MSc Multi-Machine Engineering

The role of data visibility in the control and automation of modern Supply Chains

A Model Predictive Control case study in Ferrari

Master Thesis

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The role of data visibility in the control and automation of modern Supply Chains

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by

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Master Thesis

in partial fulfilment of the requirements for the degree of

Master of Science
in Mechanical Engineering

at the Department Maritime and Transport Technology of Faculty Mechanical, Maritime and Materials Engineering of Delft University of Technology,
to be defended publicly on Thursday December 15th, 2022 at 10:45 AM.

Student number:	5389356	
MSc track:	Multi-Machine Engineering	
Report number:	2022.MME.8738	
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TU Delft

Abstract

Nowadays many companies still conceive their logistic operations as a simple material replenishment of the production plants and do not invest money and time in projects to structure their Supply Chain and bring more efficiency to the production process. In addition, the high complexity of the automotive industry and the emerging uncertainties that are characterizing a more globalized, dynamic and interconnected world give companies a huge incentive to research and innovate the management of their supplier network. Over the last years, businesses have experienced several issues along their logistic flows. Unexpected events such as the pandemic and the semiconductor crisis have put companies in research for solutions that look to improve and strengthen the partnership with their suppliers.

Digitization represents one of the most innovative and disruptive challenges in today's Supply Chains. Indeed, the increasing amount of data retrievable from logistic and production processes today is yet not exploited enough in comparison with its potential benefits. Companies still work by silos and prefer to hide their information rather than sharing them with their partners.

In this research paper, the role of data visibility is put under attention, in order to demonstrate its practical benefits in a complex automotive Supply Chain. By collaborating with Ferrari on a Supplier Relationship Management (SRM) project, this research presents the design of a Supply Chain control tower through Model Predictive Control. By simulating a MPC optimization model on a small part of Ferrari's supplier network, the coordination, efficiency and sustainability of the Supply Chain are assessed through a comparison with the current state and by evaluating the network's performances in different logistic scenarios. Although this solution is presented as a decision-support tool, it is thought as a key technology for the future development of autonomous Supply Chain operations.

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List of Abbreviations

AI	Artificial Intelligence
BOM	Bill Of Materials
CMPC	Centralized Model Predictive Control
DMPC	Decentralized Model Predictive Control
E2E	End-To-End
EDI	Electronic Data Interchange
ERP	Enterprise Resource Planning
ETA	Estimated Time Arrival
ICT	Iformation and Communication Technologies
IoT	Internet of Things
IT	Information Technologies
JIT	Just In Time
KPI	Key Performance Indicator
OEM	Original Equipment Manufacturer
MILP	Mixed-Integer Linear Programming
MIQP	Mixed-Integer-Quadratic Programming
MPC	Model Predicitive Control
MRP	Material Reuirements Planning
MVC	Minimum Variance Control
P2P	Procure-2-Pay
PI	Proportional Integral
PN	Part Number
PRP	Project Requirements Planning
RFID	Radio Frequncy IDentification
SC	Supply Chain
SCM	Supply Chain Management
SIC	Statistical Inventory Control
SRM	Supplier Relationship Management
TFT	Thin Film Transistor
WIP	Work-In-Progress

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1 Introduction

1.1 Background & Motivation

Supply Chains today represent one of the most complex, dynamic and unpredictable fields in the world of industry, as they are highly prone to uncertainty and affected by social, political and natural phenomena. Customers are nowadays more informed and demanding, requiring companies to constantly innovate in order to create and sustain the competitive advantage [41]. Over the recent years, in fact, many firms experienced an increasing demand for product differentiation, and adapted their business strategies in favor of a higher product customization. This change in perspective carried along new important requirements in the manufacturers' operations, such as a better use of information and a more structured organization of production activities. The push for innovation, as a consequence, has cascaded across all OEM's suppliers, which lead a crucial role in the final client's process.

This trend has also come with the rise of a new era in the transport network. Globalization and the rapid development of innovative and faster mobility solutions has expanded logistic flows' footprint on an international scale. On one hand, it has leveraged the opportunities for businesses to get access to resources and clients all over the world, but, on the other, it has augmented risks of stock out and block of the production lines, due to the high number of uncertainties affecting different nations and stakeholders. As a result, Supply Chains have become more complex and fragile. Indeed, many industry sectors over the past years have been impacted by several events causing high variability of demand and supply on their production. The Covid-19 pandemic deeply hit the manufacturing world, contributing to the rise of Supply Chain disruptions (Figure 1): in the automotive industry, the microchip shortages left many companies with uncovered supply, which caused an abnormal rise in demand and created a bullwhip effect on the entire chain. Furthermore, in 2021, the 20.000-container ship Ever Given wedge in the Suez canal caused the block of the maritime traffic over this strategic maritime passage (12% of global trade passes through it [48]), undermining ports congestion, container shortage, rise in transport costs and ultimately unexpected and exorbitant delays on the assembly lines.
The outburst of a new war in Europe in 2022 is showing how Supply Chains have also become crucial actors in the relationships between states. Globalization made countries highly dependent on one another in terms of trade and resources, as import and export nowadays have a high influence on a nation's economy and power.
Finally, the growth of e-commerce, which has been consolidated since the beginning of the pandemic, brought a drastic transformation of the world of logistics and transport, that today requires an ability to deal with highly dynamic markets and be flexible to the customers' needs.

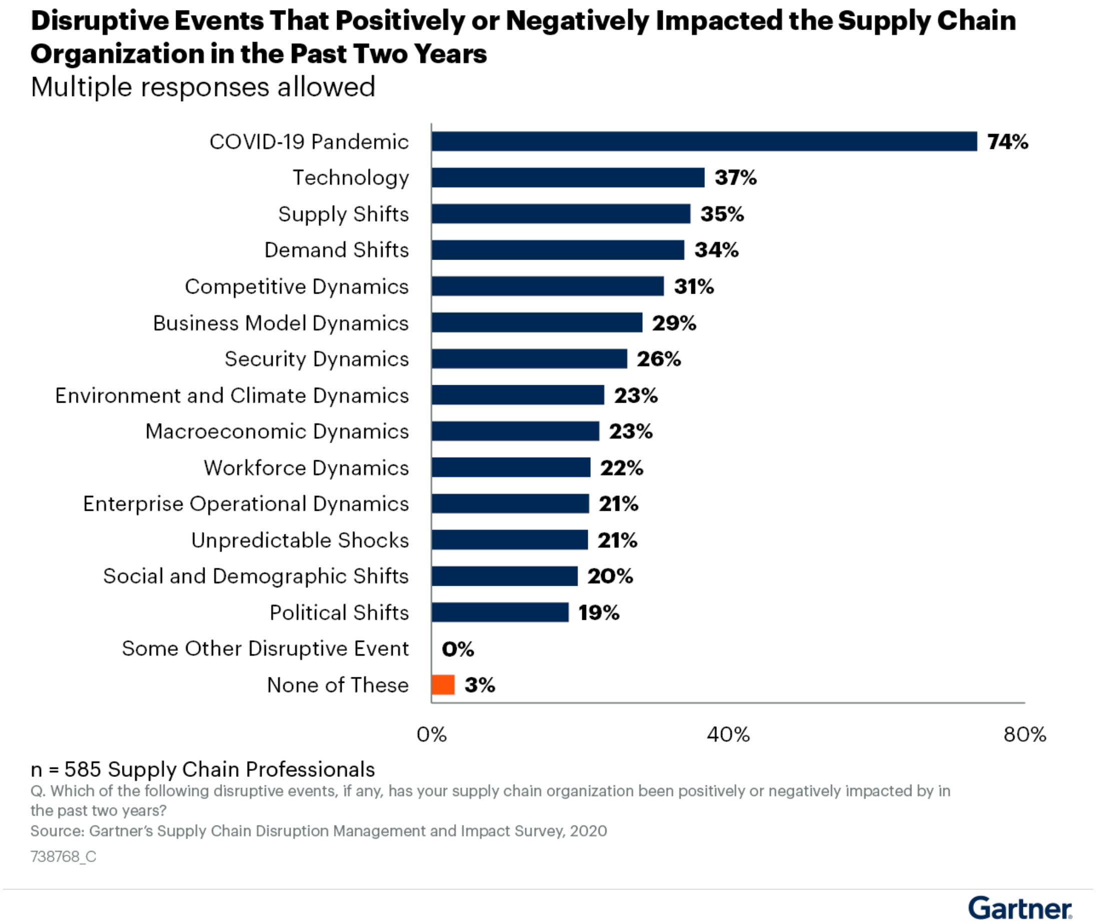

Figure 1: Common Supply Chain disruptions in the past two years [14]

In this frame, the relationship between OEMs and their suppliers is a key factor for an efficient and performing Supply Chain. In the last decades, many manufacturers (but also hospitals, restaurants and public services) have embraced the Lean philosophy, aiming to maximize the profit by organizing work efficiently, optimizing the process and reducing waste. In the automotive industry, firms have changed their logistic processes by following the "Toyota Way" [24], a material supply strategy started by the Japanese company in the 1960s and widely used in today's production systems. This ideology is built on the continuous improvement (KAIZEN) of three main pillars: the reduction of waste (Mura), overburden (Muri) and process unevenness (Mura). On a Supply Chain perspective, this led businesses to move from a Just-In-Case mindset, focused on gaining high production coverage and characterized by saturated warehouses, to a Just-In-Time (JIT) strategy, aiming to ideally receive supply materials only when they need to be used, hence optimizing the inventory costs by reducing waste and obsolescence.

Toyota became a model in the automotive industry also through the redesign of its Value Chain, which helped it become the world largest car manufacturer: instead of producing every component in-house, it was chosen to focus only on the assembly and development of the product, in order to reduce capital investments in inventory [4]. In this way, a company focuses more on its products and on its own know-how, leaving a substantial part of their Value Chain to their suppliers. In turn, this increases the importance and the responsibility of the suppliers in the company's success [41].
For a business, the choice between producing or outsourcing depends on several factors such as value, profit impact, costs and purchasing risk, which can be summarized in the Kraljic matrix in Figure 2.

