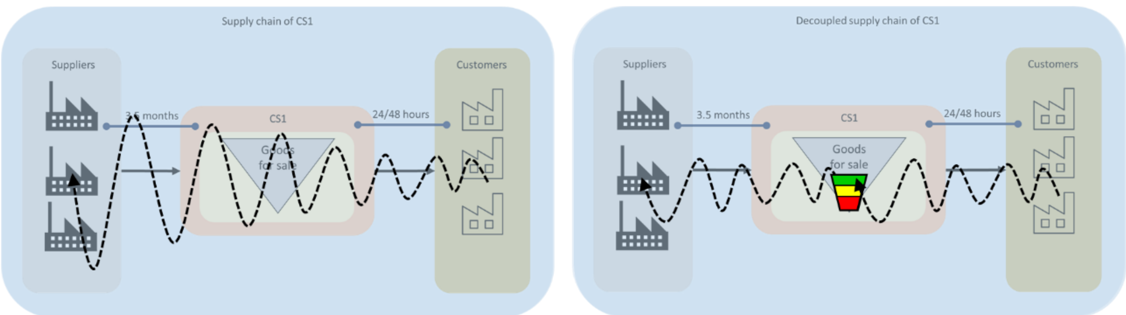


Figure 7.8: (a) Supply chain of CS1 without decoupling point and (b) with decoupling point

References were classified into families. In the case that the NFP of a reference was placed in the replenishment zone, the PPM was able to check the NFP of the rest of the references belonging to the same family. Thus, a purchase of the references that belonged to the same family and were in the replenishment zone was launched. If the purchased amount did not exceed the common MOQ, the NFP of the rest of the references were checked and a strategic purchase order of the references that had the NFP in the green zone but were close to the replenishment zone was launched. This approach provided visibility to make joint purchases of references belonging to the same family, optimizing the purchase batch of each reference and respecting the common MOQ established by the suppliers.

Before DDMRP implementation, CS1 was unable to visualize the status of family references. Therefore, when a references needed to be replenished, the company was forced to purchase the minimum amount of the common MOQ although the real need was quite lower. This resulted in a considerable increase in the on-hand inventory and reduced the turnover performance.

The dynamic adjustments allowed serving orders to customers during Chinese New Year without suffering stockouts. The buffers were resized by the adjustment factor so that enough material could be purchased to fill customer orders during supplier downtime. When suppliers resumed normal trading, the buffers adjusted accordingly.

It should be noted that when DDMRP was implemented in 2016, the need to schedule a planned adjustment to manage Chinese New Year downtime was not identified. Thus, in the Chinese New Year of 2017 the company suffered many stockouts resulting in delayed deliveries and decreased service level. To deal with this shortage, CS1 launched many rush orders, chartering aircraft to reduce the delivery time incurring considerable economic expense.

One further result was that DDMRP contributed a robust and agile methodology to carry out material planning and execution. The status of materials and purchase orders was up to date, and easily accessible providing high visibility. Thus, identification of the references requiring attention was made simpler and shortages and stockouts were prevented.

With this increased agility, CS1 increased planning frequency from once per month to once per week. This change increased the visibility and control of the status of materials and purchase orders as the alerts were checked and managed weekly. Thus, references that were in the replenishment zone were purchased and open orders that were deviated from the initial plan were correctly managed, assigning the correct priority. This was a considerable improvement on the previously implemented MRP tool as the collection of data to visualize the status of the references and plan the required purchase orders was an arduous task that consumed excessive time and resources and thus was carried out only once per month.

In addition, material planning and execution was no longer dependent on one individual. Using the color-coded alerts, anyone that was involved in material management tasks was able to check reference status and make appropriate and timely decisions. This meant that on the occasions when the PPM was absent another could relieve him.

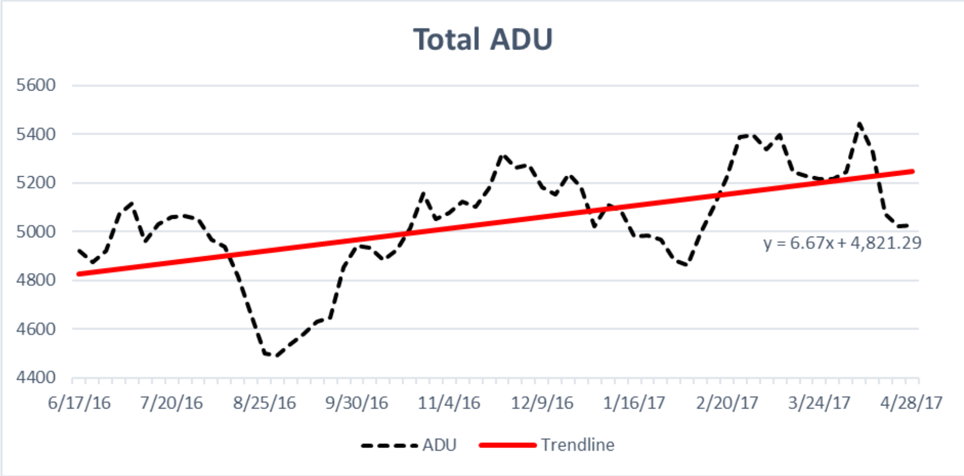
7.4.2. Quantitative results

In this Section, a global analysis of 579 references belonging to the Goods cluster was carried out (Section 7.4.2.1). This involved studying the evolution of the total consumption, total on-hand inventory and total stock coverage during 11 months. Considering the long lead time of the references, analysis over a period of 11 months allowed us to see several inventory turnover performances.

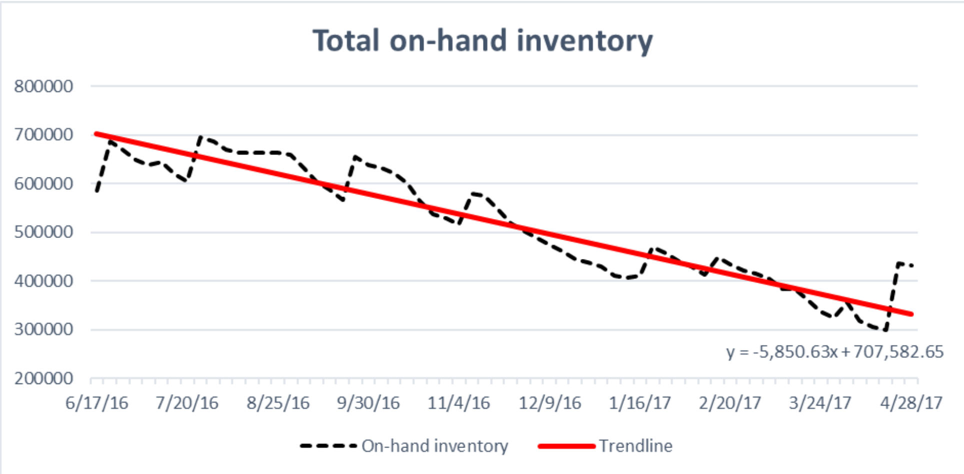
With the aim of doing more in-depth study, the most consumed family was independently analyzed (Section 7.4.2.2). This family was composed of 23 references. First, a general analysis of the whole family was done, where the total ADU, total on-hand inventory and total stock coverage was studied. Then, to see the evolution of the references in detail, the most consumed three references were individually examined. The amount of three references was considered enough to carry out this analysis, as it allowed us to see if the global pattern was repeated in the references with the highest consumption.

7.4.2.1. Global analysis

The total ADU of the 579 references analyzed during the 11 month after implementing DDMRP increased on average by 8.7% (Graph 7.1). This means that in general, the consumption of goods increased in the analyzed period of term. In a striking contrast, the on-hand inventory of this sample showed the opposite trend line, as it on average decreased by 52.53% (Graph 7.2).

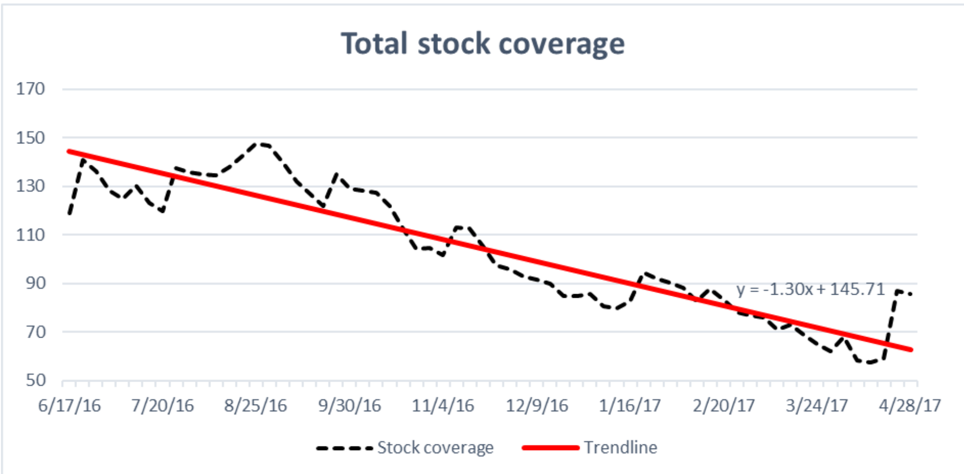


Graph 7.1: Evolution of the total ADU of 579 references belonging to the Goods cluster



Graph 7.2: Evolution of the total on-hand inventory of 579 references belonging to the Goods cluster

The evolution of the total stock coverage of these 579 references also decreased by 56.71% as set out in Graph 7.3. Therefore, after DDMRP implementation the inventory turnover of these references increased. The stock coverage was calculated dividing the total on-hand inventory by the total ADU.



Graph 7.3: Evolution of the total stock coverage of 579 references belonging to the Goods cluster

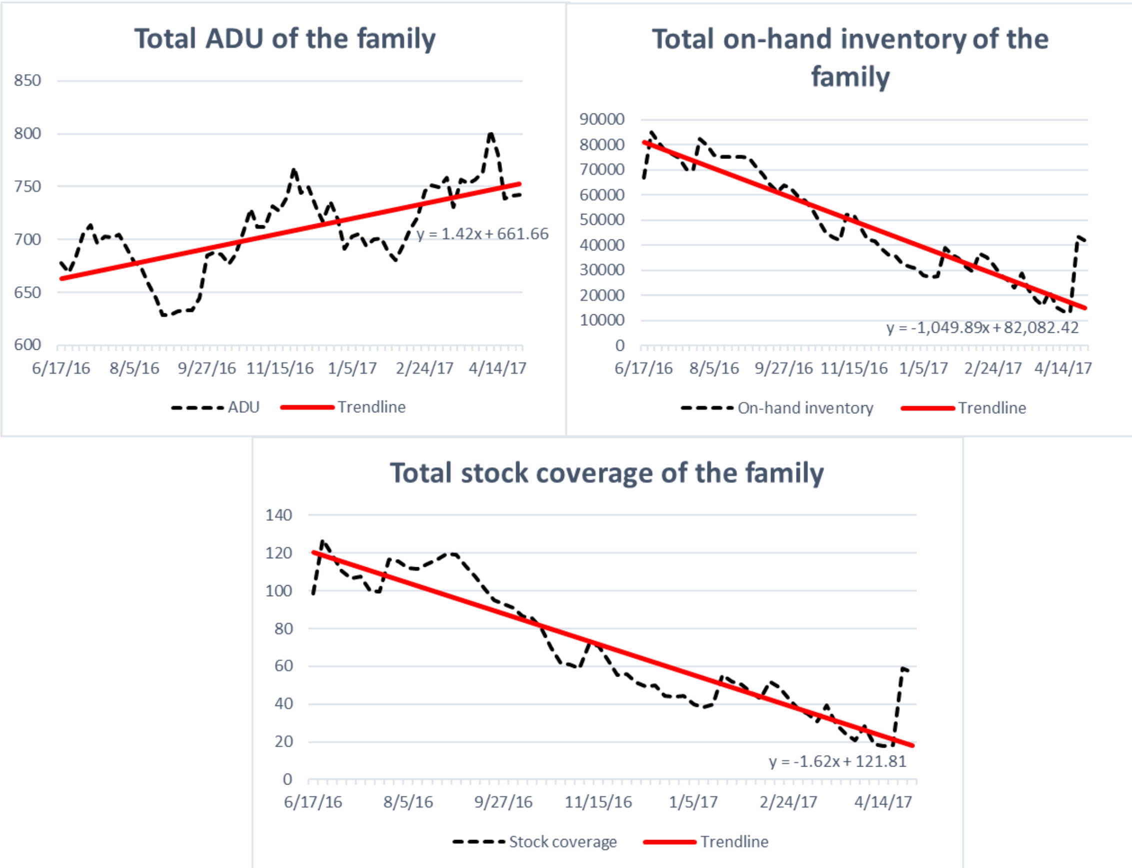
It is worth mentioning that in April the on-hand inventory level increased significantly. This was due to the Chinese New year of 2017. CS1 did not schedule any planned adjustment to serve customer orders during this downtime of the suppliers, and thus suffered several stockouts. To deal with this situation CS1 decided to increase inventory level purchasing more material than required, resulting in an increase of on-hand inventory.

When suppliers resumed normal working hours and CS1 was once again able to service customer orders in 24/48 hours, DDMRP criteria was reinstated. This resulted in a reduction of the excess on-hand inventory that was purchased to relieve the stress generated by the Chinese New Year.

7.4.2.2. Analysis of the references belonging to the most consumed family

In this section, the most consumed family is studied. This family was composed of 23 references. First, a global analysis of the whole family was done examining the evolution of the total ADU, on-hand inventory and the total stock coverage. Then the three most consumed references were individually analyzed.

Graph 7.4 depicts the total ADU, total on-hand and total stock coverage evolution of this family for a period of 11 months after DDMRP implementation. The total ADU on average increased by 13.49% while the total on-hand inventory decreased by 81.63%. The total stock coverage therefore showed the same pattern as the on-hand inventory, decreasing by 84.92%.

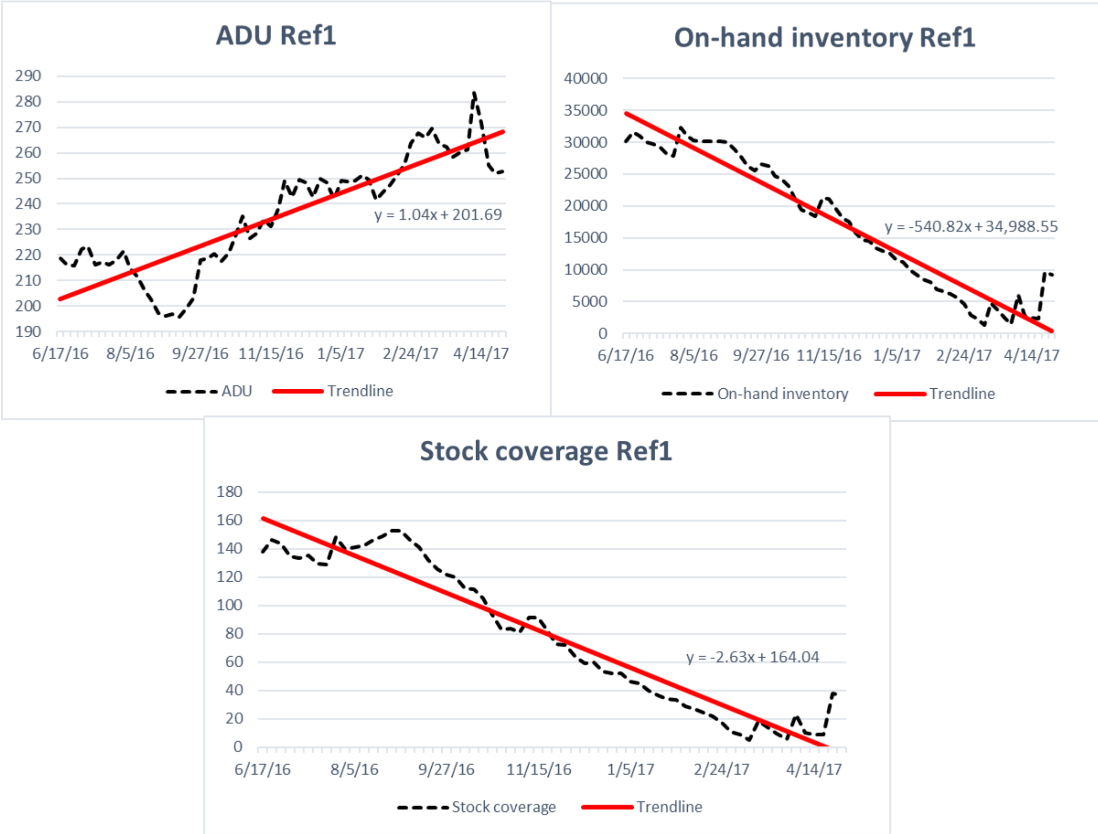


Graph 7.4: (a) the ADU, (b) on-hand inventory and (c) stock coverage of the analyzed family

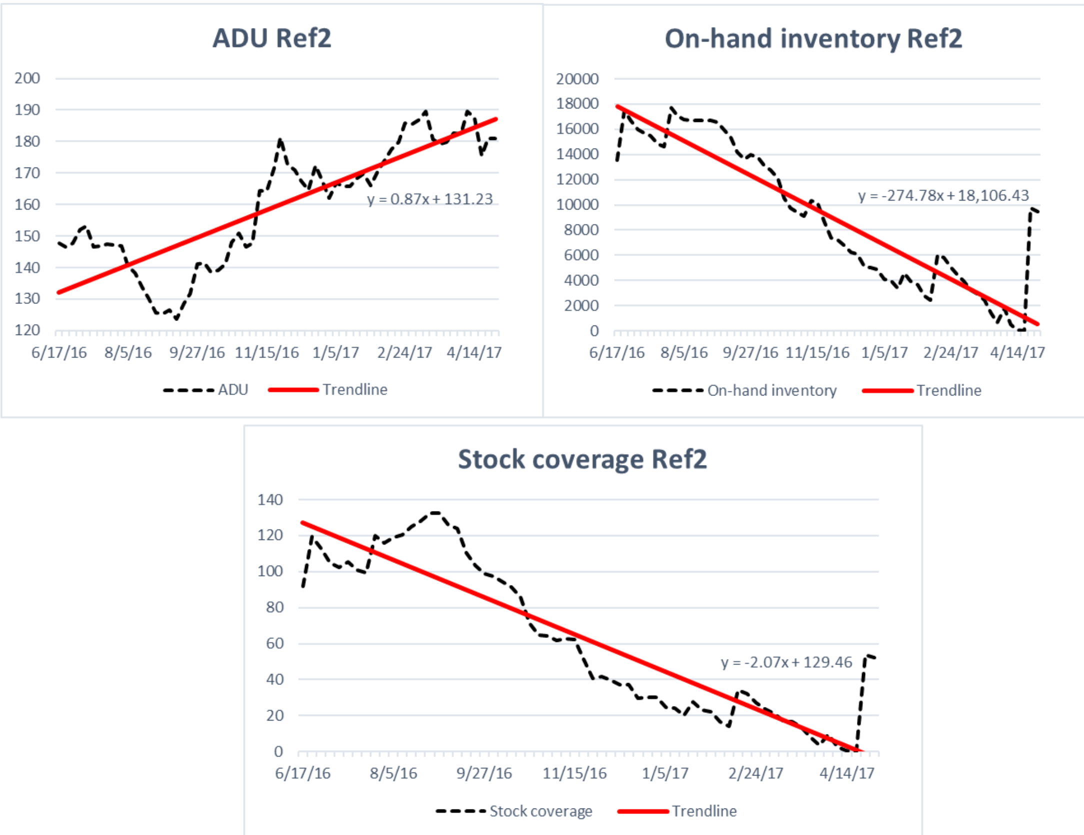
The individual analysis of the most consumed three references is summarized in Table 7-1 and set out in Graph 7.5, Graph 7.6 and in Graph 7.7. Ref1 and Ref2 had the same evolution as in the analyzed period the ADU increased while both the on-hand inventory and the stock coverage decreased significantly. The ADU of Ref3 decreased during the period of analysis. However, the on-hand inventory and the stock coverage also decreased by a much higher percentage.

Table 7-1: Evolution of the analyzed three most consumed goods of the same family

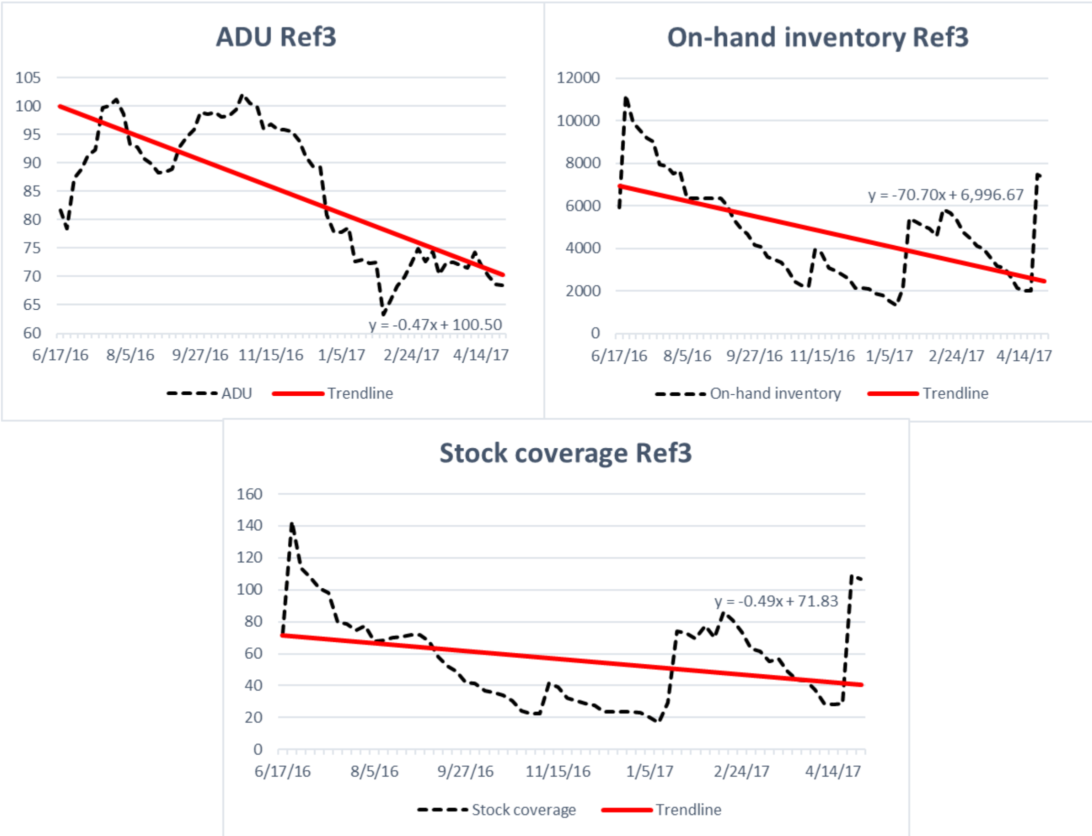
	Ref1	Ref2	Ref3
ADU	32.32%	41.49%	-29.6%
ON-HAND	-98.91%	-97.08%	-64.31%
STOCK COVERAGE	-102.65%	-102.37%	-43.27%



Graph 7.5: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref1 of the analyzed family



Graph 7.6: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref2 of the analyzed family



Graph 7.7: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref3 of the analyzed family

In summary, after DDMRP implementation a significant decrease was observed in the on-hand inventory, while the ADU increased, which resulted in an increase of the inventory turnover. Moreover, the company maintained their high service level during this period.

7.5. Main findings of case study 1

This Section summarizes the most important findings of this case study.

After DDMRP implementation, CS1 adjusted the inventory to the real demand of the customer. This adjustment translated into a significant reduction of the average on-hand inventory while the average ADU grew in the analyzed time period, resulting in a substantial reduction of the stock coverage. A similar trend in stock coverage was also observed in the three most consumed references of the most consumed family. These findings clearly indicate that the company was overbuying material prior to DDMRP implementation. Furthermore, the company achieved these results without compromising the high service level that it had before DDMRP implementation.

Another result to highlight is that DDMRP increased visibility by reducing the uncertainty and increasing material and information flow through the supply chain. Evidence of this is set out in the following points:

- Following DDMRP criteria to manage material decoupled CS1 from supply and demand variability. Uncertainty was therefore considerably reduced and CS1 was able to adjust its inventory to the real demand without the need for high levels of SS. Inventory was placed in the Goods cluster before DDMRP implementation, however this was managed following MRP criteria making it unfeasible to adjust inventory level to real consumption while maintaining the service level.
- CS1 increased planning frequency from monthly to weekly. Thus, the status of the references were controlled more frequently and the company noticed earlier when a reference required action. Weekly planning prior to DDMRP was unfeasible due to the considerable investment of resources required.
- Grouping and visualizing references in families allowed CS1 to carry out strategic purchase orders, filling the common MOQ established by suppliers. This resulted in purchase optimization, preventing the purchase of large amounts of inventory that were not required.
- The planned adjustments allowed CS1 to continue serving customer orders during the downtime of suppliers. These adjustments resized the buffers, preventing the purchase of excess material as well as stockouts. In addition, once the suppliers resumed normal working hours, the buffers were again resized to that situation.

Finally, CS1 noted that it is important to oversee the DDMRP model and double-check part designation and configuration. Market requirements change from day to day, therefore material consumption must be occasionally checked and part designation updated if required. This task requires time, but it is key to maintain optimum results.

The positive results of this case study led us to analyze a further case study, to test if similar outcomes could be achieved in a different context. A second company (CS2) which had implemented DDMRP in the purchasing area was therefore selected. In this case study we analyzed the management of the raw material with this methodology and checked if the results were repeated. In addition, the company worked with short, medium and long lead time references, allowing us to analyze the pattern of behavior in references with different lead times.

Chapter 8

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8. Case study 2

In this chapter, first the company where DDMRP was implemented is introduced and the reasons for this implementation are explained. Then, critical points that prevented material and information flow are discussed. After that, the DDMRP implementation is summarized and finally the qualitative and quantitative results, and the main findings are presented.

8.1. Introduction to the company

DDMRP was implemented in an international company founded in 1963, which develops components for household appliances that improve their performance and provide the end user with greater ease of use and safety. Nearly 300 million homes around the world are equipped with components manufactured by this company. In this thesis it is referred to as CS2.

CS2 purchased raw material from different suppliers. The raw material was manufactured in different production lines, obtaining a range of final products that were stored in the end product warehouse before delivery to customers. It is worth mentioning that the assembly of some subsets were carried out by a subcontractor (Figure 8.1).

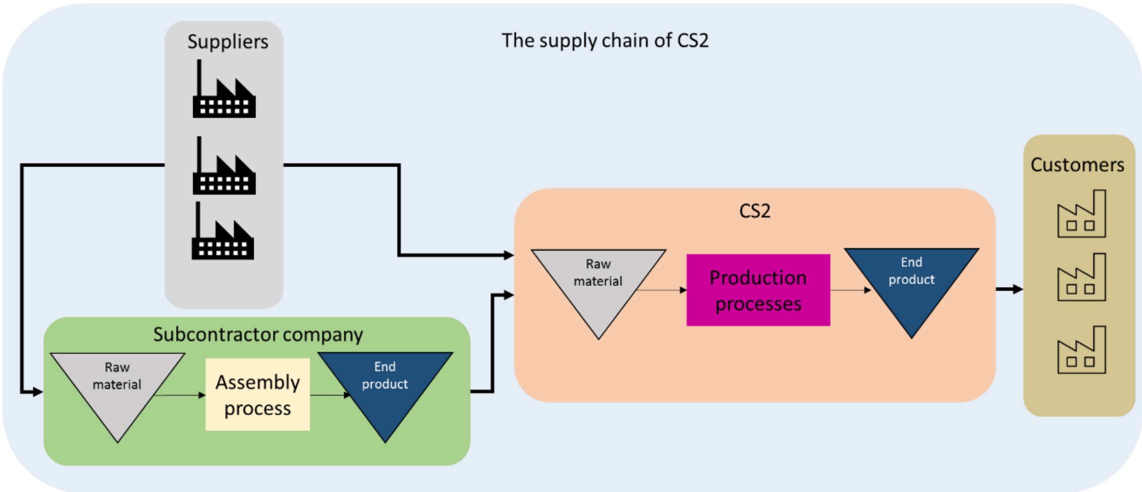


Figure 8.1: Supply chain of CS2

8.1.1. Reasons to implement DDMRP

Prior to DDMRP implementation, CS2 had nearly 100% service level. To maintain this service level the company held high levels of raw material at a significant cost. In spite of the high inventory level however, the company was still susceptible to demand and supply variability and lack of visibility, resulting in stockouts and rush orders.

CS2 managed material requirements using MRP. The production plan however was carried out by an MES that assessed MRP production recommendations and defined a production plan for the following five days. The MRP recommendations were based on customer forecast which used to change frequently. To deal with the mismatch between the forecast and real demand, the company used local spreadsheets to reschedule the production plan. These adjustments in the production plan generated a visibility reduction as the changes were not reported in the ERP resulting in: (1) required purchase orders frequently being overlooked, leading to rush orders and (2) raising orders for material that were lather no longer required. This issue is explained in greater depth in Section 8.2.1.

With the aim of increasing visibility of material and information flow in the supply chain and reducing rush orders and raw material inventory level, CS2 decided to implement DDMRP. For internal reasons, the company decided to implement DDMRP only in the purchasing area without modifying the rest of the links (Figure 8.2 marked in red).

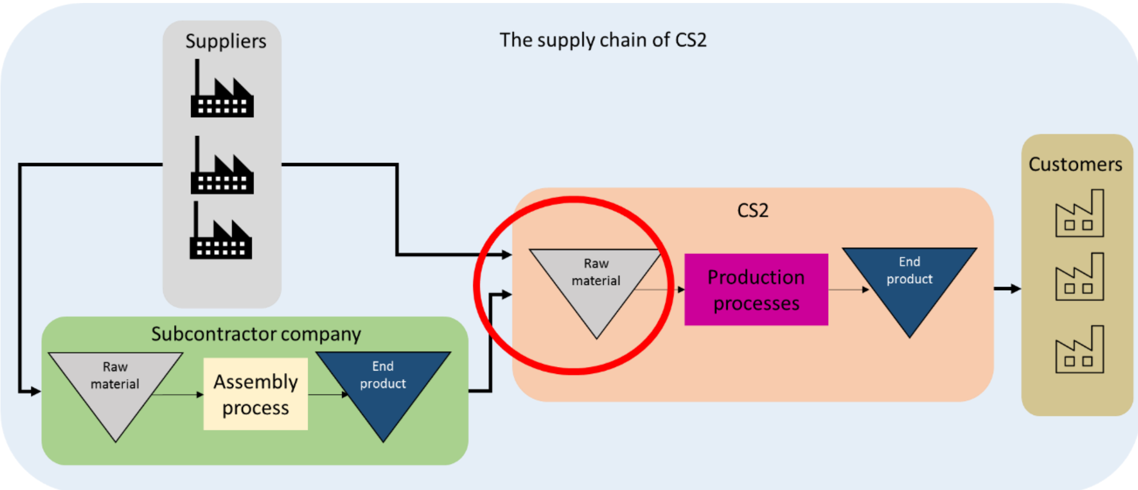


Figure 8.2: Link of the supply chain of CS2 where DDMRP was implemented

CS2 decided to implement DDMRP step by step. In this way, they could see the performance and the daily tasks that the methodology required to manage materials.

The implementation began with part of the references in July 2013 and this step was finished in January 2014. However, the company decided to test the methodology for a while before introducing the rest of the references. In June 2014, considering the attractive results achieved thus fur CS2 continued the implementation process, completing this face in January 2015.

8.1.2. The purchasing area of CS2

The purchasing area managed around 400 raw material references. CS2 decided to implement DDMRP in stages, making it easier to analyze the efficacy of the system and decide whether to continue with all references. As part of this staged implementation, the company for strategic reasons decided to exclude from DDMRP references that had long lead time and were supplied from outside the European Union. In total, this case study analyzed a sample of 203 references:

- 135 short lead time (less than 10 days).
- 58 medium lead time (between 11-29 days).
- 10 long lead time (more than 30 days).

8.2. Critical points that reduced the flow of materials and information in the supply chain

When consultants together with the collaboration of Mondragon Unibertsitatea began collecting information to implement DDMRP, they found situations that were directly affecting the flow of materials and information. Importantly, the company did not consider the following decisions (8.2.1 - 8.2.5) as problems before the implementation.

8.2.1. Planning production without considering raw material availability

CS2 planned every day what to produce within five working days. For example, on Monday, CS2 planned what to produce the following Monday and so on. To make the production plan, CS2 had a MES that considering forecast and real customer orders, proposed a production plan that optimized the production capacity (Figure 8.3).

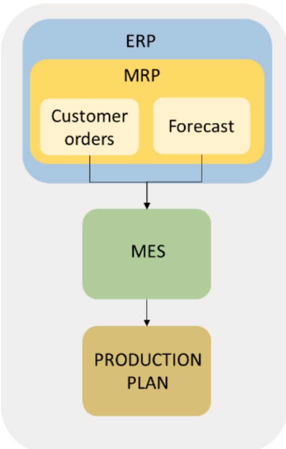


Figure 8.3: Production plan process of CS2

To better explain how MES performed, Figure 8.4 sets out an example: Suppose that in the ERP of CS2 there are two orders waiting to be planned. The MES considering these two orders and the rest of the orders that were planned previously, breaks down these orders to optimize the production batch of each day. Bearing in mind that CS2 plans in Day 0 what to produce in 5 working days, part of these 2 orders are produced in 5 days. In this example on Day 5, 35% of

Order 1 and 20% of Order 2 is produced. On the 6th day CS2 produces 40% of Order 1 and 40% of Order 2 plus the orders that are loaded in the ERP on Day 1. The rest is then produced on Day 7.

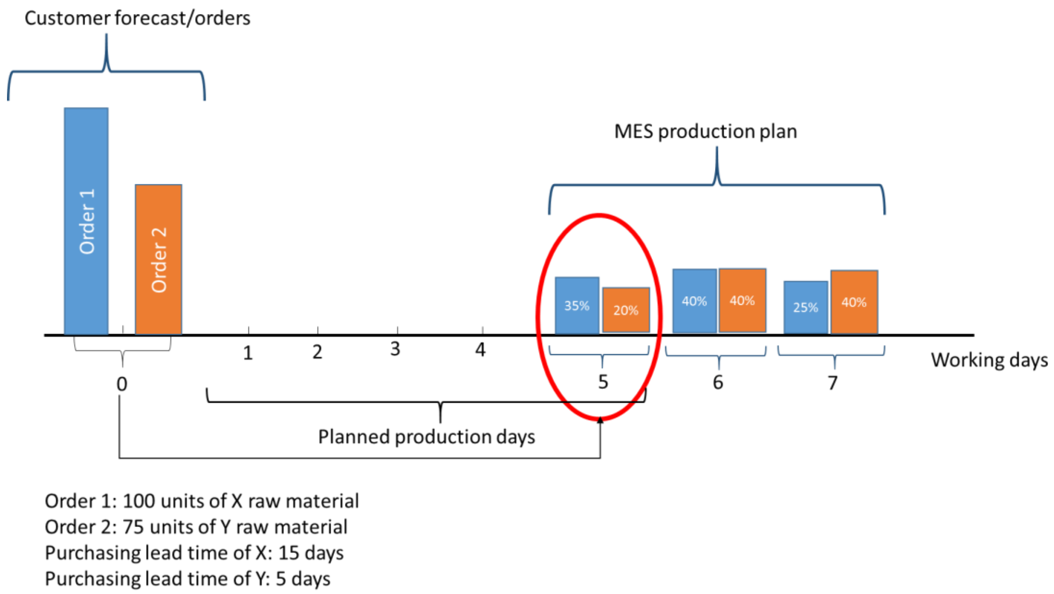


Figure 8.4: MES and Production plan performance

The aim of the MES was to obtain the optimal production plan. To this end, the MES considered the forecast reported by customers (Figure 8.3) and proposed an unchangeable or closed production plan of the following five days. In other words, the ERP did not allow any changes in this regard resulting in the following shortcomings:

1. Considering the forecast changed frequently, CS2 regularly needed to reschedule the production plan to adjust it to the updated forecast. However, the MES was not capable of meeting these needs, as the rescheduling process would not ensure the optimal production plan. To manage rescheduling, CS2 developed some local spreadsheets to adapt the production plan to the latest changes in the forecast. These changes could not be reported to the ERP and therefore the final production plan was frequently only known and managed by the Production Manager.
2. Once the production plan was defined, CS2 checked if there was enough raw material to carry out the planned production. If the stock of a part was below required levels, a new purchase order was launched. Nonetheless, depending on the lead time of the purchased part, stockouts could still occur. To explain this fact better we return to the example of Figure 8.4. Here to produce Order 1, 100 units of raw material X are required. The purchase lead time of this reference is 15 days. If only 10 units of raw material X are

held in the warehouse and in Day 5 35 units are required (35 % of total consumption), CS2 will suffer a stockout.

3. When the Production Manager rescheduled the production plan, the situation worsened as CS2 could have launched purchase orders based on the previous production plan. On the other hand, if there was not enough raw material to produce the updated production plan, the company would not realize until production started.

To alleviate these shortcomings, CS2 was compelled to launch rush orders to suppliers. A Material Gatherer was employed to handle the large number of rush orders that occurred every day.

The abovementioned situation shows that CS2 was suffering from lack of visibility. Owing to forecast uncertainty, the company was purchasing what it did not really need and not buying what was necessary resulting in a bimodal distribution. When a stockout happened, the Material Gatherer usually increased the SS level of the part to avoid future stockouts. This fact only further increased the on-hand inventory level and consequently moved the inventory level towards the right side of the bimodal distribution.

8.2.2. Automatic launching of purchase orders

The purchase orders launched by ERP were based on plan proposed by the MES. If the consumed reference achieved the reorder point, a purchase order was launched without any supervision, since reviewing these orders was time consuming and did not add value.

However, CS2 was losing visibility when purchasing references. It was purchasing items for orders that were going to be produced but, due to the purchasing lead time, would not arrive on-time for production. Moreover, if the Production Manager changed the production plan locally, the company not only ran the risk of purchasing unnecessary material but also might not purchase the required references. This latter resulted in stockouts and enhanced the bimodal distribution of the inventory.

8.2.3. Purchasing raw material before the required date

CS2 used to bring forward the delivery date of the purchased references by two days to deal with supply variability. Considering that the MES planned a period of five days, this action represented 40% of the planned time. In addition, advanced deliveries increased the inventory level of CS2 considerably, since the company had an accumulation of stock that was not going to be used during those two days.

This problem was further compounded when the Production Manager made manual changes to the production plan to tackle the uncertainty generated by the forecast. This increased the probability of buying the incorrect reference and further amplified the bimodal distribution.

8.2.4. Management of the working calendar of the suppliers

Each company usually establishes its own working calendar, and this fact can cause desynchronization in the supply chain. It is important therefore, to take into consideration the working calendar of the suppliers to have enough material to keep producing while suppliers are not.

CS2 forecast the raw material that would be needed during supplier downtimes. This was an additional factor that influenced the bimodal distribution.

8.2.5. Silo effect in the supply chain

The assembly of some components was outsourced to streamline production (Figure 8.1). To instruct the subcontractor on what was to be assembled, CS2 supplied customer forecast, and purchased and delivered the necessary raw material to the subcontractor warehouse.

However, as mentioned before, customer forecasts frequently changed with their subsequent impact on production. Thus, the references the subcontracted company assembled were frequently mismatched with the real necessities of CS2. This resulted in (1) assembling references that were no longer required, and (2) not assembling required references as constant changes in the forecast meant that some orders reached the subcontractor too late to meet the delivery date.

This lack of visibility, also called silo effect, forced the subcontractor on many occasions to manage the rush orders of CS2, disassembling assembled components and assembling new ones. Nevertheless, new assembles were not always possible since the subcontracted company frequently did not have the necessary raw material to meet the rush order. To prevent this lack of material CS2 increased the SS of the raw materials for the subcontracted warehouse.

Thus, lack of visibility increased the bullwhip effect throughout the supply chain (Figure 8.5). This made it necessary to increase the inventory level that the subcontractor had in its warehouse, skewing the inventory level towards the right side of the bimodal distribution.

Furthermore, as the subcontractor planned assembly using CS2 forecast they were saturated with fictitious needs. This considerably reduced the responsiveness of the subcontractor.

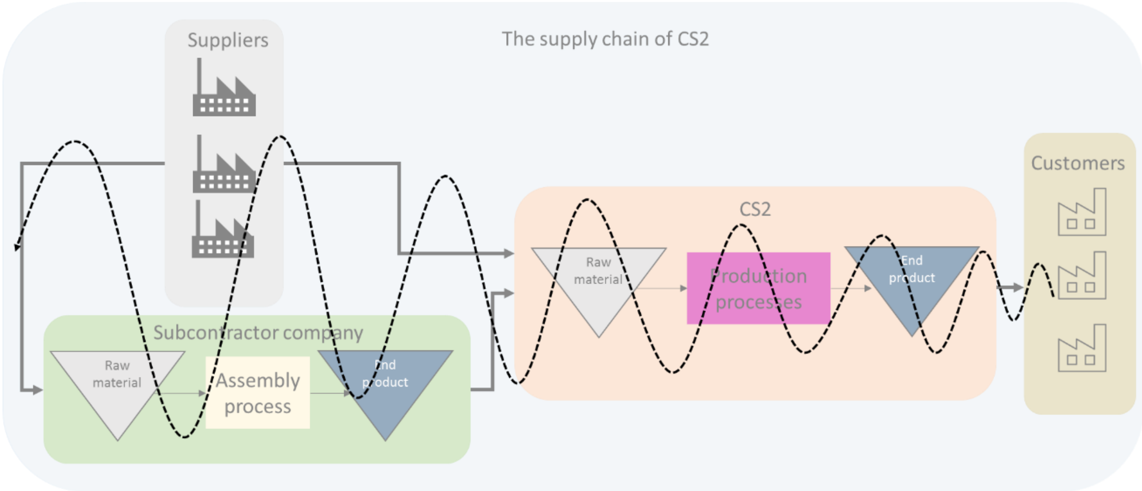


Figure 8.5: bullwhip effect in the supply chain of CS2

8.3. DDMRP implementation in CS2

In the following sections the process to implement the five components of DDMRP in CS2 is explained.

8.3.1. Strategic inventory positioning

CS2 decided to implement DDMRP in the purchasing area. Therefore, the strategic position of the inventory was positioned in the raw material inventory as set out in Figure 8.6. This inventory allowed CS2 to decouple from supplier and customer variability. In addition, this decoupling point allowed the subcontractor company to be decoupled from demand variability reported by CS2.

It is worth mentioning that CS2 already had inventory in raw material although this did not decouple CS2 from supply and demand variability.

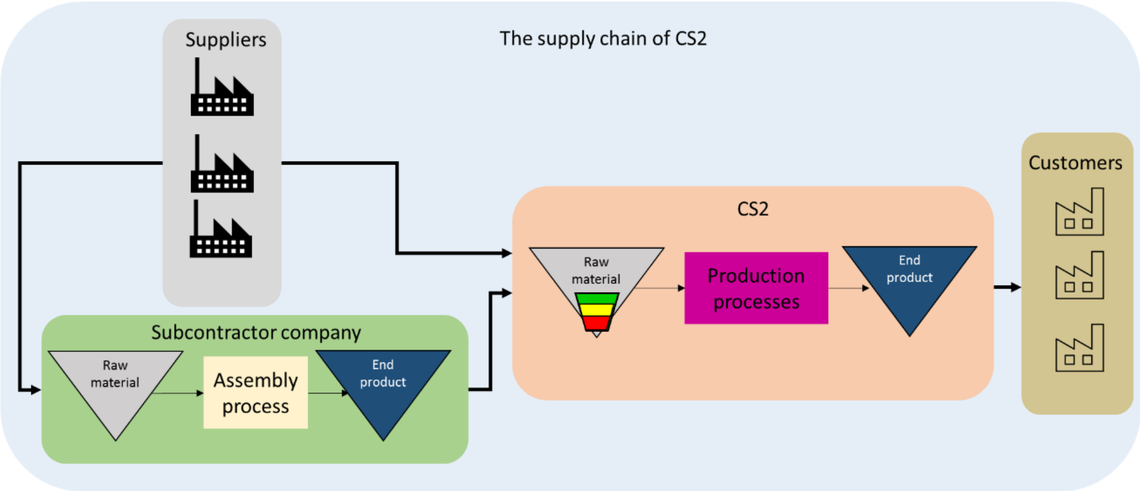


Figure 8.6: Decoupled supply chain of CS2

8.3.2. Buffer profiles and level determination

Prior to defining part designation and sizing the buffers, CS2 listed all the raw material references and defined which should be stored in the raw material warehouse and which not.

The consumption of each stored reference was analyzed to differentiate between strategic and non-strategic references. Strategic references were designated as replenished parts and a color-coded buffer was assigned. The rest were designated as MM-parts and an MM buffer was assigned. Then a double check between parts designation and the consumption pattern of the reference was done, to avoid assigning color-coded buffers to a reference whose consumption was highly variable.

After that, each buffer was sized considering both buffer profile and individual part attributes. Among the individual part attributes, real material consumption was used to calculate the ADU of each reference and size the buffer.

To centralize all this information IT technicians generated new attributes in the ERP, thus CS2 was able to save the required information for each reference such as ADU, part designation and red, yellow and green zones of the buffers in the ERP.

8.3.3. Dynamic buffers

In this component the recalculated adjustment was scheduled, so that the buffers were adjusted based on changes to individual part attributes or buffer profile adjustments.

Planned adjustments were also scheduled, to synchronize material replenishments with the working calendar of the suppliers. Thus, CS2 resized the buffers and brought forward purchase orders to have enough raw material to continue producing and serving orders while suppliers were not working. Once the suppliers resumed working, these buffers were adjusted to the standard situation.

To define the planed adjustment factor for each reference, attributes such as the lead time of the supplier, the ADU of the reference and the downtime period of the supplier were taken into account.

8.3.4. Demand driven planning

In this component CS2 was modeled following DDMRP methodology. To plan purchase orders, a spreadsheet containing the list of the raw material references, their on-hand inventory level, buffer zones, ADU, LT, real demand and open replenishment orders was exported daily from ERP. This information was imported into DDMRP software (R+).

In R+, the NFP of each reference was calculated and shown using a color-coded alert. The references that were in red were in critical situation and were analyzed carefully to understand what had happened. In addition, a supply order needed to be launched to avoid a stockout. References coded in yellow were in the replenishment zone hence, they were also purchased. The purchase quantity was the NFP subtracted from the TOG. Finally, references in green did not require any action, so they were not attended.

8.3.5. Highly visible and collaborative execution

This component provided the alerts that enabled CS2 to track the open supply orders. When the on-hand inventory level of a reference reached the red-execution zone, an alert was issued. Checking the buffer status of these references, CS2 was able to define the proper priority of each reference, contact suppliers and take actions to avoid future shortages. Figure 8.7 sets out an example of the CS2 alerts dashboard.

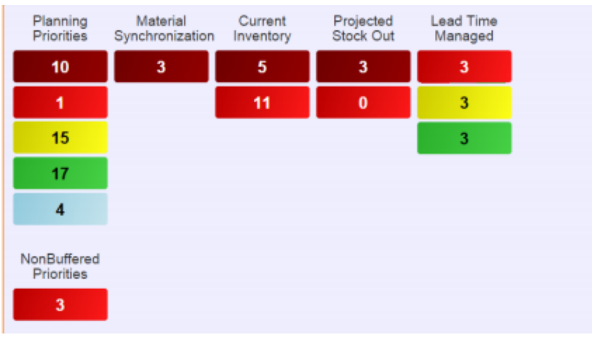


Figure 8.7: Alerts dashboard of R+

8.4. Results achieved after DDMRP implementation

The implementation of DDMRP in CS2 brought about changes in material management achieving qualitative and quantitative results that are set out in Sections 8.4.1 and 8.4.2.

8.4.1. Qualitative results

DDMRP allowed CS2 to plan supply orders based on the real demand of customers instead of forecast demand. Therefore, the company aligned the inventory level to real consumption, preventing the misalignment caused by the uncertainty of the forecast, which generated bimodal distribution in raw material stock.

To accomplish this goal, CS2 considered information such as real material consumption of the production line, supplier lead time and MOQs to adjust buffer size of raw material to the real needs and calculate the NFP. When the NFP reached the replenishment zone of the buffer, a color-coded alert warned that a new supply order of that part was required. It is worth mentioning that when the production plan was changed on a local computer, this was reported in the system since the NFP was calculated based on real production and not on forecast. Therefore, the problems caused by this lack of centralized information were eliminated.

In addition, the decoupling point allocated in raw material protected CS2 from supply variability. Therefore, it was not necessary to perform material supply ahead of time which prior to implementation had increased inventory level, emphasizing the bimodal distribution.

A further advantage is that the decoupling point absorbed variability, reducing the bullwhip effect through the supply chain (Figure 8.8). The subcontractor company began planning assembly orders considering the NFP of the buffers instead of the customer forecast supplied by CS2. CS2 later reported that the subcontractor increased its assembly capacity, as they were now assembling according to real requirements instead of wasting time assembling and disassembling based on fictitious demand. Furthermore, the inventory level of the subcontractor company also decreased.

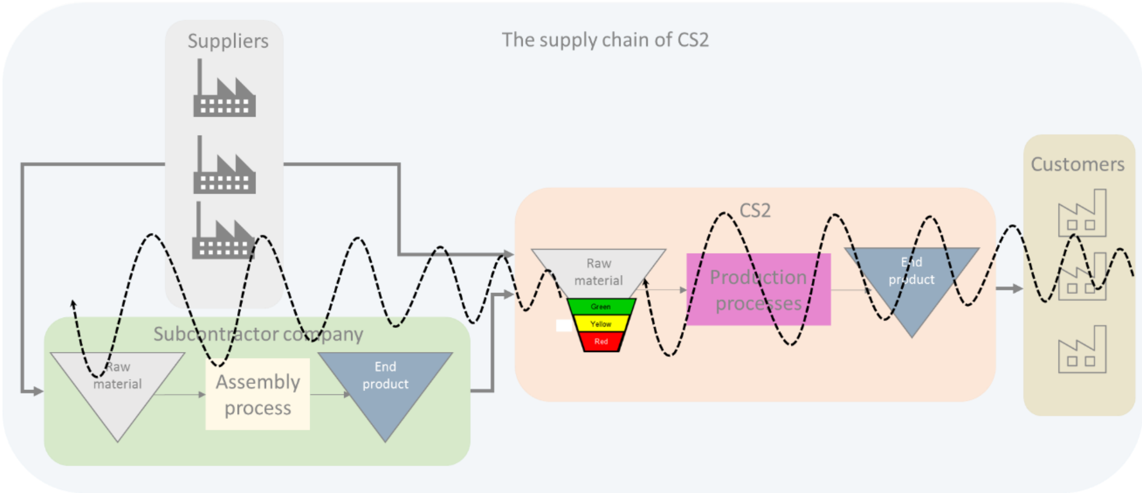


Figure 8.8: Uncertainty signal in the decoupled supply chain of CS2

It is worth noting that before DDMRP CS2 already had raw material stock, but it was not managed following DDMRP methodology and thus, stock was not aligned to the real demand. The high degree of uncertainty caused by forecast forced CS2 to maintain a large amount of raw material stock so as to serve customer orders, amplifying the bimodal distribution. In addition, this uncertainty was transmitted throughout the supply chain reducing the responsiveness of suppliers.

The implementation of DDMRP ensured that CS2 received timely and updated information about the status of the references, open purchase orders and its real consumption, resulting in an increase in supply chain visibility. This visibility streamlined the material requirements planning process. Color-coded alerts allowed easy identification of references that required attention. Thus, the raw material purchasing process became an agile and easy task. In this context the company decided to perform material requirements planning on a daily bases instead of scheduling it automatically. This process further increased the visibility and control over raw material.

An additional benefit of this visibility was that the company was able to make proper decisions in material management resulting in a dramatic reduction in rush orders. Before DDMRP implementation CS2 had a Material Gatherer that spent the whole workday managing rush orders. After implementation, rush orders almost never occurred and the Material Gatherer was able to focus the attention on preventative tasks to ensure efficient material management. Unfortunately the company did not keep a systematic record of rush orders, and we could not analyze the performance of this indicator in a quantified way.

Finally, the Dynamic Adjustment approach was also very useful to manage and synchronize with the working calendar of the suppliers. Considering the number of days that suppliers were not working and material consumption, CS2 resized the buffers and advanced purchase orders so that they continue production during supplier downtime. When the suppliers returned to work, these buffers were again adjusted according to the circumstances.

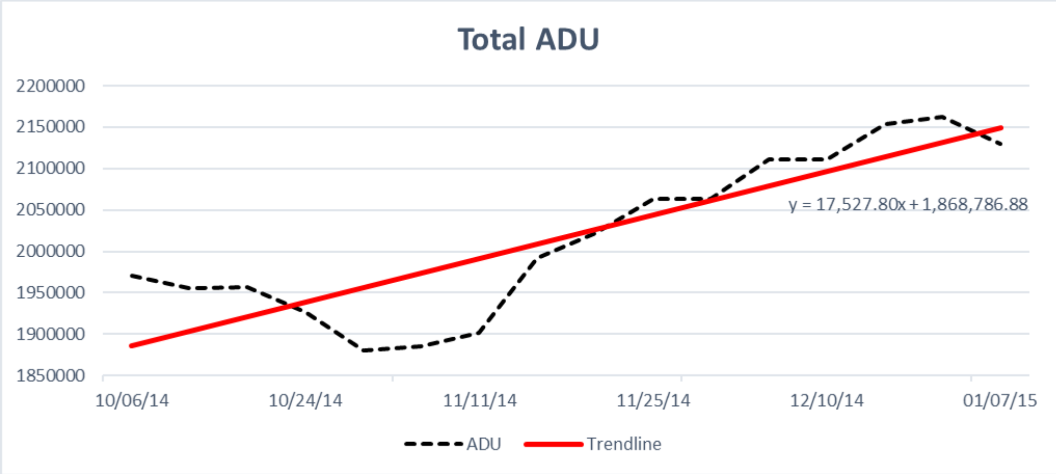
8.4.2. Quantitative results

In this section, a global analysis studying the total ADU, total on-hand inventory and total stock coverage of 203 raw material references is carried out (Section 8.4.2.1). This analysis was focused on the four months after DDMRP implementation. This period of time allowed us to see many inventory turnover performances and how inventory was adjusted to the real consumption.

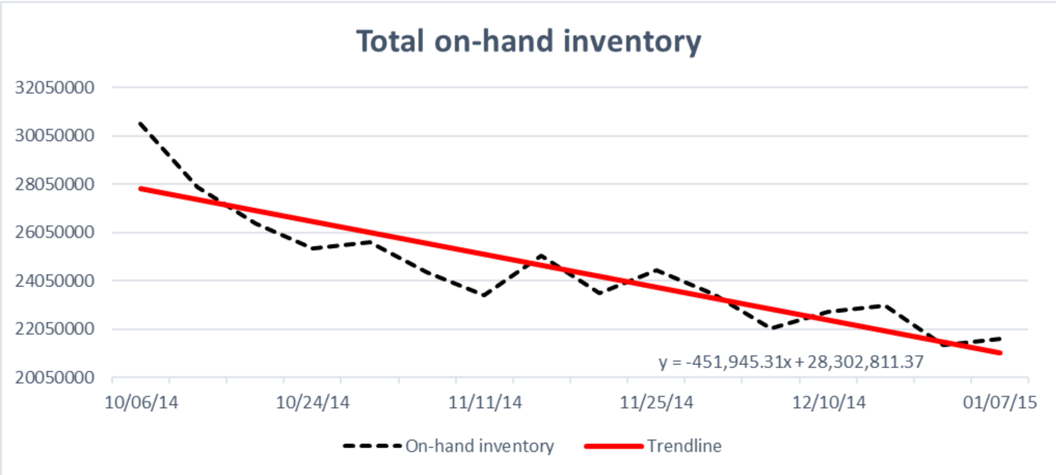
With the aim of doing a more in-depth study, references were clustered as long, medium or short lead time and the performance of each group was independently analyzed (Section 8.4.2.2). To this end, a global analysis considering the total references belonging to each group was carried out. Then to study the performance of the most consumed references of each group, the most consumed three references were individually examined. The amount of three references was considered enough to carry out this analysis, as it would let us see if the global pattern is repeated in the most consumed references.

8.4.2.1. Global analysis

The total ADU of the analyzed sample (203 references) increased during the implementation period, by an average of 13.94% (Graph 8.1). This means that the consumption of raw material increased in general terms. However, in the same period the total on-hand inventory level of the sample decreased by an average of 24.34% (Graph 8.2). These results were achieved without any loss in the high service level of CS2 (prior to implementation positioned near 100%).

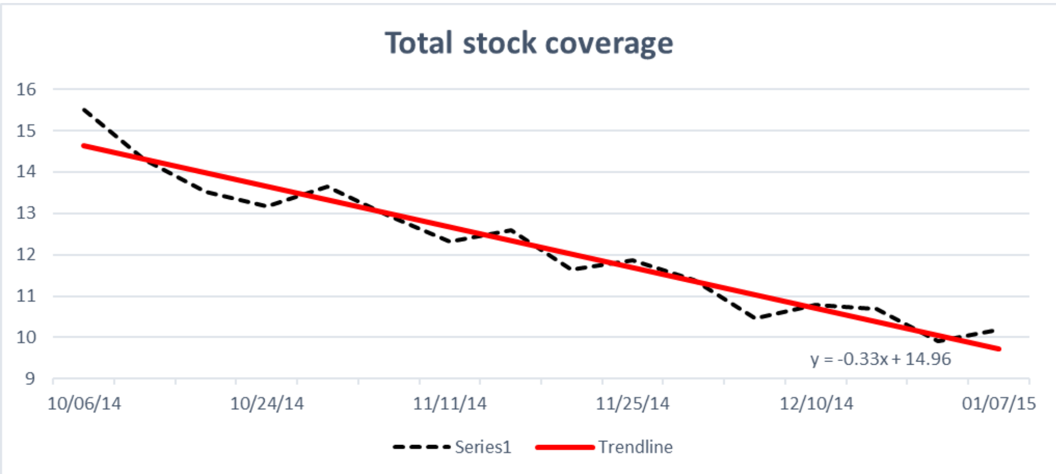


Graph 8.1 : Evolution of the total ADU of the analyzed sample



Graph 8.2: Evolution of the total on-hand inventory of the analyzed sample

As for the stock coverage, it decreased on average by 33.47%, which means that the inventory of CS2 experienced increased turnover (Graph 8.3).



Graph 8.3: Evolution of the total stock coverage of the analyzed sample

8.4.2.2. Analysis of the references according to lead time

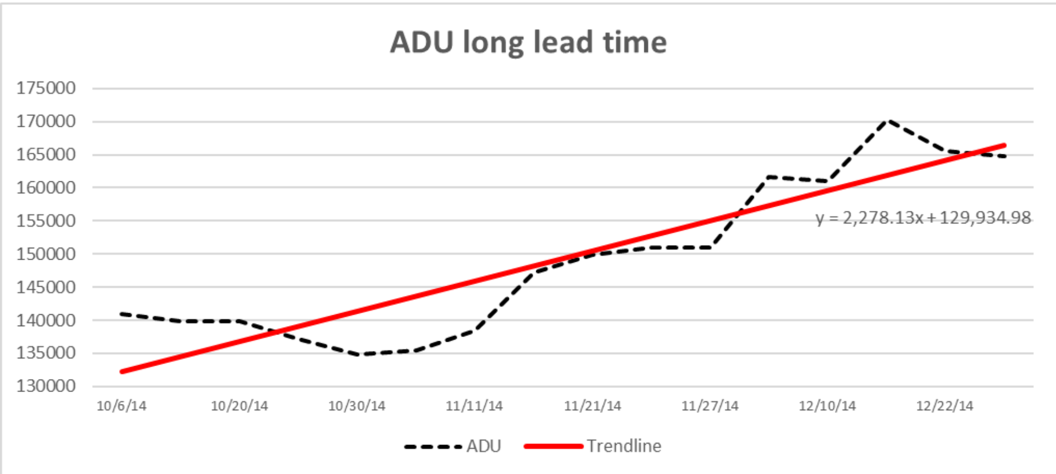
To cluster the 203 references according to lead time, three groups were created:

- **Long lead time:** references whose lead time was more than 30 days.
  10 references that accounted for 7.15% of the total ADU and 18.16% of the on-hand inventory.
- **Medium lead time:** references whose lead time was between 11 and 29 days.
  58 references that accounted for 5.87% of the total ADU and 13.15% of the on-hand inventory.
- **Short lead time:** references whose lead time was less than 10 days.
  135 references that accounted for 86.98% of the total ADU and 68.69% of the on-hand inventory.

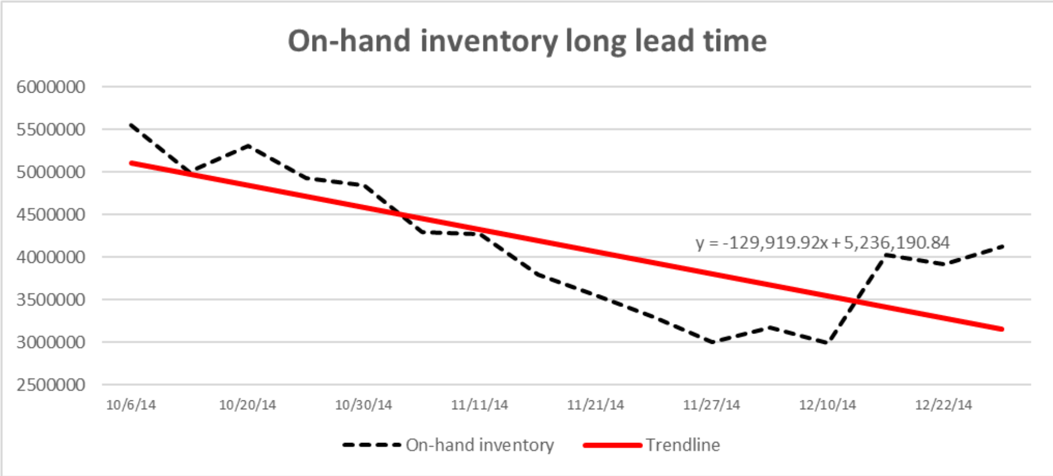
It is important to note that the volume of the cluster of short lead time was significantly greater than the rest of the clusters.

8.4.2.2.1. Long lead time references

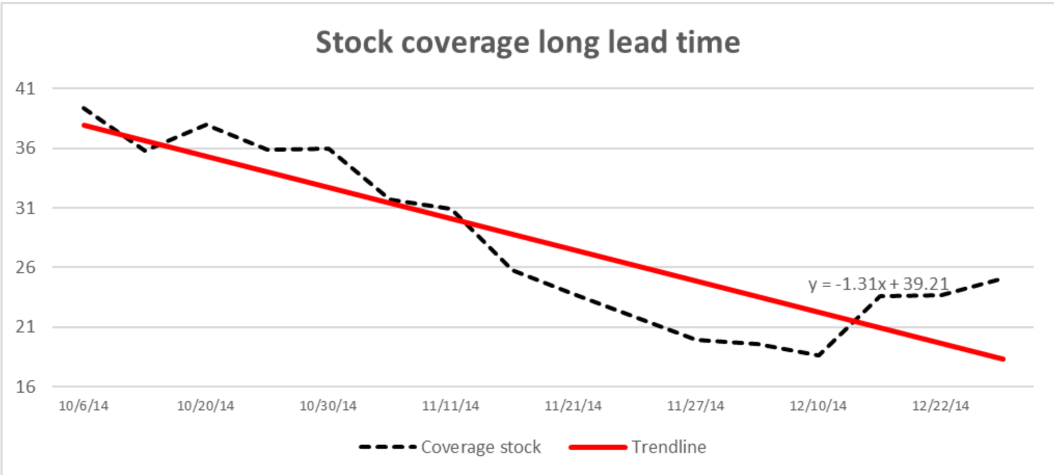
The stock coverage of long lead time references decreased by 51.85% (Graph 8.6). This is because in this period the consumption of this cluster increased on average by 25.85% (Graph 8.4) while on-hand inventory decreased on average by 38.16% (Graph 8.5).



Graph 8.4: Evolution of the total ADU of long lead time references



Graph 8.5: Evolution of the total on-hand inventory of long lead time references



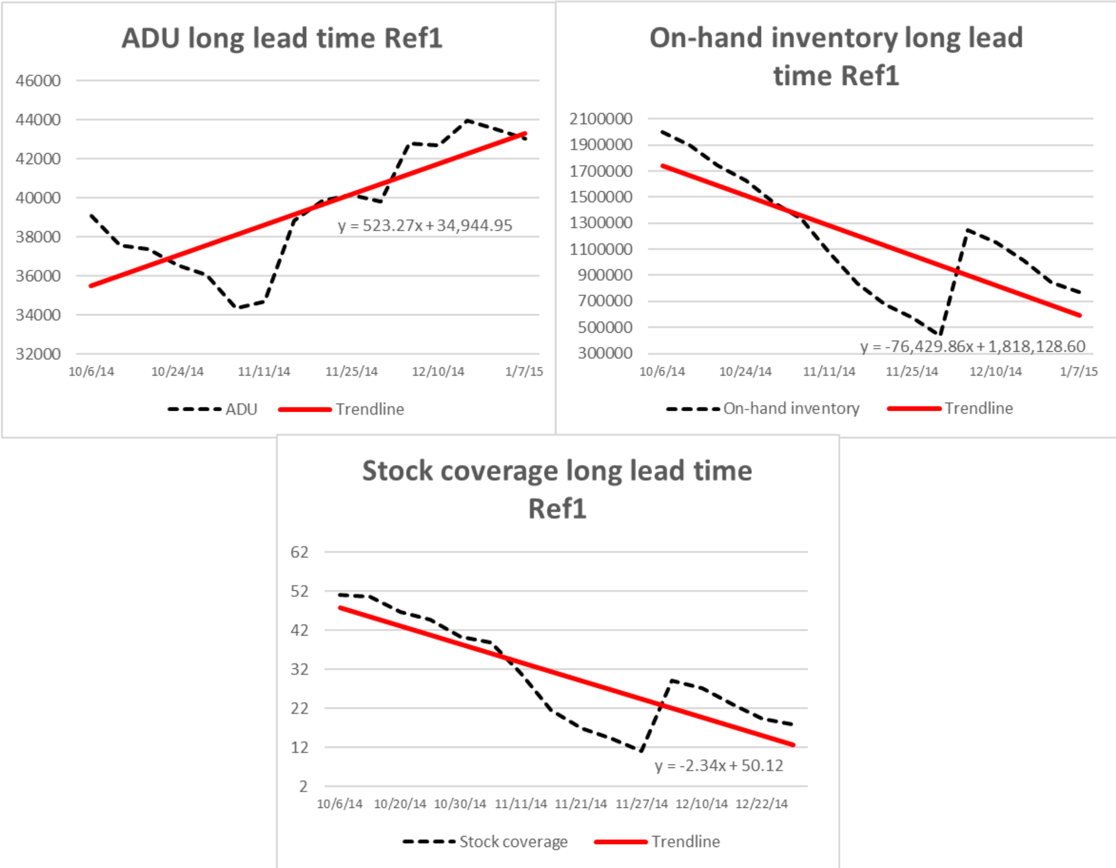
Graph 8.6: Evolution of the total stock coverage of long lead time references

To carry out a more in depth analysis, the three most consumed references belonging to the long lead time cluster were independently analyzed. Ref1 and Ref3 considerably increased their turnover as the ADU of both references increased while the on-hand inventory level and stock coverage dramatically reduced as set out in Table 8-1, Graph 8.7 and Graph 8.9.

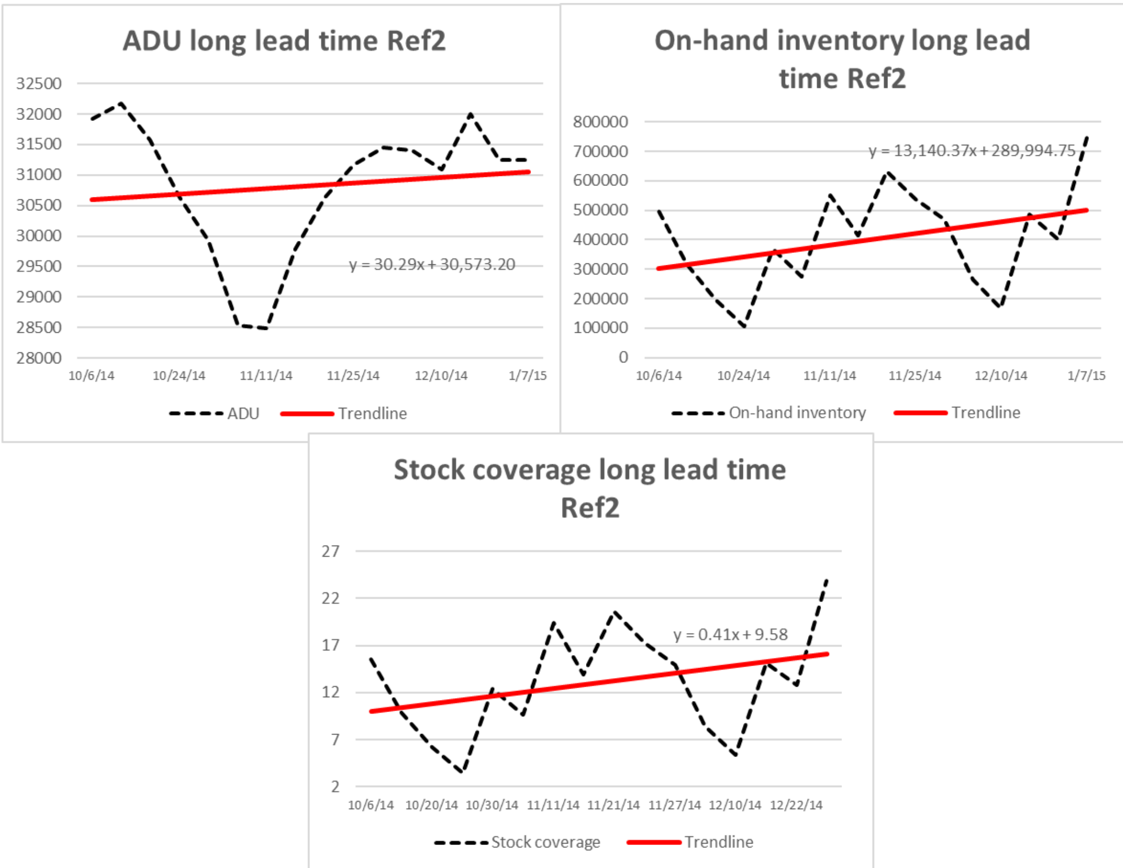
As for Ref2 all the indicators increased during the analysis as set out in Graph 8.8. This suggest that before DDMRP implementation the inventory level of this reference was not enough. In other words, this reference was located on the left side of the bimodal distribution and by adjusting the inventory to the real needs it was shifted to the right.

Table 8-1: Evolution of the three most consumed references of long lead time cluster

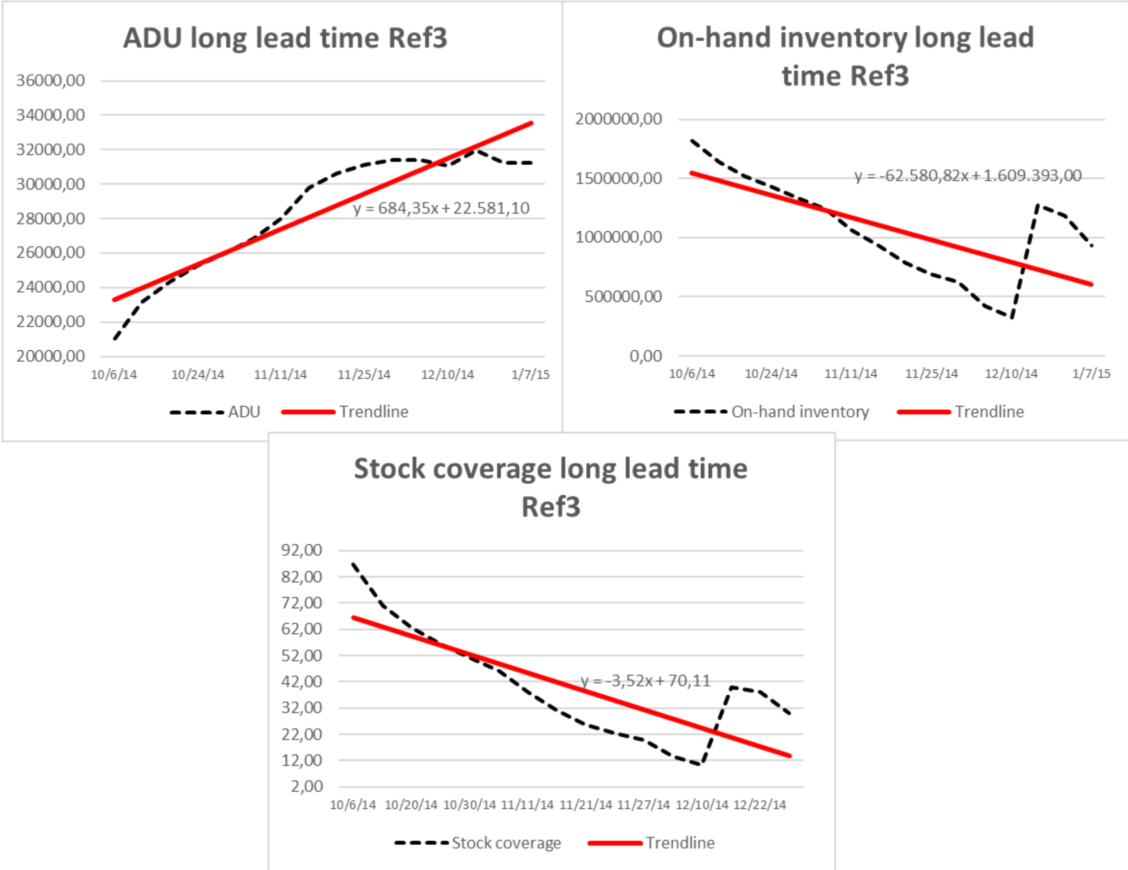
	Ref1	Ref2	Ref3
ADU	22.13%	1.48%	44.12%
ON-HAND	-65.82%	65.02%	-60.69%
STOCK COVERAGE	-73.46%	61.56%	-79.29%



Graph 8.7: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref1 in the long lead time cluster



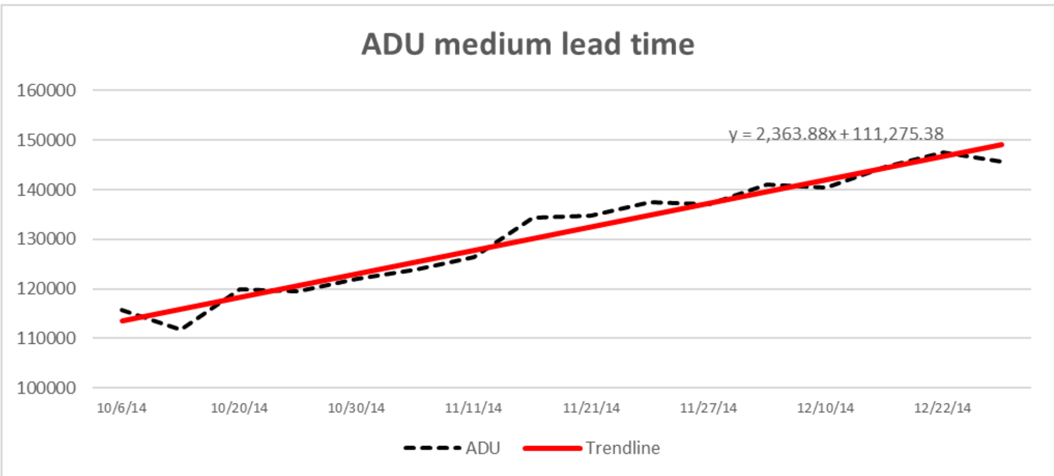
Graph 8.8: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref2 in the long lead time cluster



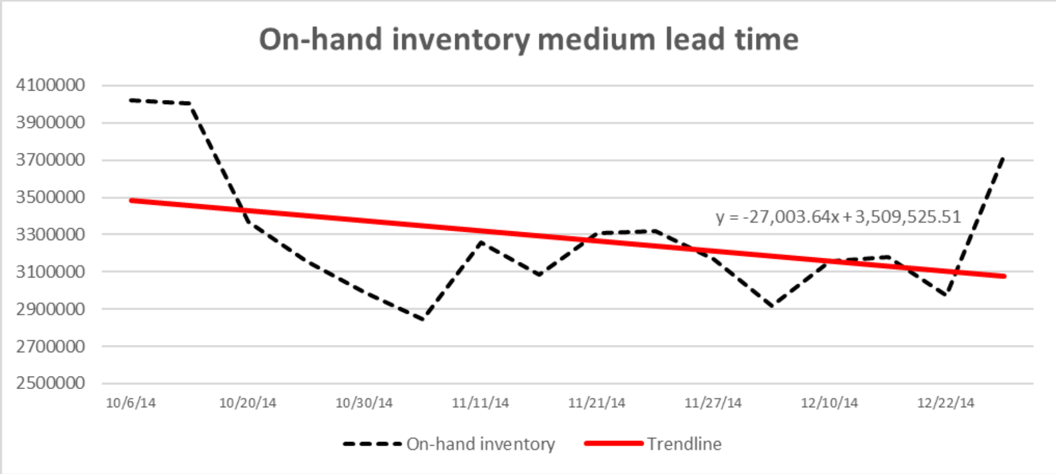
Graph 8.9: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref3 in long lead time cluster

8.4.2.2.2. Medium lead time references

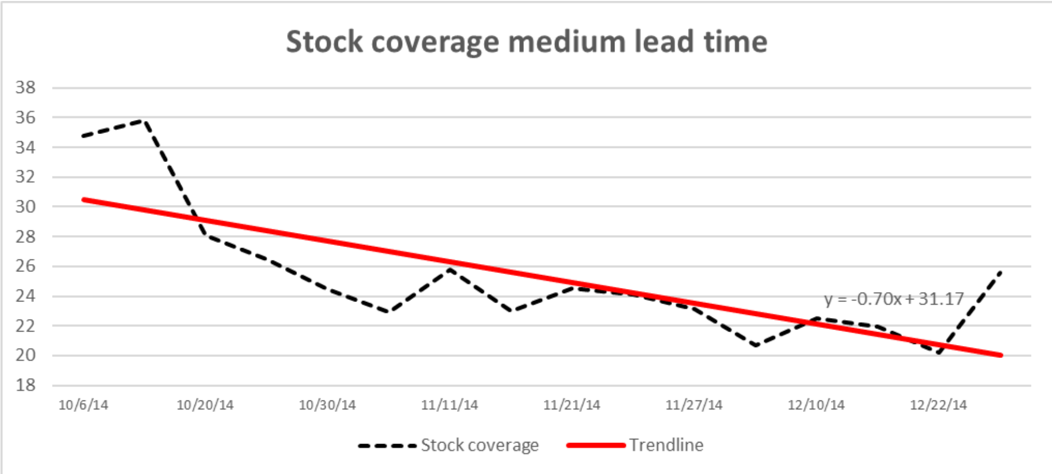
The medium lead time cluster showed the same trend as long lead time, since the on-hand inventory level and the stock coverage of medium lead time references reduced by 11.63% (Graph 8.11) and 34.46%,(Graph 8.12) while the ADU increased by 31.2% (Graph 8.10).



Graph 8.10: Evolution of the total ADU of medium lead time references



Graph 8.11: Evolution of the total on-hand inventory of medium lead time references



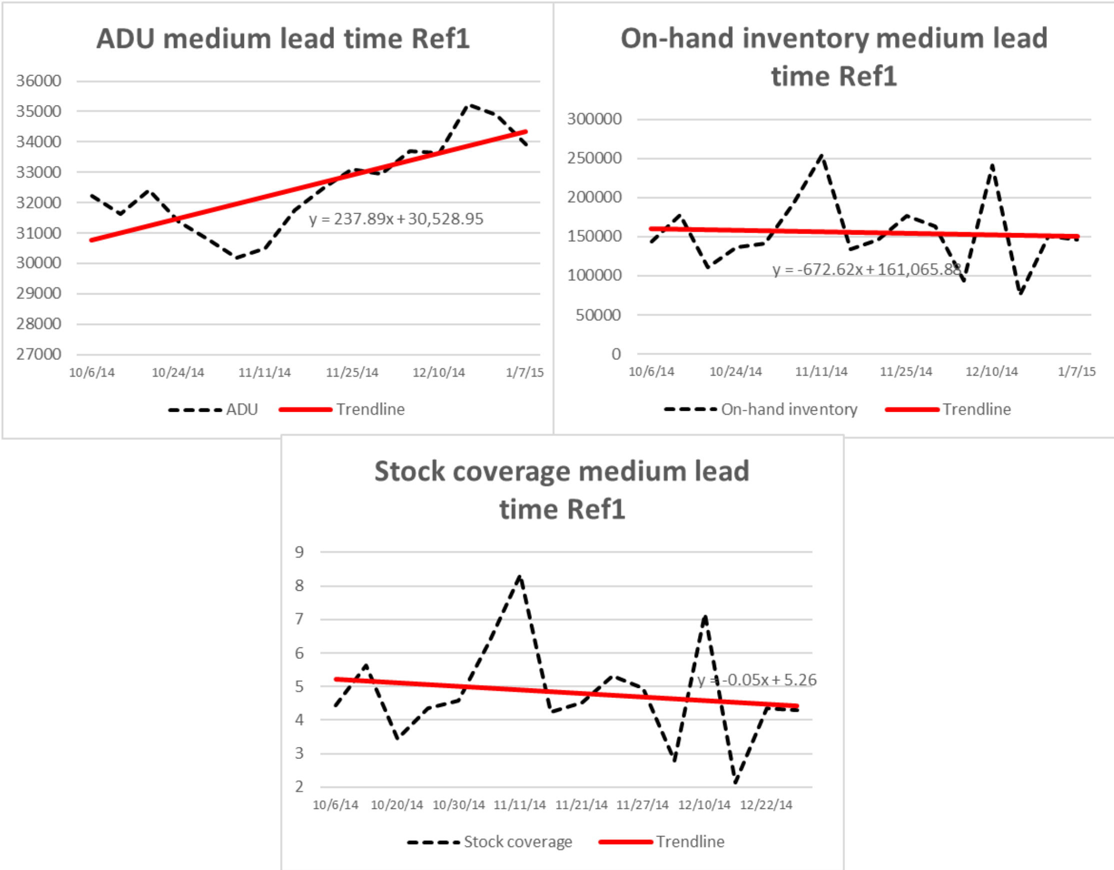
Graph 8.12: Evolution of the total stock coverage of medium lead time references

Here as well, the three most consumed references were analyzed independently. Ref1 and Ref3 increased their turnover since the ADU of both references increased while the on-hand inventory level reduced, as set out in Table 8-2, Graph 8.13 and Graph 8.15.