Figure 2: Kraljic matrix [55]

Although outsourcing takes a lot of work off the manufacturer, it enhances process complexity, as a business has to rely on other companies' production processes in terms of efficiency, resource availability and labor organization among others. In fact, with the advent of JIT purchasing and other time-based management strategies, how quickly and how well suppliers respond to the time-sensitive requests of the focal company have become very important issues [8]. This refers not only to Tier-1, but also to Tier-2 suppliers and further. As an example, the semiconductor crisis created problems not only to microchip producers but also to the the OEMs (car, videogame, computer manufacturers, etc.), who have been seriously impacted by the shortages of electronic components, and ultimately to end-costumers. As a consequence today the delivery of brand-new cars could take months or even years.

For these reasons, there is a need for Supply Chains and logistic flows to be more reactive and predictive, in order to achieve robustness to uncertainties and diminish the risk of stock-out and production block. With the globalization and increasing competition, nowadays the future of Supply Chains is based on the establishment of partnerships, strategic alliances and cooperative relationships, built on trust and the share of information, risks and profit, with the purpose of attaining higher competitive advantage [21][41][50]. Indeed, a close relationship and open communication between the focal company and its suppliers is what really leads to Supply Chain integration and enhances supplier responsiveness, product quality and chain efficiency [23].

An important role in this transition can be played by digitization. In fact, since competitiveness grows parallel with technological innovations [21], a digital transformation of the Supply Chain processes can guarantee a higher acknowledgement and control of the logistic operations along tiers, which can enable the development of a structure that can react quickly to uncertainties and disruptions in the market. An important opportunity to achieve this is represented by data visibility. The exchange of data, in fact, allows multi-machine coordination, performance monitoring and enables a faster problem detection in the system, and consequently a quicker ability to solve it. The accessibility to information and the creation of a structured and secure data network can ultimately pave the way to a the automation of the decision-making processes through both logistics and production.
With the recent advancements in Supply Chain Management (SCM), firms have deeply revolutionized their business models and significantly innovated their Supply Chain practices. One of the most remarkable changes is the upgrading of the Supply Chain systems used by manufacturers to transact with trading partners. In the Industry 4.0 era, these systems have moved away from relying on Enterprise Resource Planning (ERP) and Electronic Data Interchange (EDI) toward the adoption of digital technologies and infrastructures, such as the Internet of things (IoT), big data analytics and ultimately blockchain [56].

In this perspective, the introduction of Supplier Relationship Management (SRM) techniques have brought major solutions in the process of innovation and improvement of information flows within deep and complex logistic chains. According to [16], SRM can be defined as a systematic approach for developing relationships with suppliers into strategic partnership. It is focused on joint growth and value creation with the current and potential suppliers based on trust, open communication, empathy and a win-win orientation, with the aim of improving the Supply Chain performance and reduce costs to achieve higher competitive advantage [35]. The advantages of an OEM using this system can be summarized in the following points [16]:

1. Become 'customer of choice': gain a preferential treatment of the supplier in terms of availability, costs, access to technology, innovation and risk reduction.

2. Focus on value: increased market competitiveness through consideration of all relevant elements that determine stakeholder value.

3. Leverage on supplier capabilities: acquire an advantageous position through early involvement in the innovation and product process development.

4. Share growth, profits, risks and investments: joint objectives, efforts and resource commitments resulting in a healthy culture for continuous growth.

Therefore, SRM plays an important role in enhancing cooperation (business relationship level), coordination (process level), and communication (information systems level) between the company and its suppliers, to continuously increase efficiency and efficacy of collaboration and concurrently increase quality, security, and innovation [32].

This TU Delft research paper is focused on illustrating an application of SRM in the digitization process of an automotive Supply Chain, by analyzing a case study at luxury car manufacturer Ferrari. The aim of this collaboration is to display the benefits of data visibility in the control of the logistic flows of a complex multi-machine system, such as Ferrari's Supply Chain, and show the future development of an autonomous control tower that can govern its logistic operations. The peculiar characteristic of this OEM is that, oppositely to most of the firms among the market, it works on very low volumes and crafts a highly customized and handmade product. This gives the opportunity to analyze the impact of SRM in a particular Supply Chain characterized by high supplier diversification, that are for the majority small and middle-size companies, with a strong and historical relationship with Ferrari and whose volumes are mostly sold to the Prancing Horse.
The following section introduces the company and describes in internal production and logistic processes.

1.2 Ferrari S.p.A.

1.2.1 The Company & The Brand

Wherever part in the world, everyone knows the name Ferrari. This Italian company, based in the little town of Maranello, near Modena, and founded in 1947 by visionary and car lover Enzo Ferrari, nowadays stands as the most popular car manufacturer in the world, representing excellence, art and tradition in car design, craftsmanship and racing.

Oppositely to other auto makers, since the company's birth 75 years ago, Ferrari's vision is to challenge against time, by building fast cars, that can win both on the road and on track. After winning its first race in its foundation year, the Prancing Horse cars entered glorious races, such as the Mille Miglia (8 wins), Targa Florio (7 wins) and the 24 Hours of Le Mans (9 wins), and participated to numerous car racing championships, such as the World Sportscar Championship (13 wins) and the most popular Formula 1 Championship, that, by winning 16 Constructor World Championships and 15 Drivers World Championships, contributed to elevate the status of this brand to icon of the automotive industry. Over the years, Ferrari's race cars were driven by legendary pilots, such as Tazio Nuvolari, Alberto Ascari, Clay Regazzoni, Niki Lauda, Jody Scheckter, Gilles Villeneuve, Michele Alboreto, Nigel Mansell, Alain Prost, Michael Schumacher, Kimi Räikkönen, Fernando Alonso, Sebastian Vettel and the current F1 drivers Charles Leclerc and Carlos Sainz Jr.

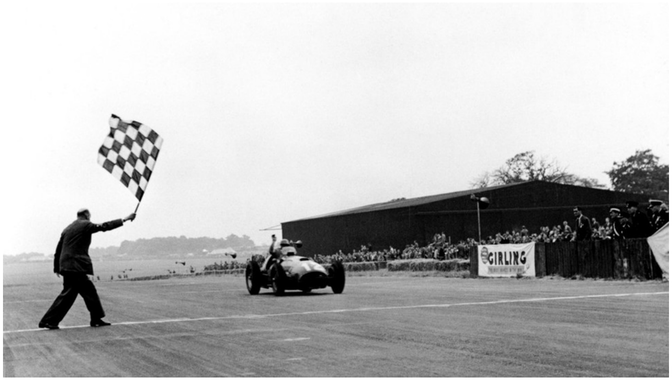

Figure 3: Ferrari's first win in F1 at Silverstone Grand Prix (1951) [11]

Over the years, Ferrari's name evolved to become a luxury sportscar manufacturer, and one of the world's strongest brands [12], now recognized as a symbol of excellence, passion and power, through its historical symbol: the Prancing Horse. Nowadays, Ferrari is exporting its luxury brand also in other sectors, first by signing partnership with firms such as Armani in 2019 [22] and Luxottica in 2017 [27], but most recently by even launching their own fashion line, with their first runaway show in Maranello's own Gran Turismo assembly line [43].

Figure 4: Ferrari's first fashion show at Maranello's GT assembly line [43]

Figure 5: The Prancing Horse, Ferrari's legendary logo

Today, the company can be considered as split in two different businesses: the Ferrari Gran Turismo, where the series luxury sportscars are produced and the Scuderia Ferrari, focused on the design and production of racing cars.
The core business of the Prancing Horse is not only the car itself, but most importantly the engine, the secret of Ferrari's high value and notoriety among the market. Every car's engine, in fact, whether it is a 6-, 8- or 12-cylinder, is manufactured internally by Ferrari, from the foundry, through the mechanical machining, and finally in the engine assembly line.

As a luxury car maker, compared to other bigger firms, Ferrari's volumes are much lower, as it focuses on a smaller and elite portion of the automotive market. In spite of this, the Italian supercar manufacturer is under a process of growth: in fact, in 2021 Ferrari has achieved a 22% increase in global sales, reaching a record of 11.155 cars sold.
While on one hand, the company is strictly attached to its roots, as the soul of this company consists of passion, tradition and craftsmanship, which implies a lower level of automation and a high amount of handmade operations, on the other Ferrari's mindset is forward-looking and increasingly focused on innovation. The vision stands in taking the best out of what has been done in the past and, by looking it with a critical perspective, bringing it into the future.
As a first step, Ferrari has been taking strategic decisions in the direction of sustainability and eco-friendliness, rather than keeping itself anchored to the roar of the old but successful technologies. After introducing its first hybrid car in 2019 (SF90 Stradale), followed by the 296 GTB in 2021, the Prancing Horse is undertaking a transition towards the production of electric powertrains, in order not to be left out-competed in the market without losing its attractiveness.
On another side, Ferrari is under a deep process of digitization, that will deeply affect multiple areas of the company, starting from new R&D solutions to the manufacturing area. A better use of data and AI technologies will be a crucial factor in the development of innovative solutions in the product and in the enhancement of the logistic and production processes' performance. This vision comes with the spirit of the new CEO, Benedetto Vigna, who has brought a consistent change to the top management and is aiming for "new competences and leanness, essential in taking advantage of the opportunities in front of us and in this scenario in rapid evolution" [38]. The charm of the traditions will not brake the Prancing Horse from thriving for change.

Figure 6: Ferrari's historical entrance

Figure 7: Scuderia Ferrari's headquarters in Maranello

1.2.2 The Product & The Process

Ferrari is well known for its prestigious and high-performance cars, developed with a 75 years know-how and a mindset always prone to improvement and innovation, that leads the company to be one of the leaders in the luxury automotive sector and a world famous brand. The core value of a Ferrari withstands mainly in two focal points: the customization and the process.

A client willing to buy a Ferrari sportscar has an exceptional freedom of choice to make it its own. Indeed, the company offers a wide selection of optionals, that creates a consistent number of combinations of configuration. These go from a simple selection of the body's color to the choice of the fabrics, leathers, woods and finishes of their cars. This makes every Ferrari coming out from Maranello's factory a genuine one-off representation of the costumer's own taste and preferences.
In addition, since 2011, the Italian company established its Tailor Made Program, which gives the customers an exclusive control of the creative process, offering a wide range of choices that enable every last

detail of their car to be tailored according to their personal desires. In this way, Ferrari is flourishing as a very unique brand among the market for its high focus on the customer and the quality of every single piece composing the car. This of course requires an accurate selection of suppliers that have to withstand the top quality standards requested by the end-costumers. For this reason, Ferrari collaborates not only with multinationals and notorious Tier-1 firms of the automotive market, but most of its supplier portfolio consists of small to medium local companies, operating on slower (often handmade) processes and contributing to preserve the Made in Italy essence of the Ferrari product.

The current models of engine mounted on a Ferrari are of 3 types: V6 (6-cylinders), V8 (8-cylinders) and V12 (12-cylinders). With the introduction of hybrid vehicles, these engines can now be seen coupled with electric motors. The car portfolio varies from year to year and is mainly divided in two parts: the series sportscars and the special series sportscars and consists of the following models:

- **812 GTS:** characterized by a V12 anterior engine, this model has a 0-100 km/h transit time of 3 seconds and delivers 800 hp, which makes it the most powerful series spider car on the market
- **296 GTB:** this model represents a revolution in Ferrari, as it presents a central-posterior V6 engine, coupled with an electric plug-in motor, which combined are capable of delivering 830 hp and reaching 200 km/h in just 7.3 seconds (107 metres)
- **296 GTS:** this spider model is the newest creation of the Prancing Horse and is powered by a V6 engine coupled with an electric plug-in motor, which delivers a maximum power of 830 hp.
- **SF90 Stradale:** Ferrari's first hybrid car is the expression of the most advanced technology ever developed in Maranello. With a maximum of 780 hp, this is the most powerful V8 supercar in Ferrari's history. The remaining 220 hp are delivered by the hybrid powertrain, for a peak of 1000 hp.
- **SF90 Spider:** the first hybrid spider in Ferrari's history is a driven by a combination of a V8 engine and a plug-in electric motor, for a total peak of 1000 hp and a 0-100 km/h transit time of 2.5 seconds
- **F8 Spider:** the spider version of the F8 model is capable of deliver 720 hp through its optimized V8 Turbo engine and reach a speed peak of 340 km/h
- **Ferrari Roma:** this car, inspired by Rome's 50s-60s "Dolce Vita" lifestyle, is an expression of elegance. Driven by a V8 Turbo engine, this car is able to deliver a maximum power of 620 hp.
- **Ferrari Portofino M:** the modified version of the Ferrari Portofino is a spider model, characterized by a V8 Turbo engine, and able to deliver a maximum power of 620 hp
- **812 Competizione:** this 12-cylinders sportscar belongs to the special series offered by the Maranello's company and presents a V12 able to reach a maximum power of 830 hp.
- **812 Competizione A:** the spider version of the 812 Competizione belongs to the special series of the Prancing Horse and is powered by a V12 that delivers a 830 hp of maximum power.
- **Purosangue:** the Ferrari Purosangue is the newest explosive model of the Prancing Horse. It represents a revolution for the Maranello's brand as it is the first four-door and four-seats model in Ferrari's history. It is powered by a V12 engine able to deliver a maximum power of 725 hp.
- **Ferrari Daytona SP3:** this car belongs to the icon series and highly limited edition offered by Ferrari to its premium clients. It is powered by a 12-cylinder engine able to deliver a maximum power of 840 hp. It has recently won the 2022 Red Dot design award.

An overview of the Ferrari models is given in Table 1.

Table 1: Ferrari's models (June 2022) [11]

Launch Year	V8	V12	Icon
2018	Portofino M 		
2019	SF90 Stradale  F8 Spider 	812 GTS 	
2020	Roma 		
2021	SF90 Spider 	812 Competizione  812 Competizione A 	
2022	296 GTB  296 GTS 	Purosangue 	Daytona SP3 

The other factor that makes a Ferrari a symbol of excellence stands in the production process itself. In fact, while most of the car manufacturers have developed semi- or fully-automated assembly lines by investing in smart technology and Industry 4.0 solutions, Ferrari kept innovating but maintaining its roots. Despite the company's ambition is also to increase its volumes in the next years, Ferrari's business strategy is built on the quality of its product, for which it is recognized worldwide. This is the result of a combination of cutting-edge technology and craftsmanship, and an obsession for the detail in every single production stage. Indeed, Ferrari's process is still highly composed by artisan works rather than faster and automated operations. A clear example is the tapestry, where seamstresses work with sewing machines on the creation of the car interiors.
Ferrari, following the strategy of several other automakers (Chapter 1), decided to focus on the assembly of the car and the production of the engine, that is fully operated internally, from foundry, through mechanical machining and to the final assembly. Most of the components is then left to the company's suppliers, who produce every part that need to be assembled into the final Ferrari engine or car. As a consequence, Ferrari's DNA, which is characterized by exceptional quality and handmade refinements, does not belong only to Ferrari's processes but also to its suppliers. This means that many of the businesses composing Ferrari's Supply Chain need to respect its quality standards. In fact, every material composing a Prancing Horse car needs to pass an initial quality check, which needs to be respected for the whole duration of the product supply contract.

Ferrari's production involves the whole vehicle assembly, from the chassis to the final product, but also the engine, which is the heart of its sportscars. The process flow that gives birth to a Ferrari in Maranello's factory is represented in Figure 8.

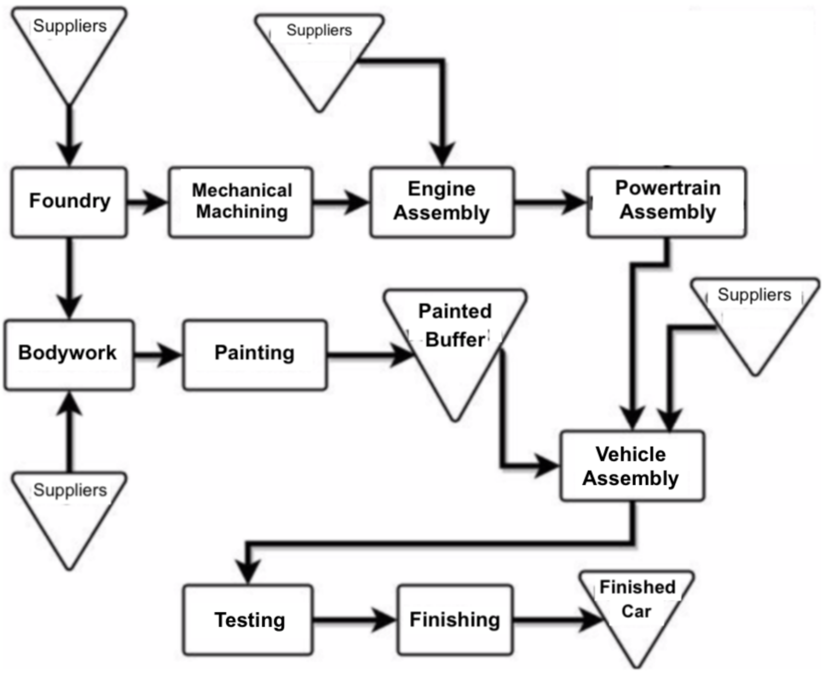

Figure 8: Ferrari's production process overview

The engine and vehicle assembly run on two parallel production lines.
A Ferrari's engine is created into the foundry, where the bodies are obtained by a fusion of special alloys, which are the secret of such a high-performance machine (Figure 9). The engine then goes trough the mechanical machining department, where high-tech automated machines work the engine's base and shafts to obtain the designed dimensions. Finally, in the assembly department, all the elements are gathered to create a complete Ferrari engine (Figure 10).

Figure 9: Ferrari's foundry in Maranello [11]

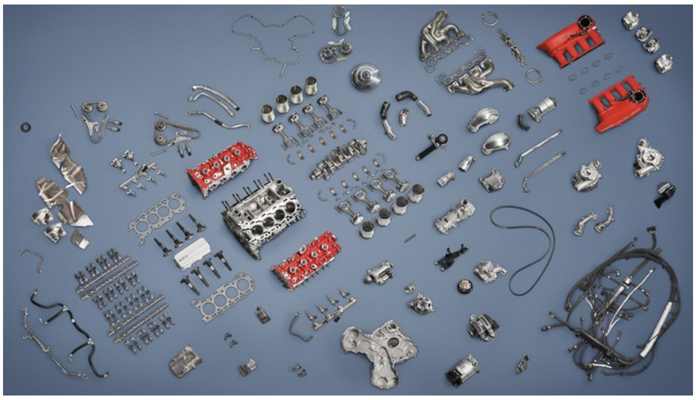

Figure 10: An exploded view of a Ferrari V8 engine [11]

The vehicle, instead, follows a different process, which starts in Modena, at the Scaglietti factory (the only production area outside of Maranello), where everyday 62 cars are shaped through 36 stations (Takt Time: 16 min). Here while the 8-cylinders vehicles follow partially automated process, the 12-cylinders are entirely build with manual operations, thanks to a meticulous work of aesthetics and precision, which aims to guarantee that every Ferrari looks like a single, unique piece (Figure 11)[11]. From Modena, the cars arrive in Maranello, and go through the painting process, composed by 21 steps (Figure 12). After a cataphoresis bath, which protects the vehicle against corrosion, the car is completely painted through a combination of automated operations done by robots and manual refinements, since the human eye can see details that a robot is not able to perceive [11].