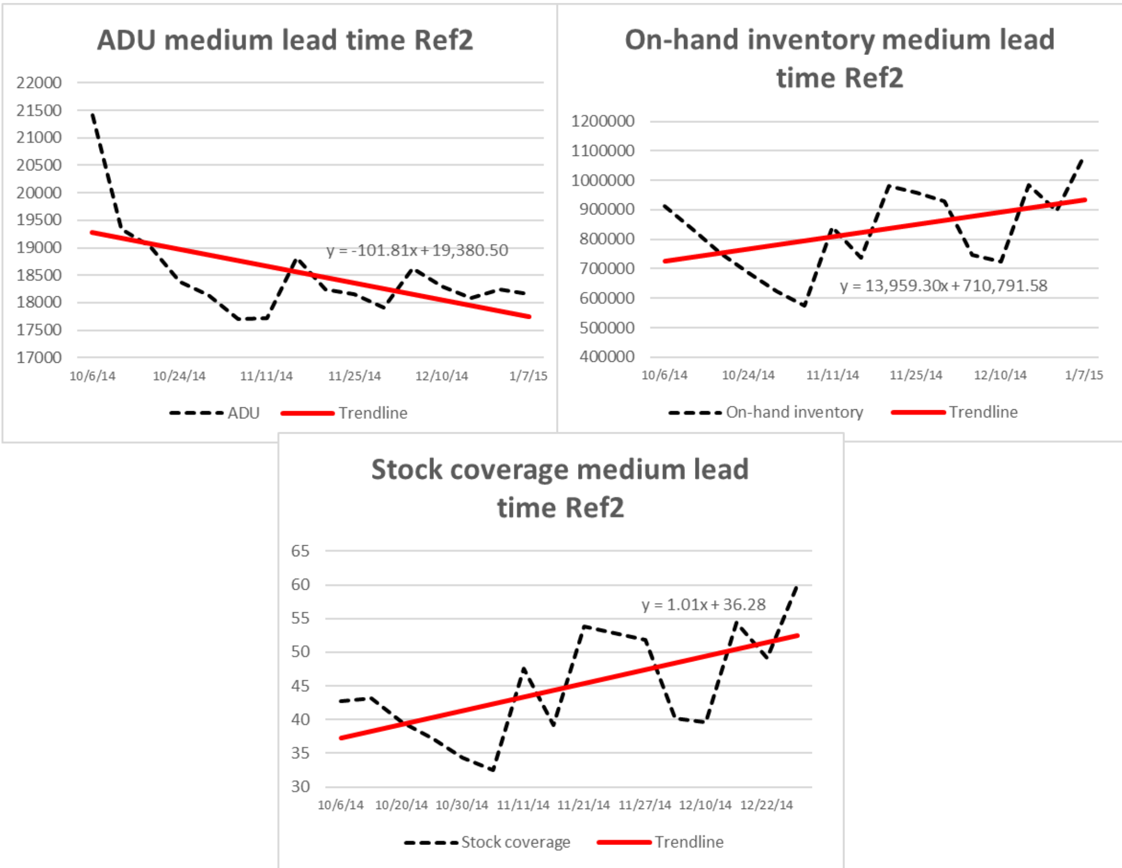
As for Ref2 the ADU decreased while the on-hand inventory and stock coverage increased which suggest that before DDMRP implementation the inventory level of this reference was not enough to meet the demand. In other words, this reference was located on the left side of the bimodal distribution and by adjusting the inventory to the real needs, it was shifted to the right.

Table 8-2: Evolution of the three most consumed references of the medium lead time cluster

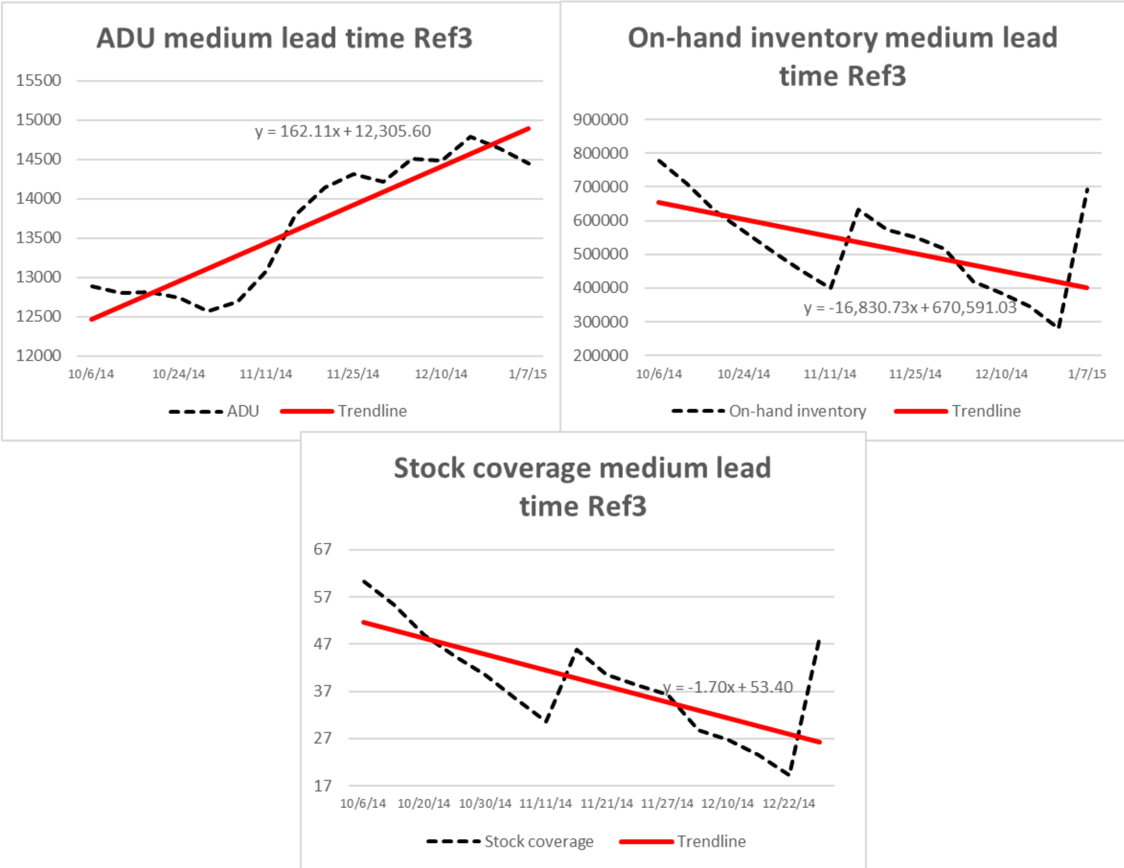
	Ref1	Ref2	Ref3
ADU	11.6%	-7.92%	19.5%
ON-HAND	-6.29%	28.89%	-38.62%
STOCK COVERAGE	-14.4%	40.63%	-49.32%



Graph 8.13: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref1 in the medium lead time cluster



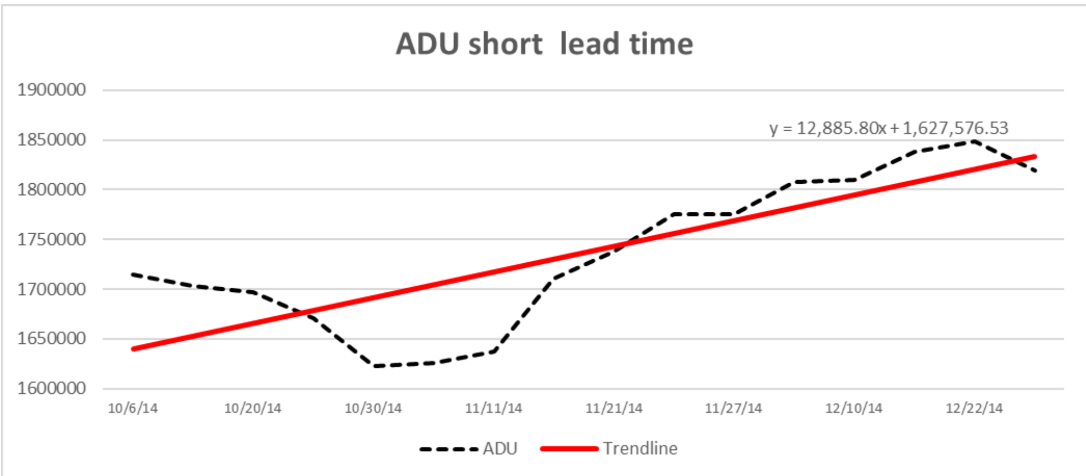
Graph 8.14: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref2 in the medium lead time cluster



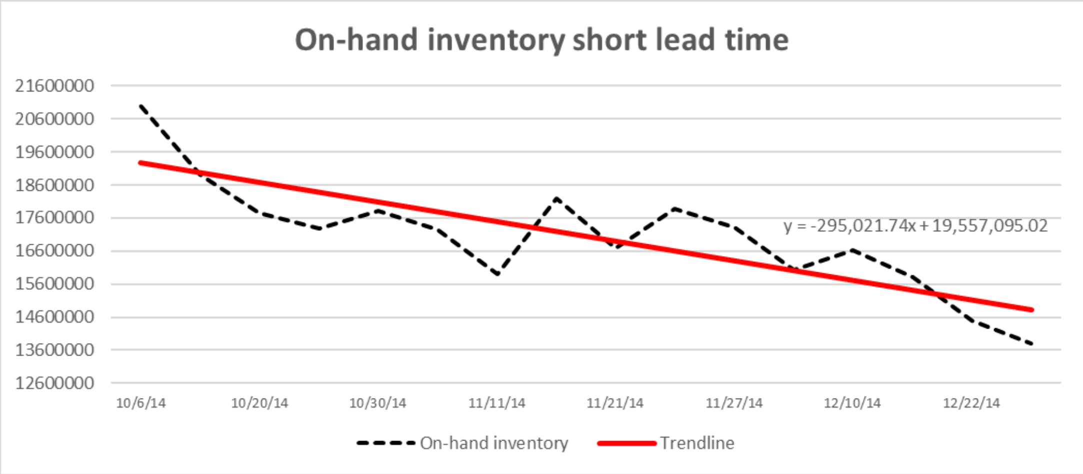
Graph 8.15: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref3 in the medium lead time cluster

8.4.2.2.3. Short lead time references

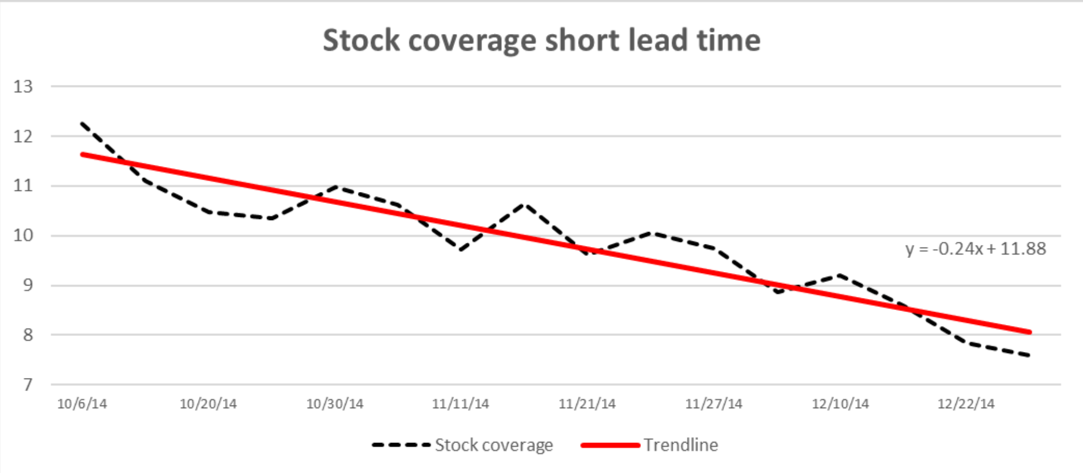
The short lead time cluster showed the same trend as the long and medium lead time clusters. The on-hand inventory level and the stock coverage reduced by 22.97% (Graph 8.17) and 30.93% (Graph 8.18) while the ADU increased by 11.78% (Graph 8.16).



Graph 8.16: Evolution of the total ADU of short lead time references



Graph 8.17: Evolution of the total on-hand inventory of short lead time references

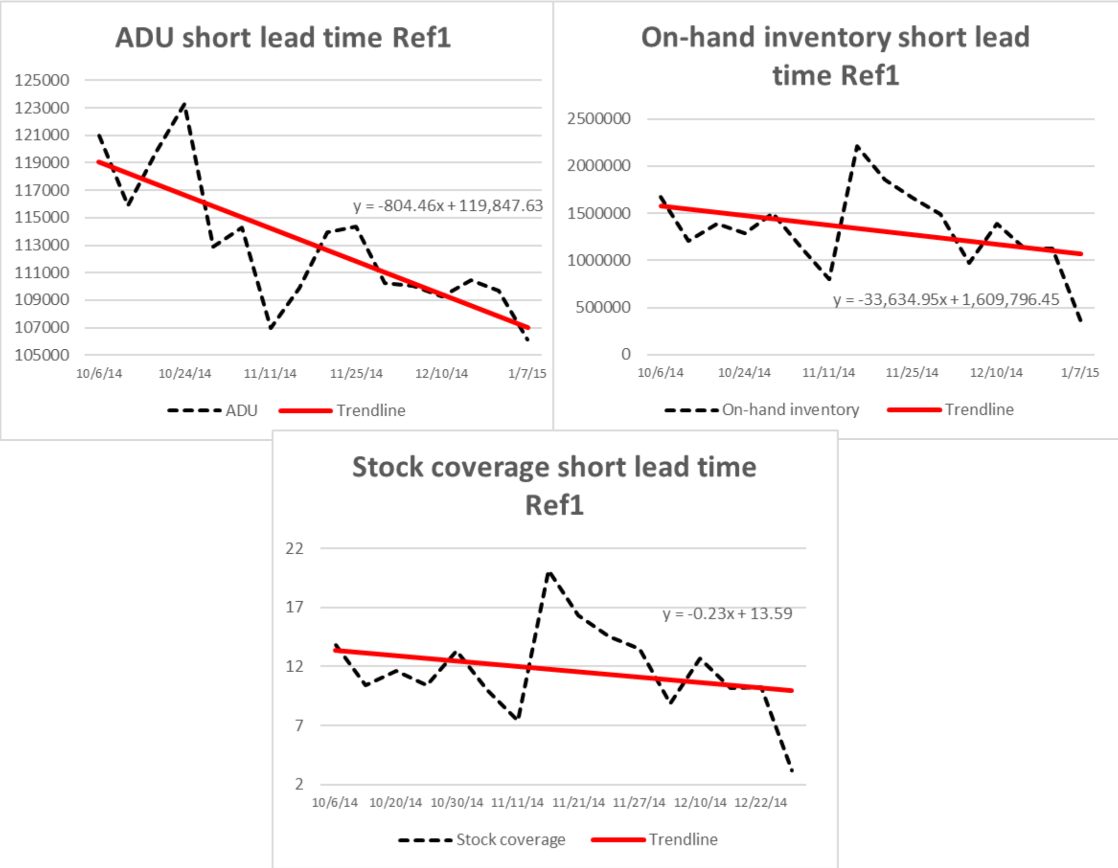


Graph 8.18: Evolution of the total stock coverage of short lead time references

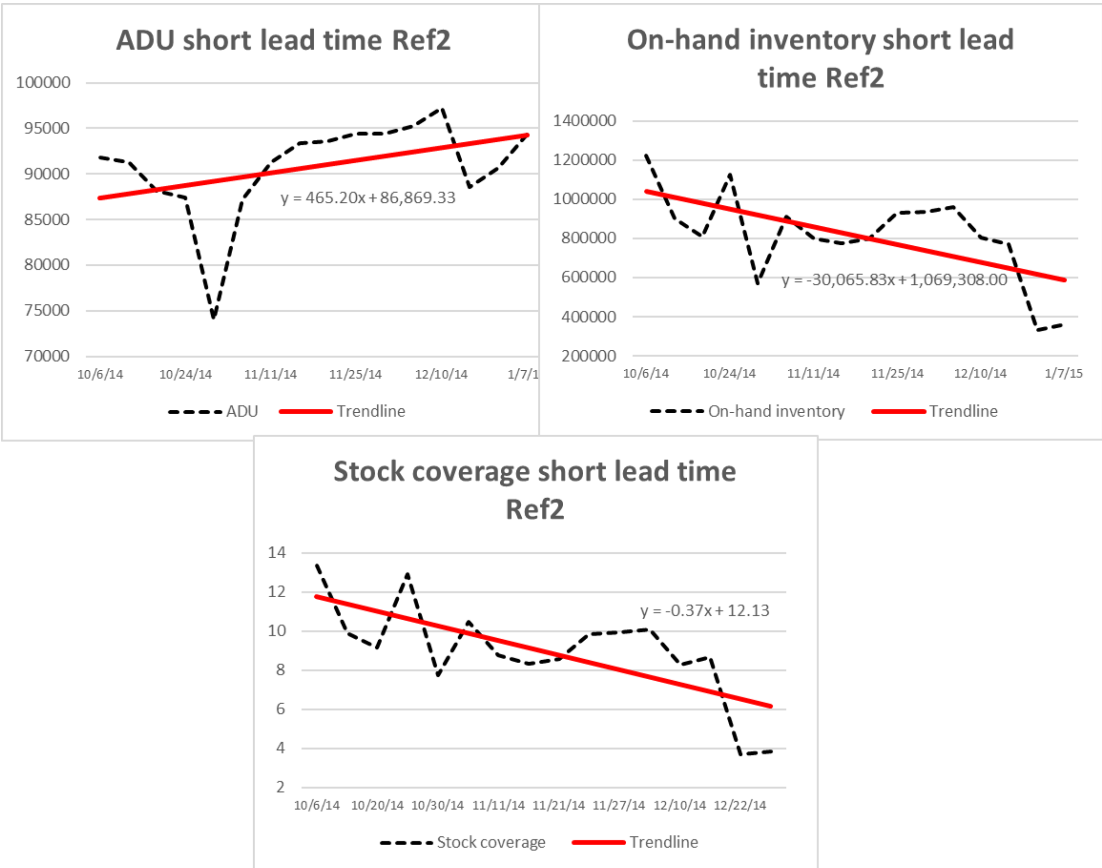
As for the individual analysis of the three most consumed references, the results are summarized in Table 8-3. In the case of Ref2 and Ref3 it is important to note that although the ADU increased, the stock coverage reduced considerably (Graph 8.20, Graph 8.21). As for Ref1, the ADU decreased and the on-hand inventory even more so. Thus, the stock coverage also decreased (Graph 8.19).

Table 8-3: Evolution of the three most consumed references of the short lead time cluster

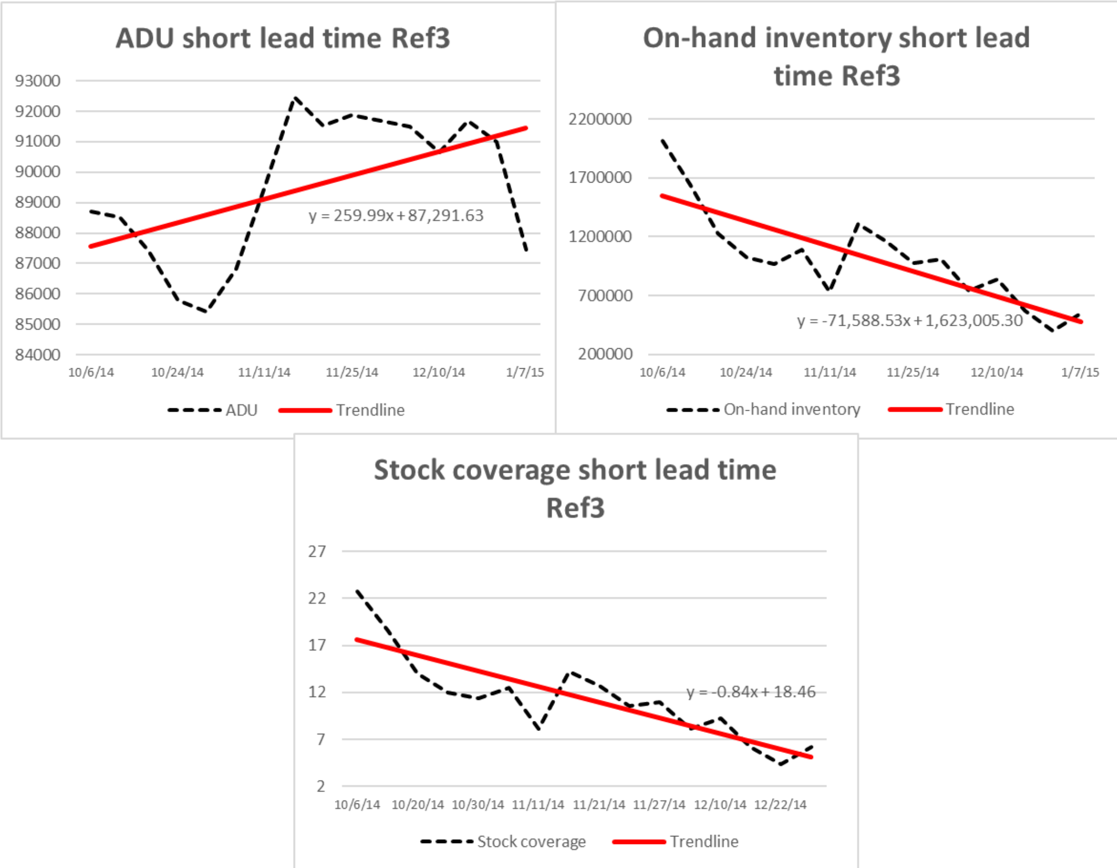
	Ref1	Ref2	Ref3
ADU	-10.14%	7.99%	4.45%
ON-HAND	-32.01%	-43.40%	-69.22%
STOCK COVERAGE	-25.82%	-47.19%	-71.51%



Graph 8.19: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref1 in the short lead time cluster



Graph 8.20: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref2 in the short lead time cluster



Graph 8.21: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref3 in the short lead time cluster

8.5. Main findings of case study 2

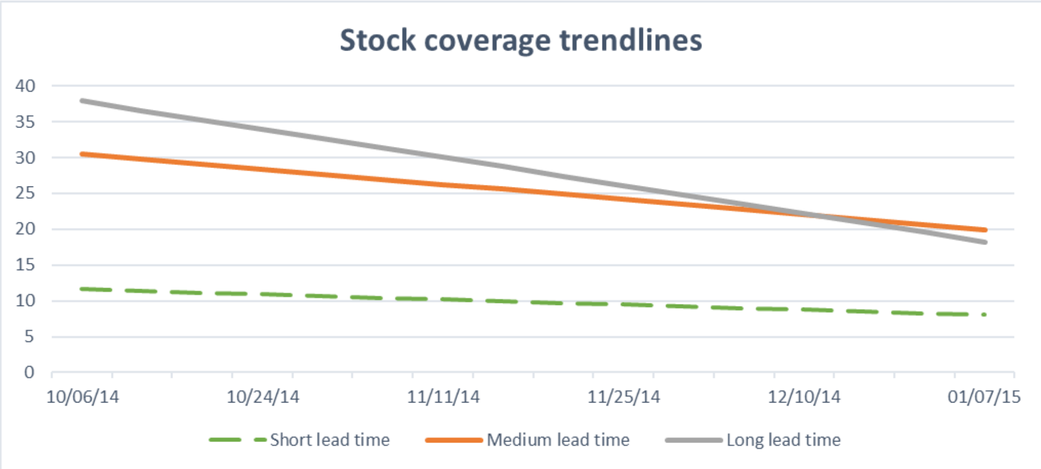
This Section summarizes the most important findings of this case study.

After DDMRP implementation, CS2 was able to face greater demand with less inventory level while maintaining nearly 100% on-time delivery. The stock coverage evolution also reinforces this statement. Thus, it can be said that before DDMRP implementation, CS2 was in general terms overbuying many references (Table 8-4). This was confirmed by the PPM of CS2. She explained that before DDMRP the raw material warehouse experienced storage problems, whereas after implementation they had free space.

Table 8-4: Summary of the global results of each cluster

CLUSTER	Ref1	Ref2	Ref3
Long lead time	25.85%	-38.16%	-51.85%
Medium lead time	31.20%	-11.63%	-34.46%
Short lead time	11.78%	-22.97%	-30.93%

It is worth highlighting the evolution of the stock coverage of long lead time references, since this was reduced by 51.85% on average during the implementation (Graph 8.22). This indicates that CS2 was overbuying these references to prevent shortages caused by forecast errors, long delivery times and shipment cost, resulting in more stock than required. However, the use of DDMRP protected CS2 from variability, resulting in a reduction of uncertainty and increase of visibility. Thus, the company was able to align raw material inventory level to real consumption, reducing the on-hand inventory and increasing the inventory turnover.



Graph 8.22: Evolution of the stock coverage of each cluster

Long and medium lead time references on average had more days of inventory than short lead time references (Graph 8.22). This fact was directly related to the lead time and significant MOQ of the references. CS2 therefore, was buying more parts than needed, affecting the on-hand inventory level and, consequently, the stock coverage.

The service level that CS2 provided to customers did not change after the implementation. Neither was it a goal, since CS2 provided nearly 100% of service level. However, it is important to emphasize that the service level existing before DDMRP was based on the ability of suppliers to serve rush orders, forcing them to work with high SS. After implementing DDMRP, the bullwhip effect was reduced, suppliers increased their capacity and were better able to meet CS2 requirements. In summary, the company maintained the high service level it had before the implementation of DDMRP, but at a lower cost.

DDMRP increased material and information flow through the supply chain of CS2. The following points show how CS2 increased its visibility implementing DDMRP.

- Rush orders were reduced considerably in CS2 due to decoupling points allocated in the raw material warehouse. The particular case of the subcontracted company is an example of this, since it was able to identify what to produce considering the information provided by the buffer stocks located between two linkages. This fact considerably reduced the uncertainty between the subcontractor and CS2, and prevented the bullwhip effect. As a result (1) the subcontractor was able to provide a more effective response to CS2 requirements, and (2) CS2 had more visibility about material requirements of the subcontractor resulting in a significant reduction of raw material inventory level in the subcontractor warehouse.

- During the interviews, CS2 staff stated that dynamic adjustments were very useful for synchronizing raw material requirements with the working calendars of the suppliers. CS2 used this approach to estimate the required material for Christmas and it worked properly. They did not have any incidences in that period and were able to calculate and purchase the correct amount of raw material. Importantly, this component seems to be able to adjust inventory levels to deal with volatile market requirements.
- Due to the color-coded alerts, CS2 was easily able to identify the degree of attention each reference required in any particular moment and thus, was able to prioritize critical state references. Moreover, owing to the visibility and information that this methodology provided, staff was able to react on-time in light of a possible shortage. Consequently the number of rush orders were dramatically reduced.

After analyzing this second case study, it was found that although the DDMRP was implemented in a different environment to the case study 1, even in a specific link such as the purchase area of the supply chain, the results obtained were similar. The company adjusted its inventory to the real needs maintaining the service level. On the other hand, this methodology allowed the company to considerably increase the visibility within the supply chain with all the advantages that this entails.

The positive results of this case study led us to analyze a further case study, to test if similar outcomes could be further achieved in a different context. A third company (CS3) which had implemented DDMRP in the whole supply chain was therefore selected. This case study allowed us to check if the results were repeated when managing suppliers and raw materials. On the other hand, this case study analyzed how DDMRP manages the production and end products of a company to meet the demand of customers.

Chapter 9

9. Case study 3

In this chapter the company where DDMRP was implemented is introduced and the reasons why they decided to implement DDMRP are explained. Then, critical points that prevented material and information flow are discussed. After that, DDMRP implementation is summarized and finally the qualitative and quantitative results and main findings are presented.

9.1. Introduction to the company

This case study is based on a company that produces and distributes special parts for the automotive industry. The company is composed of three factories: (1) a production plant that manufactures parts using hot and semi-hot forging in the Basque Country and (2) two machining plants, one located in the Basque country and the other in Romania (Figure 9.1).

The company had close to 100% of service level and is worth highlighting that several times it has been recognized as best supplier due to the quality and service level. In this thesis it is referred to as CS3.

CS3 offers a catalog of finished products to its customers. To this end, the forging plant purchases raw material and tools from various suppliers and produces semi-finished or final products. Semi-finished products are sent to machining plant A or B and final products directly to the customer (Figure 9.1).

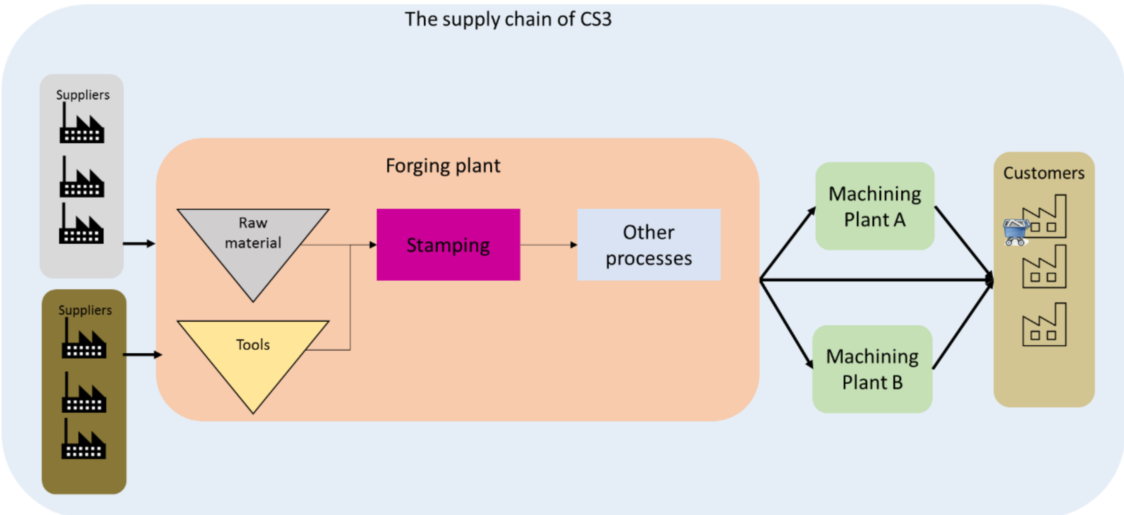


Figure 9.1: The supply chain of CS3

9.1.1. Reasons to implement DDMRP

Before DDMRP implementation, the purchase and production orders were planned using MRP. The PPM considered the information of the BOM of the references, the forecast provided by final customers, the inventory level of each reference and the inverse calendar to develop the production plan and the purchase orders for the following week.

The forecast information provided by customers was not reliable as it changed frequently in substantial amounts. As a consequence, the production plan that the company defined for the following week was hardly ever implemented. Thus, time and resources were wasted replanning the production to manage the required rush orders so as to meet the updated forecast.

In addition, the PPM was the only one who knew how to carry out the purchase and production planning since there was no systematic procedure established company wide. However, the retirement of this person forced the company to develop a spreadsheet that imported planning input data from the ERP to manage production planning. Nevertheless, this solution proved impractical since it took more than 8 hours to gather all the information and propose a production plan. In addition, the results were frequently unsatisfactory.

In light of this situation, CS3 decided to implement a robust methodology for production planning and purchase orders. After analyzing different alternatives, CS3 decided to implement DDMRP throughout the supply chain (Figure 9.2 marked in red). This implementation was done between May and July 2013.

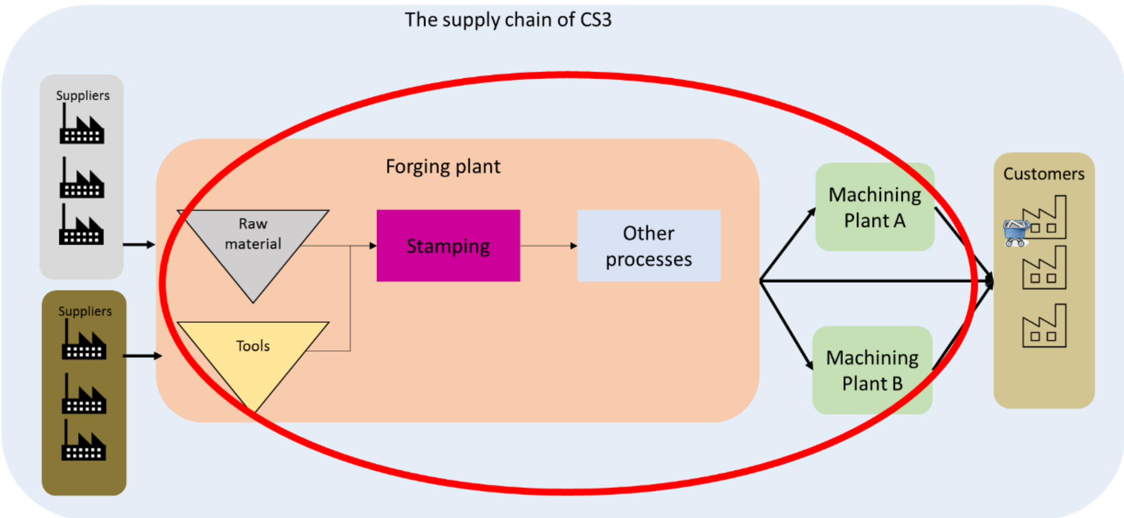


Figure 9.2: Links of the supply chain of CS3 where DDMRP was implemented

9.1.2. The supply chain of CS3

Every Thursday the forging plant planned the production of the following week (Monday to Friday) considering the BOM of the references, the forecast provided by the final customer, the inventory level of each reference and the inverse calendar. This plan identified purchase and production orders to be raised.

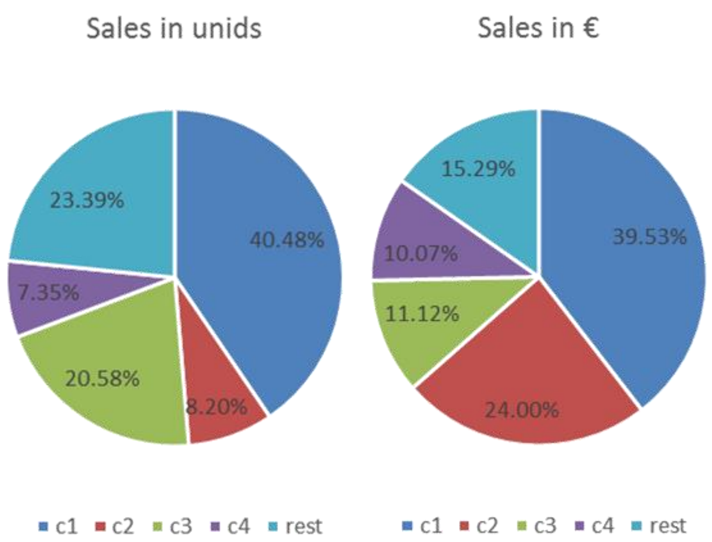
The forging plant managed around 60 raw material references that were supplied by different suppliers. All those references had a long lead time of around two months.

The nature of the stamping process meant that production in the forging plant was subject to certain limitations. Each stamped reference needed its own equipment and tools and thus the setup had to be taken into account as part of the planning process. Upon the completion of stamping one production batch, it was critical to have the equipment and tools ready for the reference that was going to be stamped next. Proper planning meant that the downtime of the stamping machine during setup was less, with less impact on production.

CS3 managed around 400 end product references. Some of them needed to be machined in the machining plant before deliver to the customer, while others were directly delivered from the forging plant (Figure 9.1).

The company had 34 customers, 4 of which ordered products following the make to stock strategy. These customers represented almost the 85% of the sales in € and 77% of the sold units (Graph 9.1). The remaining 30 customers (indicated as “rest” in Graph 9.1) used the make to order strategy, and represented 15.29% of the sales in € and 23.39% of the sold units.

Considering the large volume of the 4 biggest customers in the portfolio, and that the rest of the customers followed make to order strategy, this case study is focused on these 4 customers.



Graph 9.1: Percentage of sales of each customer

The supply chain of each customer is detailed below:

- **Customer 1 (C1):** This customer consumed 28 end products that were produced using 7 raw material references. C1 provided the demand forecast of the next 6 months on a daily basis, although according to the PPM the reliability of this data was very low. As for the lead time of these end products, parts machined in machining plant A took 4 weeks whereas those from plant B took 5 weeks (Figure 9.3). On average this customer purchased 2,600,000 units per month that accounted for 39.53% of the turnover (Graph 9.1).

  C1 held consignment stock[2] in their warehouse that was managed by CS3. In other words, C1 stipulated the minimum and maximum amount of each end product to be made available in the warehouse. To this end, CS3 received daily reports about material consumption of the preceding day, however these reports rarely matched the forecast.

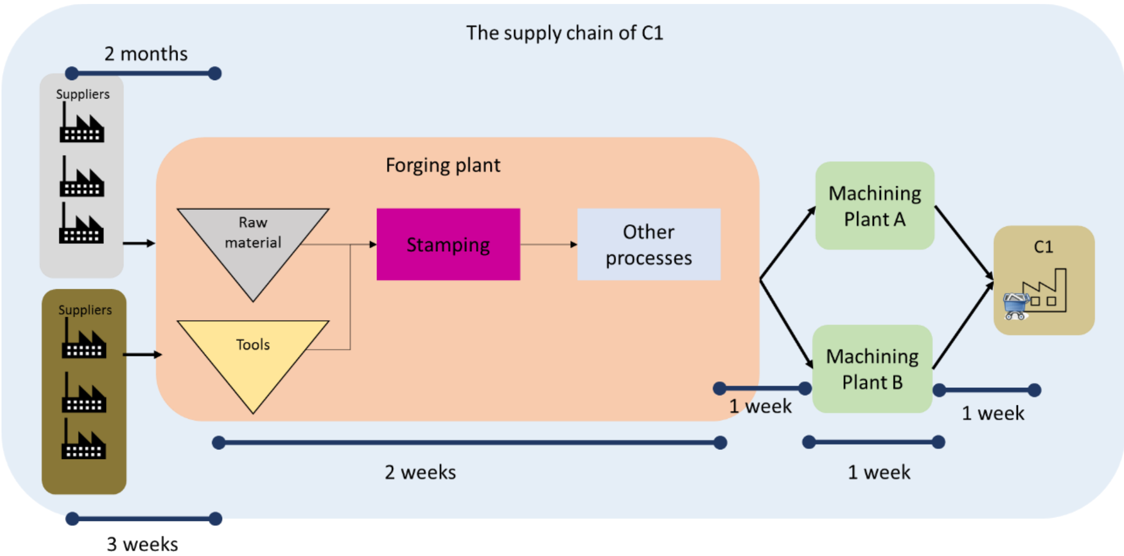


Figure 9.3: Supply chain of C1

- **Customer 2 (C2):** This customer consumed 26 different end products that were produced using 9 raw material references. On average this customer purchased 534,000 units per month that accounted for 24% of the turnover (Graph 9.1).

  C2 reported the demand forecast of the following 6 months to CS3 on a daily basis. According to the company, the reliability of the forecast was quite high.

  CS3 was required to meet C2 orders with a 24-hour turnaround time. To this end, the company planned SS for each end product to be able to answer the demand in 1 day.

[2] Figure in Figure 9.3 represents a consignment stock

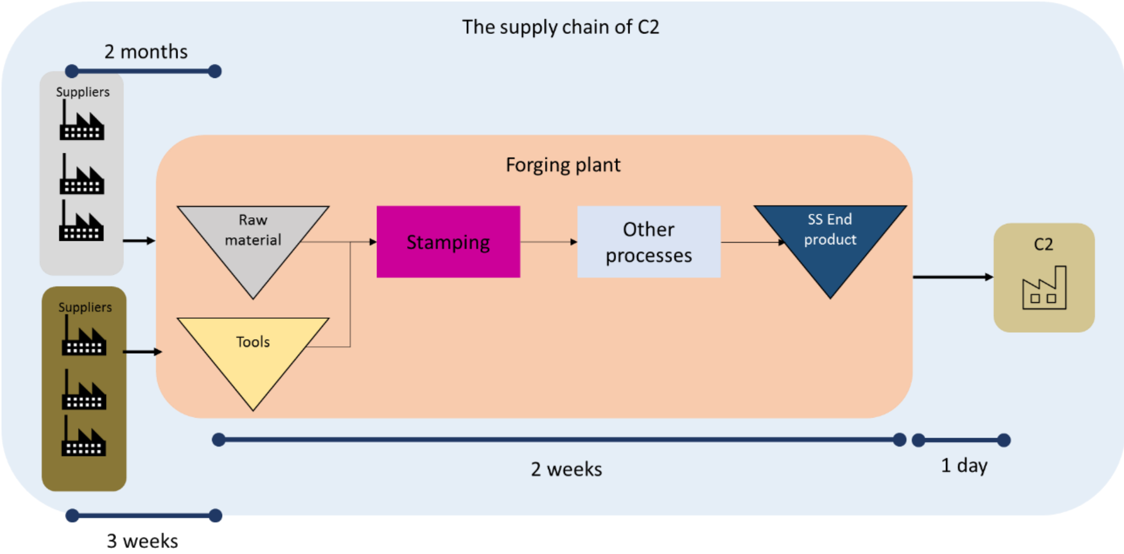


Figure 9.4: Supply chain of C2

- **Customer 3 (C3):** This customer consumed 8 different references that were produced using 2 raw material. They purchased 1340,000 units per month that accounted for 11.12% of the turnover (Graph 9.1).

  C3 reported the demand forecast of the following 6 months to CS3 on a daily basis. According to the company the reliability of the forecast was quite high.

  The supply chain of this customer is shown in Figure 9.5.