Figure 11: Ferrari's Scaglietti factory in Modena [11]

Figure 12: Ferrari's painting process [11]

The final stage of the vehicle production is the assembly factory. Here, the painted car frames arrive and, with all the material delivered from the suppliers, they are finally assembled. Here there is also the "mariage" between the car frame and the engine, where they are united to finally give birth to a Ferrari (Figure 13).
The assembly building is divided over two floors. In the base floor, the V8 cylinders cars are produced (the so called 8-cylinders line), while at the first floor are built a combination of 8- and 12-cylinders vehicles (the so called 12-cylinders line) and there is the special series line, where the icon, highly limited models are produced.
Downstream to the assembly line, there are the testing line where the last components are mounted on the car and a few drive tests are undertaken, and the finishing line, where the last imperfections are solved and the car is prepared to be stocked in the finished product warehouse and finally delivered to the client.

Figure 13: Ferrari's assembly line [11]

1.2.3 Ferrari Supply Chain

Automotive Supply Chains can be certainly considered between the most complex logistic systems ever managed. Indeed, as a car presents thousands of components in its Bill of Materials (BOM) to be assembled together, it is pretty clear how an auto manufacturer needs a structured, well organized and robust logistic network that can allow an efficient material flow on both a local and global scale, a meticulous and solid warehouse management, and a strong infrastructure for the exchange of information such as demand and planning between the OEM and its suppliers, but also along the whole Supply Chain. With a market trend that goes towards product customization and the increasingly higher and variable mix of optionals that car brands offer to their customers, it is essential for an automotive OEM to develop a logistic network that can guarantee a flexibility on both the product and the process. Many of the innovations and philosophies that nowadays are being taken on by plant managers to improve the industrial efficiency were usually developed in the automotive industry, which shows the high rate of complexity that characterizes this type of Supply Chain.

In this frame, Ferrari's logistic chain can be described as a unique network, which, despite the global presence of only one plant (located in Maranello), can be considered of high complexity and intricacy, due to the exceptionally high customization offered to its clients.
As most of automotive Supply Chains, Ferrari has a hierarchical structure of its supplier network, which is divided in tiers, as displayed in Figure 14.

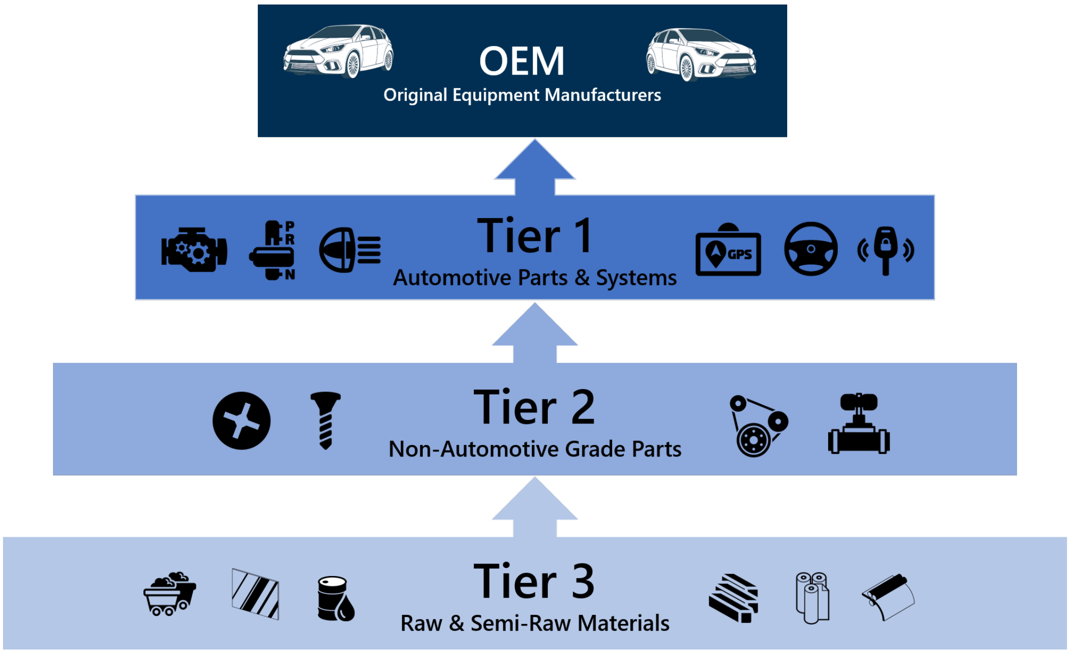

Figure 14: An automotive Supply Chain structure [20]

The peculiarity of Ferrari's Supply Chain is its high difference and variability within its suppliers, which differ in industrial operations, business strategies and work culture.
Indeed, while many Tier-1 and Tier-2 suppliers are multinationals, high-revenue businesses, with production plants and clients all over the world, many others are small realities of only hundreds (if not less) employees, which work on a local scale and produce much smaller volumes. If this might seem a disadvantage for a prime automotive brand like the Prancing Horse, it is instead a strategic choice. In fact, in order to achieve the exceptional high quality standards of its products, Ferrari decided to build solid partnerships with local manufacturers, which not only help to certify the Made in Italy and handcrafted fame to its cars, but are also highly attentive towards Ferrari's production, as it usually represents by far the major source of their yearly sales.

While the material flow from the suppliers all over the world to Maranello and the warehouse operations are managed by external service providers, the information flow between Ferrari and its partners is entirely under the control of Ferrari. The manufacturing plants work based a pull system, driven exclusively by the client request, which is translated into a production order, that includes all the features and optionals that the customer desires for its Ferrari. Based on every choice, the BOM is defined and,

depending on the production planning and scheduling, the supply orders are automatically sent on a weekly base to the suppliers all over the world.
Since every Ferrari is a unique piece, material planning is managed through three different strategies, depending on the type of component:

- **Material Requirements Planning (MRP)**: this strategy affects the standard components (with a medium-high value), which are ordered based on the warehouse and WIP stock, the BOM, the supply lead times and the supplier waste rates (e.g., batteries, antennas, wires, tubes, etc.).
- **Statistical Inventory Control (SIC)**: specific for low-value components (e.g, screws), this strategy orders batches based on warehouse stocks and minimum reorder thresholds.
- **Project Requirements Planning (PRP)**: the components following this supply strategy are personalized and therefore job-specific (e.g., bumpers, seats). They are oredered based on the daily production planning , and are received in a sequential order based on the line vehicle scheduling.
- **Third-party assemblies**: these suppliers (belonging to the Tier-1 class) deliver sub-assemblies to Ferrari's assembly line (e.g., brake-suspension system) under a Just-In-Time logic. They are supplied both by Tier-2 and other Tier-1 suppliers.

This mix of material planning strategies of course makes Ferrari's Supply Chain a complex system to manage, characterized by a combination of open and closed orders sent to the suppliers, depending on the type of component and the level of customization that the client can choose from.

While Ferrari's Supply Chain is built to guarantee a top quality standard, high supplier commitment and low logistic costs, the choice of local businesses usually does not match with a structured cooperation method within the material and information flows. In fact, to reach the excellent quality of their cars, Ferrari invests much on the product, but leaves much space of improvement in the process. These historical partnerships with suppliers usually lead to keep the current way of working rather than investing into the process, that remains in many cases highly flexible and very low structured. Indeed, many suppliers tend to guarantee the production continuity of Ferrari's assembly line, but focus on making their own interests, therefore hiding problems in their processes and limiting the communication and the visibility with their client. As a consequence they are not able to organize their production by following the client's orders and prefer to work day by day to produce and ship what Ferrari needs and asks for. If this method on one hand does not compromise the yearly volumes currently made by the Prancing Horse, it may become an issue if the company wants to grow and increase its production throughput. Moreover, these process inefficiencies lead to high waste and logistic extra costs and weigh on the company's yearly profit.

Over the last years, Ferrari started a path to improve its Supply Chain operations. Through the development of a SCM system, some Key Performance Indicators (KPIs) were introduced to monitor suppliers' service levels and the quality of the inbound logistics.
The goal of the project currently under study in Ferrari's manufacturing department is to introduce a SRM platform able to create a uniform communication channel for all buyer-supplier interactions, in which the client and the provider can exchange precious data and information. In this interface, the OEM can show its demand on a long-term horizon, and the suppliers can let their client know about any problem in the production plan that could create backlog or even material stock out. In this way, the client has the opportunity to predict any risk to its assembly processes and prevent in time any type of critical issue resulting from having missing parts in the production lines. In an industrial world where every agent tends to keep its own information without sharing it outside, SRM represents a step forward in transforming the relationships between businesses into solid partnerships, that by improving the process efficiency and the responsiveness of the entire chain, creates benefits also for the single stakeholders.

This research paper has the aim to investigate the potential of data visibility in automating the decision-making processes in Supply Chain operations. By working alongside Ferrari on the SRM project, the collaboration with TU Delft aims to go further in the innovation process and develop a solution that exploits data sharing between tiers, to create a Supply Chain control tower that, based on the production demand of an OEM, can compute the choices and strategies to manage the logistic operations over a desired time horizon, both for the material and information flow.
The definition of the study problem and the research questions answered in this paper are summarized in Section 1.3

1.3 Problem Definition

Thanks to globalization and a very demanding, highly customized market, Supply Chains are increasingly getting more complex and difficult to control. Despite the progress of transport technologies and IT are paving the way for a higher flexibility and responsiveness of the logistic flows in industrial networks, several businesses tend to make their own interests rather than enhancing collaboration with their partners. Main factors such as lack of information, mistrust and the companies' focus on cost and risk reduction cause high demand shocks in case of disruptions, creating bullwhip effects over the Supply Chain and increasing the instability of resource availability and material flow. For this reason, manufacturers and suppliers are usually split, self-focused elements rather than partners collaborating for their mutual benefit.
The advent of the data era, digital technologies and Industry 4.0 is a great opportunity for buyers and suppliers to strengthen their relationship. The exchange of information and the visibility of the production processes could help Supply Chains face the high uncertainty characterizing the market, react to market disruptions and ultimately reduce the risks of shortages and production blockages.

This research project aims to answer to the following main research question:

> "How can data visibility reduce the seamless split between manufacturers and suppliers and enhance the control and automation of Supply Chain processes?"

In order to address the research goal, the following subquestions will be answered:

1. What are the state-of-the-art technologies involved in improving the information flow and the visibility within the Supply Chain?
2. What is Supplier Relationship Management, how can it help to optimize the inbound material flow and guarantee the efficiency of an automotive Supply Chain?
3. What are the Model Predictive Control applications in Supply Chain operations?
4. What are the research gaps in Supply Chain digitization?
5. What is the current state of the system and where is the waste in the process?
6. How can a Supply Chain be modelled and controlled with MPC thanks to process visibility?
   (a) What are the variables and the control actions involved?
   (b) Which parameters does a Supply Chain control agent try to optimize?
   (c) Which control theories can better represent the current and future state of the system?
7. How can data visibility and Model Predictive Control make autonomous decisions for Supply Chain Operations?
8. What are the KPIs that can help monitor a supplier's logistic performance?
9. What are the simulation parameters chosen for a MPC Supply Chain application?
10. What scenarios can put at risk a Supply Chain and should be controlled by an autonomous control agent?
11. How do Centralized MPC and Decentralized MPC perform in a Supply Chain control tower?
    (a) How do CMPC and DMPC perform in a standard situation with zero backlog?
    (b) How do CMPC and DMPC manage to recover initial backlogs over the Supply Chain tiers?
    (c) How do CMPC and DMPC control the Supply Chain in case of disruption?
    (d) How much are CMPC and DMPC sensitive to a rapid variation of the OEM's demand?

The project undertaken by Ferrari's logistic department has the goal to develop a Supplier Relationship Management tool to increase data sharing with its suppliers and optimize the material flow to the assembly factory. This tool will be piloted by some structured suppliers, possibly already working with a SRM solution. The intent is to bring it to the whole Tier-1 level, by integrating both multinational companies and local businesses, with the ambition of eventually extending it to the whole Supply Chain.
This thesis aims to contribute to the project, by developing a digital solution that can use data visibility and multi-machine coordination research, through MPC control theory, to build an autonomous control agent that can govern the material and logistic flow in an optimal manner, in order to increase the efficiency of logistic processes, reduce waste along the process and bring value to businesses and Supply Chains.

1.4 Research Approach

This Master thesis is being written during the course of an internship in Ferrari's logistic department, where the student is working as a vehicle material planner. By managing 15 suppliers of Ferrari's assembly line, a practical understanding of the logistic flows within Ferrari's Supply Chain is achieved, which is a crucial aspect for the development of a system that aims to radically improve the efficiency and communication of the relationships between Ferrari and its suppliers.

Within this frame, two different approaches are being undertaken to investigate this research topic and will be merged and integrated to evaluate the practical benefits of this innovation related to Industry 4.0 and Supply Chain digitization (Figure 15):

- **Academic approach:** with the support of TU Delft know-how and "Multi-Machine Coordination for Logistics" research team, the goal of this work is to explore how a better data accessibility and visibility throughout the Supply Chain can be helpful for the control and coordination of the logistic flows, reduce risks of shortages and achieve the performance objectives set by the manufacturer. Model Predictive Control theory will be the key knowledge used to answer the research questions.

- **Business approach:** by participating in the SRM project management activities in Ferrari, the economical benefits of this innovation are being investigated, along with the benefits that SRM could bring in eliminating non value-adding activities, especially regarding time management and communication efficiency with the suppliers.

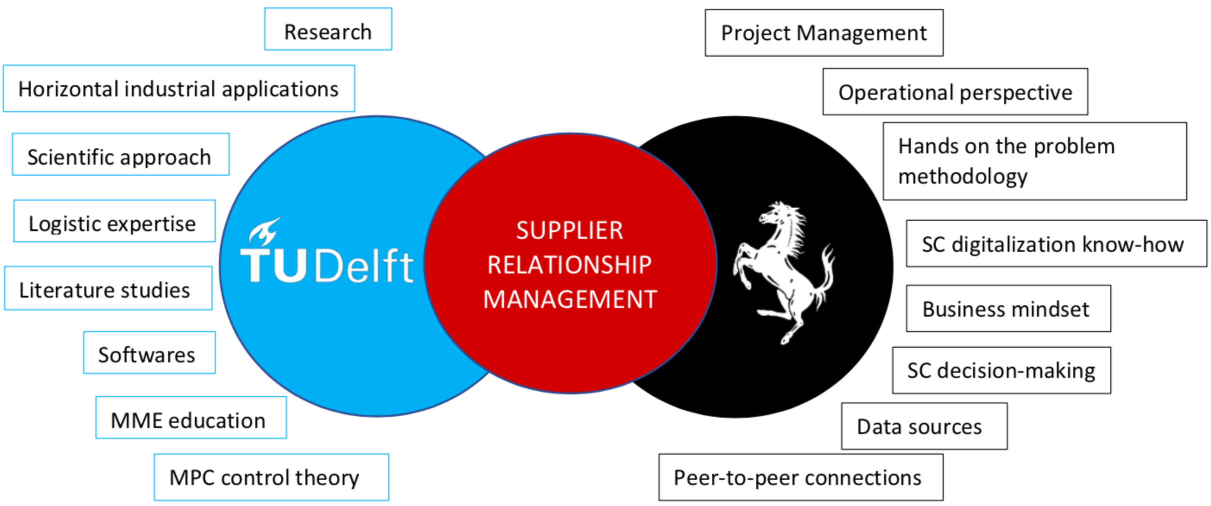

Figure 15: Academic and company approach integration scheme

1.4.1 Research Methodology & Organization

This research is structured based on the SIMILAR approach, introduced in 1998 as part of Systems Engineering (SE) [3]. This method is composed by seven phases, which are here listed:

- **S**tate the problem
- **I**nvestigate alternatives
- **M**odel the system
- **I**ntegrate
- **L**aunch the system
- **A**ssess Performance
- **R**e-evaluate

It is important to note that the SIMILAR Process is not sequential, but the functions are performed in a parallel and iterative manner. Indeed, it can be seen as an iterative process road map, that, in line with the SE perspective, indicates a way of thinking that not only notices an entire system, but includes how parts within such a system interrelate.
A representation of the SIMILAR approach can be observed in Figure 16:

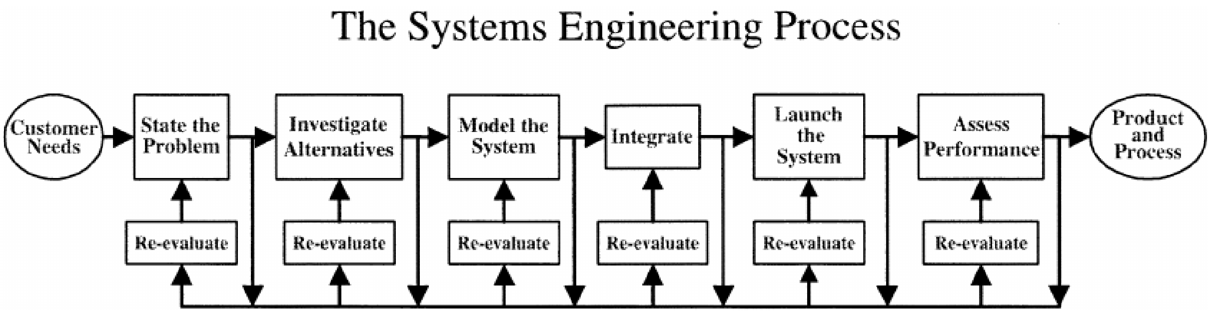

Figure 16: The SIMILAR approach [3]

In line with the SIMILAR approach, this paper is organized as following. This introductory chapter is focused on the definition of the research frame and of the process under study. In Chapter 2, the state-of-the-art solutions in the literature are displayed in a detailed review, in order to present the current digital technologies implemented in different industries aiming to reduce the relationship gap between clients and suppliers. In particular, Supply Chain control models are analyzed and classified according to their characteristics, objectives and functionalities. In Chapter 3, the current state of the process are analyzed, to understand the quantitative impact of the research problem on the Supply Chain operations. The modeling of the system is presented in Chapter 4, where, by taking inspiration from the literature, the design phase of the Supply Chain control model is explained, by describing in depth the development of a Model Predictive Control (MPC) scheme applied to Ferrari's Supply Chain and adapted to its peculiarities. Furthermore, the future state of the system are introduced, along with the KPIs of the MPC model, in order to assess the Supply Chain performance. Following, the integration of SRM is assessed by describing the model application on the current and the future state, where two different versions of the MPC model are compared, to demonstrate the benefits of a centralized solution over a decentralized strategy. A few scenarios are simulated within a restricted group of suppliers through Ferrari's database, in order to understand how SRM could enhance Supply Chain' performance. In Chapter 6, the control models are verified in order to guarantee their validity and the results are finally presented and explained. Finally, the research questions are finally answered in the conclusion. The organization of this paper and the correlation with the research questions is summarized in Table 2

Table 2: Chapter organization

Chapter	Content	Research questions	SIMILAR Approach
1. Introduction	Problem definition, research approach	-	**S**tate the problem
2. Literature Review	Supply Chain digitization, SRM, MPC applications	1,2,3,4	**I**nvestigate alternatives
3. Current State	Issues in Ferrari's SC, TIMWOODS, DMPC analogy	5	**M**odel the system, **I**ntegrate
4. MPC control model & Future State	MPC model definition, future state description, KPIs definition	6a,6b,6c,7,8	
5. MPC Simulation	Model objectives, introduction of the simulated scenarios	6c,7,9,10	**L**aunch the System, **A**ssess Performance
6. Results	Simulation outputs and discussion of the results verification, validation	11	
7. Conclusion	Answers to research questions, future research	-	-

2 Literature Review

In this chapter, a literature overview of the progress recently undertaken in the field of logistics will be displayed, in order to locate the research area of this academic paper and investigate the state-of-the-art technologies involving Supply Chain digitization. In particular, the following research sub-questions will be answered:

- What are the state-of-the-art technologies involved in improving the information flow and the visibility within the Supply Chain?
- What is Supplier Relationship Management, how can it help to optimize the inbound material flow and guarantee the efficiency of an automotive Supply Chain?
- What are the Model Predictive Control applications in Supply Chain operations?
- What are the research gaps in Supply Chain digitization?