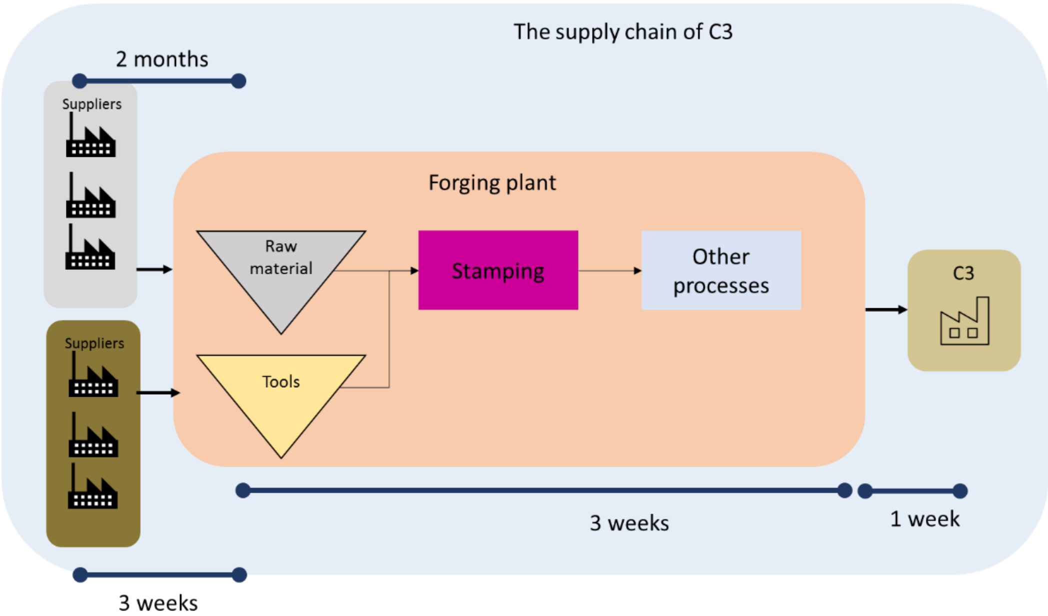


Figure 9.5: Supply chain of C3

- **Customer 4 (C4):** This customer consumed 110 different end products that were produced using 13 raw materials. The lead time of these end products were 4 weeks. On average, this customer purchased 478,500 units per month that accounted for

10.07% of the turnover (Graph 9.1). C4 reported the demand forecast of the following 6 months to CS3 on a daily basis. However, in this case the forecast reliability was poor. Due to the long setup time of the machines, CS3 configured large production batches. However, C4 usually ordered considerably fewer units than that of a regular production batch. Therefore, the overproduction references were stocked as end product (Figure 9.6). This stock was not planned.

When planning production CS3 took into account the level of previously accumulated SS. If there was insufficient stock to cover forecast demand, they would produce a new batch in regular quantities. Once the order was satisfied, the overproduction was again stored in the end product buffer.

C4 and CS3 had an agreement where in a period of three years, C4 should purchase the material that was forecast. Hence, CS3 ensured that the stocked end product caused by the overproduction would be consumed in future purchases.

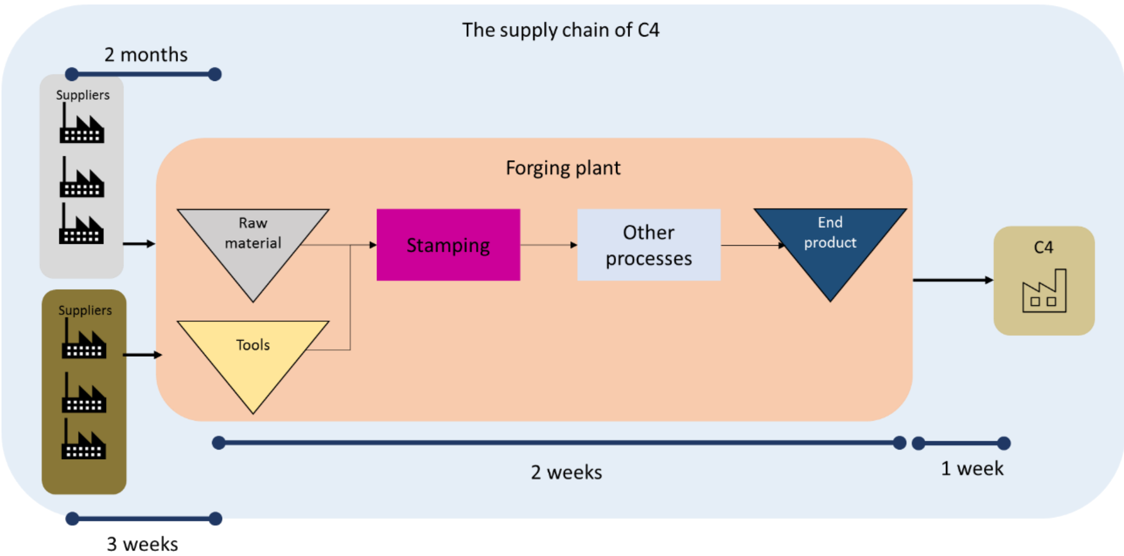


Figure 9.6: Supply chain of C4

9.2. Critical points that reduced the flow of materials and information in the supply chain

When consultants together with the collaboration of Mondragon Unbertsitatea began collecting information to implement DDMRP, they found situations that were directly affecting the flow of materials and information. Importantly, the company did not consider the following decisions (9.2.1 - 9.2.4) as problems before the implementation:

9.2.1. Lack of visibility to changes in forecast

Before DDMRP implementation, CS3 planned the production plan of the following week (Monday to Friday) every Thursday. To do this, the company developed a spreadsheet as mentioned in Section 9.1.

This spreadsheet had as input data the BOM of the articles, the forecast reported by customers and the inventory level of each reference. The spreadsheet produced the production plan of the following week however, the processing was lengthy taking on average 8 hours.

The forecast of customers however, changed daily meaning that a weekly planning process was insufficient to effectively service demand. Table 9-1 presents a real example of the volatility of the forecast that a customer sent to CS3. This volatility generated significant uncertainty in the supply chain.

Table 9-1: Example of the forecast and real demand of a reference in units

	CUSTOMER FORECAST	REAL DEMAND
Week 1	15,400	0
Week 2	20,300	15,400
Week 3	20,300	0
Week 4	20,300	0
Week 5	20,300	0

Clearly, in this uncertain environment planning once per week reduced the visibility of the company considerably. The impact of this was felt on three ways:

- If the customer or machining plant did not notify forecast changes directly to the forging plant, these changes would not be noticed until the following Thursday. This lack of visibility caused a loss of reaction capacity since, if CS3 had been aware of these changes when they happened, the company would have had extra days to react, gaining additional flexibility.
- Due to the variability of the forecast, CS3 frequently was forced to set aside the plan, improvise and manage rush orders in order to face new demand. This in turn led to performing more setups than planned, increasing downtime and reducing production capacity.
- Rush orders caused considerable disruptions to the production plan. It was frequently the case that by the time a rush order was received CS3 had already produced parts that

would not be required. The converse was also true, in that CS3 frequently had shortfalls in parts brought about by scheduling changes.

In summary, the company was saturated by fictitious demand causing a bimodal distribution. This in turn caused incorrect purchase orders to be raised (explained below) skewing further the bimodal distribution.

9.2.2. Purchase of raw material according to the forecast of the customers

CS3 used forecast information provided by customers and the inverse calendar of the MRP to launch purchase orders. On average, the purchase lead time of the raw material was two months. Such a long lead time meant the uncertainty in the customer forecast could cause a significant difference between purchased material and real requirements. This further amplified the bimodal distribution in the raw material inventory.

In addition, considering the purchase lead time of the raw material, the company could not launch rush orders of these references in case of a shortage. Consequently, CS3 was forced to have a large SS level of all raw material references in order to be able to face the demand that had not been forecast. If sufficient raw material was not available CS3 would be unable to service customer requirements, with a subsequent negative impact on service level.

9.2.3. Silo effect between forging and machining plant

Five weeks before the delivery date, the forging plant planned production of the references identified in the forecast. Once these parts were produced, they were delivered to the machining plants to be mechanized as shown in Figure 9.3.

The machining plants planned the production, two weeks before the delivery date, considering the forecast provided by C1. However, due to the volatility of the forecast, what the machining plant was supposed to produce, frequently did not match the material sent by the forging plant. That is to say, the forecast data that the forging plant employed to plan the production changed, and when this material was delivered to the machining plants, it was no longer required by the customer. The machining plants had therefore, an amount of inventory that did not correspond to the forecast demand of the customer, and at the same time with a lack of material that was needed for the updated forecast. This lack of synchronization between the forging plant and the machining plants contributed to the bimodal distribution of the inventory.

To deal with this situation, the machining plants sent rush orders to the forging plant. This interrupted the production plan of the forging plant, forcing the company to carry out unplanned setups and disrupting planned production. This had a negative impact on production capacity.

To better understand this problem an example is explained (Figure 9.7): suppose that within 5 weeks the forecast provided by C1 for a particular reference “X1” is 200 units and “X2” is 0 units. The forging plant plans and produces 200 units of “X1” and does not produce any “X2”. Nonetheless, three weeks later, when these parts arrive at the machining plant B to be mechanized, the machining plant has a different production plan because C1 has updated its forecast. In other words, the current forecast of C1 is 500 units of “X2” and 0 units of “X1”. The forging plant however, did not produce any X2 since this was not forecast three weeks ago. Hence, the machining plant B sends a rush order of 500 units of X2 to the forging plant. At the same time, the 200 units of X1 are stored in the machining plant B to be used in the future, although this is not a planned inventory.

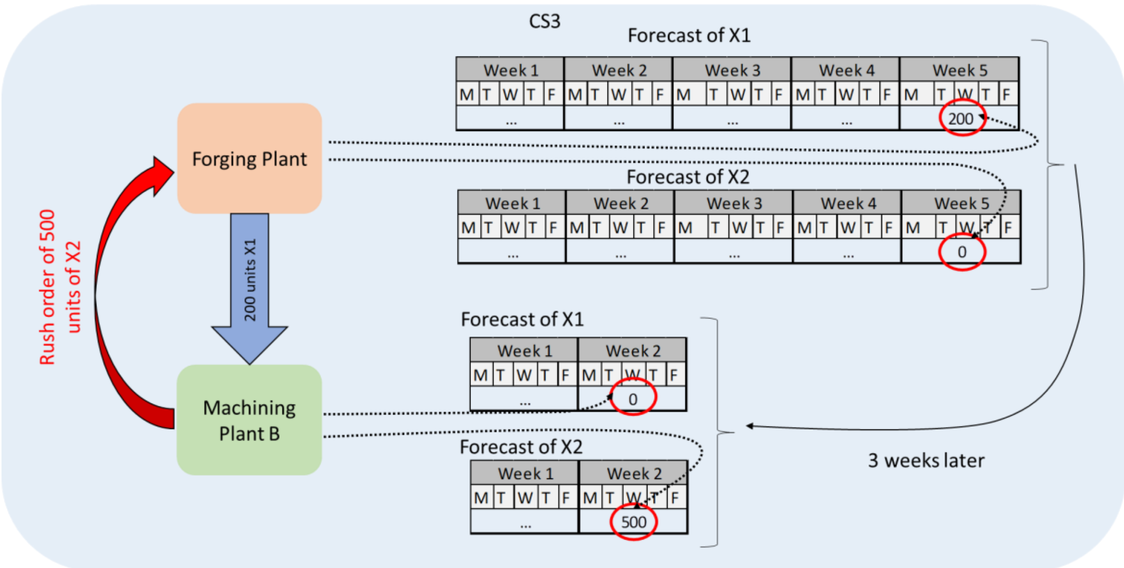


Figure 9.7: Example of a lack of synchronization between the forging plant and the machining plant

The forging plant, under regular production conditions, had a lead time of 3 weeks: 2 weeks of production and 1 week to send the material to Romania (Figure 9.3). However, when the machining plants sent rush orders, the forging plant prioritized this task. Hence, these orders jumped the queue and were the first to be processed. There were even cases where the stamping machine was interrupted to produce a rush order which required a new setup. To further exacerbate the problem, in some cases when this rush order reached the machining plant, it was no longer required since the customer forecast had again changed. Therefore, CS3 frequently found themselves in the position of stopping production to meet rush orders that afterwards were no longer required by the customer.

The unplanned intermediate stock in the machining plants, together with a lack of required material emphasized bimodal distribution. At the same time, the forging plant was saturated managing fictitious rush orders.

9.2.4. Loss of production capacity due to rush orders

Every week the forging plant planned what to produce the following week and identified the required setups. To perform a setup various tools and equipment were required. These were supplied by many suppliers and had a purchase lead time of three weeks. Therefore, the company had a planned stock of the tools and equipment to carry out the setups (Figure 9.1).

Before performing a setup, the maintenance workers of the forging plant prepared the appropriate tools and equipment to carry out that particular setup task. Once all the material was ready, these workers needed on average three hours to complete the setup. This considerable setup time meant that, the forging plant scheduled large production batches to reduce the amount of setups and hence the downtime of the machines.

However when a rush order happened, the forging plant had to set aside the production and setups plan and perform more setups than originally planned. As a result, the stamping machines were longer in setup mode increasing the downtime and reducing the busy time.

On average, the forging plant had 4-5 unplanned setups every week. If all the required tools and equipment were ready, the setup would last three hours at best. Therefore, on average, the forging plant was losing 12-15 hours of production-time every week, resulting in an important reduction of production capacity, which caused a certain feeling of suffocation or stress in the production plant.

9.3. DDMRP implementation in CS3

The implementartion of the five components of DDMRP is set out below.

9.3.1. Strategic inventory positioning

In this component, the strategic position of the inventory is identified. The supply chain of each customer is explained, since each of them had a different context which required a distinct strategy to allocate inventory.

- **C1:** In the supply chain of customer C1, 4 links were identified as strategic to allocate inventory as set out in Figure 9.8.
    - The allocation of inventory in raw material was considered strategic in order to decouple CS3 from the variability of suppliers. Before DDMRP CS3 already had inventory in this link.
    - To synchronize the forging and machining plants inventory was also allocated in each machining plant. Thus, the forging plant would plan production considering the real consumption of the machining plants, instead of taking into account the forecast of C1. Before DDMRP CS3 did not have planned inventory in this position.
    - Inventory was also placed in the consignment stock of C1, hence the machining plants produced considering the real consumption of C1 instead of the forecast data. Before DDMRP CS3 had inventory placed in this location.
    - Tools inventory was also identified as strategic to allocated inventory. However, the company prioritized implementing DDMRP in materials first, and delayed implementation in tools.

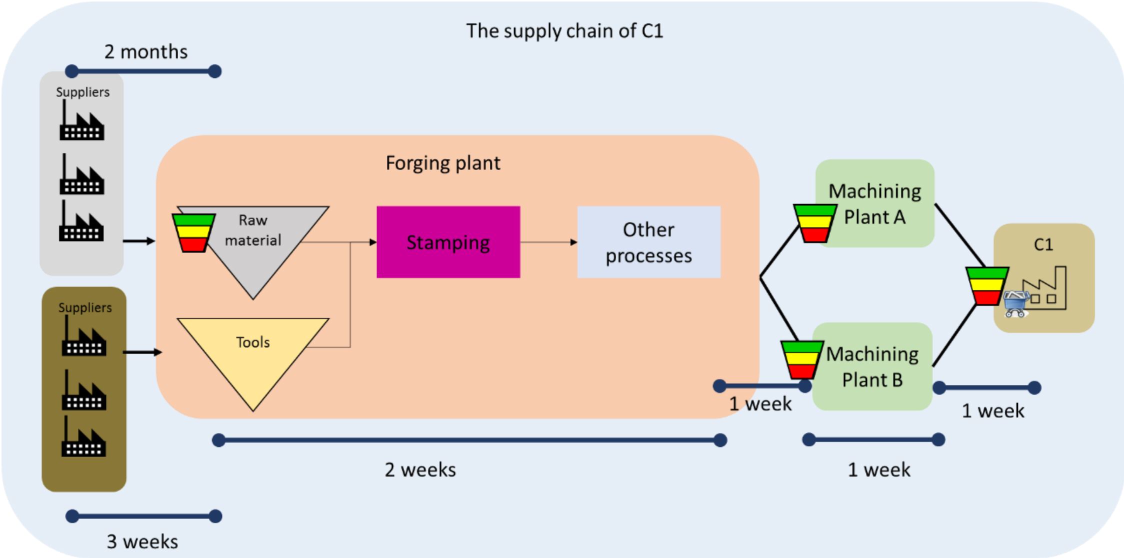


Figure 9.8: Decoupled supply chain of C1

- **C2:** In the supply chain of customer C2 the inventory was allocated in the following links (Figure 9.9):
  - As in C1, with the aim of decoupling from the variability of suppliers, inventory was allocated to the raw material inventory. Here as well CS3 already had inventory in this link before DDMRP implementation.
  - Inventory was also allocated to the end product inventory of the forging plant to decouple the plant from the demand variability of customers. Thus, the forging plant planned production considering real consumption instead of the forecast reported by customers. Before DDMRP, CS3 had inventory placed in this link.

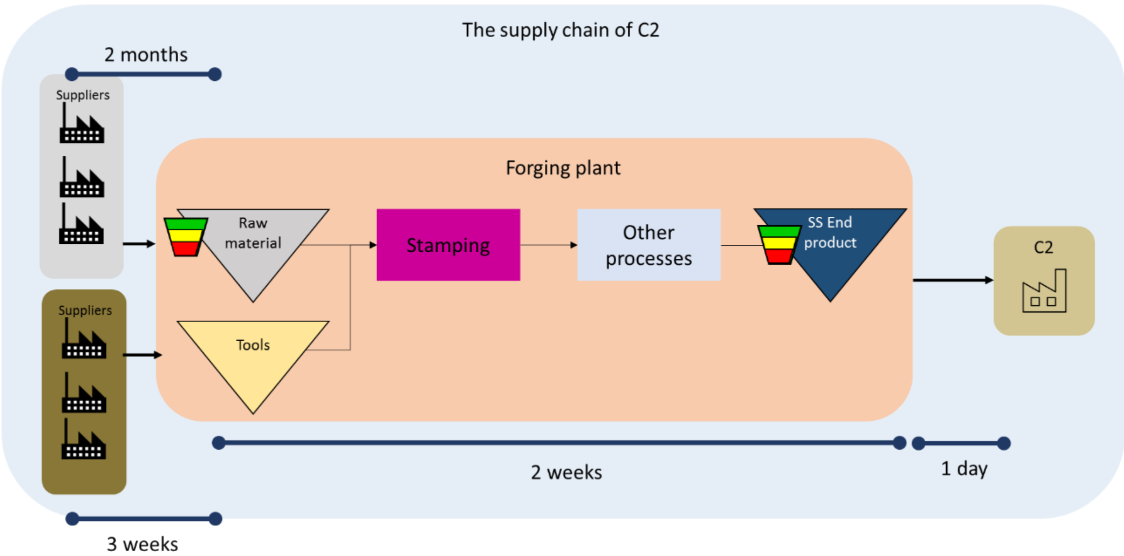


Figure 9.9: Decoupled supply chain of C2

- **C3:** In the supply chain of customer C3 the inventory was allocated in the following links (Figure 9.10):
    - As in C1 and C2, with the aim of decoupling from the variability of the suppliers, inventory was allocated to the raw material inventory. Prior to DDMRP CS3 already had inventory placed in this link.
    - Inventory was also allocated to the end product in the forging plant to protect from customer variability. This decoupling point led the forging plant to plan production requirements considering the real consumption and ignoring the forecast data reported by C3. Before DDMRP implementation, CS3 did not have planned inventory in this link.

      During the implementation, C3 requested consignment stock to be located in its plant. This consignment stock was managed by C3, therefore CS3 ruled out managing it using DDMRP.

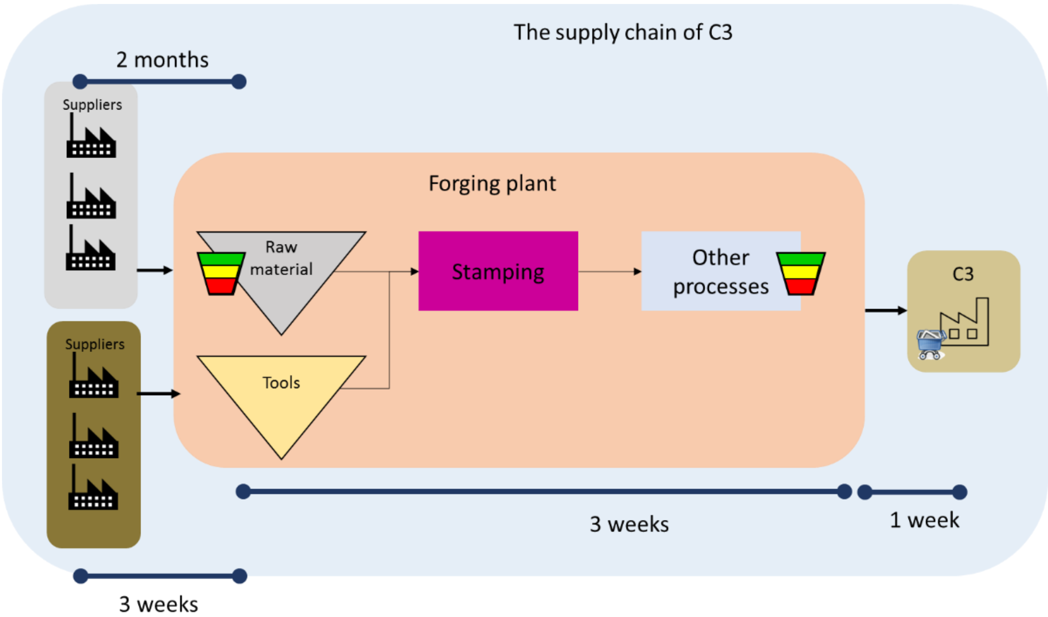


Figure 9.10: Decoupled supply chain of C3

- **C4:** In the supply chain of customer C4 inventory was allocated to two links as set out in Figure 9.11.
    - Like the other customers, the aim of decoupling from supplier variability, the raw material inventory was considered a strategic location to place inventory. Before DDMRP implementation the company already had inventory placed here.
    - Inventory was also allocated to the end product stock to decouple from demand variability. Here as well CS3 already had inventory placed.

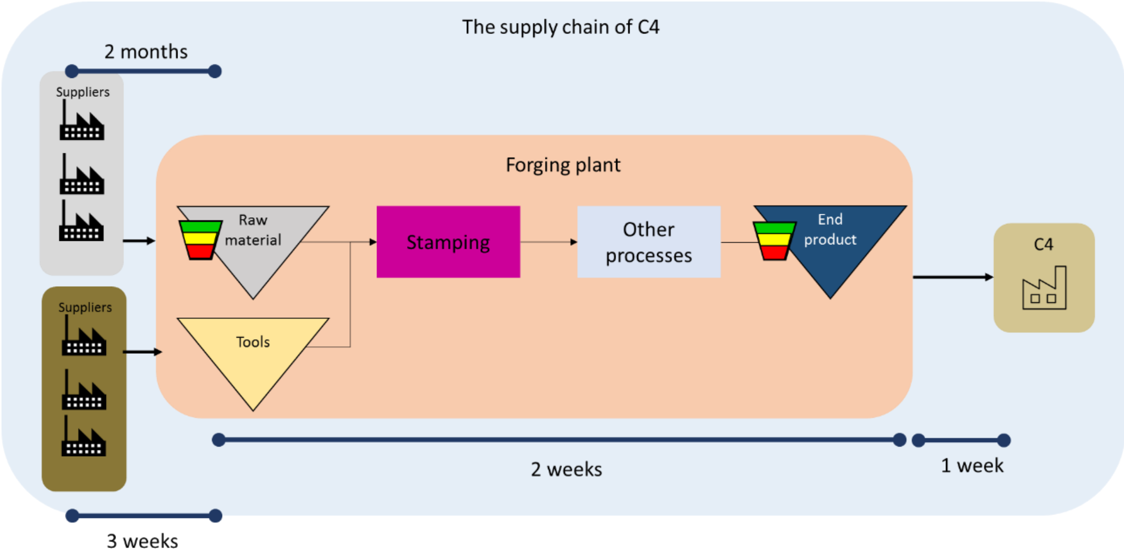


Figure 9.11: Decoupled supply chain of C4

9.3.2. Buffer profiles and level determination

Prior to defining part designation and sizing the buffers, CS3 listed all the references and defined which should be stored and which not. To this end, an analysis of the consumption of each reference was undertaken, and strategic and non-strategic references were identified.

The strategic references were defined as replenished parts and a color-coded buffer was assigned. The rest, depending on the consumption, were defined as MM-part and an MM buffer was assigned, or were defined as Non-Buffered references and were managed by make to order strategy.

After that, each buffer was sized considering both buffer profile and individual part attributes. Among the individual part attributes, real material consumption was considered to calculate the ADU of each reference and size the buffer.

To centralize all this information new attributes were generated in the ERP, and thus CS3 was able to save the required information for each reference such as ADU, part designation, red, yellow and green levels of the buffers in the ERP.

9.3.3. Dynamic buffers

By this point in the process all the buffers were sized. However, as supply and consumption conditions can change it is necessary to be able to adapt and update the supply chain to the new context. Thus, recalculated adjustments were scheduled, allowing CS3 to adjust the inventory and material requirements based on changes to individual part attributes or buffer profile adjustments.

In the implementation stage, the company did not identify a need for scheduling planned adjustments, although they did not rule out the possibility of taking such action in the future.

9.3.4. Demand driven planning

Once CS3 had finished modeling the material context, it was time to start material and production requirements planning. To this end, a spreadsheet that contained the list of material references, the on-hand inventory level, buffer zones, ADU, lead time, real demand and open replenishment orders was exported from the ERP to the DDMRP software (R+).

R+, calculated the NFP of each reference and showed it using a color-coded alert. Thus, CS3 was able to check material status on a daily basis and plan the purchase and production orders of those whose NFP was in the replenishment zone.

9.3.5. Highly visible and collaborative execution

This component involved executing and checking the purchase and production to ensure that they were proceeding as planned. Execution alerts were used for this purpose to identify which orders were in a critical situation and required special action.

Figure 9.12 shows the dashboard of execution alerts. The first column depicts the priority of the alert. References colored in dark red are identified as critical and are the first to be attended. For instance, the first reference in the list is in a critical situation as there is a requirement for 3000 units, but there are only 1263 units in on-hand inventory and there are no open supplies. Therefore, if the company does not launch and expedite an order immediately it will suffer a stockout. In addition to the dark red alerts, there are references in light red, which means that they needed to be attended but their situation is not as critical as the former. Finally, the green coded references do not need any attention.

	Priority	% of Buffer	Part	On Hand	Demand Allocations	Supply Orders	Issued	Available Stock	Reorder Qty
	Critical	0 %	440712	1,263	3,000	0	0	-1,737	10,000
	Critical	0 %	440939	19,857	25,000	0	0	-5,143	25,000
	Critical	0 %	445396	4,132	4,500	0	0	-368	20,000
	Critical	0 %	445501	0	5,000	0	0	-5,000	10,000
	Critical	0 %	445851	0	5,000	0	0	-5,000	15,000
	Critical	0 %	445852	1,420	4,500	0	0	-3,080	10,000
	Critical	0 %	445926	5,947	7,000	0	0	-1,053	10,000
	Critical	0 %	445933	178	3,000	0	0	-2,822	10,000
	Critical	0 %	445973	10,745	12,000	0	0	-1,255	2,000
	Critical	0 %	448510	0	5,400	0	0	-5,400	6,000
	High	-	446002	0	85,000	0	0	-85,000	85,000
	High	-	446011	0	300	0	0	-300	1,000
	High	-	446012	0	300	0	0	-300	1,000
	High	-	446013	0	10,000	0	0	-10,000	10,000
	High	-	448535	1,312	5,200	0	0	-3,888	4,000
	Low	0 %	440154	0	0	0	0	0	-
	Low	0 %	440275	0	0	0	0	0	-
	Low	0 %	440862	0	0	0	0	0	-
	Low	0 %	440880	0	0	0	0	0	-
	Low	0 %	445595	0	0	0	0	0	-

Figure 9.12: Alert dashboard of R+

9.4. Results achieved after DDMRP implementation

The implementation of DDMRP in CS3 brought about changes in material management achieving qualitative and quantitative results that are set out in Sections 9.4.1 and 9.4.2.

9.4.1. Qualitative results

DDMRP enabled the company to plan purchase/production requirements based on real demand instead of the forecast reported by customers. Before this methodology was implemented, CS3 used MRP based on forecast to plan purchase and production requirements. However the forecast was highly unstable, and the company required high SS levels as protection from demand and supply variability, and to prevent stockouts.

The strategic positioning and management of inventory with DDMRP criteria enabled the company to decouple from demand and supply variability, significantly reducing uncertainty. Hence, CS3 no longer required high SS levels and could adjust the inventory level according to real needs. This resulted in a substantial reduction of the stock coverage (quantitative results are set out in Section 9.4.2).

The strategic allocation and management of inventory between the forging and machining plants brought about several improvements that are set out in the following points:

- It allowed synchronization between plants as the machining plants became customers of the forging plant. Thus, when the forging plant defined the production plan it only considered the consumption of the machining plants avoiding any forecast reported by C1. This change enabled the machining plant to have the correct material to serve the demand of the customer.

- The decoupling explosion prevented the transmission of nervousness upstream, providing CS3 with visibility and enabling the identification of real requirements (Figure 9.13). In other words, when a buffer of the consignment stock of C1 reached the replenishment zone, this did not mean that the forging plant should produce this reference. The forging plant would only produce this reference when the buffer of the machining plants reached the replenishment zone.
- This change also reduced the delivery time to C1 from 20 to 10 days (Figure 9.13). Before DDMRP implementation, serving an order in 10 days was infeasible as (1) CS3 did not have visibility of real requirements, and (2) to move material from forging to C1 required more than 10 days.

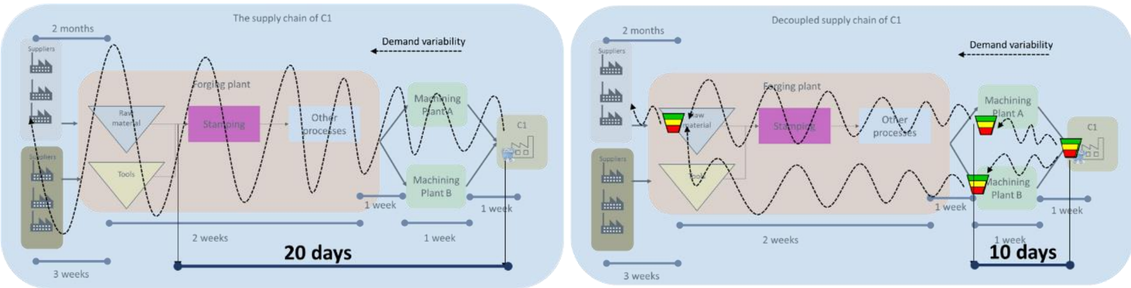


Figure 9.13: Supply chain of C1 (a) without decoupling points and (b) with decoupling points

The uncertainty reduction through the supply chain increased visibility in material and information flow. This allowed the company to know the status of materials, almost entirely eliminating rush orders and unplanned setups. Therefore, the company was able to identify real material and production requirements, and avoid wasting time producing fictitious demands. An additional benefit of this was the reduction of rescheduling tasks and unplanned setups, which led to a significant increase in production capacity. It is worth noting that after DDMRP implementation the shop-floor workers reported surprise at the calm and constant rate of production that they were experiencing in the production line with no stress. Some even came to question if CS3 was suffering a drop in demand. The truth was rather different however, as the company was having record turnover. The general increase of the ADU of the analyzed references is set out in the qualitative results (Table 9-14).

According to CS3, with MRP material and production planning was an onerous, time consuming, complex task which was not feasible to carry out daily. In addition, this approach did not incorporate execution functionality, making order tracking a challenging process. In contrast, the use of DDMRP enabled daily reviews of material status, identifying immediately the references to be replenished. In addition, the color-coded alerts allowed the company to carry out the execution process, prioritizing and focusing first on those references whose buffer status was more critical.

The company stated that they were able to efficiently check the status of the references, identifying and focusing only on those materials that really needed an action. They concluded that the planning and execution process was significantly improved by DDMRP.

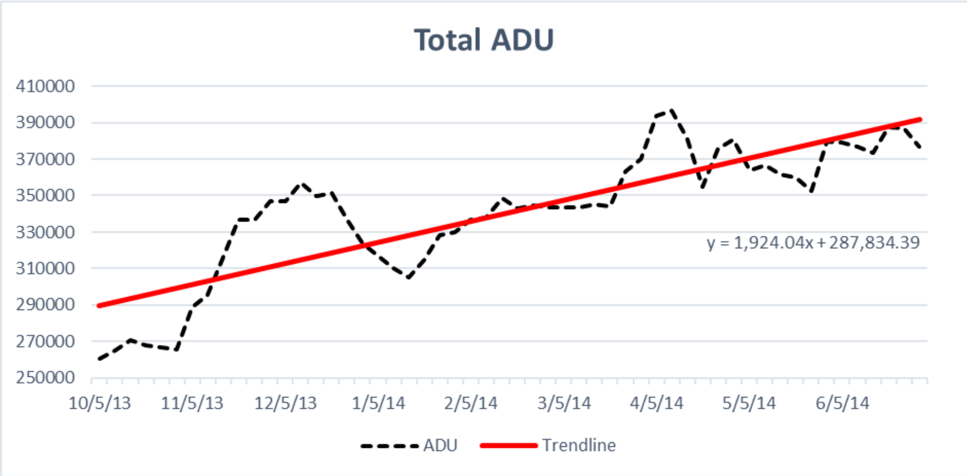
9.4.2. Quantitative results

In this section, a global analysis of 228 references was carried out (Section 9.4.2.1). This involved studying the evolution of the total consumption, total on-hand inventory and total stock coverage for a period of 9 months, which allowed us to see several inventory turnover performances.

With the aim of doing a more in-depth study, references were clustered as long, medium or short lead time, and the performance of each group was independently analyzed (Section 9.4.2.2). In addition, the behavior of the decoupling points of customers C1, C2, C3 and C4 were independently studied (Sections 9.4.2.3 - 9.4.2.6). To this end, a general analysis of each decoupling point was done, where the total ADU, total on-hand inventory and total stock coverage was studied. Then, to see the evolution of the references in detail, the most consumed three references were individually examined. The amount of three references was considered enough to carry out this analysis, as it allowed us to see if the global pattern was repeated in the references with the highest consumption.

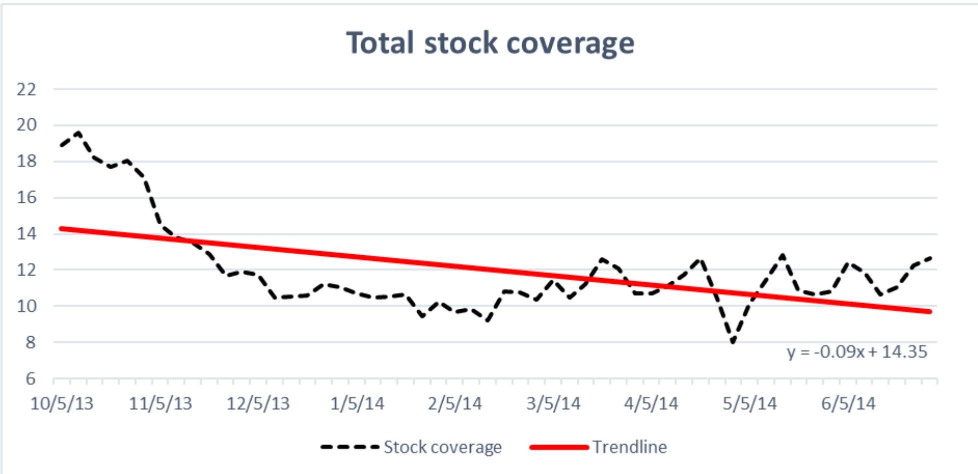
9.4.2.1. Global analysis

During the analyzed period the ADU on average increased by 35.19% (Graph 9.2) while both the on-hand inventory and the stock coverage decreased by 1.84% (Graph 9.3) and 33.62% (Graph 9.4). Prior to implementation, the company had on average 14 days of inventory in the warehouse, while at the end of analyzed period this value was less than 10 days. In other words, the inventory turnover increased.



Graph 9.2: The total ADU of CS3

Graph 9.3: The total on-hand inventory level of CS3



Graph 9.4: The total stock coverage of CS3

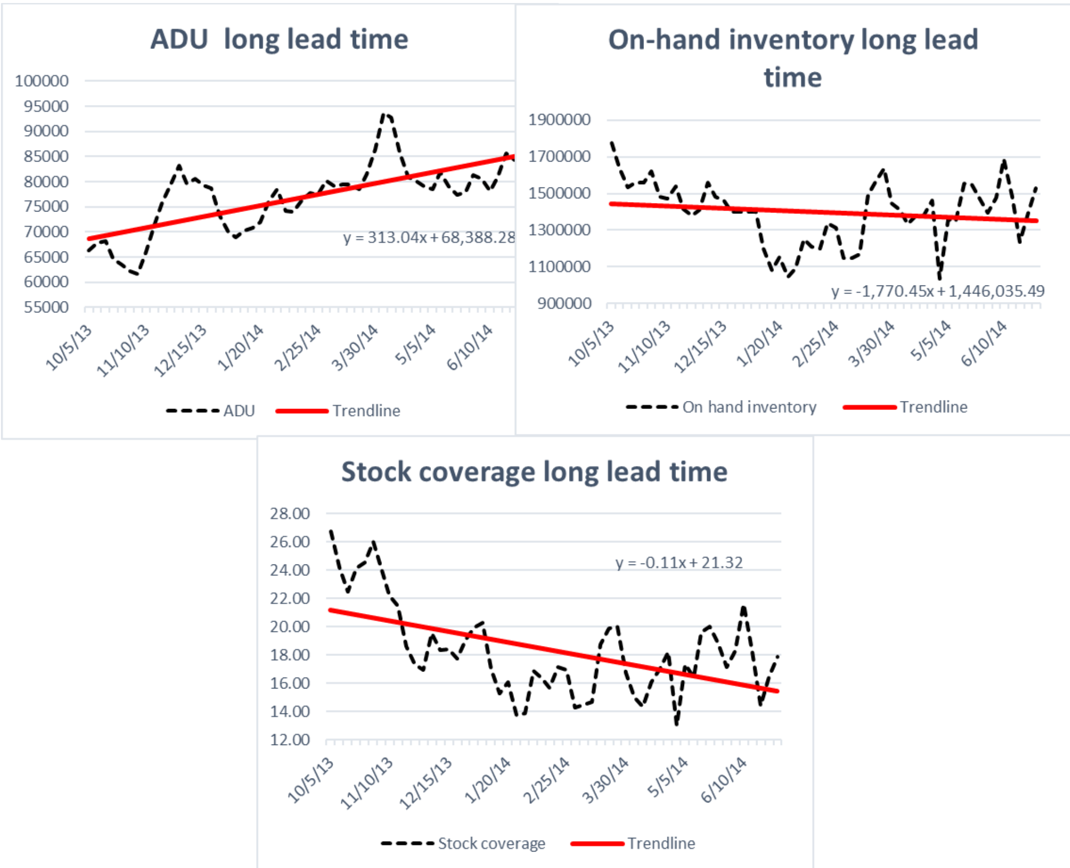
9.4.2.2. Analysis of the references according to lead time

An analysis of the references classified according to lead time was carried out to see if the pattern of the second case study (CS2) was repeated in this case study. To accomplish this, 228 references were classified as follows:

- **Long lead time:** 113 references whose lead time was greater than 30 days and represented 23% of total ADU and 35% of the total on-hand inventory.
- **Medium lead time:** 49 references whose lead time was between 11 and 29 days and accounted for 27% of total ADU and 12% of the total on-hand inventory.
- **Short lead time:** 66 references whose lead time was less than 10 days and made up 50% of total ADU and 53% of the total on-hand inventory.

9.4.2.2.1. Long lead time references

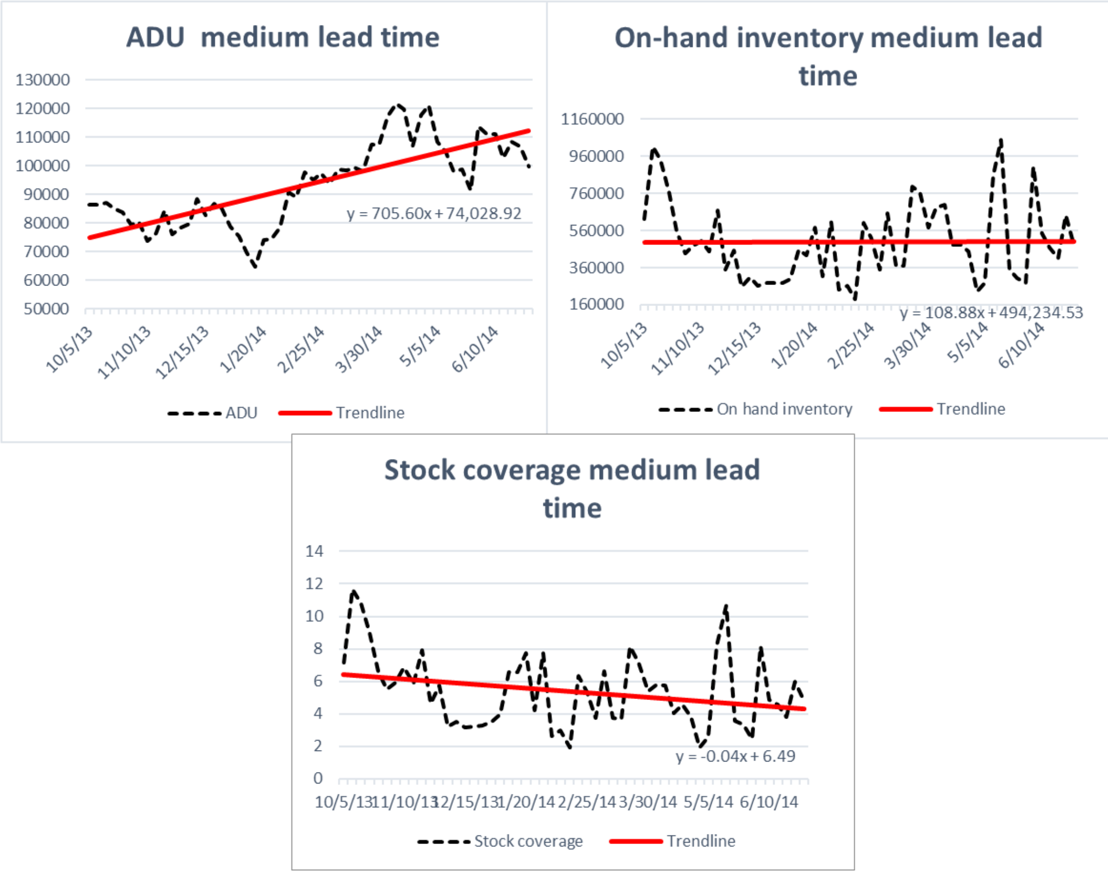
The stock coverage of long lead time references decreased by 27.49%. This is because in the period of analysis the consumption of this cluster increased on average by 26.73% while the on-hand inventory decreased on average by 6.5% (Graph 9.5).



Graph 9.5: (a) the ADU, (b) on-hand inventory and (c) stock coverage of long lead time cluster

9.4.2.2.2. Medium lead time references

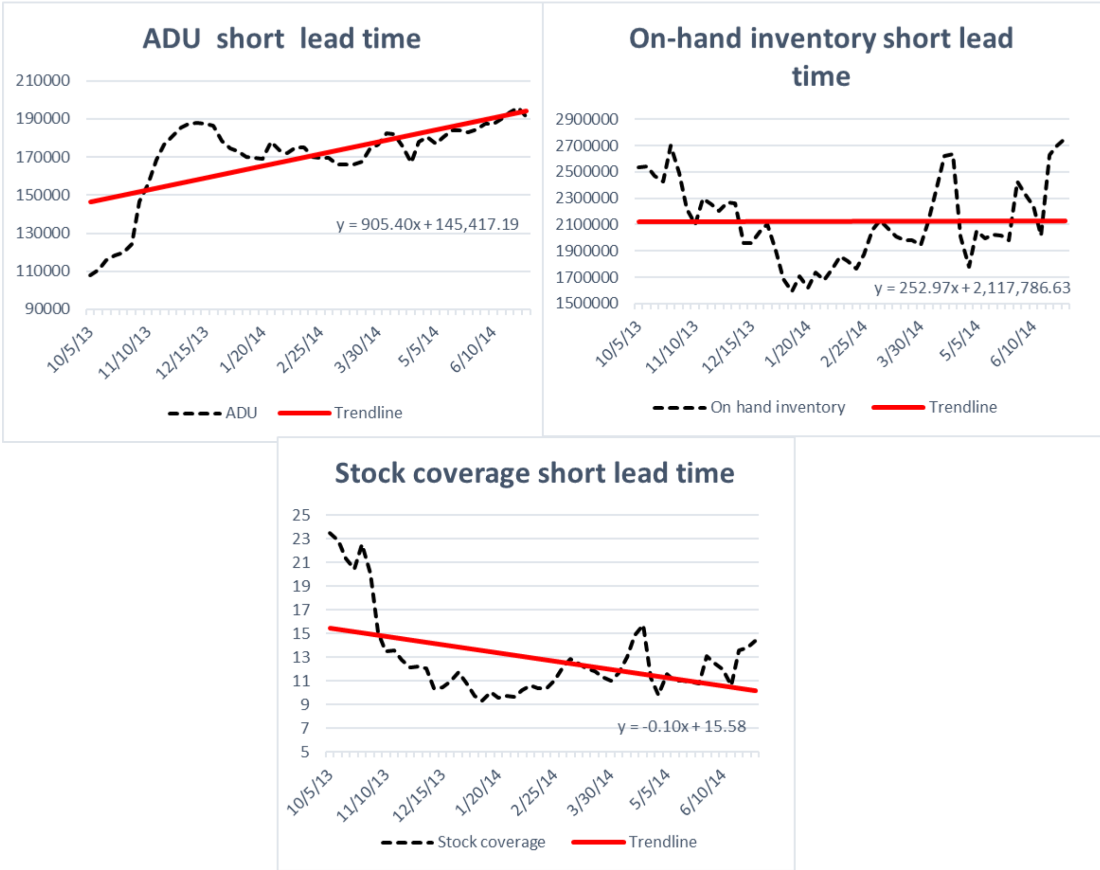
The consumption of the medium lead time cluster references increased by 50.04% while the on-hand inventory increased by only 1.17%. Therefore, stock coverage reduced on average by 32.87% (Graph 9.6).



Graph 9.6: (a) the ADU, (b) on-hand inventory and (c) stock coverage of medium lead time cluster

9.4.2.2.3. Short lead time references

The short lead time cluster showed the same trend as the long lead time cluster. The on-hand inventory level and the stock coverage were reduced by 0.63% and 34.24% while the ADU increased by 32.79% (Graph 9.7).



Graph 9.7: (a) the ADU, (b) on-hand inventory and (c) stock coverage of short lead time cluster

To see if the global trend was repeated in the supply chain of all customers, a detailed analysis of each customer follows:

9.4.2.3. Results achieved in C1

Following the implementation of DDMRP in the supply chain of customer C1, three decoupling points were placed (Figure 9.8). The evolution of each of these decoupling points is analyzed below.

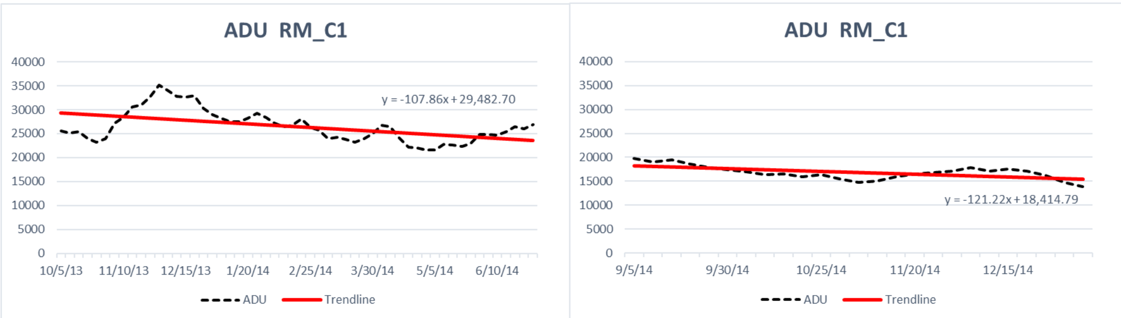
9.4.2.3.1. Decoupling point raw material C1:

Here a sample of 7 references were analyzed. On average they had a lead time of 49 days. It is worth mentioning that for internal reasons CS3 decided to delay the implementation of DDMRP in these references until September 2014, and continued planning with MRP. For that reason, we considered it interesting to analyze two periods: (1) between October 2013 and June 2014 (before DDMRP implementation) and (2) between September 2014 and January 2015 (after DDMRP implementation). July and August were not taken into account in this analysis as they were considered exceptional months in terms of production. That is to say, the company produced an oversupply of references in July to be able to serve orders in August, when production was stopped for holidays.

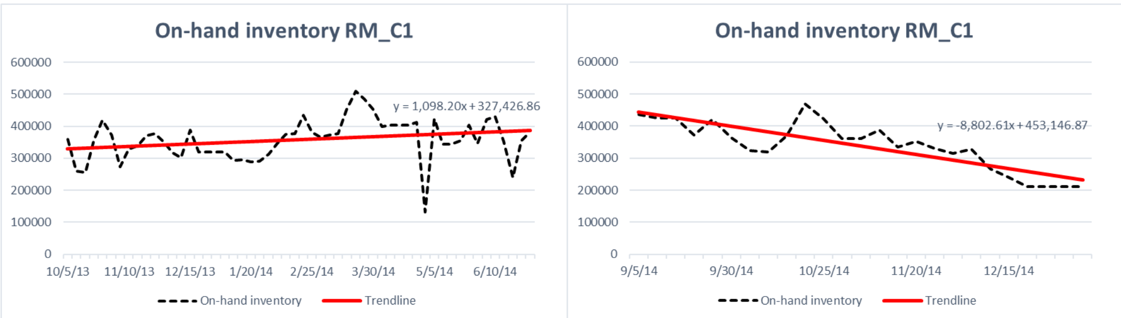
Table 9-2 summarizes the performance of these references. In the first period of analysis, although the ADU decreased the on-hand inventory increased, and consequently the stock coverage. In the post DDMRP implementation period, however, a marked change in the trend is evident, with a decrease of the on-hand inventory and the stock coverage. Graphs 9.8, 9.9 and 9.10 clearly show that the on-hand inventory decreased considerably from November, the date that coincided with the implementation of DDMRP in these buffers.

Table 9-2: Evolution of the raw material of C1

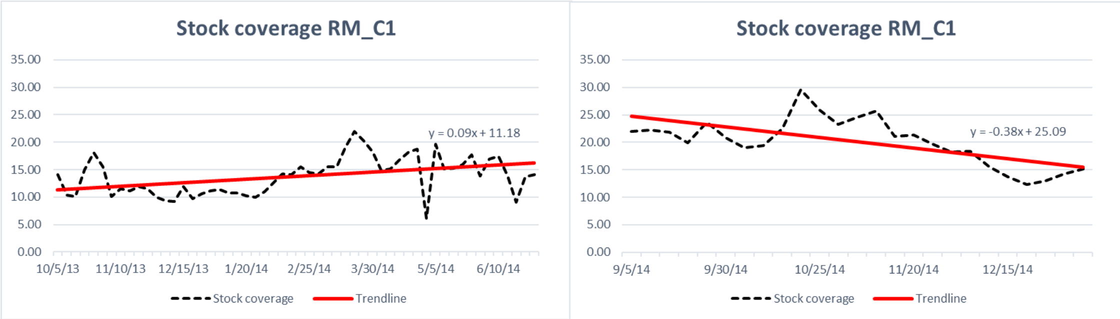
	Oct 2013- Jun 2014	Sept 2014 –Jan 2015
ADU	-19.46%	-15.9%
ON-HAND	17.72%	-47.54%
STOCK COVERAGE	42.32%	-36.91%



Graph 9.8: Total ADU of the raw material of C1 (a) period Oct 2013-June 2014 (b) Sept 2014-Jan 2015



Graph 9.9: Total on-hand inventory of the raw material of C1 (a) period Oct 2013-June 2014 (b) Sept 2014-Jan 2015



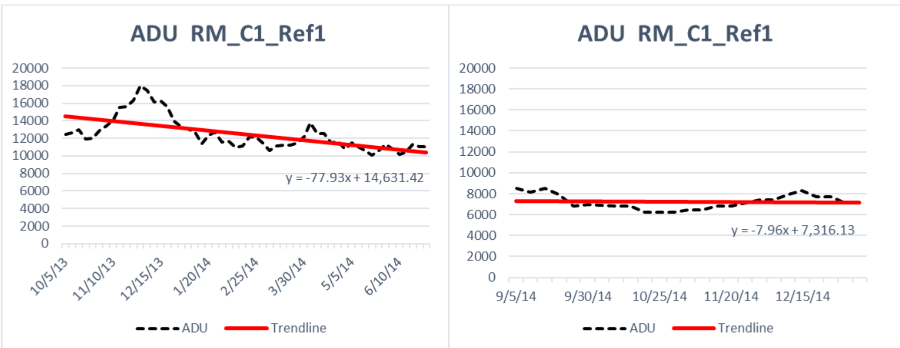
Graph 9.10: Total stock coverage of the raw material of C1 (a) period Oct 2013-June 2014 (b) Sept 2014-Jan 2015

To better undestand the behaviour of each reference independently, three out of 7 references are analyzed. The references with the highest consumption and greates variability were selected.

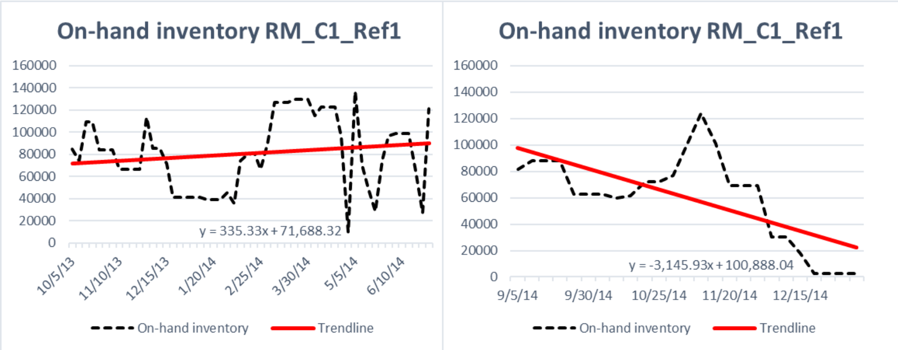
Between October 2013 and June 2014 the ADU of Ref1 decreased and the on-hand inventory increased and as a consequnece so did stock coverage. However, after DDMRP implemenation in November the pattern changed. The ADU remaind stady while the on-hand inventory and thus stock coverage decreased (Graph 9.11, Graph 9.12 and Graph 9.13).

Table 9-3: Evolution of Ref1 of raw material of C1

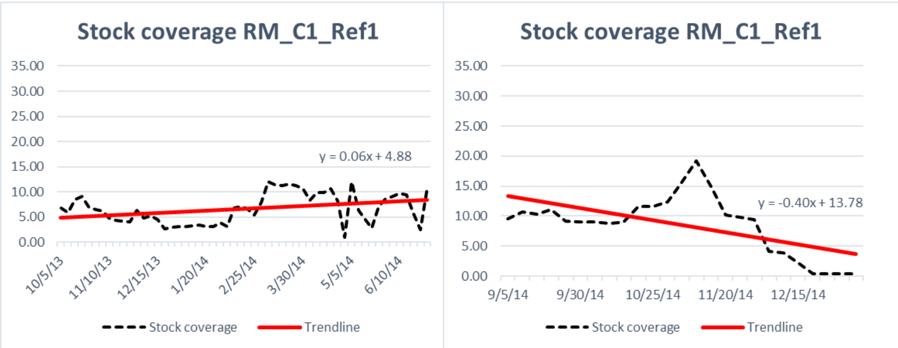
	Oct 2013- Jun 2014	Sept 2014 –Jan 2015
ADU	-28.38%	-2.61%
ON-HAND	31.91%	-16%
STOCK COVERAGE	82.28%	-14.05%



Graph 9.11: ADU of Ref1 of the raw material of C1 (a) period Oct 2013-June 2014 (b) Sept 2014-Jan 2015



Graph 9.12: On-hand inventory of Ref1 of the raw material of C1 (a) period Oct 2013-June 2014 (b) Sept 2014-Jan 2015

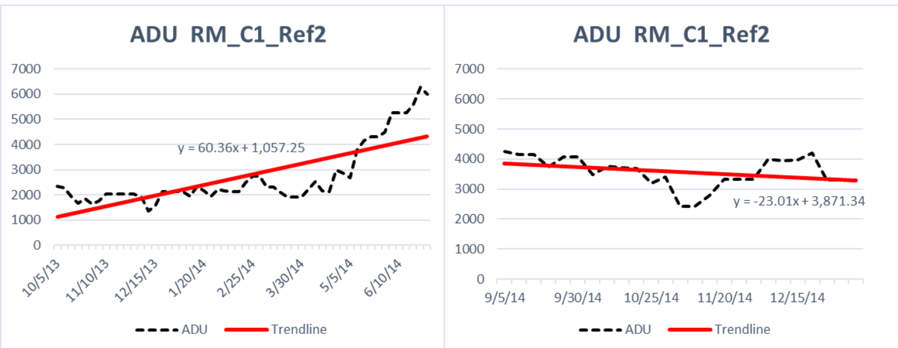


Graph 9.13: Stock coverage of Ref1 of the raw material of C1 (a) period Oct 2013-June 2014 (b) Sept 2014-Jan 2015

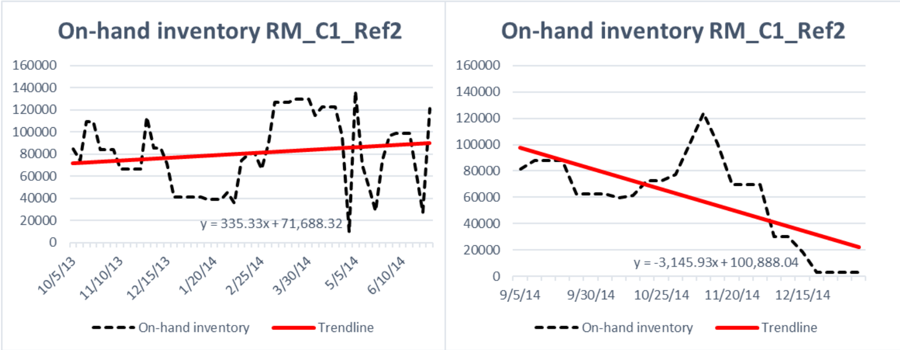
As for Ref2, in the first period of analysis the ADU increased considerably. On-hand inventory also increased but not to the same extend, resulting in stock coverage with a negative trend. In the post implementation period, the ADU decresed by 14.35% and the on-hand inventory showed a significant decrease of 77.25% (Table 9-4). Graph 9.15b clearly shows the dramatic shift in trend after November 2014.

Table 9-4: Evolution of Ref2 of raw material of C1

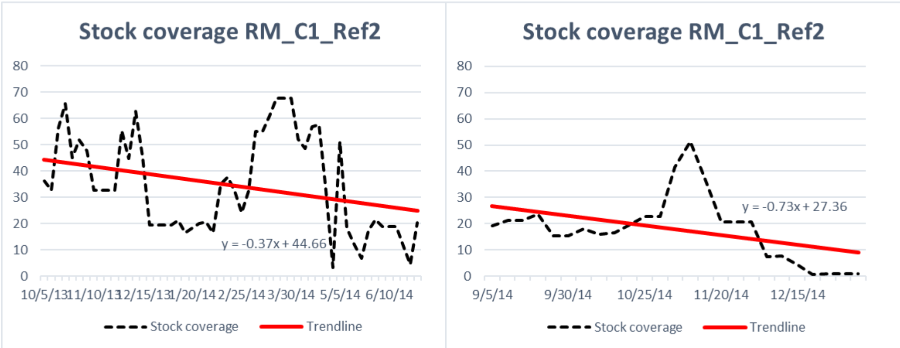
	Oct 2013- Jun 2014	Sept 2014 –Jan 2015
ADU	286.24%	-14.35%
ON-HAND	24.68%	-77.25%
STOCK COVERAGE	-44.28%	-65.79%



Graph 9.14: ADU of Ref2 of the raw material of C1 (a) period Oct 2013-June 2014 (b) Sept 2014-Jan 2015



Graph 9.15: On-hand inventory of Ref2 of the raw material of C1 (a) period Oct 2013-June 2014 (b) Sept 2014-Jan 2015

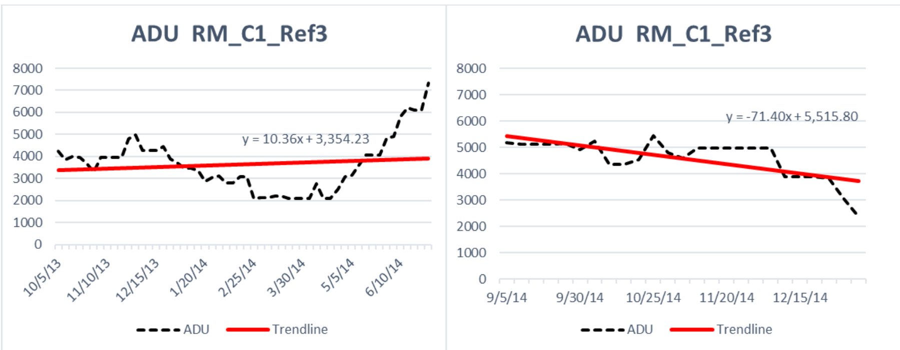


Graph 9.16: Stock coverage of Ref2 of the raw material of C1 (a) period Oct 2013-June 2014 (b) Sept 2014-Jan 2015

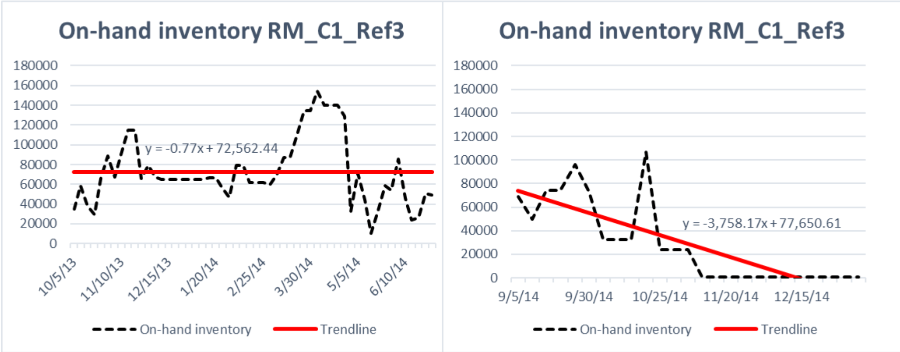
Along similar lines, Ref3 showed a sustancial reduction in the on-hand inventory and thus stock coverage from November onwards (Graph 9.18b, Graph 9.19b and Table 9-5).

Table 9-5: Evolution of Ref3 of raw material of C1

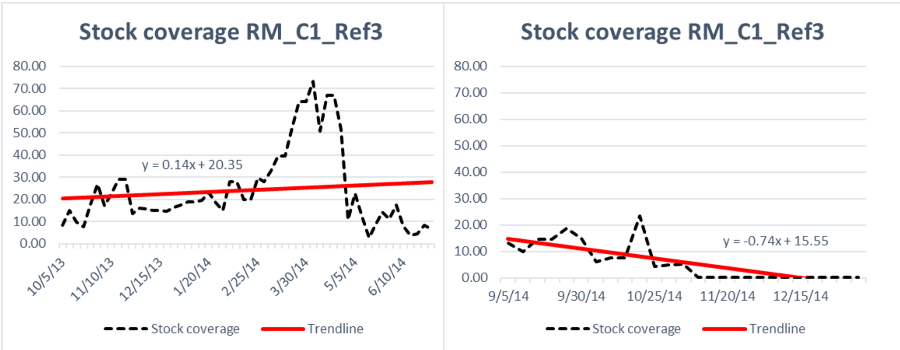
	Oct 2013- Jun 2014	Sept 2014 –Jan 2015
ADU	16.32%	-31.74%
ON-HAND	-0.06%	-122.06%
STOCK COVERAGE	36.21%	-119.92%



Graph 9.17: ADU of Ref3 of the raw material of C1 (a) period Oct 2013-June 2014 (b) Sept 2014-Jan 2015



Graph 9.18: On-hand inventory of Ref3 of the raw material of C1 (a) period Oct 2013-June 2014 (b) Sept 2014-Jan 2015

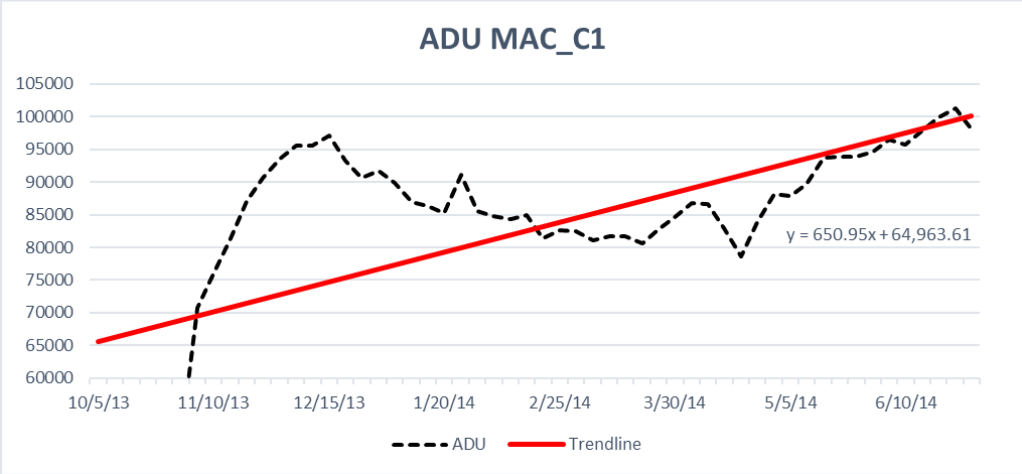


Graph 9.19: Stock coverage of Ref3 of the raw material of C1 (a) period Oct 2013-June 2014 (b) Sept 2014-Jan 2015

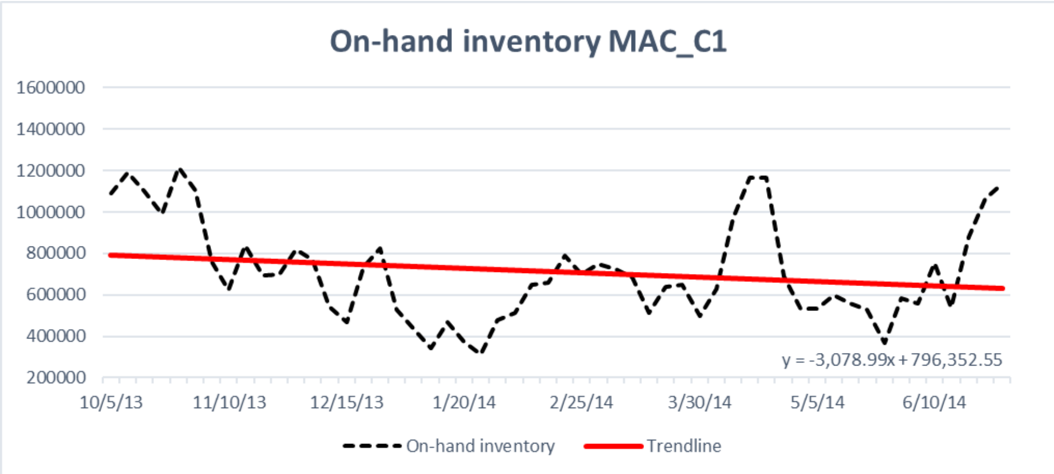
9.4.2.3.2. Decoupling point Machining C1

These buffers were located in the machining plants of CS3. To carry out the study a sample of 25 references were analyzed, with an average lead time of 6 days.

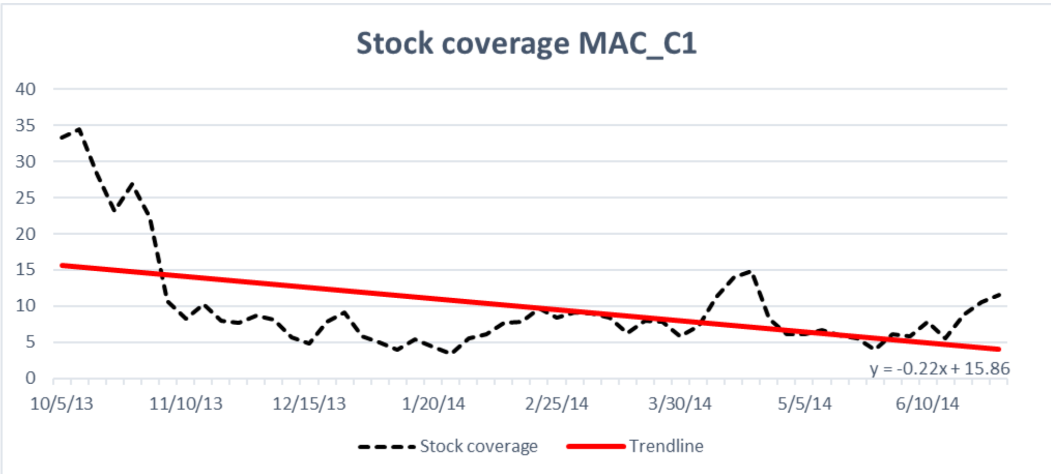
The analyzed period was from October 2013 to June 2014. In this period the ADU of the sample on average increased by 52.58% while the on-hand inventory decreased by 20.57% (Graph 9.20, Graph 9.21). Therefore, the stock coverage also decreased by 74.55% (Graph 9.22). That is to say, the 15 days of inventory held prior to implementation was reduced to just 4 days post DDMRP (Graph 9.22).



Graph 9.20: Total ADU of C1 in machining plants



Graph 9.21: Total on-hand inventory of C1 in machining plants



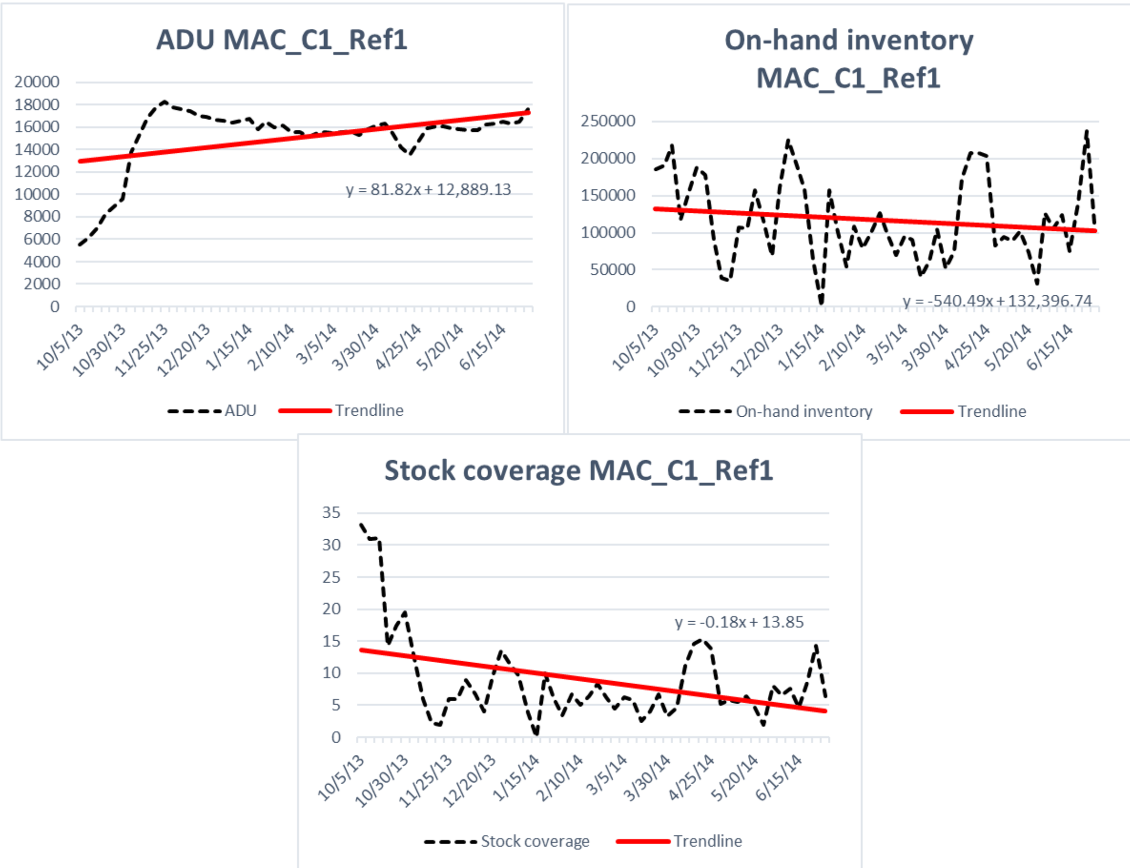
Graph 9.22: Total stock coverage of C1 in machining plants

To carry out the individual analysis, here as well the three most consumed references with the greatest variability are studied. Table 9-6 summarizes the performance of these three references. In each of them the trend was the same, ie. the ADU increased while the on-hand inventory level and the stock coverage decreased.

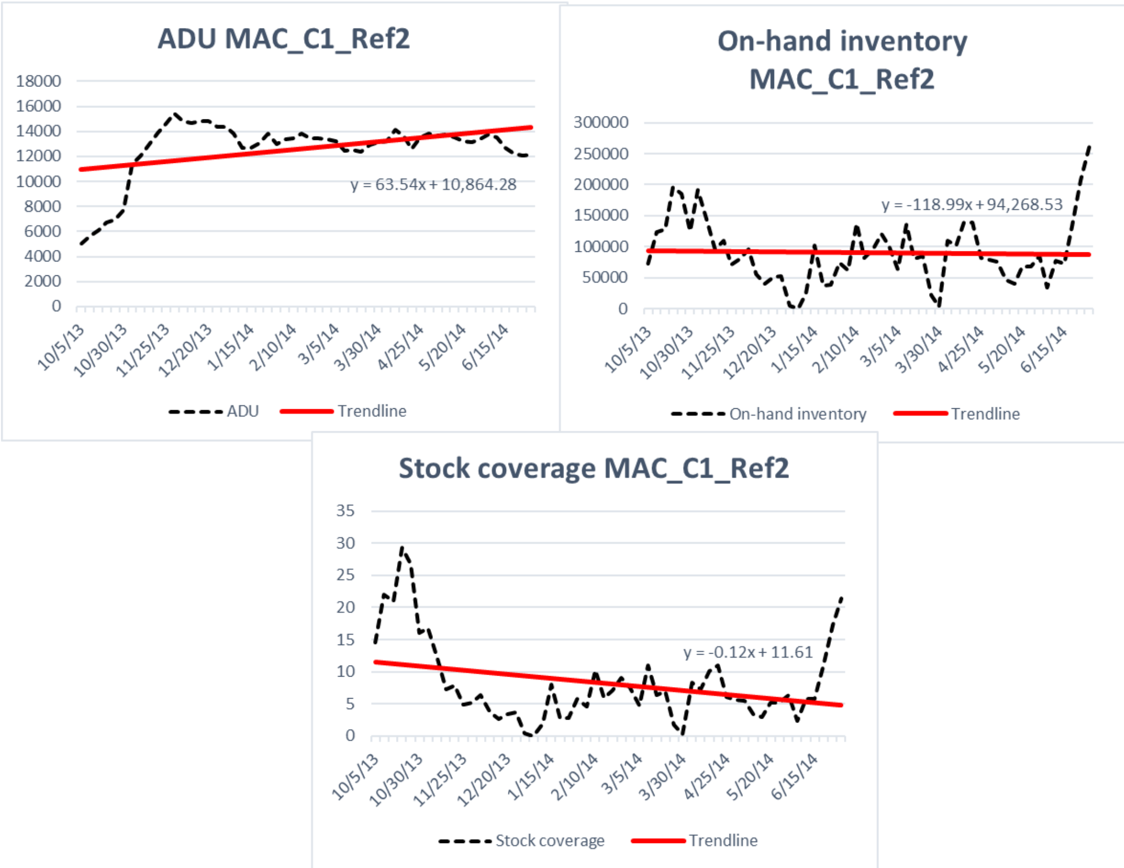
Table 9-6: Evolution of the analyzed three most consumed references of C1 in machining plants

Cluster	Ref1	Ref2	Ref3
ADU	33.43%	30.82%	56.55%
ON-HAND	-27.73%	-6.70%	-18.22%
STOCK COVERAGE	-69.79%	-55.35%	-74.91%

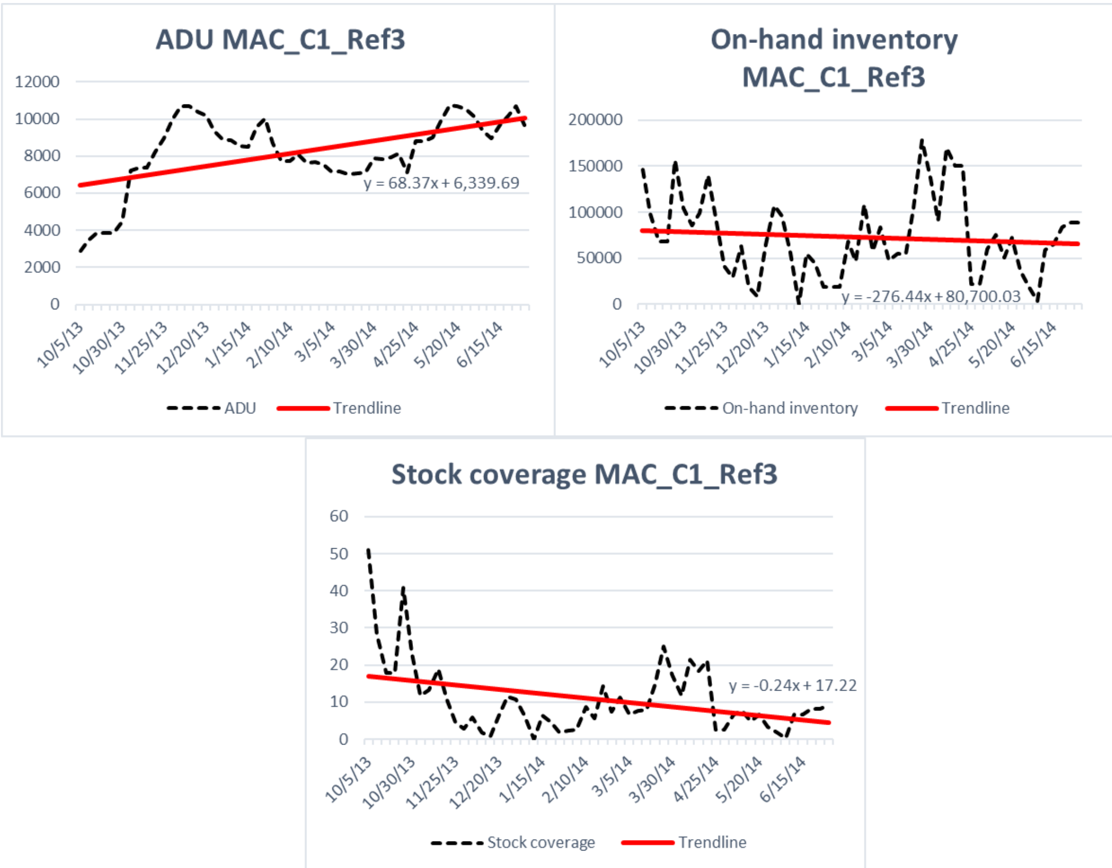
Graph 9.23, Graph 9.24 and Graph 9.25 show the performance of the three references during the analyzed period.



Graph 9.23: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref1 of machining plants



Graph 9.24: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref2 of machining plants

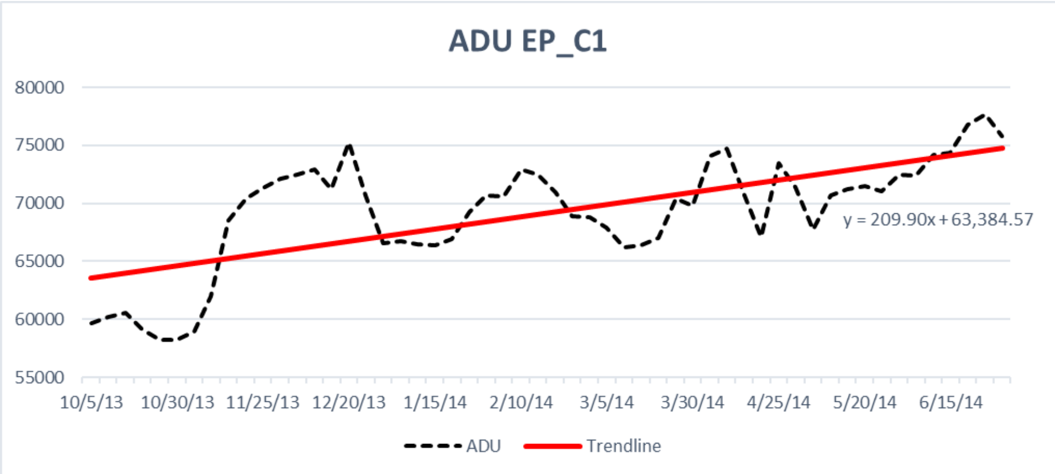


Graph 9.25: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref3 of machining plants

9.4.2.3.3. Decoupling point end product C1

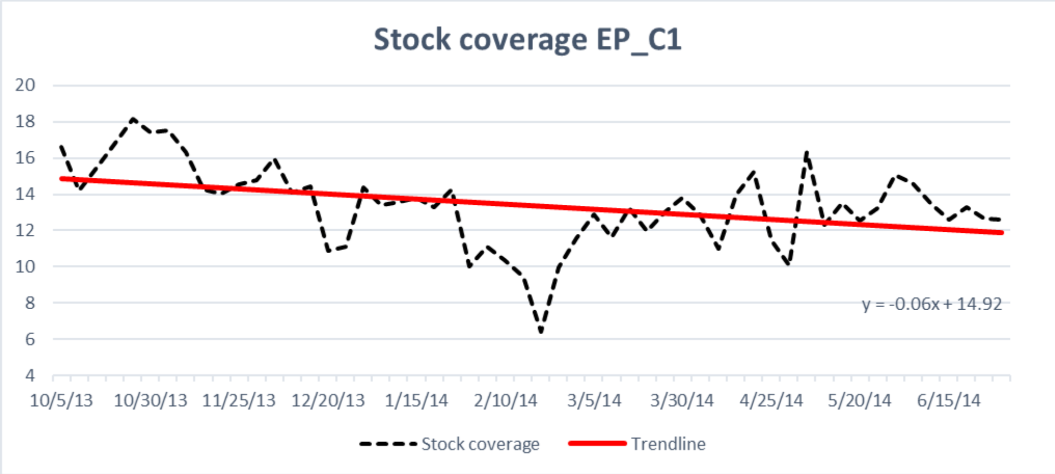
These buffers were located in the consigment stock of C1 (Figure 9.8). To carry out the analysis a sample of 28 references were studied with an average lead time of 14 days.

The same trend was observed as in the previous decoupling points. Between October 2013 and June 2014 the ADU of the sample increased on average by 17.49% while both the on-hand inventory and stock coverage decreased by 4.01% and 21.4% respectively (Graph 9.26, Graph 9.27, Graph 9.28).