2.1 Supply Chain Digitization

Over the last thirty years, logistics has undergone a tremendous change: from a purely operational function that reported to sales or manufacturing and focused on ensuring the supply of production lines and the delivery to customers, to an independent Supply Chain Management function that in some companies is already being led by a CSO, the Chief Supply Chain Officer [2]. The focus of the SCM function has been shifted thanks to several innovative solutions that are changing the operations between suppliers and clients. The introduction of emerging digital technologies, such as Internet of Things, advanced robotics, and data analytics, are altering traditional ways of working and are requiring companies to rethink the design of their Supply Chain. Besides the need to adapt, businesses have the opportunity to reach the next level of operational effectiveness, leverage innovative logistic business models, and initiate a transition to a digital Supply Chain [2].
This digitization process is necessary in order to adapt logistic flows to today's market, characterized by an unsteady and dynamic behaviour, which requires Supply Chains to be:

- **Faster**, through new approaches of product distribution that reduce the delivery time (e.g. demand forecasting, predictive shipping) [2].
- **More flexible**, by adopting ad hoc and real-time planning strategies that are able to react to variable demand or supply situations. Frozen periods should be minimized, while transforming planning into a continuous process, able to follow any changing requirement or constraint [2].
- **More granular**: as the demand of customers for more and more individualized products is continuously increasing, many firms are adapting to microsegmentation and mass customization, by offering a broader spectrum of suited products [2].
- **More accurate**, in terms of real-time, end-to-end visibility and transparency throughout the Supply Chain, which ensures that all stakeholders steer and decide based on the same facts. The span of information reaches from supplier KPIs, such as overall service level, to very deep process data, such as the exact position of trucks in the network [2].
- **More efficient**, through the development of smart, automated technologies on an operational side, and enhanced communication and trustworthiness between different Supply Chain stakeholders

Undertaking a digital transformation of a Supply Chain is not a fast and linear process, but indeed it may take several years to be completed. In order to fulfill the objectives described above and optimize the process, the sources of waste need to be identified and eliminated. These include cutting all non-value adding activities, distributing resources and workforce optimally and reducing bureaucracy and operations that slow down the entire logistic flow.
The use of data is certainly an important weapon to reach a substantial improvement in operational efficiency. Machine automation and intelligent management systems are main pillars over which Industry 4.0 will develop the future production systems and Supply Chains. Warehouses will look nothing like the current labor-intensive buildings: early communication with trucks on their location and Estimated Time Arrival (ETA) will optimize Just-In-Time delivery. RFID sensors will reveal what's been delivered, and

send the track-and-trace data horizontally across the entire Supply Chain, bypassing reception procedures that consume plenty of time, slowing down the inbound logistics process. The management system will automatically allot storage space for the delivery, assign the appropriate autonomous equipment to move the goods to the right locations and constantly update inventory in real time, through the use of sensors embedded in the goods and the warehouse itself. Innovative transport solutions will consist of self-driving vehicles and other robotic innovations that will play an increasing role in moving goods around the world, while wireless connections between vehicles and the road itself will provide additional information that will speed up traffic flow and reduce roadway congestion and accidents [44]. As a further step, data could be exploited not only to have visibility and knowledge on the current state of the chain, but also to predict what the future state could be. Big Data Analytics, in this regard, work as a decision support tool for managers, by analyzing signals coming from the market and translating them into demand for production capacity, storage and logistics needs, and changes in raw materials requirements. Tools such as prescriptive analytics systems enhance the ability to "prescribe" how the Supply Chain should operate, depending on different factors and circumstances, in order to reach a specific goal (e.g minimizing costs, maximizing revenue, speed up delivery time). Ultimately, prescriptive analytics will be able to offer scenarios at a very fine level of detail, describing how shifting to a new supplier might affect product quality, or how the risk of a natural disaster or a global pandemic could impact the entire Supply Chain.

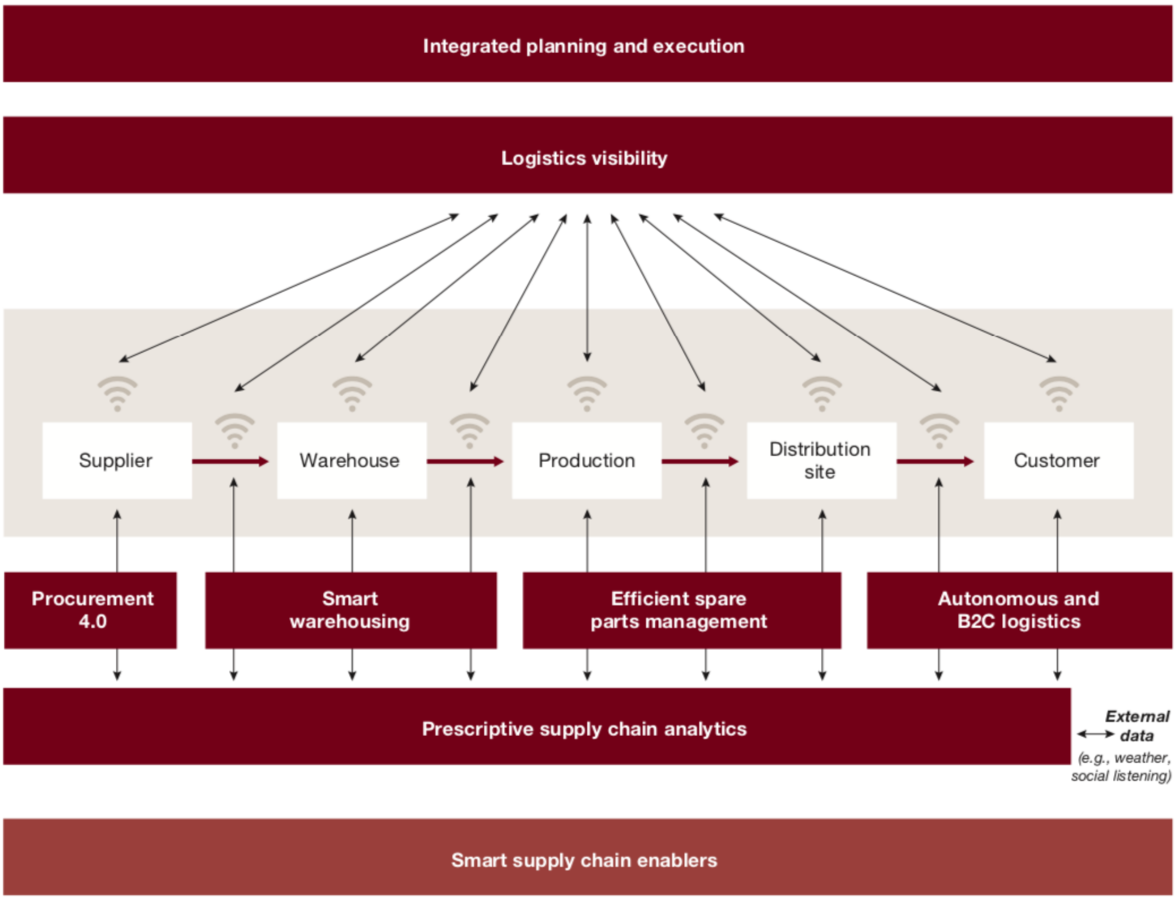

Figure 17: A digital Supply Chain [44]

Risks of Supply Chain digitization

Despite their high utility, digital technologies cannot show their whole potential if not managed in an efficient manner. In fact, many companies undertaking a digital transformation today are still working with a sub-optimal strategy and present many sources of digital waste.

First, much of the data capturing is handled manually and not updated regularly. For example, if the lead time of a supplier is continuously increasing, a warning should be sent out to make planners aware of the situation and enable them to mitigate supply disruptions at an early stage. In current systems, this signal will not be recognized and will lead to a lower supplier service level reported at the end of the month. This issue will eventually cause trouble in the assembly line replenishment and operational

problems [2].
Another important point is integration. Data has the power to measure, analyze and eventually control a complex system, but, in a Supply Chain composed by several stakeholders, communication and transparency become crucial factors. Many companies have started to implement integrated processes, but very often this is still done in silos (both horizontally and vertically), and not all information is leveraged to achieve the best result possible [2]. Although businesses are concerned about data leakage and therefore tend to augment privacy and protection, the key to success for any Supply Chain is an efficient exchange of information, which boosts the agility of the entire process [44] and helps develop solid relationships between partners, reducing the seamless split between the client and its suppliers.