Graph 9.26: Total ADU of the consignment stock of C1

Graph 9.27: Total on-hand inventory of the consignment stock of C1



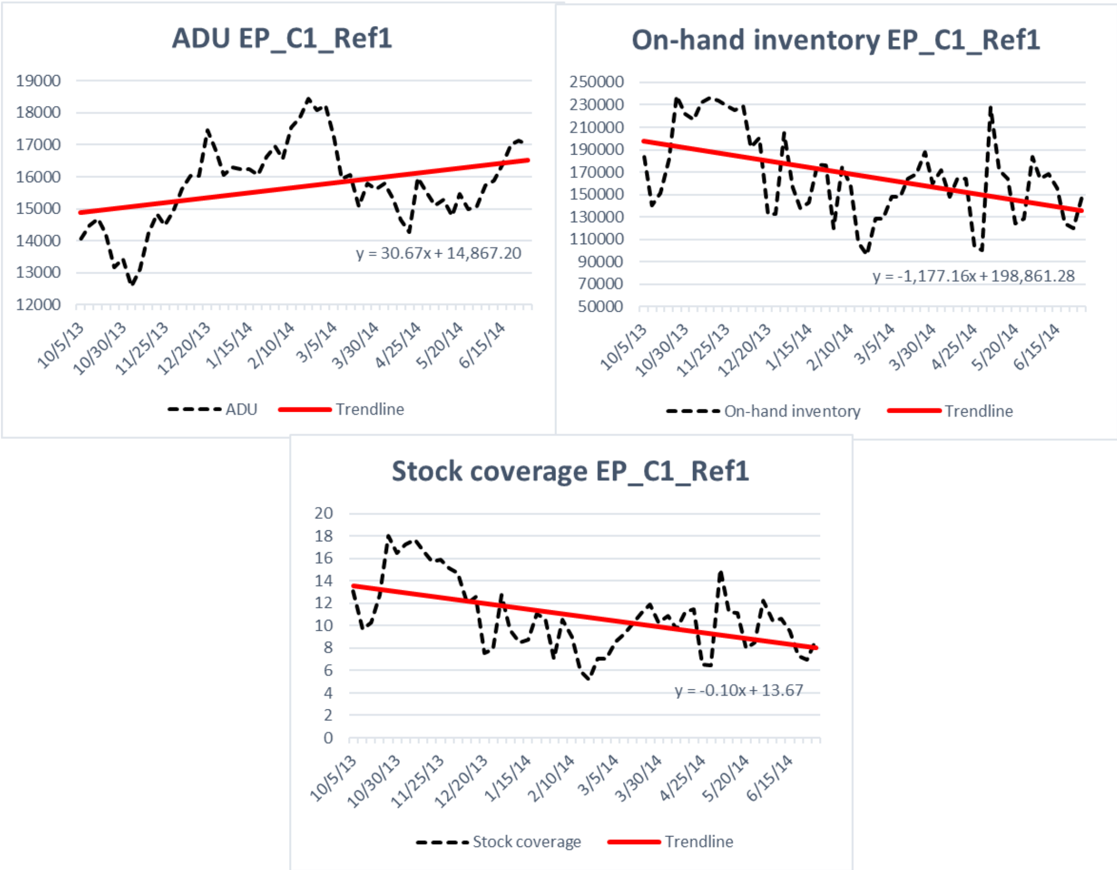
Graph 9.28: Total stock coverage of the consignment stock of C1

The most consumed three references were analyzed individualy to compare with the pattern observed in the global analysis (Table 9-7). Ref1 and Ref3 showed the same trend, ie. the ADU increased while the on-hand inventory and stock coverage decreased.

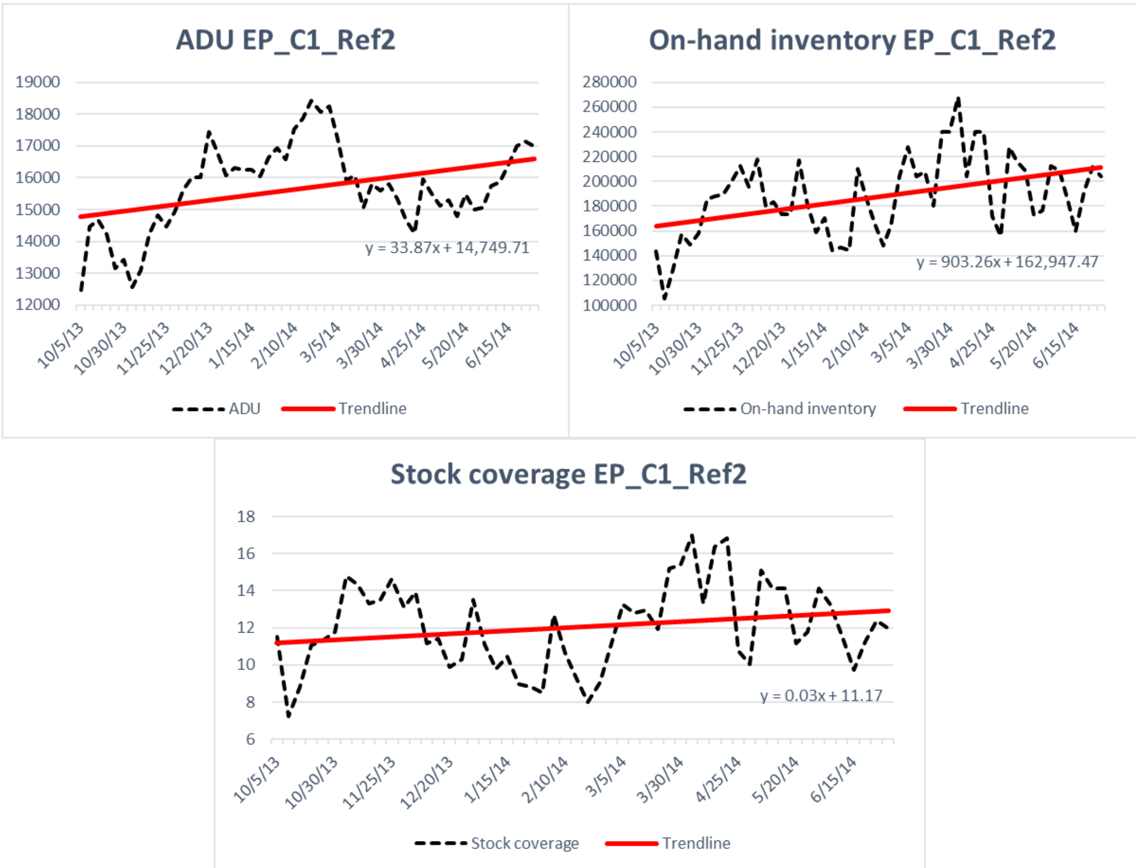
Ref2 however, had a different pattern that it is worth exploring. Although the ADU increased, the on-hand inventory and the stock coverage further increased (Table 9-7, Graph 9.30). Interviews with the PPM revealed that prior to DDMRP the company had maintained insuficient on-hand inventory of this references, resulting in a frequent stockouts. During the DDMRP implementation process, a decision was made to increase the stock level of this reference so as to adjust to the real demand and better protect against shortages.

Table 9-7: Evolution of the analyzed three most consumed references of C1 in machining plants

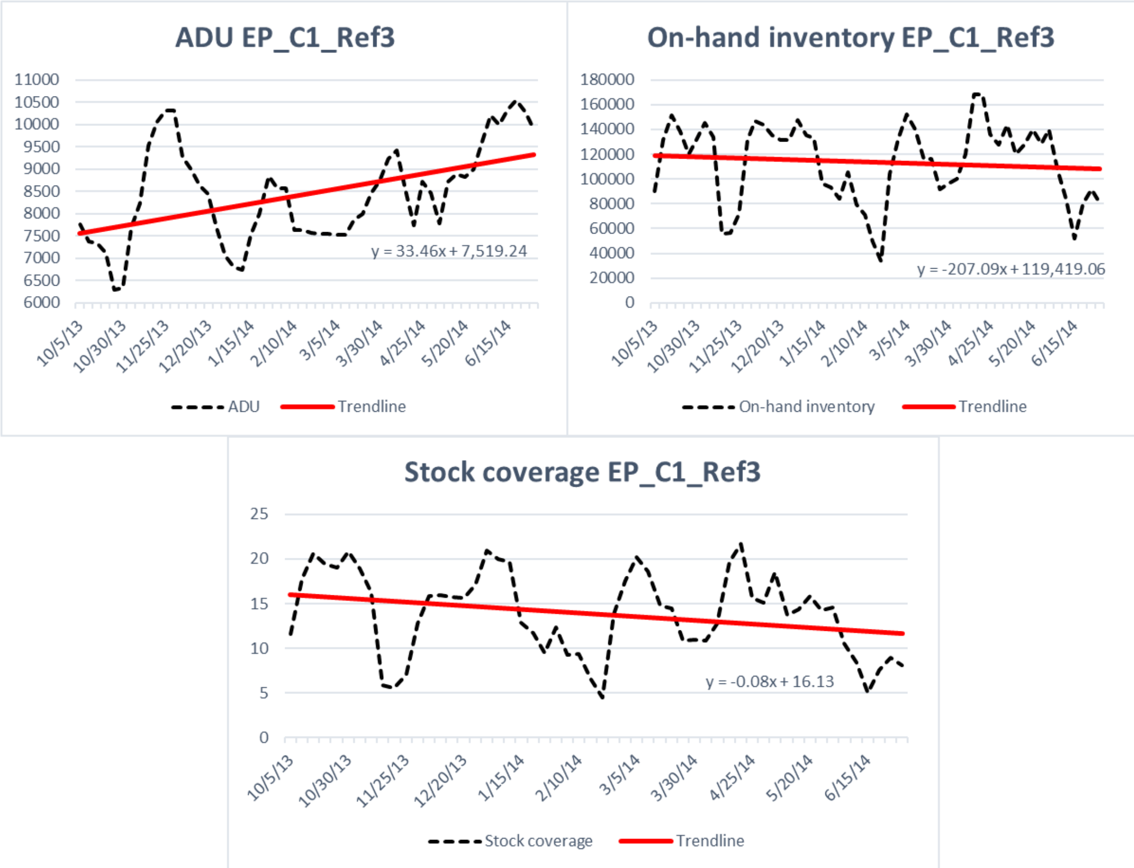
Cluster	Ref1	Ref2	Ref3
ADU	10.91%	12.14%	23.48%
ON-HAND	-31.56%	29.22%	-9.21%
STOCK COVERAGE	-39.06%	14.20%	-26.42%



Graph 9.29: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref1 in consignment stock.



Graph 9.30: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref2 in consignment stock



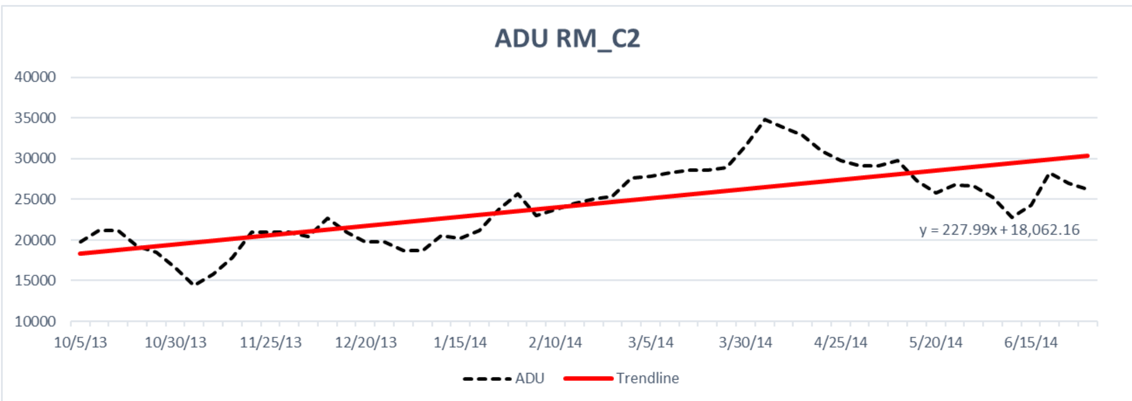
Graph 9.31: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref3 in consignment stock

9.4.2.4. Results achieved in C2

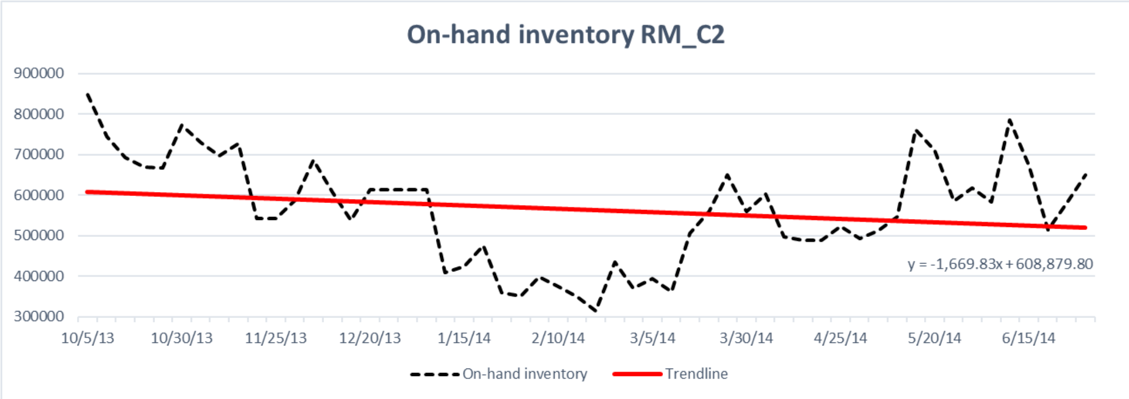
Next, the supply chain of customer C2 is analyzed. As depicted in Figure 9.9 two decoupling points were located in this supply chain: one in raw material and the other one in end product.

9.4.2.4.1. Decoupling point raw material C2

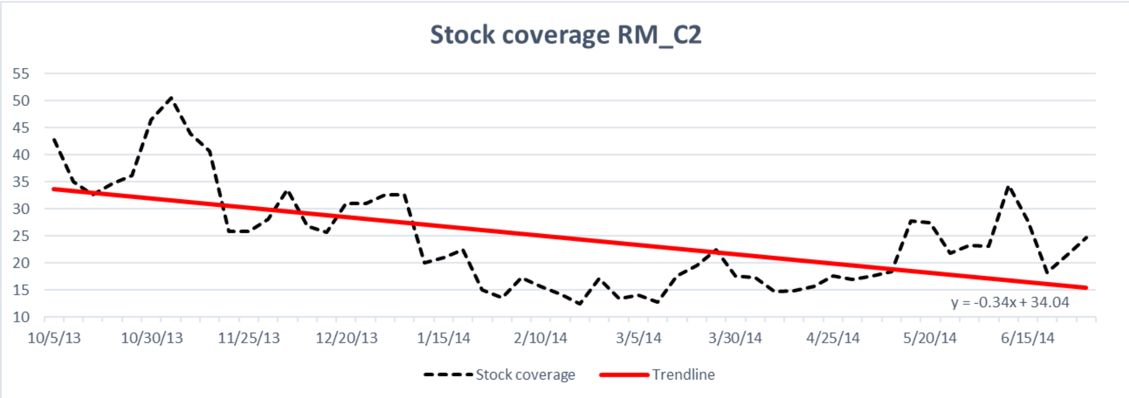
A sample of 9 references was analyzed with an average lead time of 50 days. In general, the ADU of the sample increased by 66.07% while the on-hand inventory reduced by 7.98%. Hence the stock coverage reduced by 29.26%.



Graph 9.32: Total ADU of the raw material of C2



Graph 9.33: Total on-hand inventory of the raw material of C2



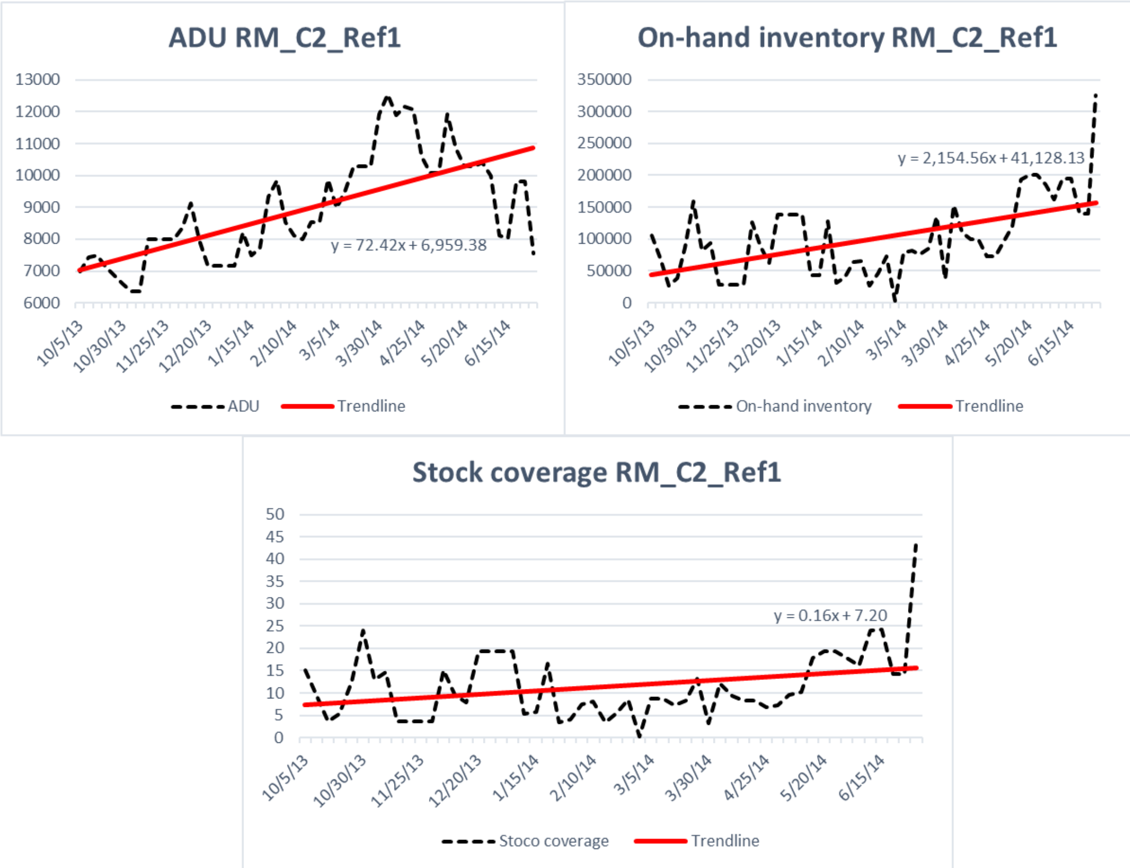
Graph 9.34: Total stock coverage of the raw material of C2

To carry out a more in depth analysis the three most consumed references were analyzed individually. In Ref1 and Ref2 the on-hand inventory increased by a larger amount than the ADU resulting in an increase of the stock coverage. This occurred for the same reason as Ref2 of the decoupling point of the end product C1 (Section 9.4.2.3.3), that is to say, post implementation the inventory level was adjusted to the real consumption involving a rise in stock. Thus, these references were better protected against shortages.

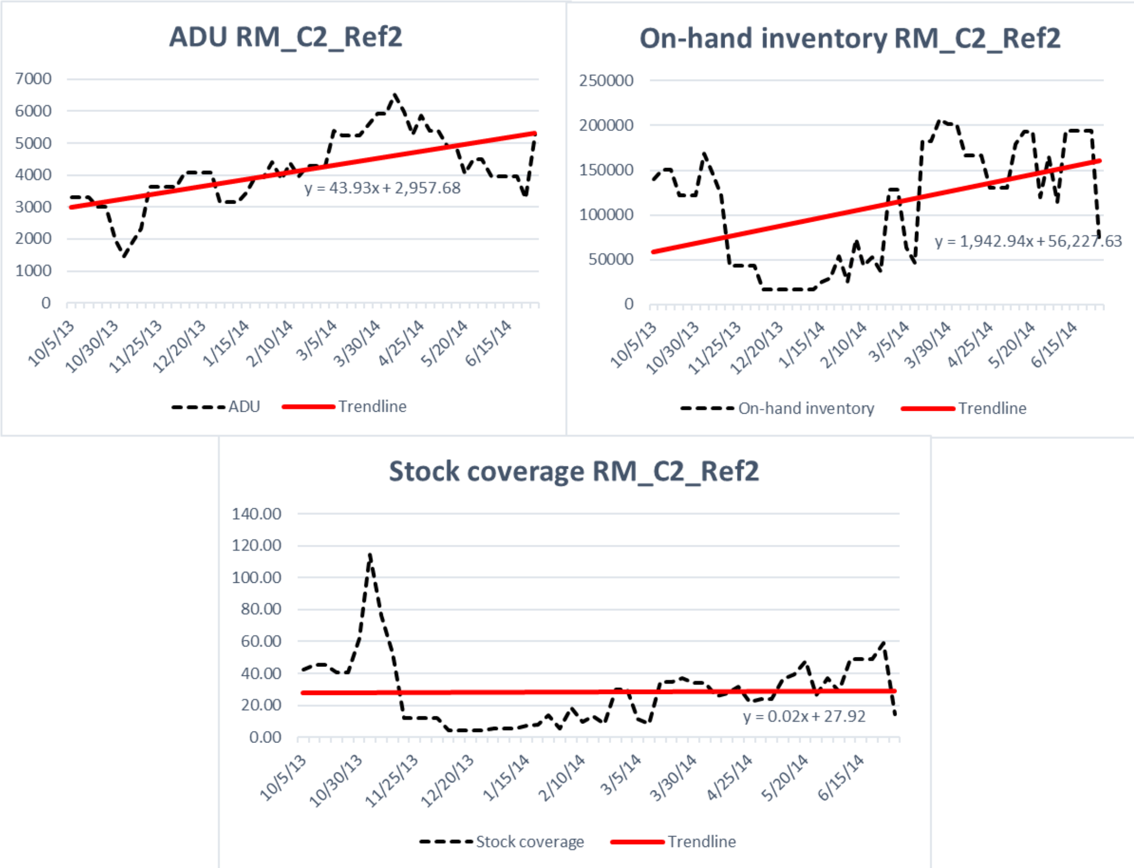
The pattern of Ref3 was markedly different, as the ADU increased dramatically while the on-hand inventory and thus stock coverage showed a large reduction.

Table 9-8: Evolution of the three most consumed references of C2 in raw material

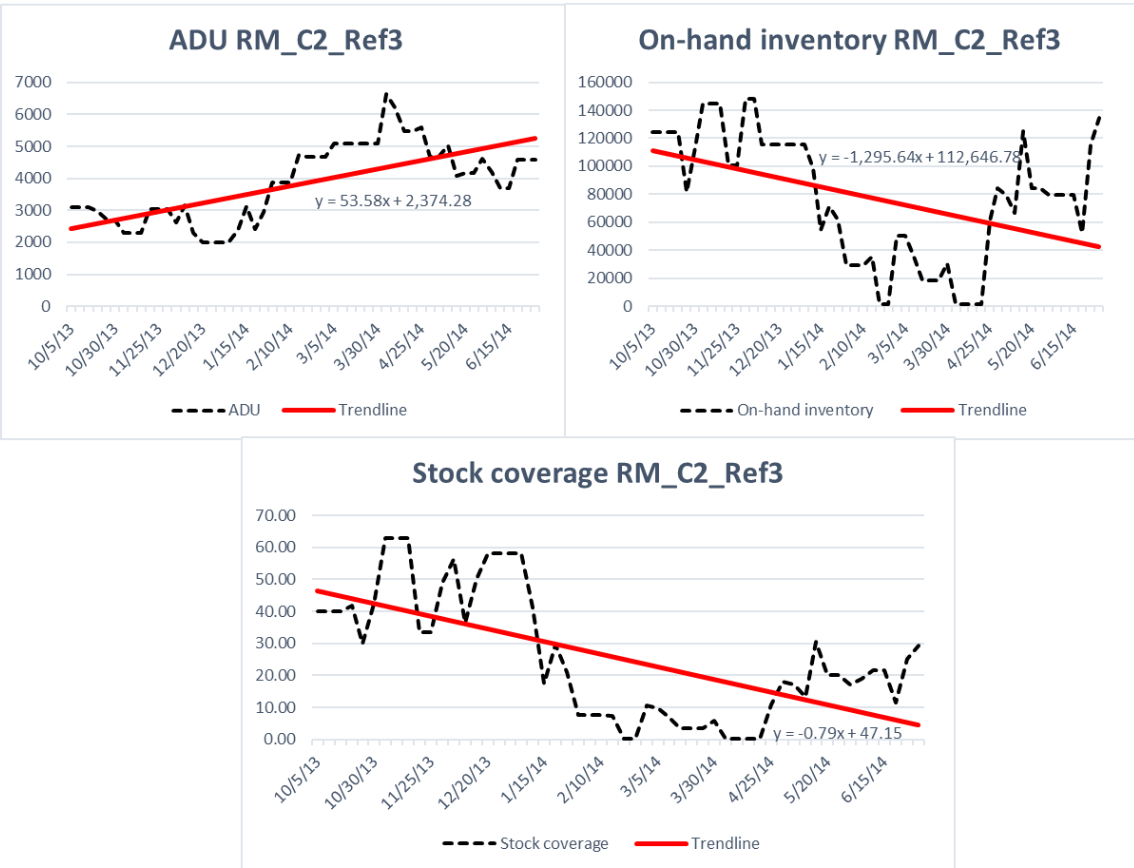
Cluster	Ref1	Ref2	Ref3
ADU	54.58%	77.57%	116.96%
ON-HAND	263.83%	177.02%	-61.67%
STOCK COVERAGE	115.22%	3.79%	-90.31%



Graph 9.35: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref1 in raw material



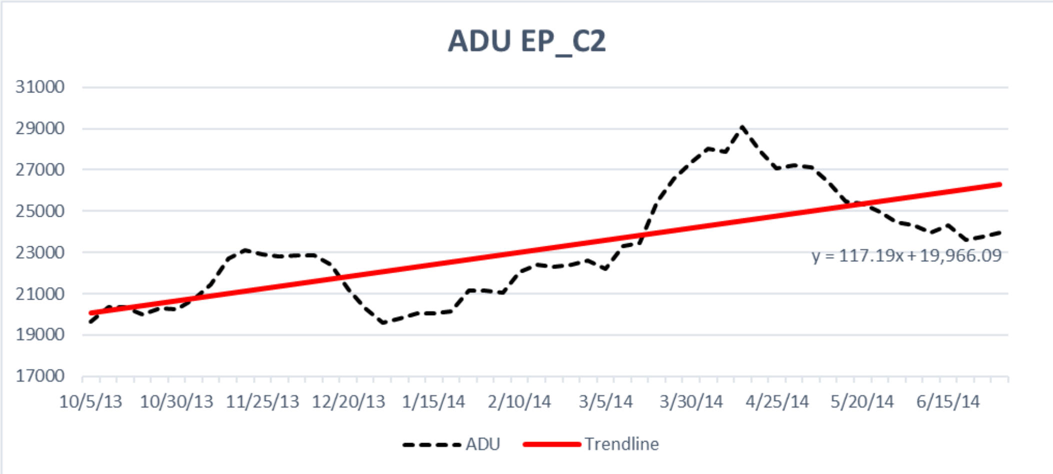
Graph 9.36: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref2 in raw material



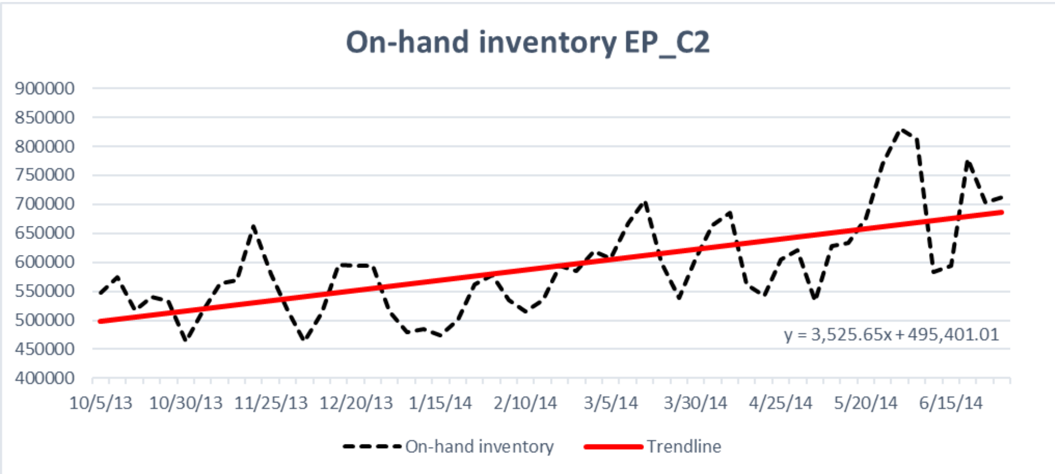
Graph 9.37: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref3 in raw material

9.4.2.4.2. Decoupling point end product C2

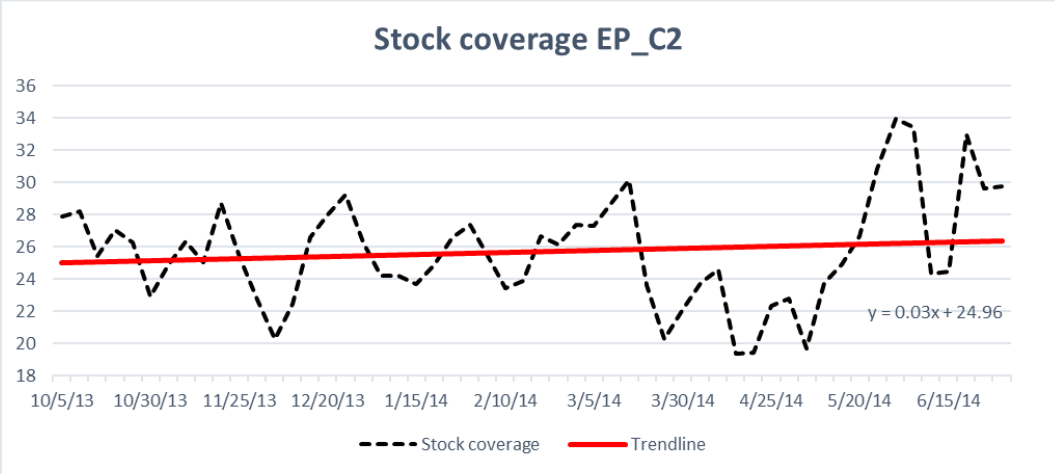
As for the end product buffers, a sample of 26 references were analyzed with an average lead time of 6 days. In the global analysis the ADU increased by 30.93%, the on-hand inventory by 37.45% and the stock coverage by 6.36% (Graph 9.38, Graph 9.39 and Graph 9.40).



Graph 9.38: Total ADU of end product of C2



Graph 9.39: Total on-hand inventory of end product of C2



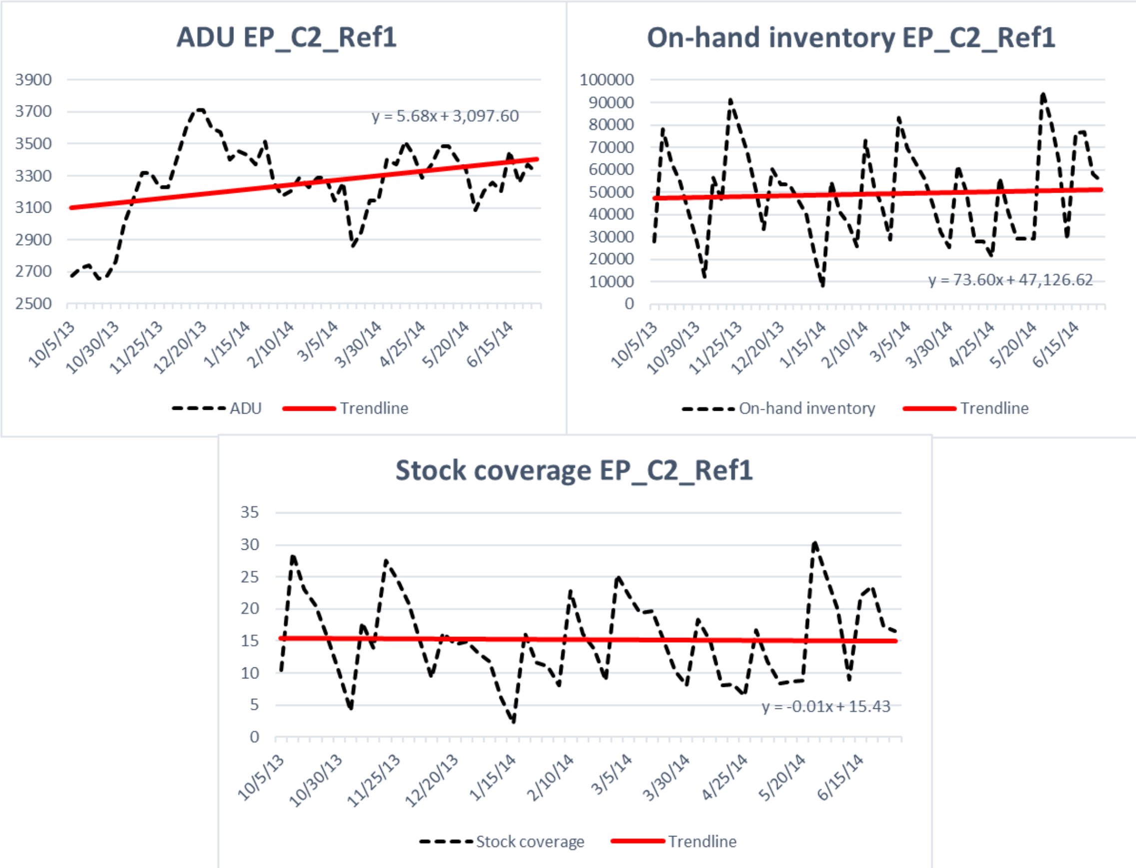
Graph 9.40: Total stock coverage of end product of C2

With regards to the most consumed three references, the ADU of Ref1 showed a greater increase than the on-hand inventory level, resulting in a decrease in stock coverage (Graph 9.41, Table 9-9).

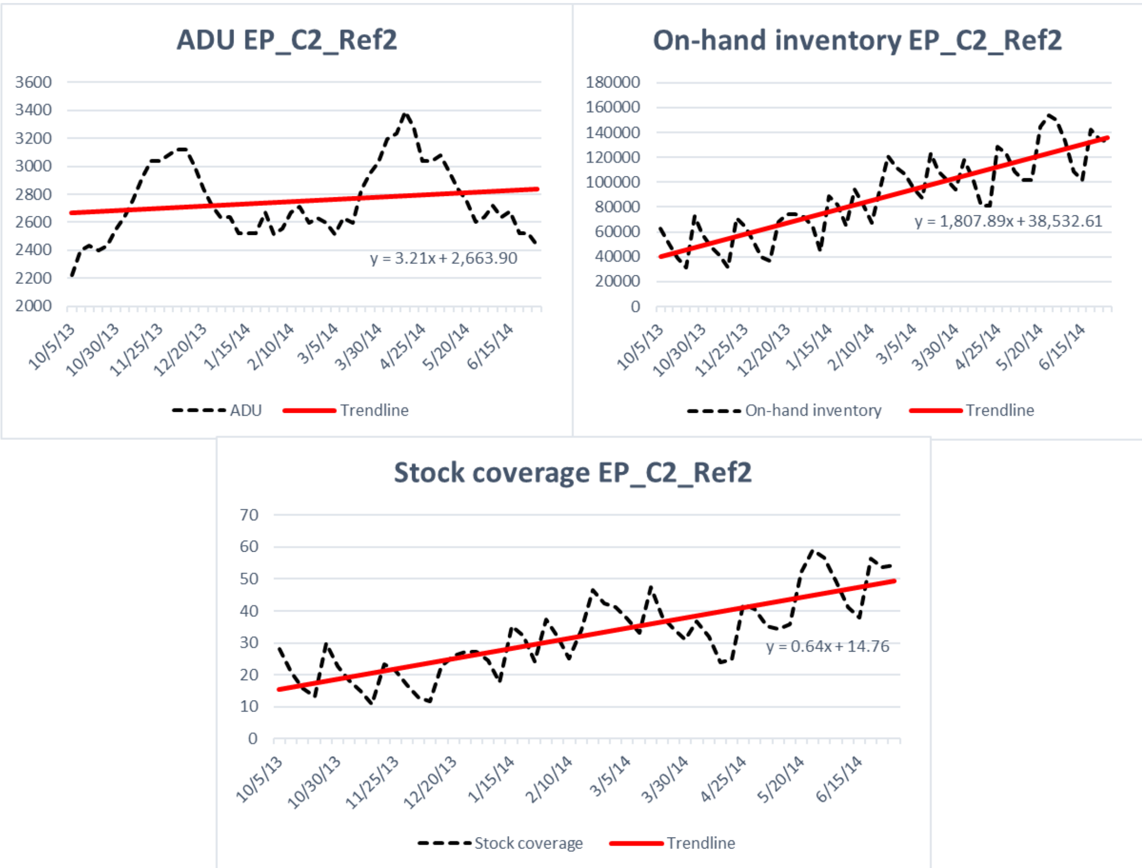
The ADU of Ref2 increased slightly, in contrast the on-hand inventory level and the stock coverage saw a dramatic increase. This fact was verified by CS3. They stated that the on-hand inventory of this reference was set to very low levels causing rush orders. After implementation, the inventory level was adjusted to real demand, resulting in a dramatic increase (Graph 9.42, Table 9-9).

Table 9-9: Evolution of the three most consumed references of C2 in end product

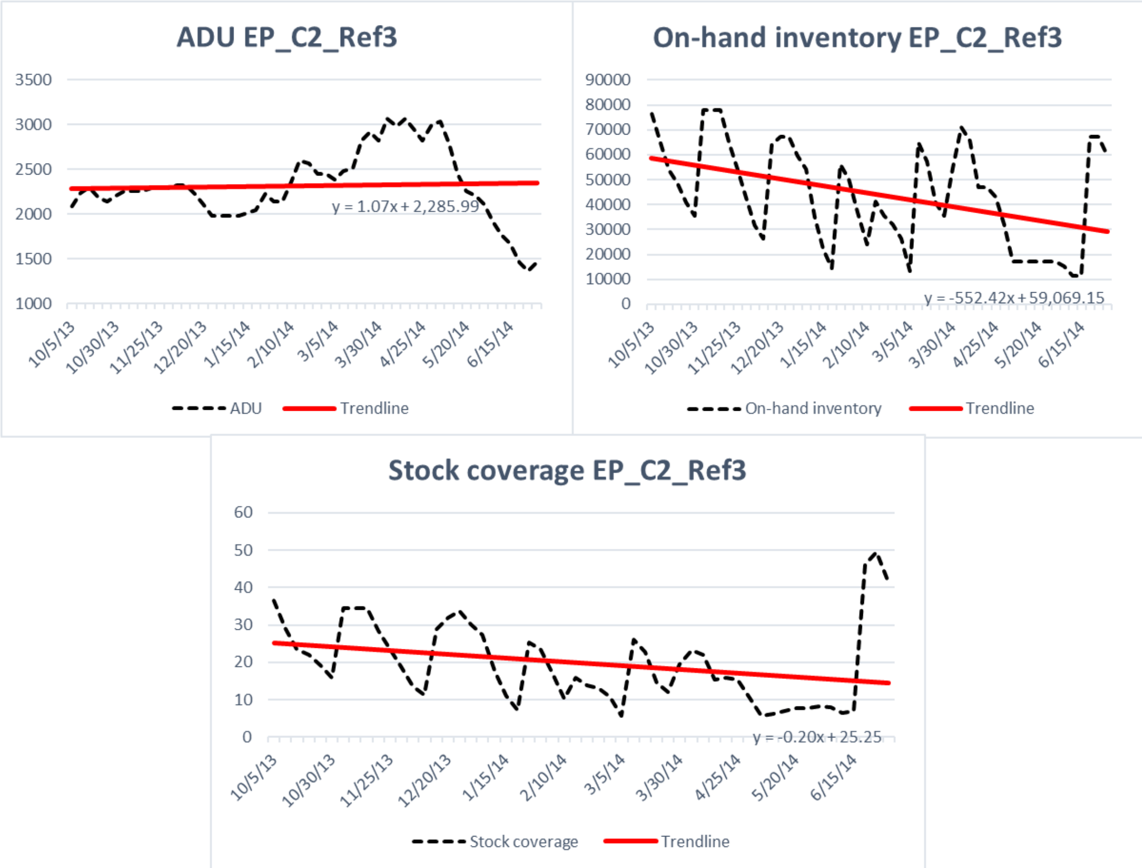
Cluster	Ref1	Ref2	Ref3
ADU	9.7%	6.38%	2.48%
ON-HAND INVENTORY	8.26%	237.52%	-50.03%
STOCK COVERAGE	-3.44%	220.26%	-42.32%



Graph 9.41: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref1 in end product



Graph 9.42: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref2 in end product



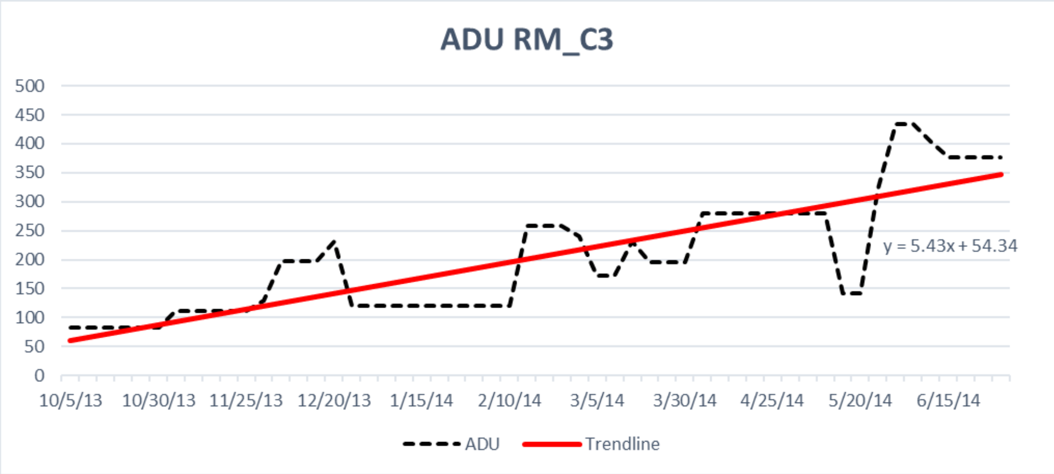
Graph 9.43: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref3 in end product

9.4.2.5. Results achieved in C3

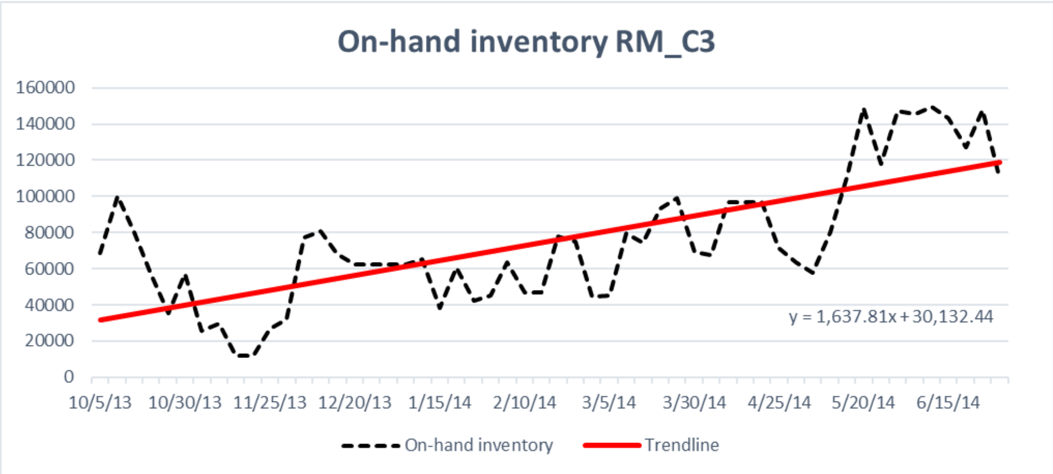
In the supply chain of C3, two decoupling points were placed: one in raw material and the other one in end product (Figure 9.10).

9.4.2.5.1. Decoupling point raw material C3

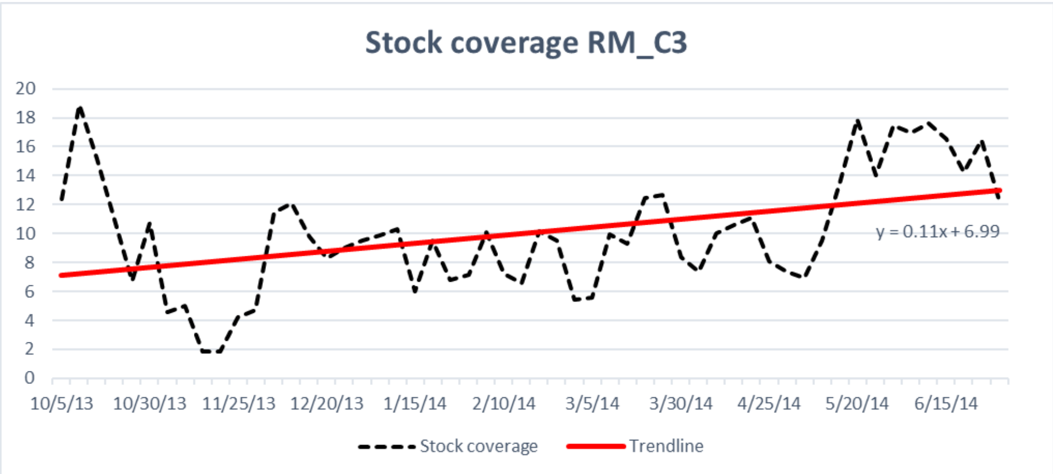
The raw material decoupling point was composed of 2 references which had on average a lead time of 50 days. During the analyzed period, the ADU of the sample increased by 481.5%, the on-hand inventory by 273.22% and the stock coverage by 82.11%. Due to the large increase of the ADU and the on-hand inventory level, this decoupling point was analyzed in detail with the company. They explained that in this period new projects were launched that consumed these raw materials resulting in a dramatic increase in the ADU. DDMRP adjusted the on-hand inventory level according to this consumption and thus the on-hand inventory level and stock coverage also increased (Graph 9.44, Graph 9.45 and Graph 9.46).



Graph 9.44: Total ADU of the raw material of C3



Graph 9.45: Total on-hand inventory of the raw material of C3



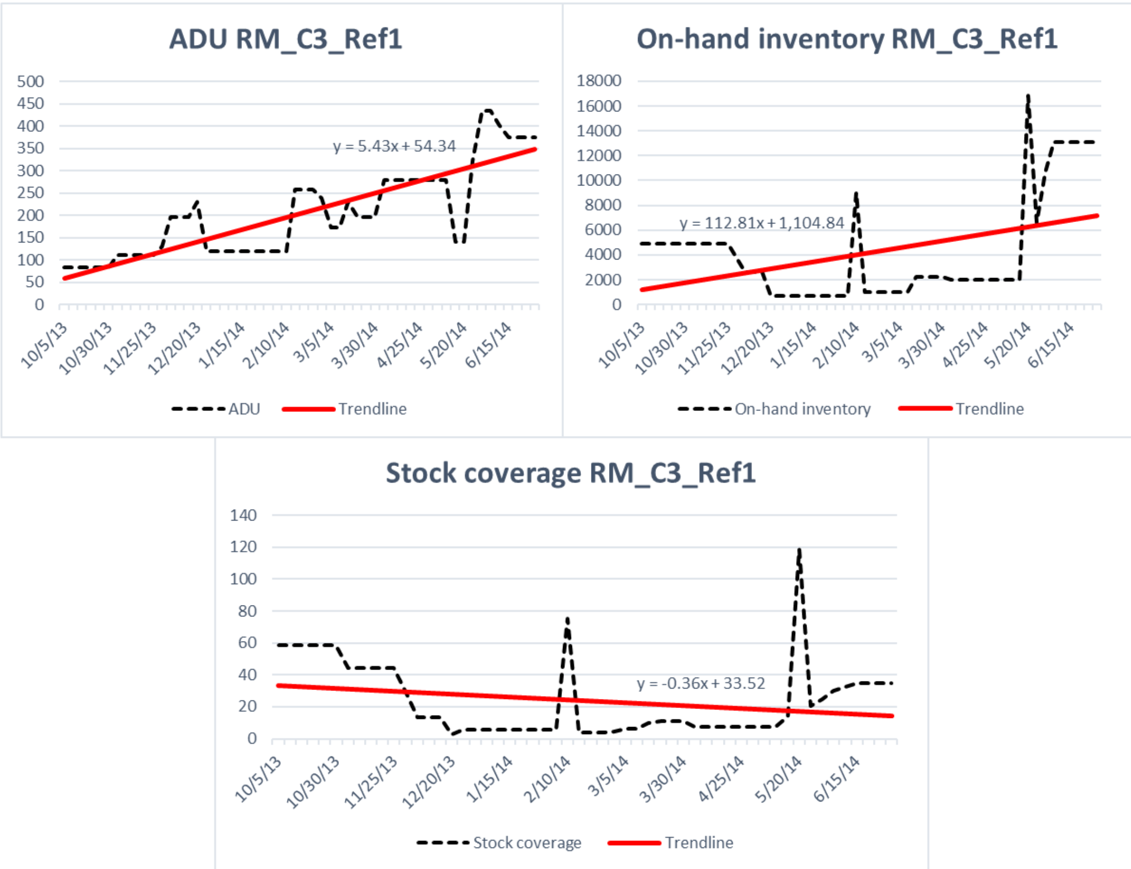
Graph 9.46: Total stock coverage of the raw material of C3

As for the individual analysis of both references (Table 9-10), in Ref1 the ADU increased by 481.5% and the on-hand inventory level by 491.02%. In contrast the stock coverage decreased by 57.54% (Graph 9.47).

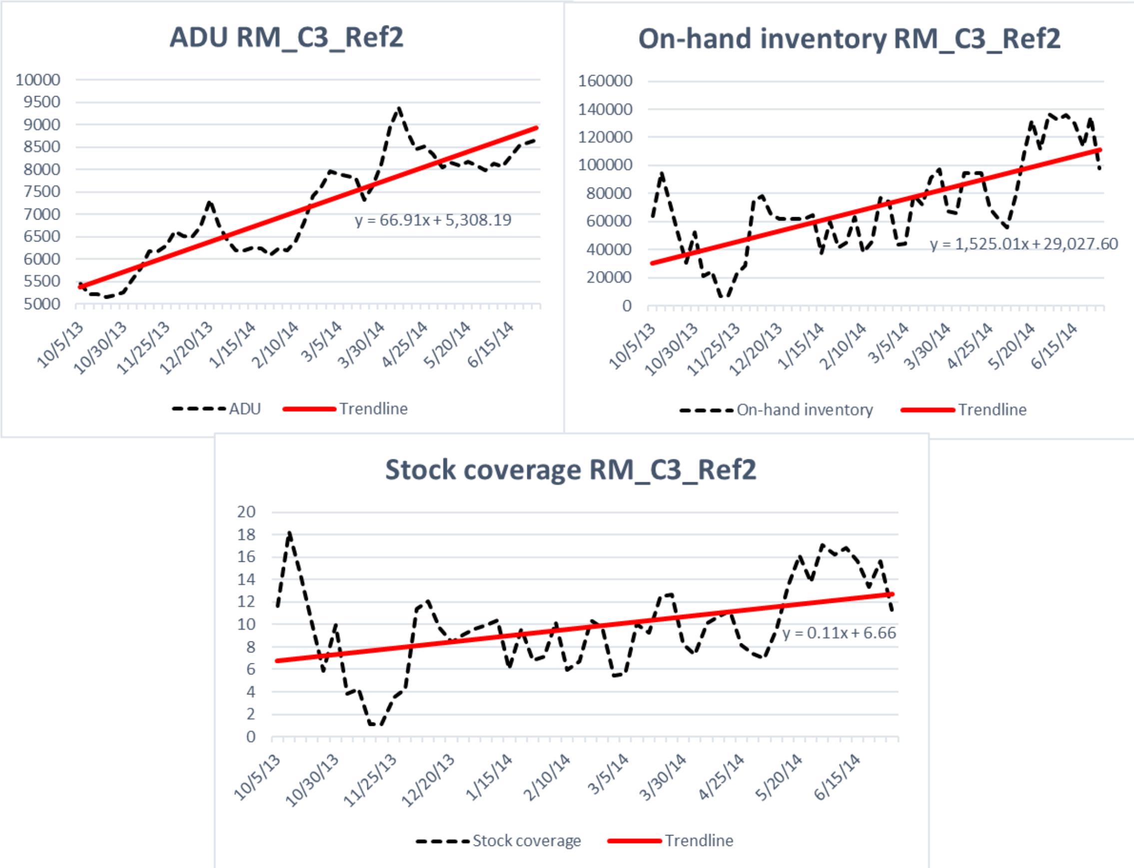
The on-hand inventory level of Ref2 showed a greater increase (264.55%) than the ADU (65.98%). Hence the stock coverage also increased by 86.12%. This surprising results were analyzed in detail with the company. They explained that before DDMRP this reference had shortages causing 9% of the unplanned stops in production. Hence, when CS3 adjusted the inventory level to the real demand and supply variability the inventory level increased considerably (Graph 9.48).

Table 9-10: Evolution of the two analyzed references of C3 in raw material

Cluster	Ref1	Ref2
ADU	481.5%	65.98%
ON-HAND INVENTORY	491.02%	264.55%
STOCK COVERAGE	-57.54%	86.12%



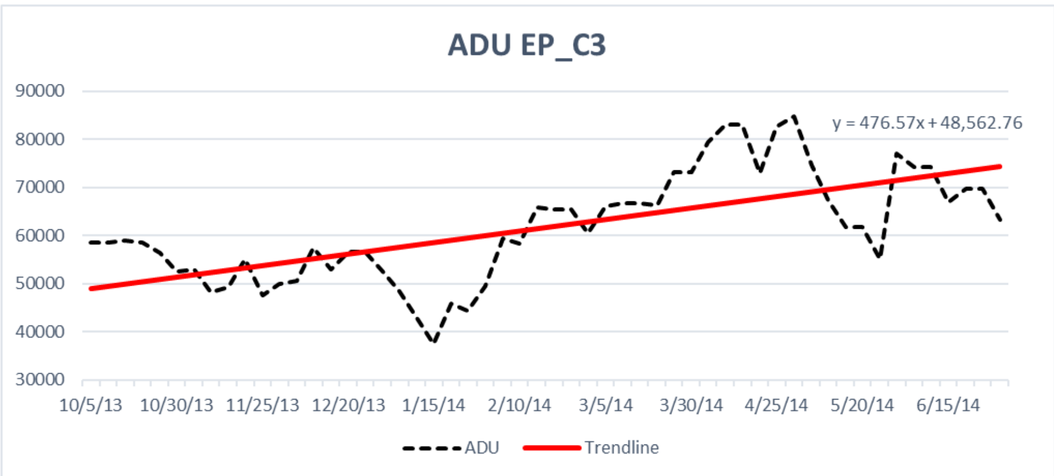
Graph 9.47: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref1 in raw material



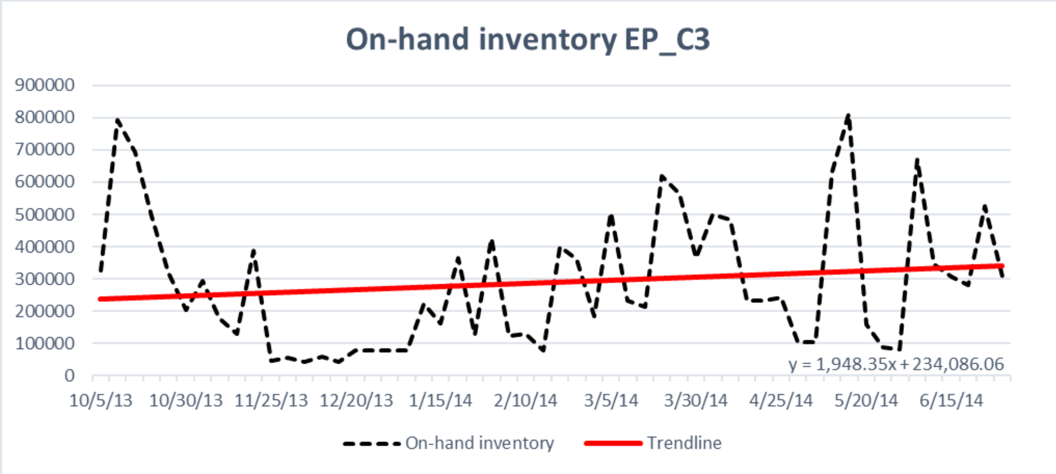
Graph 9.48: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref2 in raw material

9.4.2.5.2. Decoupling point end product C3

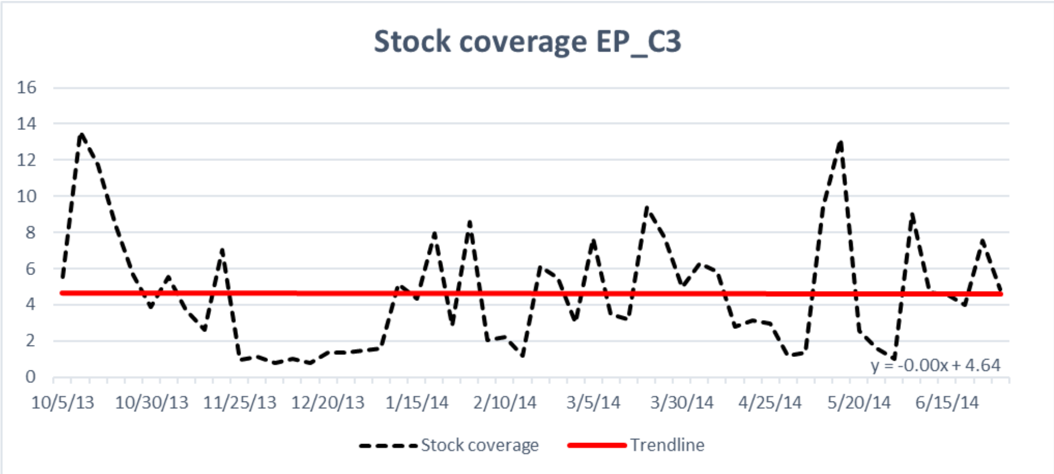
A sample of 8 references was considered with an average lead time of 16.25 days. In global terms the ADU of the sample increased by 51.51% and the on-hand inventory also increased by 43.75%. The stock coverage remained at 4.64 days on average (Graph 9.49, Graph 9.50 and Graph 9.51).



Graph 9.49: Total ADU of the end product of C3



Graph 9.50: Total on-hand inventory of the end product of C3



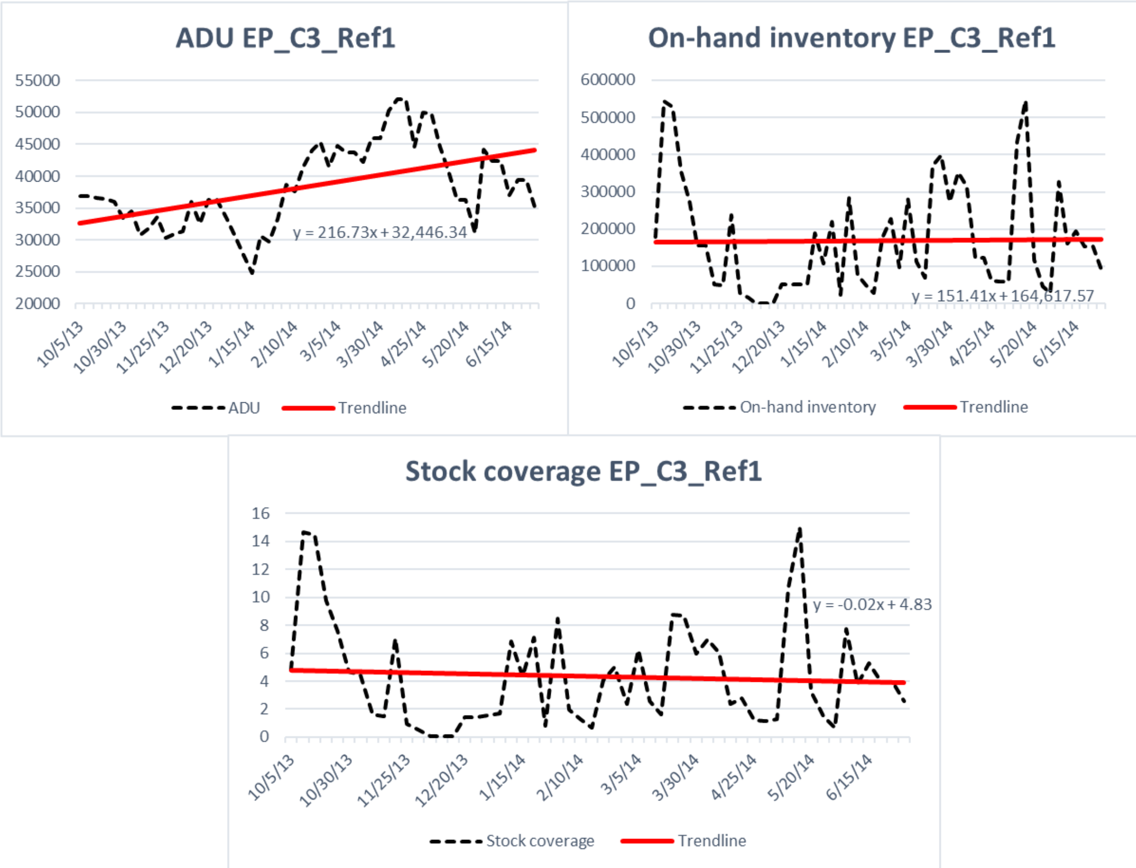
Graph 9.51: Total stock coverage of the end product of C3

In the individual analysis of the three most consumed references, Ref1 and Ref3 had the same trend. Both, the ADU and the on-hand inventory level increased while the stock coverage of both references decreased (Graph 9.52, Graph 9.54, Table 9-11).

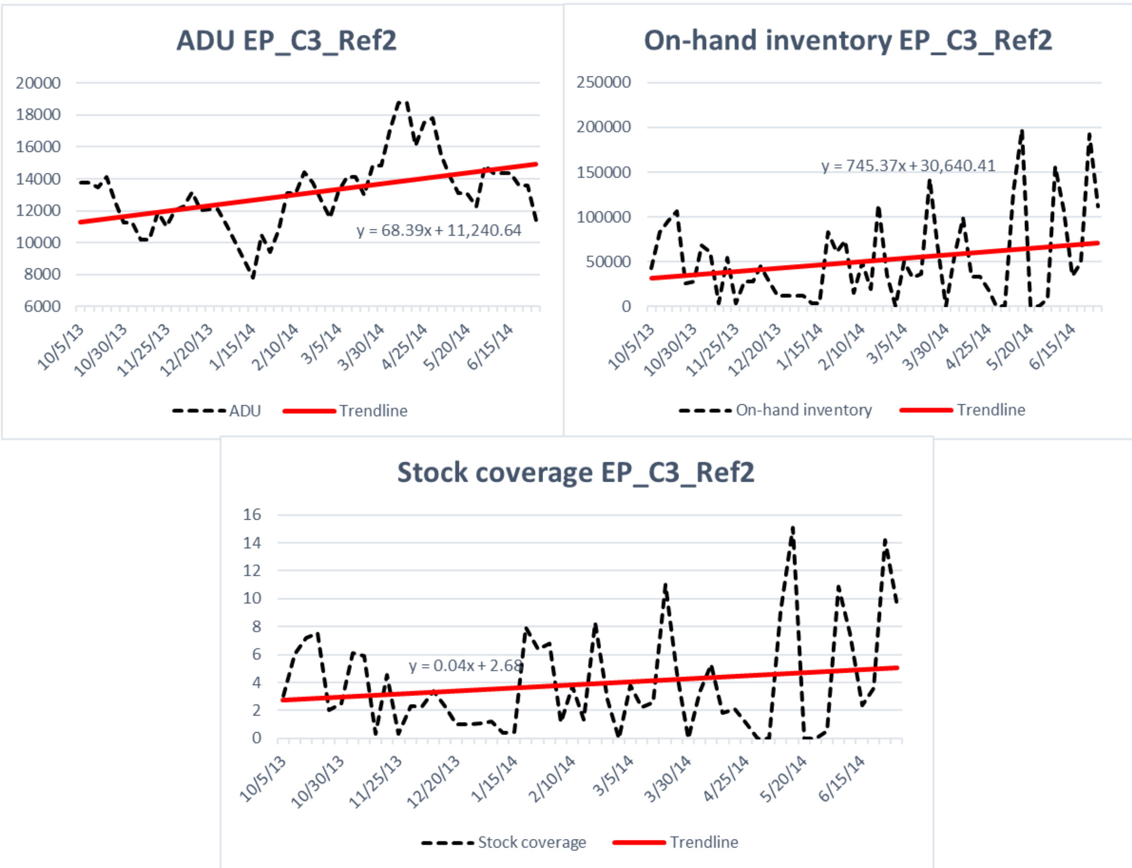
As for the Ref2, the ADU, on-hand inventory and the stock coverage all increased. This occurred for the same reason as Ref2 of the decoupling point of the end product C1 (Section 9.4.2.3.3), that is to say, post implementation the inventory level was adjusted to the real consumption involving a rise in stock. Thus, these references were better protected against shortages.

Table 9-11: Evolution of the three references of C3 in end product

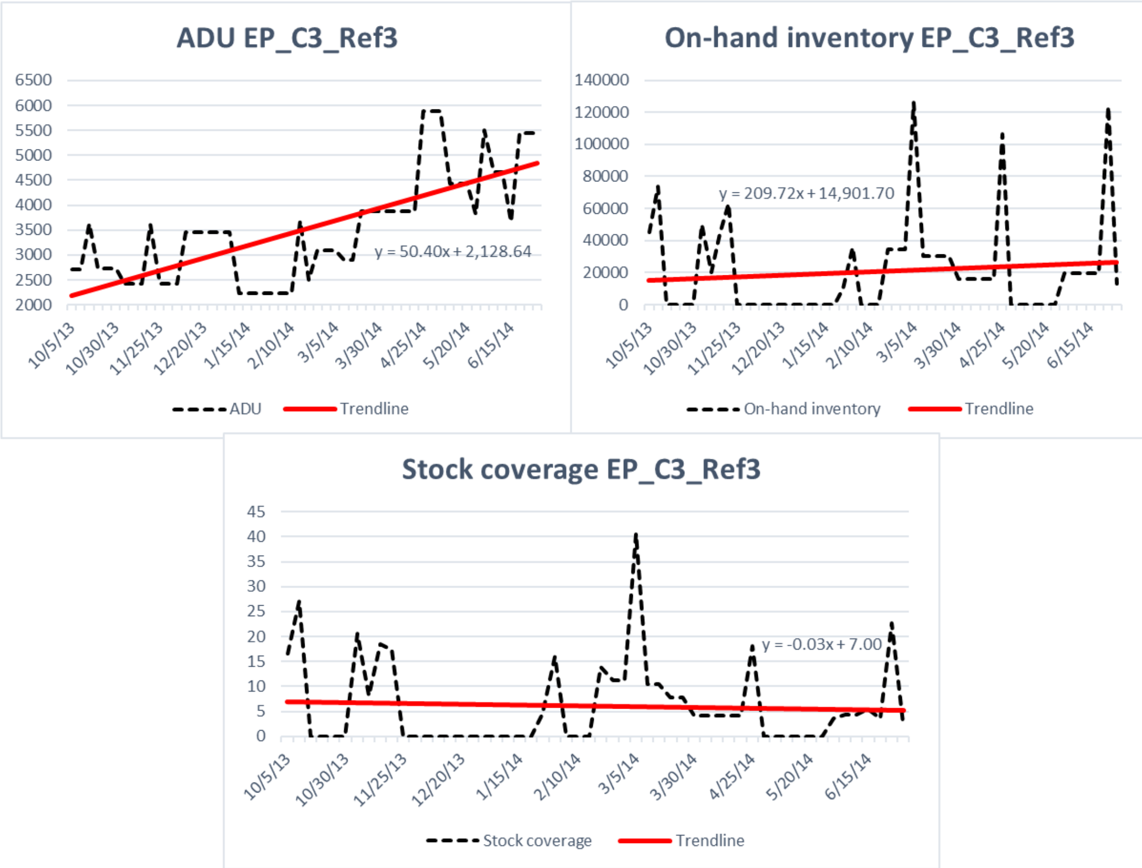
Cluster	Ref1	Ref2	Ref3
ADU	35.17%	32.05%	122.59%
ON-HAND	4.87%	125.87%	73.55%
STOCK COVERAGE	-22.04%	77.94%	-22.81%



Graph 9.52: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref1 in end product



Graph 9.53: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref2 in end product



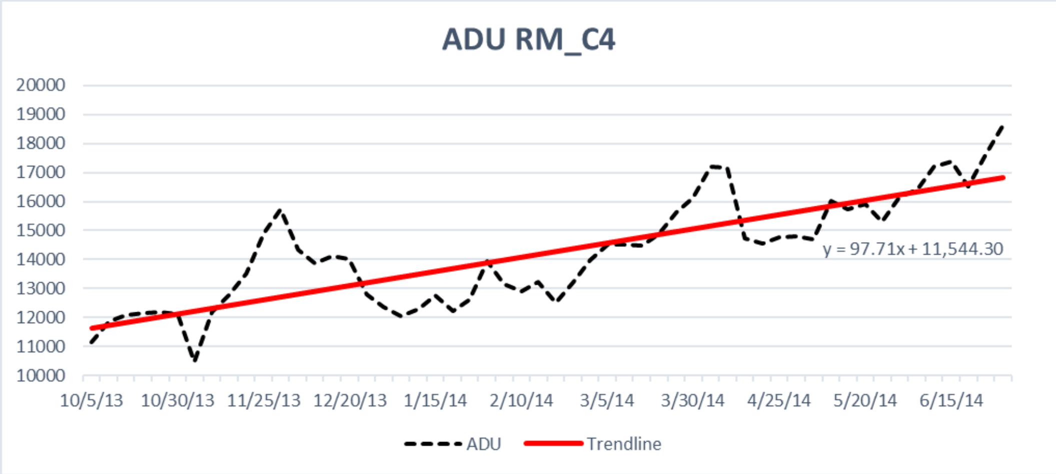
Graph 9.54: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref3 in end product

9.4.2.6. Results achieved in C4

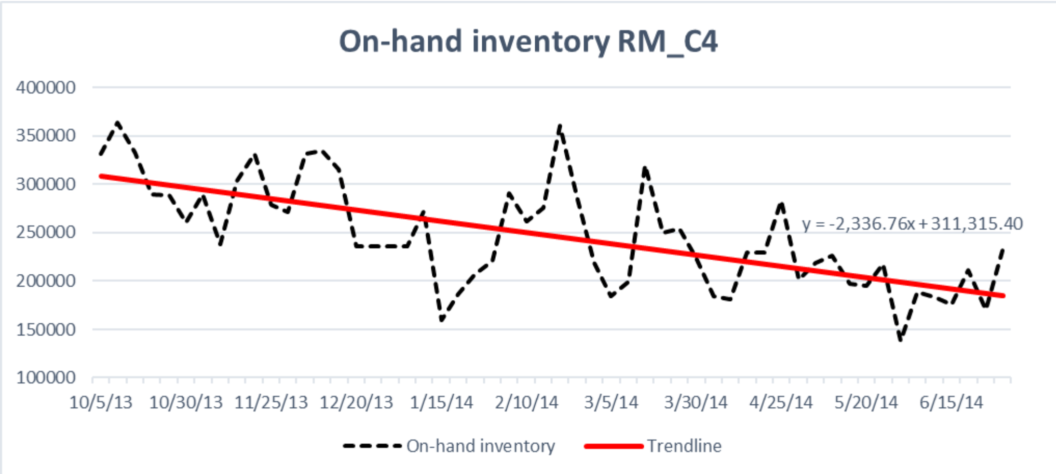
To complete the study the supply chain of C4 was analyzed. Here two decoupling points were allocated: in raw material and in end product (Figure 9.11).

9.4.2.6.1. Decoupling point raw material C4

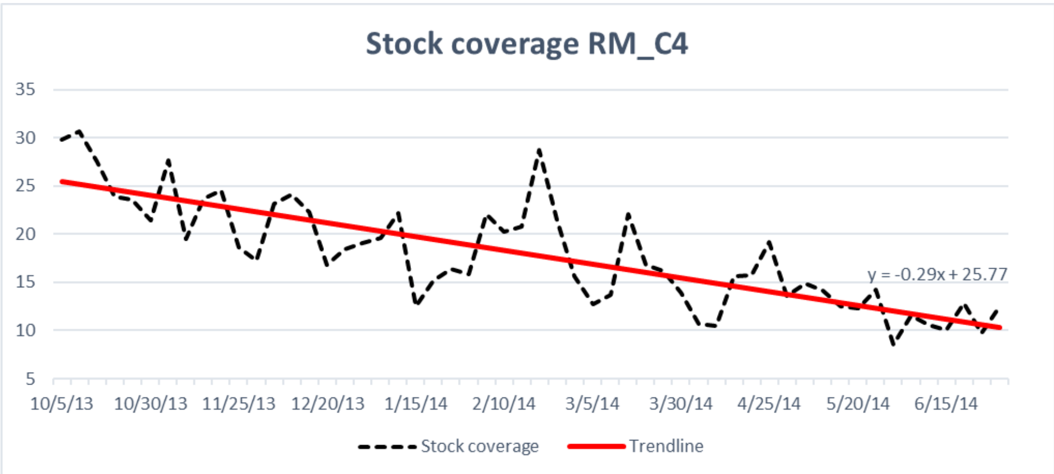
A sample 13 references was analyzed with an average lead time of 50 days. In global terms the ADU of the sample increased by 44.48% while both the on-hand inventory and stock coverage decreased by 40.08% and by 60.32% respectively (Graph 9.55, Graph 9.56, Graph 9.57).



Graph 9.55: Total ADU of the raw material of C4



Graph 9.56: Total on-hand inventory of the raw material of C4



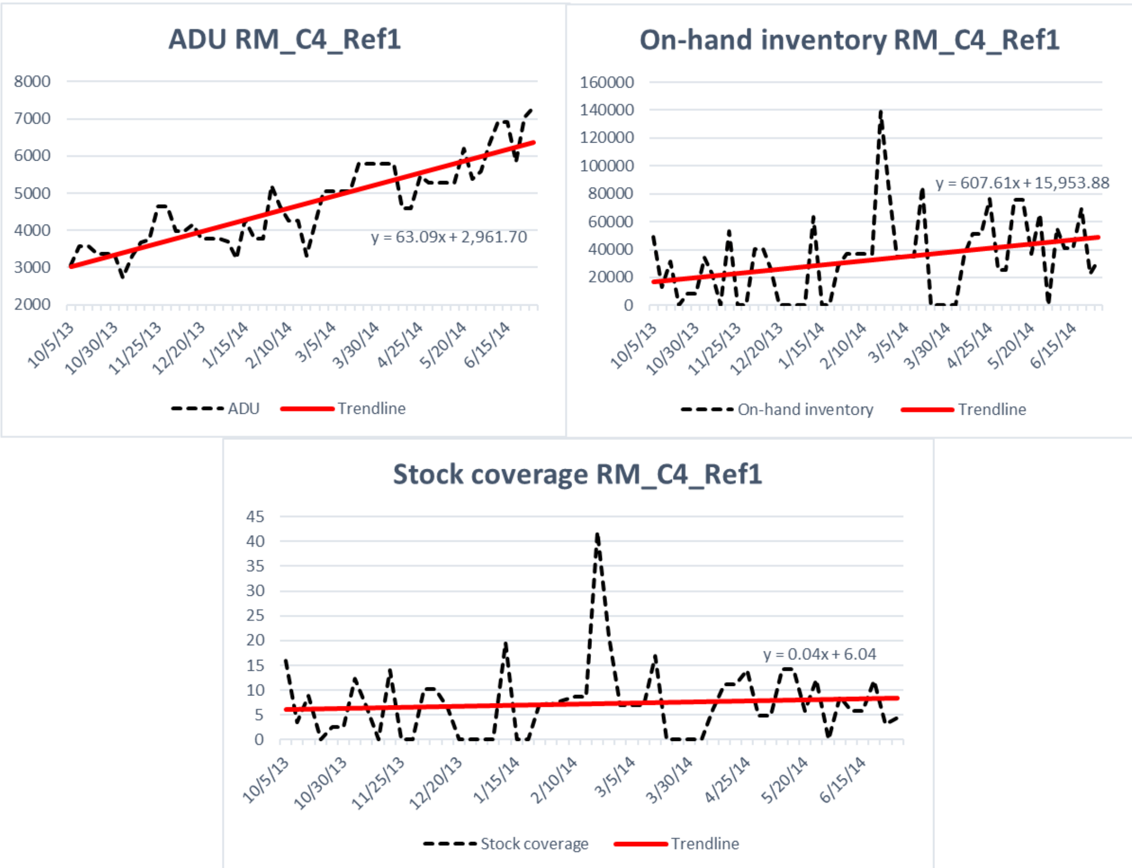
Graph 9.57: Total stock coverage of the raw material of C4

In the individual analysis of the three most consumed references, the pattern of Ref1 and Ref3 were similar. The ADU, the on-hand inventory and the stock coverage all increased (Graph 9.58, Graph 9.60, Table 9-12). This occurred for the same reason as Ref2 of the decoupling point of the end product C1 (Section 9.4.2.3.3), that is to say, post implementation the inventory level was adjusted to the real consumption involving a rise in stock. Thus, these references were better protected against shortages.

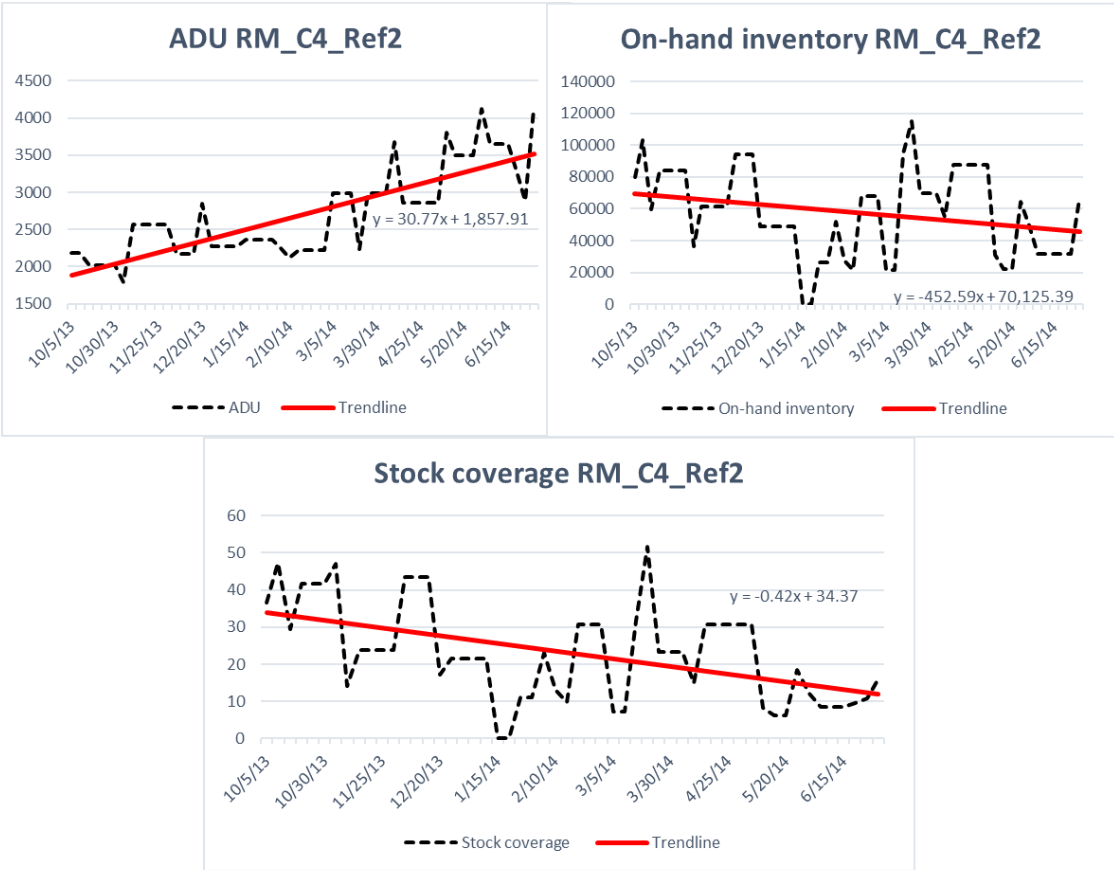
As for Ref2, the ADU increased considerably while the on-hand inventory and the stock coverage decreased (Graph 9.59, Table 9-12).