According to McKinsey [2], this bond can be improved by improving four main areas of interface:

Planning
Production planning is a core activity inside modern Supply Chains, as it generates a supply demand and, as a consequence, has a direct effect on the supplier's own production organization.
In today's market, characterized by high uncertainty and dynamicity, it is very important for companies across all tiers to be flexible and responsive on both planning and execution level to demand changes. Furthermore, the globalization phenomenon caused a large variability of supplier's lead times, that now does not only depend on the production process itself, but it could be mostly influenced by transit times and transport operations. For this reason, it is essential to plan in advance by using data to elaborate forecasts of the demand that could be generated months forward. In this way, the Supply Chain will become more flexible in tackling any problem that could be presented anywhere in the flow and be able to prevent it rather than cure it.
Today, not all the information collected is used in the most optimal way, and is rarely shared between a manufacturer and its suppliers. In addition, it can frequently be observed that automatically determined planning or statistical forecast data is manually overwritten by planners. Especially for parts moving at medium or high speed, the manual overwrites are time-intensive and usually have a negative impact on the forecasting accuracy.
With advanced digital systems support, 80 to 90% of all planning tasks can be automated and ensure better quality results, by gaining benefit from big data and advanced analytics. In particular, two examples of modern planning strategies are [2]:

- *Predictive analytics in demand planning*: by analyzing thousand of demand influential variables with Bayesian networks and Machine Learning approaches, demand forecast accuracy will be improved (30-50% error reduction). Also, advanced algorithms will provide probability distributions of the expected demand volume rather than a single forecast number.
- *Closed-loop planning*: instead of using fixed safety stocks, each replenishment planning considers the expected demand probability distribution and replenishes to fulfill a certain service level. Furthermore, depending on the stock levels, expected demand, and capability to replenish, prices can be dynamically adapted to optimize the overall profit made and minimize inventories at the same time.

Order Management
Order management allows a business to coordinate the entire fulfillment process: from order collection, inventory and delivery visibility to service availability. It starts when a customer places an order and ends once they receive their package or service [17].
In order to achieve end-to-end (E2E) visibility between client and supplier, order management is a critical part in the logistic process. In fact, in many cases today, even if costumers send out long-term programs, with planned and forecast quantities, they don't always have the opportunity to receive back from the suppliers an information about their ability to fulfill the demand. This creates high uncontrollability of the material flows and inevitably develops a tendency for vendors to keep any production or supply problem hidden from the client, which often ends up to work on the daily urgency.
In a future state, characterized by supplier management systems involving portals where demand is shared and real-time updated, suppliers must give information about their capability of meeting - either fully or partially - or not the costumer's demand. This tool would be useful on both sides: the client would be able to gain visibility on the supplier's demand absorption and anticipate any supply problem that may happen in the near or long future, working on the exception rather than the urgency; on the other hand, the provider has the opportunity to monitor any difference in demand among different weeks and check

if the costumer is respecting the terms agreed by contract.
The ultimate objective is to have complete "no-touch" processes, where no manual intervention is required between order intake and order confirmation, and to use order date confirmations to enable real-time replanning through instantaneous, in-memory elaboration of the production schedule and replenishment in consideration of all production and supply constraints [2].

Performance Management
A supplier's performance management is the ability to visualize, track and report on Key Performance Indicators (such as service-level agreements, quality and delivery performance) and qualitative ratings (such as internal stakeholder feedback and innovation) by supplier and/or contract [14]. Companies are willing to monitor their suppliers and their performance, in order to anticipate problems, minimize the number of failures and improve their capacity.
This task over the recent years has been changing tremendously: while in the past KPIs were only available at aggregated levels, nowadays data is available in real time from internal and external sources. This moves the performance management process from a regular, often monthly process to an operational process aimed at exception handling and continuous improvement. Planners can be pointed to critical Supply Chain disruptions and further supported by an automatic handling of minor exceptions or potential solutions for the larger ones. For example, the automated root cause analysis approach, by conducting big data analyses and Machine Learning techniques, allows the performance management system to identify the origin of the exception and then automatically trigger countermeasures, such as activating a replenishment order or changing parameter settings in the planning systems (e.g safety stocks)[2].

Collaboration
According to [41], nowadays Supply Chains are connected to relational factors rather than transactional factors, and client-supplier relationships play a key role in Supply Chain management. In a global scenario characterized by high volatility, it is important for companies to build strong relationships based on flexibility and adaptability, in order to produce an effective response to the changes in supply and demand [46]. In a highly supportive, trustful and reciprocal atmosphere, manufacturers and suppliers feel less vulnerable to partner exploitation and are more likely to collaborate to achieve mutual objectives, rather than behave opportunistically [56]. For this reason, businesses started to focus on exchanging information with their suppliers, share risks and profit, and improve communication, in order to increase products quality and process efficiency [31].
In the Industry 4.0 era, firms in different industries have started adopting digital technologies and infrastructures in Supply Chain Management activities, such as Internet of things (IoT), big data analytics and blockchain, to pave the way for more interconnected digital assets and more transparent information flows between Supply Chain partners [56]. A major field within collaboration is the end-to-end/multi-tier connectivity, already implemented by some automotive companies, which leaves space for much lower inventories through an exchange of reliable planning data, lead time reduction through instantaneous information provision and an early-warning system that gives the entire chain the ability to react fast to disruptions anywhere [2]. Supply Chain cloud can be considered the next level of collaboration. They are joint platforms between customers, the company, and suppliers, providing either a shared logistics infrastructure or even common planning solutions. Especially in noncompetitive relationships, partners can decide to tackle Supply Chain tasks together to save admin costs, and also to leverage best practices and learn from each other [2].
Such IT integration requires greater digital asset investment from the manufacturer than from the supplier and is likely to create the lock-in situation in which the manufacturer cannot avoid opportunistic risks. On the other hand, supply visibility, which provides high-quality information about the major supplier's production and delivery processes, reduces uncertainty and facilitates monitoring in the transactional and logistic process to help mitigate supplier opportunism.
In this context, information exchange and improved communication can also be a base for supplier development strategies. In fact, considering the purchasing function as a significant source for competitive advantage, it is in the interest of the manufacturer to make investments in development of suppliers' capabilities, since enhancing their numbers creates a benefit for the manufacturer itself, as well as for the whole Supply Chain [45].

Beyond the improvement of the buyer-supplier relational ties, Supply Chain 4.0 will be driven by several changes in the material flow, which will take advantage of better connectivity, advanced analytics, additive manufacturing, and advanced automation systems, such as autonomous vehicles and robotic

arms, which will bring a revolution in the transport network and in warehouse flows. Furthermore, following the need for further individualization and customization, companies are changing their Supply Chain strategy, undertaking a process of segmentation of the logistic departments. In fact, tailored products provide optimal value for the customer and help minimize costs and inventory in the Supply Chain.
According to McKinsey, the adoption of these new technologies alongside the elimination of digital waste, could be a major lever to increase the operational effectiveness of logistic flows. In the next two to three years, Supply Chain 4.0 is estimated to cut up to 30% of operational costs and 75% of lost sales and inventory, while at the same time increasing processes' agility and robustness.

2.2 Supplier Relationship Management

Procurement logistics encapsulates the process chain extending from the purchasing of goods, through the shipment of the materials, to the receiving warehouse. This process is based on the exchange of contractual data and information relating to suppliers products, purchase prices, discounts, raw materials characteristics, delivery terms, and many other variables. Rapid advancements in digitization are reshaping global Supply Chains and transforming the current modus operandi within companies. One of the most remarkable changes is the upgrading of the Supply Chain systems used by manufacturers to communicate and transact with trading partners, aiming to improve operational efficiency and performance. As the needs of companies become more complex, many innovations are adopted to support and advance procurement logistics functions in terms of predictability, transactional automation and Supply Chain management. Digital upgrades such as Internet of Things (IoT) and 5G networks enhance real-time information sharing and visibility between Supply Chain partners, paving the way for more interconnected digital assets and more transparent information flows between Supply Chain partners [42][56].

Supplier Relationship Management (SRM) is the practice of planning, implementing, developing and monitoring company relationship with the current and potential suppliers [1]. SRM solutions provide the foundation upon which supplier management, supplier risk, supplier performance, and sourcing strategies are based, and help organizations monitor and better plan for the major supply shifts experienced in supplier health, material availability and price volatility. Despite supplier management is focused primarily on activities after contract signature related to procurement and logistic operations, it can also support strategic sourcing processes, by providing information about potential and existing suppliers for new opportunities. For this reason, its role in a buyer-supplier relationship can be represented by the following diagram [30]:

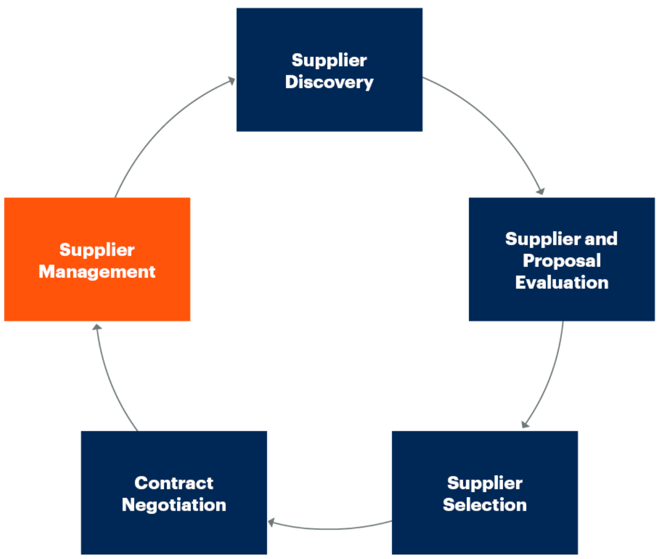

Figure 18: Supplier Management's role in a buyer-supplier relationship [30]

The main functions gained with the use of a SRM system are collecting and managing supplier information, keeping track of and managing supplier interactions (supplier governance), tracking and monitoring supplier performance, assessing, monitoring and preventing supplier risk, developing suppliers and managing supplier innovation, which benefit a manufacturer by building a better supplier base, coping with significant problems easily, acting better coordinated and more consistent, and enhancing value creation for customers [30][46].