Table 9-12: Evolution of the three references of C4 in raw material

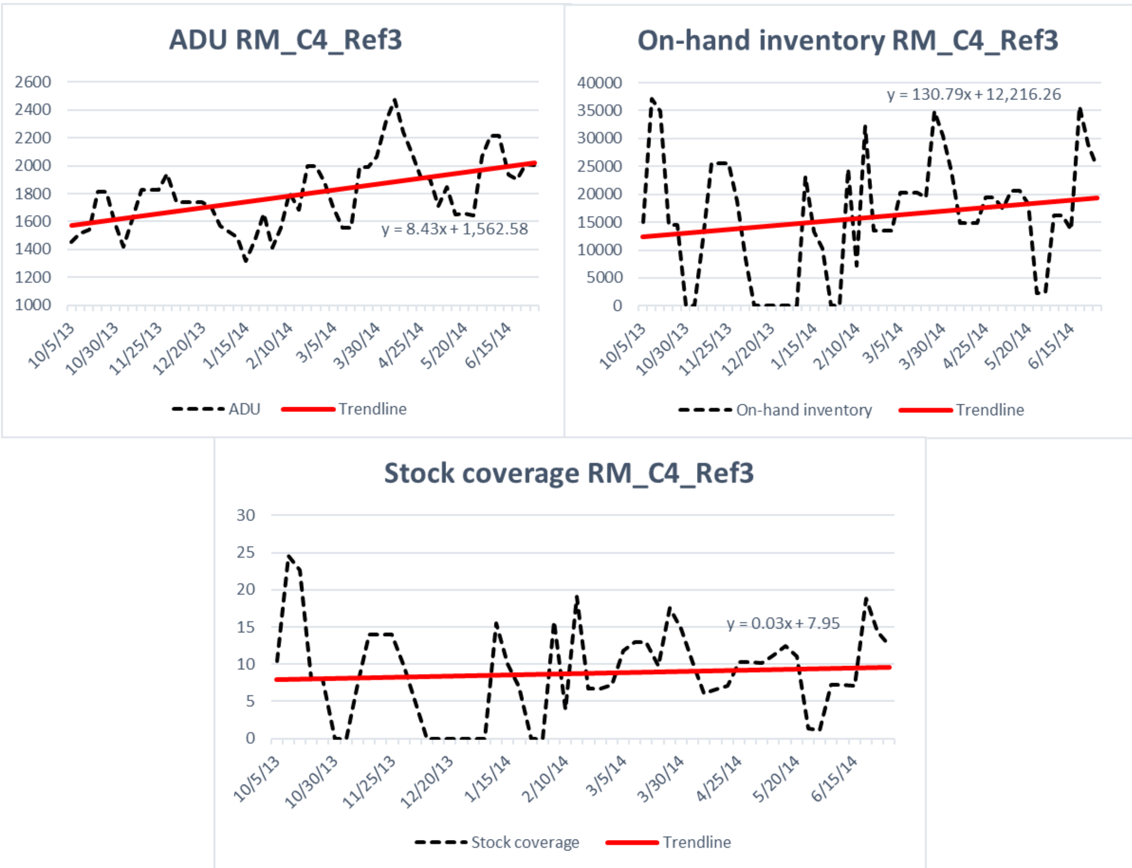
Cluster	Ref1	Ref2	Ref3
ADU	110.55%	86.35%	28.44%
ON-HAND	194.45%	-34.43%	56.14%
STOCK COVERAGE	34.87%	-65.57%	19.92%



Graph 9.58: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref1 in raw material



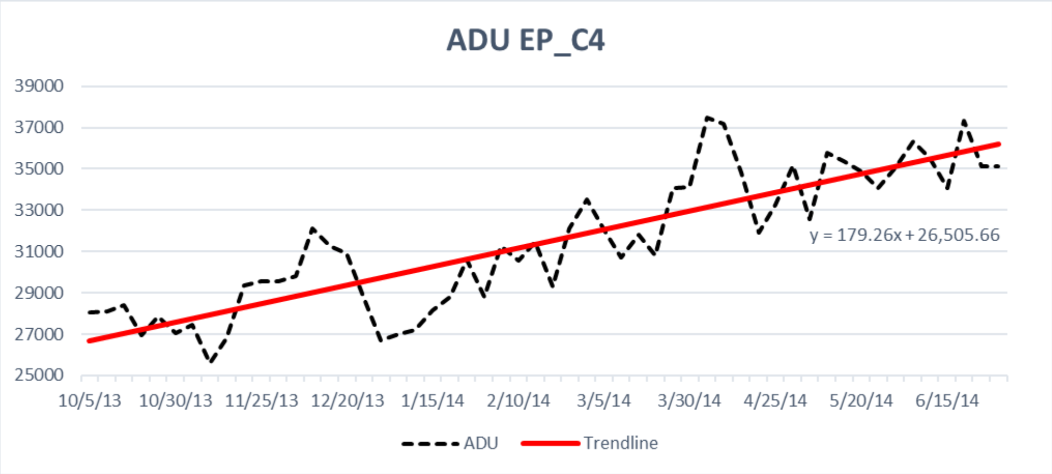
Graph 9.59: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref2 in raw material



Graph 9.60: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref3 in raw material

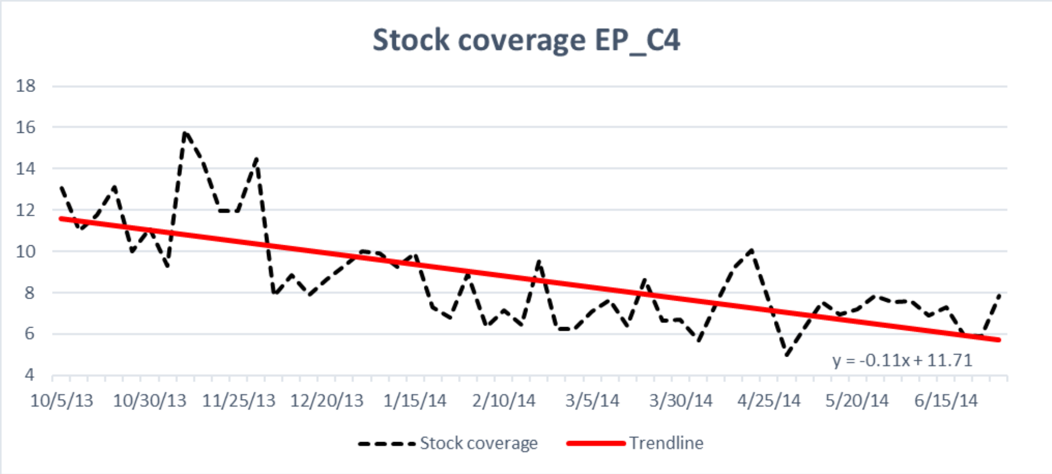
9.4.2.6.2. Decoupling point end product C4:

A sample of 110 references was considered with an average lead time of 30 days. In global terms the ADU of the sample increased by 35.6% while the on-hand inventory decreased by 30.71%. Therefore the stock coverage also decreased by 50.26%.



Graph 9.61: Total ADU of the end product of C4

Graph: 9.62: Total on-hand inventory of the end product of C4



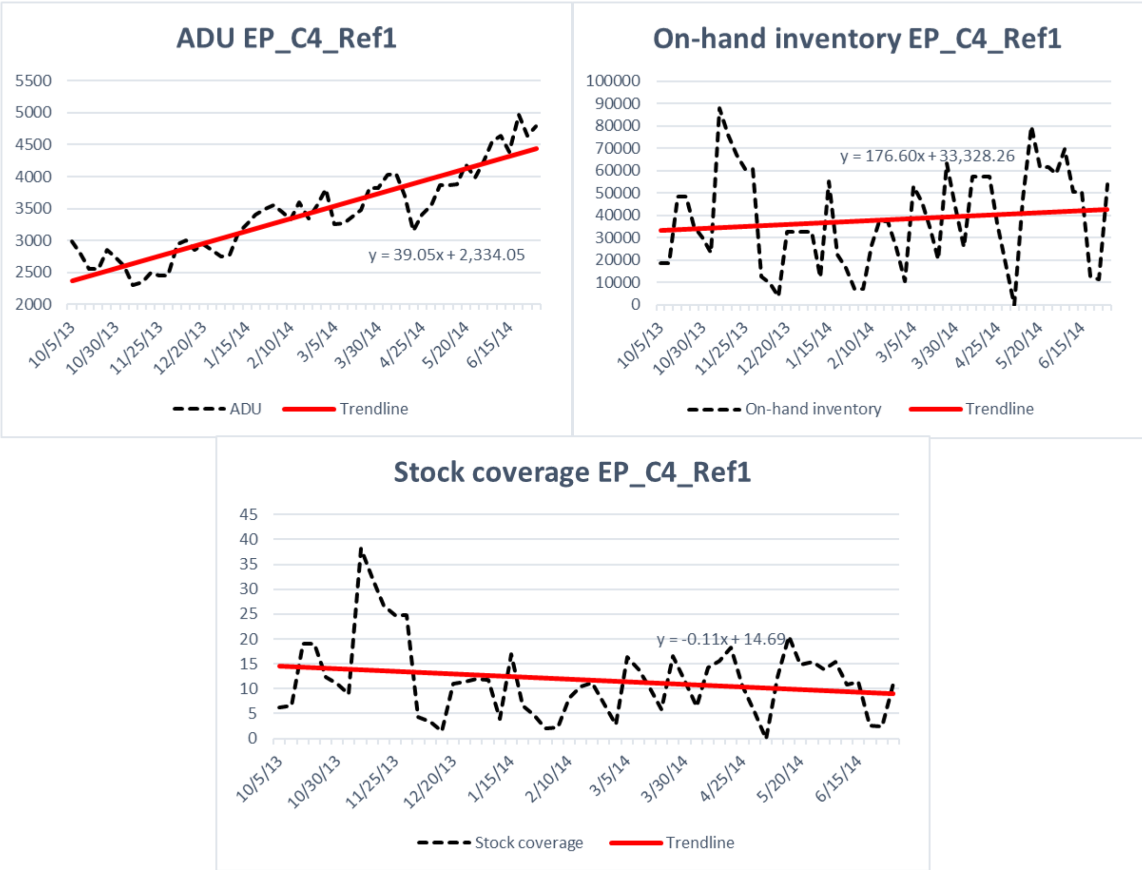
Graph 9.63: Total stock coverage of the end product of C4

In the individual analysis of the three most consumed references, the ADU of Ref1 increased by a larger amount (87.21%) than the on-hand inventory level (27.94%). Thus the stock coverage decreased by 39.99% (Graph 9.64, Table 9-13).

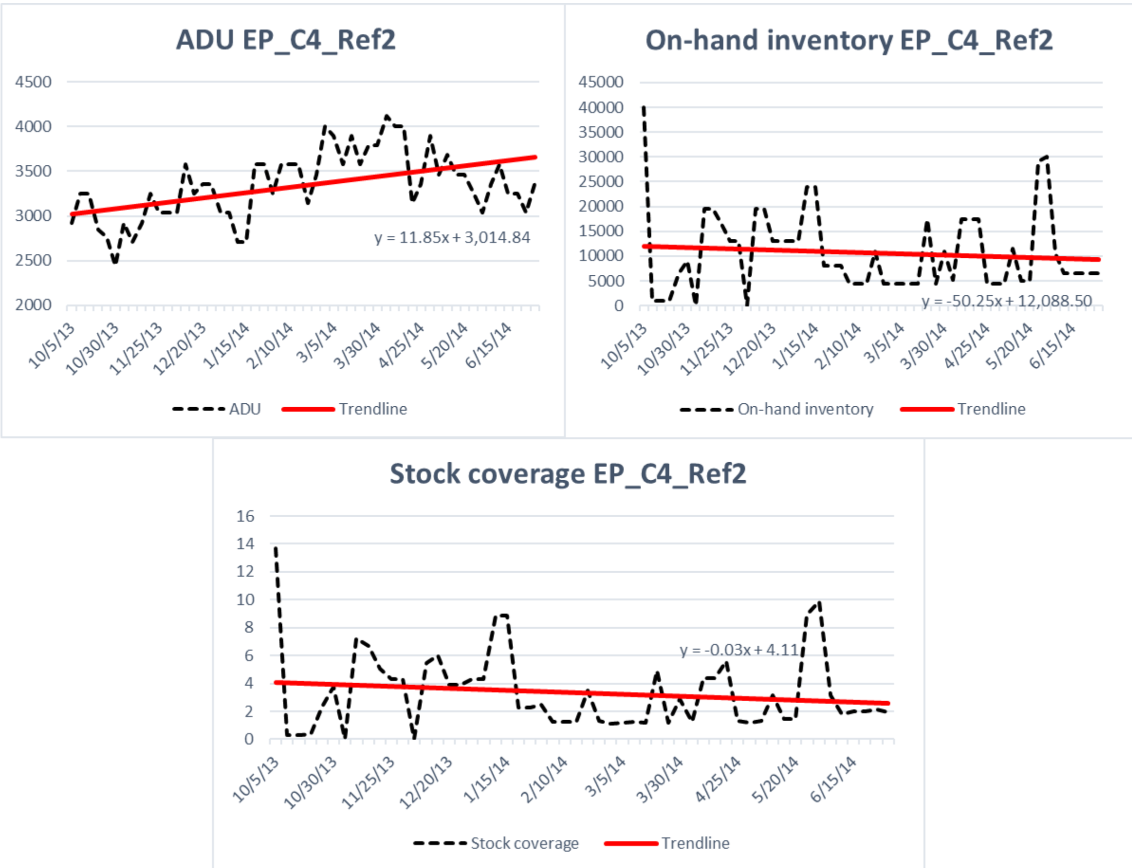
Ref2 and Ref3 showed the same trend. The ADU increased during the analyzed period, while the on-hand inventory and thus stock coverage decreased (Graph 9.65, Graph 9.66, Table 9-13).

Table 9-13: Evolution of the three references of C4 in end product

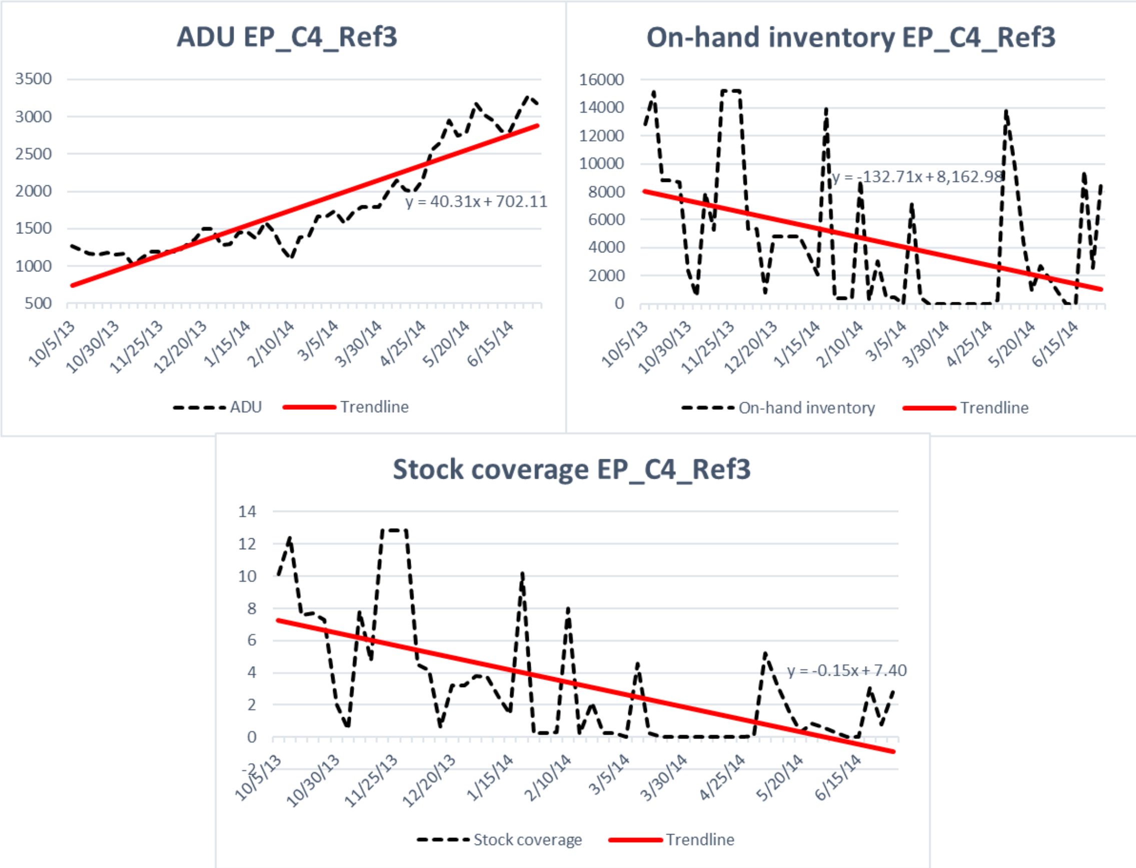
Cluster	Ref1	Ref2	Ref3
ADU	87.21%	20.75%	287.77%
ON-HAND	27.94%	-22.12%	-87.59%
STOCK COVERAGE	-39.99%	-38.97%	-109.66%



Graph 9.64: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref1 in end product



Graph 9.65: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref2 in end product



Graph 9.66: (a) the ADU, (b) on-hand inventory and (c) stock coverage of Ref3 in end product

9.5. Main findings of case study 3

The management of materials and production with DDMRP increased material and information flow through the supply chain of CS3. This is shown in the following points:

- CS3 used real material consumption to size the buffers and plan material and production requirements instead of relaying on forecast information. Considering the volatility of the forecast, this change resulted in a significant reduction of uncertainty in the supply chain and hence, provided visibility in material status. The company therefore, was able to quickly identify and plan real requirements on a daily basis.
- The allocation and management of the decoupling points based on real pull strategy brought about a significant change in the material and production planning process. For instance, the decoupling point allocated between the forging and machining plants converted the machining plants into customers of the forging plant, enabling their synchronization. Thus, the machining plants planned production requirements considering the material consumption of C1. These production orders consumed material from the decoupling point allocated between the forging and machining plants and provided the forging plant with the correct signal of what to produce and what raw

material to purchase. Therefore, the forging plant ignored the final customer forecast, completely eliminating the uncertainty that this forecast used to generate. This change (1) improved the information flow between the forging and machining plants, resulting in a significant reduction of the rush orders that the forging plant had to manage before DDMRP implementation, (2) eliminated the unplanned production orders and setups that the forging plant carried out to serve the rush orders required by the machining plants (resulting in machine downtime of 12-15 hours per week), and (3) reduced the lead time to service the orders of C1 from 20 to 10 days.

Planning and execution became agile, simple and intuitive. CS3 was thus able to daily check material and open orders status and plan real requirements. In addition, these plans were implemented, preventing the company from wasting time and resources due to constant replanning actions typically carried out prior DDMRP.

It is worth mentioning that increasing planning from weekly to daily provided flexibility to the company. When a material required an action CS3 would realize the following day at the latest, having more days to manage the situation. Planning frequency is not the only key factor however, accurate and reliable data is also essential. Prior DDMRP implementation, even if the company had planned on a daily basis, the replanning process would still have occurred as at that time CS3 used forecast information which changed daily.

The increase in visibility was also reflected in the inventory, as the company adjusted the on-hand inventory level according to real demand preventing the bimodal distribution. This adjustment involved a global stock coverage reduction by 33.62%, which means that CS3 was meeting higher demand with less on-hand inventory level. In addition, the methodology better protected vulnerable references that previously were causing stockouts and rush orders.

Table 9-14: Summary of the performance of the decoupling points

	Decoupling point	ADU	On-hand inventory	Stock coverage
C1	Raw material	-15.90%	-47.54%	-36.91%
	Machining plant	52.58%	-20.57%	-74.55%
	End product	17.49%	-4.01%	-21.40%
C2	Raw material	66.07%	-7.98%	-29.26%
	End product	30.93%	37.45%	6.36%
C3	Raw material	481.50%	273.22%	82.11%
	End product	51.51%	43.75%	-4.64%
C4	Raw material	44.48%	-40.08%	-60.32%
	End product	35.60%	-30.71%	-50.26%

The conclusions of the analysis of the decoupling points of each customer is set out below:

- **C1:** Three decoupling points were positioned in the supply chain of this customer:
    - **Raw material:** It is worth noting that during the implementation CS3 decided to continue managing these references with MRP. In this period, the ADU decreased by 19.46% but the on-hand inventory increased by 17.72%, resulting in an increase of the stock coverage by 42.32%. However, when the company began managing these references with DDMRP the pattern changed. The total ADU decreased by 15.9% but the on-hand inventory decreased in a greater amount, by 47.54%, resulting in a decrease of the stock coverage by 36.91%. The three most consumed references of this decoupling point showed the same trend. These results show that before the implementation on average the references that belonged to this decoupling point were skewed to the right of the bimodal distribution. Moreover, the company stated that low reliability of the forecast of this customer forced them to have high SS levels to avoid stockouts. This decision caused an even greater deviation to the right of the bimodal distribution.

      DDMRP, being based on real consumption, considerably reduced the uncertainty enabling the company to adjust the inventory to real requirements. In this case, the adjustment was a greater reduction of the on-hand inventory level than the ADU, resulting in a decrease in the stock coverage.
    - **Machining plants:** The general analysis of the references belonging to this decoupling point and the most consumed three references showed the same trend. The ADU increased during the period of analysis. However, the on-hand inventory decreased resulting in a reduction of the stock coverage. Here as well there is evidence that before DDMRP these references were skewed to the right of the bimodal distribution. However, the reduction of the uncertainty increased visibility and enabled the adjustment of the on-hand inventory levels to the real needs, resulting in a significant reduction of the on-hand inventory level.
    - **End product:** The ADU of these references increased by 17.49% while the on-hand inventory decreased by 4.01% resulting in a decrease of the stock coverage. In the individual analysis of the three most consumed references, the ADU increased in all of them. However, the on-hand inventory did not follow the same pattern in three of them. Two references decreased their on-hand inventory resulting in a decrease of the stock coverage. However, the third reference had a larger increase of the inventory level than the ADU, resulting in

an increase of the stock coverage. The evolution of these references was checked and validated with CS3. They stated that before DDMRP, they were having many shortages with this reference that used to cause many rush orders. An increase of the inventory level of this reference enabled the company to better protect against any unexpected circumstance.

- **C2:** Two decoupling points were positioned in the supply chain of this customer:
  - **Raw material:** The total ADU increased by 66.07% and the on-hand inventory decreased by 7.98% with a resultant decrease of 29.26% in the stock coverage. In the individual analysis of the references, only one of them showed the same pattern. The other two references had a larger increase of the on-hand inventory level than the ADU, producing an increase in the stock coverage. These results were checked and validated with CS3. They explained that they were having many shortages with these references that caused production downtimes. Using DDMRP CS3 adjusted the inventory level of these references, resulting in an increase of inventory, which lead us to conclude that these references were skewed to the left of the bimodal distribution.
  - **End product:**_The total ADU increased by 30.93% but the on-hand inventory increased by a larger amount, 37.45% resulting in an increase of the stock coverage by 6.36%. The individual analysis of the three most consumed references showed different patterns. The ADU of Ref1 increased in a larger amount than the on-hand inventory, and thus stock coverage decreased. Ref3 also saw a decrease in the stock coverage due to a significant reduction of the on-hand inventory level. Hence, these references were skewed to the right of the bimodal distribution, and with DDMRP the inventory level shifted to the normal distribution.

    Ref2 had a completely different pattern as the on-hand inventory level significantly increased and consequently the stock coverage. Discussions with CS3 established that this was another reference with frequent shortages causing many rush orders.

    Using DDMRP CS3 adjusted the inventory level of these references resulting in an increase of inventory, which lead us to conclude that this reference was skewed to the left of the bimodal distribution.
- **C3:** Two decoupling points were positioned in the supply chain of this customer:
  - **Raw material:** This decoupling point was composed of two references. In the analyzed period Ref1 had a significant increase of the ADU because the

references began being used in new projects. The on-hand inventory level of Ref1 also increased significantly but on average less than the ADU, therefore the stock coverage decreased. Thus, the company was able to serve the orders of Ref1 with less inventory level. Ref2 had a decrease of the ADU while the on-hand inventory increased dramatically, therefore increasing the stock coverage. The performance of this reference was discussed with CS3 who stated that before DDMRP they were having many production downtimes caused by a stockout of this reference. It can therefore be said that this reference was skewed to the left of the bimodal. With the introduction of DDMRP the buffer size was adjusted according to the real needs resulting in an important increase in the on-hand inventory level.

  - **End product:** The total ADU increased by 51.51% and the on-hand increased by 43.75% resulting in a stock coverage that remained stable. As for the individual analysis, the ADU of all of them increased as did the on-hand inventory. However, the stock coverage did not follow the same pattern, as Ref1 and Ref3 showed a decrease in the stock coverage, which means that these references were able to serve higher demand with less inventory. The on-hand inventory level of Ref2 however increased dramatically, resulting in an increase of the stock coverage by 77.94%. This is another example of a reference skewed to the left of the bimodal distribution which after DDMRP shifted to the normal distribution.

- **C4:** Two decoupling points were positioned in the supply chain of this customer:
  - **Raw material:** The total ADU of this decoupling point increased by 44.48% while the on-hand inventory level reduced by 40.08%, producing a significant reduction of 60.32% in the stock coverage. As for the individual analysis of the most consumed three references, Ref2 had the same pattern. However, the on-hand inventory level of Ref1 and Ref3 increased in a greater amount than the ADU resulting in an increase of the stock coverage. These results indicate that these references were vulnerable and the use of DDMRP increased the on-hand inventory level, protecting them against any unexpected circumstances.
  - **End product:** The total ADU increased by 35.6% while total on-hand inventory decreased by 30.71%, with a consequent reduction of the stock coverage by 50.26%. The individual analysis of the most consumed three references showed a significant decrease of the stock coverage whilst the ADU of all of them

increased. That means that before DDMRP these references were skewed to the right of the bimodal distribution.

This case study clearly shows that DDMRP efficiently managed both material and production requirements and allowed the company to carry out the execution of open orders, quickly identifying when deadlines were not met. In addition, we can see that there is a clear relationship between uncertainty and the on-hand inventory level. The reduction of uncertainty through the supply chain increased visibility of material/production status and information between links, enabling the company to take decisions based on real requirements instead of groping in the dark. The dramatic reduction of the stock coverage of the references of customers C1 and C4 are clear evidence of that. It is worth recalling that forecast provided by C1 and C4 had very low reliability and varied on a daily basis, causing uncertainty in the supply chain. This lack of visibility challenged material and production requirements planning with the result that the company was forced to keep an overstock so as to maintain customer service level.

The forecast that C2 and C3 provided had higher reliability, with the result that the company understocked certain references. When the forecast and real demand did not match, the company was then forced to manage the mismatch using rush orders. These rush orders had a negative impact on the production capacity as they required unplanned setup changes. Therefore, an increase of the stock coverage after implementation is considered positive as DDMRP provided better protection for these references against any unexpected circumstances.

Chapter 10

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10. Cross-case study

In this section a cross-case analysis is carried out in order to identify the most relevant outcomes and verify whether the same events occurred across each of the case studies. We then, compare the results with the propositions of this thesis to determine if they are supported.

10.1. Analysis of the context before DDMRP

Table 10-1: Context summary of the case studies before DDMRP

BEFORE DDMRP			
	CS1	CS2	CS3
MPC system	MRP	MRP	MRP
Material planning frequency	Monthly	Automatically launch purchase orders daily	Weekly
Service level	Nearly 100%	Nearly 100%	Nearly 100%
Uncertainty due to demand and supply variability	Yes	Yes	Yes
Strategy to manage uncertainty in the supply chain	SS	SS and rush orders	SS and rush orders
Bimodal distribution in the inventory	Yes	Yes	Yes

Before implementing DDMRP, the three case studies used MRP to plan material requirements, with forecast as the input data. In each of these companies, forecast and real demand never matched, causing uncertainty, and consequently a lack of visibility, throughout the supply chain. In spite of this challenge, all of them were able to serve practically all customer orders on time with nearly 100% of service level. To be able to do this, the companies followed the same strategy: to have a large amount of SS inventory which skewed the bimodal distribution of the inventory to the right. When stockouts occurred, CS2 and CS3 managed them by launching rush orders. CS1 was unable to use rush orders however, as their references were shipped by boat with long lead times. It is important to note that in all case studies the companies believed that the only way to maintain their service level was by having high inventory levels that implied significant costs.

All three companies suffered from a lack of updated information on material status. For instance in CS1 gathering this information consumed considerable time and effort making it unfeasible to plan material requirements more frequently than once per month. CS2 had automated the launch of purchase orders, since they considered that reviewing these orders was time consuming and did not add value. As the planning tool of CS3 required more than 8 hours to gather all the information and propose a production plan, this task was carried out weekly and the results were frequently unsatisfactory.

In spite of this context, it is important to note that the companies analyzed in this thesis are well established global companies, who sell their products around the world. They are each considered to be leaders in their sector and with a strong client satisfaction level.

10.2. Analysis of the context during DDMRP implementation

Table 10-2: Context summary of the case studies during DDMRP implementation

DDMRP IMPLEMENTATION			
	CS1	CS2	CS3
Main goal with DDMRP	• To implement a robust methodology to manage material requirements. • Reduce on-hand inventory level.	• Increase visibility of material status to agile material management. • Reduce on-hand inventory and rush orders.	• To implement a robust methodology to manage material requirements.
Link of the supply chain where DDMRP was implemented	Goods	Purchase area (only raw material)	Entire supply chain
Number of decoupling points in the supply chain	1	1	2-3 depending on the customer
Dynamic buffers approach	• Recalculated adjustments. • Planned adjustments: manage and synchronize with the working calendar of the suppliers.	• Recalculated adjustments. • Planned adjustments: manage and synchronize with the working calendar of the suppliers.	• Recalculated adjustments.
Demand driven planning	Management of planning alerts to plan material requirements based on real demand.	Management of planning alerts to plan material requirements based on real demand.	Management of planning alerts to plan material requirements based on real demand.
Highly visible and collaborative execution	Management of execution alerts to quickly identify references requiring attention.	Management of execution alerts to quickly identify references requiring attention.	Management of execution alerts to quickly identify references requiring attention.

When the analyzed companies decided to implement DDMRP, they were looking for a methodology that efficiently managed material requirements. In addition, CS1 had the aim of reducing the on-hand inventory level while CS2 also wanted to reduce the on-hand inventory and rush orders.

As for the implementation process, the three companies followed the five components of DDMRP. However, the implementation was customized based on the sector, business activity and individual company needs. To position the inventory strategically, each company identified the most appropriate links to allocate the decoupling points:

- CS1 distributed goods without modifying them; hence, the decoupling point was positioned in Goods.
- CS2 purchased raw material and transformed them into end products. However, the company decided to only implement DDMRP in the purchase area to manage raw material. Thus, the decoupling point was positioned in this area.
- CS3 purchased raw material and transformed them into end products and they decided to take the plunge and implement DDMRP to manage the entire supply chain. The position of the decoupling points was determined taking into account the supply chain of each customer. Mainly raw material and end products were chosen to locate the decoupling points. A decoupled point was also positioned in semi-finished products, between the forging and machining plants to synchronize these plants.

Regarding the dynamic buffer approach in all case studies, recalculated adjustments were scheduled. Therefore, buffers were sized according to real consumption. In CS1 and CS2, planned adjustments were also scheduled to synchronize with supplier downtime. Hence, before the suppliers interrupted the supply, these companies brought forward the required raw material purchase so as to keep serving customer orders during supplier downtime. To this end, the size of the buffers were rescheduled according to material consumption and downtime period. Once the suppliers resumed work and supplied material normally, these buffers were again resized in line with the regular characteristics. CS3 did not schedule planned adjustments. However, considering the feedback of CS1 and CS2 about this approach, it is the recommendation of the author that CS3 should reconsider implementing it, as it would allow the company to adjust the inventory and avoid any shortage resulting from a lack of synchronization with supplier calendars.

The material planning and execution process was carried out as established by the methodology in all three cases. The planning alerts enabled the companies to identify when a reference was positioned in the replenished zone, and therefore required a purchase/production order to be launched. The execution of the open orders was carried out by execution alerts. These alerts facilitated making decisions to expedite the delivery of launched orders whose buffer status was critical, preventing an imminent stockout.

10.3. Analysis of the results achieved

Table 10-3: Summary of the results achieved in the case studies after DDMRP implementation

AFTER DDMRP IMPLEMENTATION			
	CS1	CS2	CS3
Uncertainty caused by demand and supply variability	• Buffers protect against supply and demand variability. • Material requirements based on real demand.	• Buffers protect against supply and demand variability. • Material requirements based on real demand.	• Buffers protect against supply and demand variability. • Material requirements based on real demand.
Material planning frequency	Weekly	Daily	Daily
Monitoring the status of materials and open orders	Daily	Daily	Daily
Rush orders to manage unexpected demand	Hardly ever	Hardly ever	Hardly ever
Synchronization between links of the supply chain	Increased	Increased significantly (subcontractor)	Increased significantly (forging and machining plant)
Bimodal distribution in the inventory	No, Inventory adjusted to the real demand	No, Inventory adjusted to the real demand	No, Inventory adjusted to the real demand
Total ADU trend	8.70%	13.94%	35.19%
Total on-hand inventory trend	-52.53%	-24.34%	-1.84%
Total stock coverage trend	-56.71%	-33.47%	-33.62%
Service level with DDMRP	Nearly 100%	Nearly 100%	• Nearly 100%. • Delivery date reduction from 20 to 10 days in C1.

After DDMRP implementation, the three companies sized the buffers considering real demand, and material requirements were planned based on the NFP, thus eliminating the need for forecast to manage material requirements. Uncertainty caused by forecast volatility was dramatically reduced providing visibility about material status. In other words, the three companies have access to the updated material status on a daily basis (CS1 decided to plan on a weekly basis due to the long lead time of the references). This enables simple and agile planning of material requirements, and the ability to manage reference status, gaining flexibility and avoiding rush orders and shortages.

The implementation has brought about a fundamental change in the material planning process in each of the three companies. Previously it was considered unfeasible to plan on a daily basis, as the process of gathering information was time consuming and unwieldy. In contrast, using DDMRP the companies can determine material requirements more efficiently and with considerably less effort.

The buffers protect the supply chain from supply variability. The company is notified by execution alerts when a supply is delayed and the references reach the critical zone, which enables them to expedite the delivery of launched orders preventing imminent stockouts. The material status can be quickly reviewed on a daily basis, thus increasing reaction rate against upcoming shortages and dramatically reducing the rush orders.

The information flow throughout the supply chain has improved considerably in the three companies. This improvement is reflected in a different manner in each case, due to the particular characteristics of the environment in which each company operates:

- Before DDMRP CS1 did not have the capacity to visualize material status by families and therefore could not determine the optimal joint purchase order for the established common MOQ of a family. CS1 had no choice but to set this MOQ to each reference individually, thereby buying more units than required. The effect of this was to considerably increase the on-hand inventory and reduce the turnover performance. With DDMRP things changed. The visibility that this methodology provided enabled the company to make joint purchases of references belonging to the same family, optimizing the purchase batch of each reference and respecting the common MOQ established by the suppliers.
- To instruct the subcontractor on what was to be assembled, CS2 supplied customer forecast, and purchased and delivered the necessary raw material to the subcontractor warehouse. However, customer forecasts frequently changed. Thus, the references the subcontracted company assembled were frequently mismatched with the real necessities of CS2 resulting in (1) assembling references that were no longer required, and (2) not assembling required references. To deal with these shortages, the

subcontractor was on many occasions disassembling assembled components and assembling new ones reducing considerably its responsiveness. DDMRP however, enabled the subcontractor to plan assembly orders considering the real consumption of CS2 instead of the fictitious demand generated by customer forecast. This change resulted in an important increase in the assembly capacity of the subcontractor. Furthermore, the inventory level of the subcontractor company also decreased.

- The forging plant of CS3 planned production requirements based on customer forecast. This material was delivered to the machining plants to continue with the rest of the process. However, due to the volatility of the forecast, the pieces the machining plants were supposed to produce, frequently did not match the material sent by the forging plant. The machining plants had therefore, an amount of inventory that did not correspond to the forecast demand of the customer, and at the same time suffered from a lack of material that was needed for the new requirements. To deal with this situation, the machining plants sent rush orders to the forging plant. This interrupted the production plan of the forging plant, forcing the company to carry out unplanned setups and considerably increasing the downtimes. With DDMRP however, the strategic allocation and management of inventory between the forging and machining plants enabled synchronization, preventing nervousness transmission upstream. This change (1) improved the information flow between the forging and machining plants, resulting in a significant reduction of the rush orders that the forging plant had to manage before DDMRP implementation, (2) eliminated the unplanned production orders and setups that the forging plant carried out to serve the rush orders required by the machining plants (resulting in machine downtime of 12-15 hours per week), and (3) reduced the lead time to service the orders of C1 from 20 to 10 days.

The reduction of the uncertainty adjusted the on-hand inventory level to the real needs, converting a bimodal distribution into a NORMAL distribution. In each of the companies this adjustment involved an on-hand inventory reduction while the ADU increased resulting in a reduction in stock coverage. Using DDMRP the companies are able to meet higher demand with less inventory level. Importantly, this improvement was achieved without a reduction in the service level.

- CS1 increased the total ADU by 8.70% while the on-hand inventory was reduced by 52.53% resulting in a reduction of the stock coverage by 56.71%.

- CS2 increased the total ADU by 13.94% while the on-hand inventory was reduced by 24.34% resulting in a reduction of the stock coverage by 33.47%. Considering these results it is the recommendation of the author that CS2 extend the implementation of DDMRP to the whole supply chain.
- CS3 increased the total ADU by 35.19% while the on-hand inventory was reduced by 1.84% resulting in a reduction of the stock coverage by 33.62%. Considering these results it is the recommendation of the author that CS3 extend the implementation of DDMRP to tool and equipment management.

In CS2 and CS3, with the aim of doing a more in-depth study, references were clustered as long, medium or short lead time and the performance of each group was independently analyzed (in CS1 this analysis was not possible as all references had long lead times).

- In CS2 the evolution of the stock coverage of long lead time references was greater than medium and short lead time references. This indicates that before DDMRP CS2 was overbuying these references to prevent shortages caused by forecast errors, long delivery times and shipment cost. However, the use of DDMRP aligned the raw material inventory level to real consumption, reducing the on-hand inventory and increasing the inventory turnover. CS2 decided to exclude from DDMRP long lead time references supplied from outside the European Union. Considering the performance of long lead time references, it is the recommendation of the author that CS2 reconsider this decision, as these references would also experience similar results to those analyzed in this case study.
- In CS3 long, medium and short clusters showed a similar pattern, the ADU of the three clusters increased while the on-hand inventory decreased, resulting in a decrease of the stock coverage. An interesting avenue for future research could be to analyze the factors that cause such a marked difference between cases.

10.4. Comparison between results and propositions

In this section the results of the three case studies are compared to the propositions defined in this thesis, which are as follows:

- **Proposition 1:** A company that manages its materials with DDMRP increases the visibility of the flow of materials in the supply chain, reducing the number of unplanned rush orders.
- **Proposition 2:** A company that manages its materials with DDMRP is able to offer the same or even higher service level with less inventory level.

As the outcomes of each case showed, after DDMRP implementation, the three companies considerably reduced their stock coverage. Namely, they were able to service the same demand with less inventory level. **These results support proposition 2.**

The reason why the companies achieved these results is directly related to the elimination of the uncertainty generated by the variability in demand and supply. This uncertainty acted as a blindfold, making it challenging for the companies to adjust the inventory level to real needs.

However, the decoupling points of DDMRP serve as a breakwall, disrupting the variability wave through the supply chain. As a consequence, all three cases showed an increase in visibility when managing the flow of materials and information throughout the supply chain. The companies reported that after implementation they were able to visualize the updated status of the material and open orders. In addition, using the color-coded alerts, they were able to efficiently plan material requirements and identify the references that were in a critical situation and required attention.

The visibility that this methodology provided allowed CS1 to make optimal joint purchases while complying with the common MOQ imposed by suppliers. The rush orders that CS2 was forced to manage on a daily basis were eliminated. Moreover, the subcontracted company gained responsiveness capacity due to the elimination of the fictitious demand that was saturating the assembly line with unnecessary assemblies. A similar result was achieved by CS3, as the strategic allocation and management of inventory between the forging and machining plants enabled synchronization, preventing unplanned production orders and setups and their resultant machine downtimes. **These results therefore support proposition 1.**

Chapter 11

11. Conclusions and future lines

11.1. Conclusions

Efficient supply chain management is key to achieving a sustainable competitive edge, and over the years many MPC systems have been developed to manage this process. However, such systems have been found to be lacking in a dynamic production environment as (1) MRP was constructed under a "push and promote" mentality where the market was more tolerant of longer LT and shortages, (2) JIT defined inventory as waste, thus companies using this approach reduced inventory level considerably making the supply chain too brittle when demand and supply are volatile, and (3) buffer management based on classic TOC tools was difficult and ineffective because the system does not accurately plan material requirements.

In 2011 DDMRP was published to help companies face the challenges posed by variability. This methodology adjusts the inventory level while maintaining, or even increasing, the service level to the customer. In addition, it simplifies the job of planning material requirements and improves information flow and visibility.

A number of studies were found in the literature, which indicated that DDMRP manages material efficiently. However Ihme (2015) and Shofa and Widyarto (2017) stated that few studies have scientifically proven the performance of DDMRP. Miclo et al. (2018) also pointed out the need for further research to study in detail the value of this approach for manufacturing organizations. In addition, Lee and Jang (2014) highlighted the lack of studies of a real implementation of DDMRP in a company, to demonstrate that it achieves the theoretical results.

In this thesis therefore, we have contributed to the gap in the literature by analyzing a real implementation of DDMRP in three manufacturing companies. We analyzed in detail the changes that these companies underwent in moving from an MRP environment to a DDMRP context. In the analysis, special emphasis was placed on visibility and inventory levels.

The results obtained in all three cases are in line with (1) the claims made by the authors of the methodology (Ptak and Smith, 2011, 2016), and (2) the findings obtained in different simulated environments and cited in the Critical study of the state of the art (Chapter 4).

The main findings of this research is that as a result of the implementation of DDMRP, CS1, CS2 and CS3 achieved a competitive advantage. Indeed, in all cases the companies were capable of handling greater demand with less inventory while maintaining their near 100% on-time delivery service level. In addition, the visibility of the material flow was also improved in all cases, and consequently rush orders were considerably reduced. These logistic factors are considered to be key to achieving both customer satisfaction and competitive advantage as explained in Chapter 1. The following aspects are highlighted as key to achieving these results:

- The implementation of DDMRP led to a considerable reduction of uncertainty in the system, as the insertion of buffers to manage inventory in the strategically positioned decoupling points softened system nervousness and the bullwhip effect. Furthermore, DDMRP was based on real demand instead of forecasts, preventing artificially created material needs. As a result, the methodology efficiently aligned the inventory level to real demand.
- DDMRP dynamically resized the buffers according to the real demand. In addition using planned adjustments the company was able to manage special situations such as the working calendar of suppliers.
- DDMRP improved the performance between the links of the supply chain. There was evidence that the flow of materials and information between CS2 and the subcontractor or between the forging plant and machining plants improved. This reduced the stress throughout the supply chain and increased the responsiveness of internal and external suppliers.

The results obtained in this analysis and the positive feedback received from each of the three companies leads us to conclude that DDMRP optimizes material management in the supply chain. Using this methodology companies are better able to adapt to market changes and respond efficiently to customer needs, thus increasing competitive advantage.

11.2. Future research

Based on a real-world experience, this research project went a step further in expanding the knowledge related to DDMRP. Future studies could usefully analyze different DDMRP implementations, as this would provide further evidence to verify to what extent DDMRP improves logistical factors of companies while providing a competitive advantage. The following topics of analysis would be fruitful areas for further work:

- Analyze the implementation of DDMRP in different sectors such as health, retail, and the food industry to determine whether this methodology can manage the particular characteristics of these sectors.
- Analyze complex supply chains composed of many wholesalers and retailers, where different links in the chain implement DDMRP.

- Study implementations in companies with different BOM structures to determine how the methodology performs in each case.
- Develop a DDMRP implementation methodology that defines the tasks to be undertaken at each stage of the process.
- Analyze the causal links between the variables involved in DDMRP.

Chapter 12

12. References

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Chapter 13

13. Academic results

Table 13-1: Academic results

YEAR	JOURNAL OR CONFERENCE	TITLE
2018	Article accepted for publication in Journal of Industrial Engineering and Management	Material Management without forecasting: From MRP to Demand Driven MRP
2018	12th International Conference on Industrial Engineering and Industrial Management (ICIEIM). XXII Congreso de Ingeniería de Organización (CIO). Girona	Demand Driven MRP - Nuevo método para la gestión de la Cadena de Suministro: un estudio de caso
2018	Article accepted for publication in Dirección y Organización	Demand Driven MRP - Nuevo método para la gestión de la Cadena de Suministro: un estudio de caso