The market of SRM solutions is very wide and fragmented. Vendors offer different types of solutions, depending on their interpretation and definition of supplier management. On the other hand, buying organizations may have their own vision and therefore, in order to select the best system, it is crucial to understand what is the problem to be solved. Obviously, most organizations want to work with all of the capabilities listed above, and there is often overlap among them.
On a general side, it is important to distinguish two main parts of the Value Chain where SRM can reduce the seamless split between a manufacturer and its suppliers: on one hand purchasing and procurement departments look for Procure-to-Pay (P2P) solutions that can be integrated with ERP systems and bring efficiency to the procurement and invoice payment process. On the other hand, SRM can also be applied to the material flow between buyers and suppliers, by enhancing end-to-end visibility in logistic operations and improving the information flow along the whole chain. The improvements brought by digitization in these two relational sides of a manufacturer with its suppliers will be presented in the next paragraphs.

2.2.1 Procurement 4.0

Digitization brought a major evolution of the procurement function during the last ten years. From a traditional process supported by systems that promoted "one-to-one" communication between buyer and supplier, nowadays electronic procurement (or e-procurement) has brought many possibilities for collecting information on a digital platform which can be accessed, shared and processed in a visible manner with all Supply Chain partners. This creates a new real-time operating model with "many-to-many" communications capabilities, which make it possible to rapidly create networks which incorporate the entire production processes and integrate ICT systems at different stages of the business planning [42]. Multiple digital tools and information technologies have already been introduced to support the process of purchasing and companies' overall procurement. Big Data involves a range of technologies that enable the management, structuring and usage of data in various ways including the processing of larger volumes of data in a shorter time period and with high precision [7]. While in many cases firms keep their information storage in silos by department or function, without extracting its whole potential value, big data along with analytics aims to improve companies' capability and speed in decision making, by turning unstructured historical data regarding purchasing transactions contracts, pricing information, and supplier performance attributes into an organized bank of insightful information. The many benefits include improved operational planning, enhanced forecasting capabilities, partner collaboration and reduced lead times.
Leading-edge technologies such as Artificial Intelligence (AI) and Machine Learning algorithms can bring significant contributions to the field of procurement in Supply Chain management, by automatizing transactional processes, increasing the accuracy, and therefore urging the procurement function managers to concentrate on related strategic problems. In fact, cognitive computing and AI will enable procurement managers to rapidly categorize unstructured spend, cost, contract, and supplier data, enhancing efficiency and cutting down non value-adding activities.
Internet of Things (IoT) brings further incremental change to business and consumers via connections among physical objects. This avant-garde technology comprises the use of sensors, actuators, and data communication technology built into physical objects (e.g., various types of RFID tags including environment sensing tags, wireless sensor networks, GPS, etc.) that assist in identifying physical objects, track and trace, coordinating or controlling their movement across the internet and generate data that will be gathered, routed through internet-based cloud storage and subsequently analyzed by the concerned information system. In doing so, the volume of available information necessary for decision-making process increases substantially.

2.2.2 Supply Chain Control Tower

Supply Chains are complex structures characterized by highly interconnected systems, whose behavior affects the performance of the entire system. Therefore, when making decisions for running efficient logistic flows, it is necessary to consider all the interactions and limitations among these elements, in order to deliver a maximised performance and high profitability. To achieve this goal, Supply Chain managers need to consider not only operating factors and constraints such as the processing times, production capacity, availability of raw materials, inventory levels, transportation times, but also the dynamics of the market, which brings high uncertainty in the whole system. Since the decision making process is not an easy task, decision support tools are helpful in this process [37]. In fact, companies that lack visibility across their Supply Chains often experience inefficiencies, disruptions and excessive costs for everyone in the value network. For this reason, organizations have been increasing demands for real-time visibility into their orders, shipments and inventory across the network of business partners [49].

In this frame, Supply Chain control towers represent an essential innovation towards logistic integration. These tools are defined as connected, personalized dashboard of data which enable organizations to fully understand, prioritize and resolve critical issues in real time [17]. Control towers facilitate a coordinated network to continuously manage complexity and execute at levels that cannot otherwise be managed easily by humans [26]. By creating a complete digitization of the flow between the manufacturer and its suppliers, enhancing communication and transparency ("one source of truth"), Supply Chain control towers offer key value-adding services that improve the material flow in the Supply Chain network and exploit the collection of data, by designing personalized dashboard focused on monitoring order status, stock and supplier performance. The end goal of this innovation refers to gaining control of the information flow around transportation, inventory and order activity, and managing those activities from a single location [21].

Important changes and innovations brought by a Supply Chain control tower are [17][52]:

- **Real-Time Order Planning:** to improve customer service levels, a control tower captures and leverages key data in real-time, such as the delivery time, inventory availability, and transportation costs. Doing so allows to always select the best and most cost-effective order flow.

- **Exceptions Management:** establishing end-to-end visibility across the Supply Chain and correlating data across siloed systems with external event information helps to better predict disruptions. Smart alerts provides insights into the upstream and downstream impact of events in the Supply Chain and induce a company to work more on the exception.

- **Granular Visibility & Collaborative information sharing:** in addition to track and trace, a control tower would ideally provide granular visibility into the details of each order to effectively fulfill on every required element. Furthermore, a better collaboration through data exchange, exceptions management and AI-powered resolution rooms help the Supply Chain to increase its responsiveness to unplanned events and global disruptions, driving its overall efficiency and performance.

- **Optimization of the logistic effort:** improving the data visibility along the Supply Chain enhances a better management of the logistic processes and helps to prioritize a business' effort and resources. For this reason, SRM solutions reduce the workload of the material planners, who would get access to a higher amount of information, without requesting it personally to the suppliers. Also, this induces an optimization of the transport operations and production activities, by reducing urgent deliveries and production delay recoveries.

To summarize the main benefits of a Supply Chain control tower, Figure 19 depicts a clear representation of how the information flow could differ from a traditional Supply Chain model.

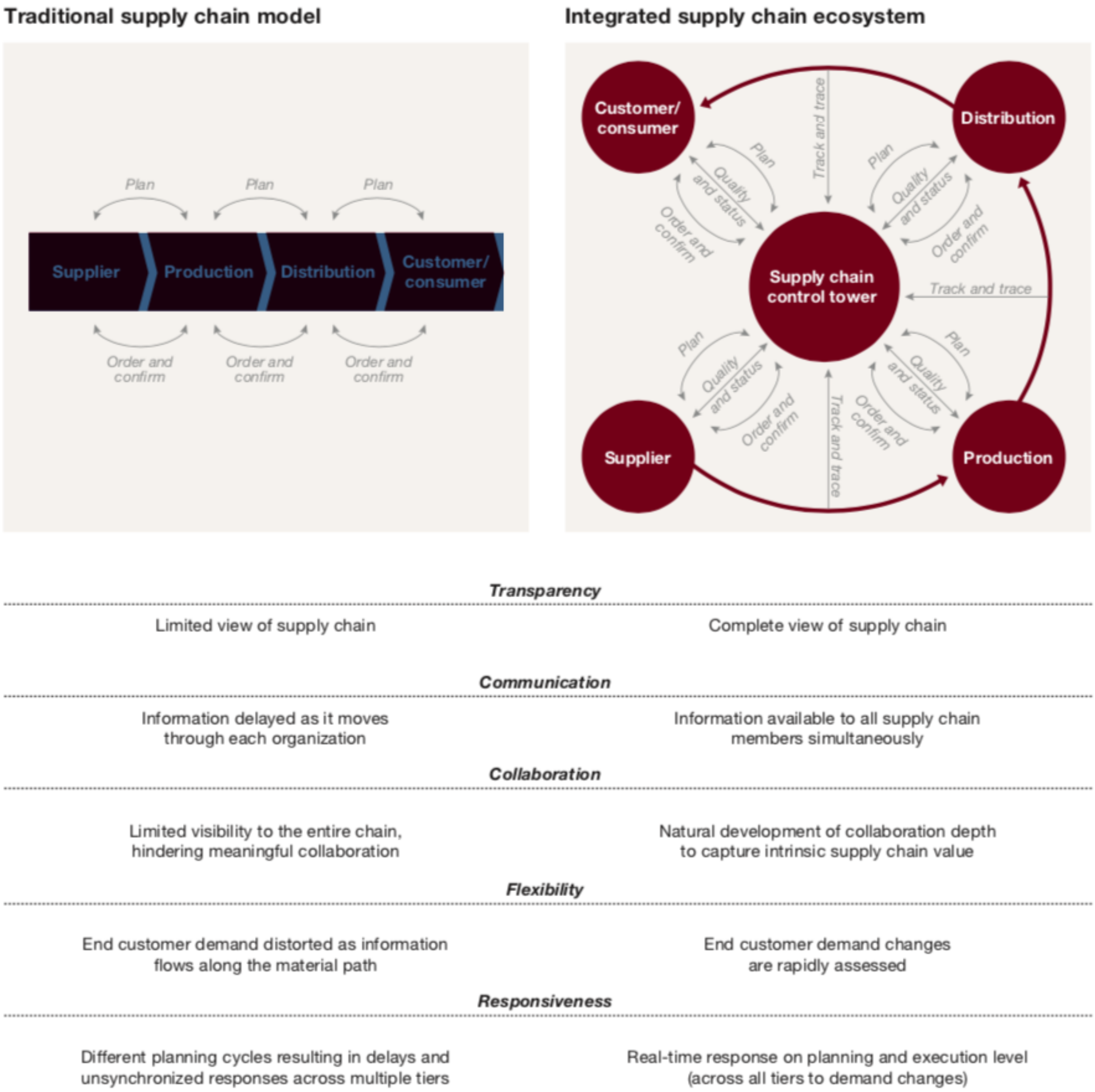

Figure 19: The digitally enabled supply ecosystem vs. traditional linear Supply Chain [44]

Supply Chain digitization is not a rapid process, as it usually requires a high resettlement of the IT infrastructures, a certain level of coordination between the stakeholders for the on-boarding, and it needs to be coupled with the education of the end-users, from the single employees to the suppliers themselves. According to [19], control towers can be deployed in four stages for high returns at low risk and with minimal disruption (Figure 20):

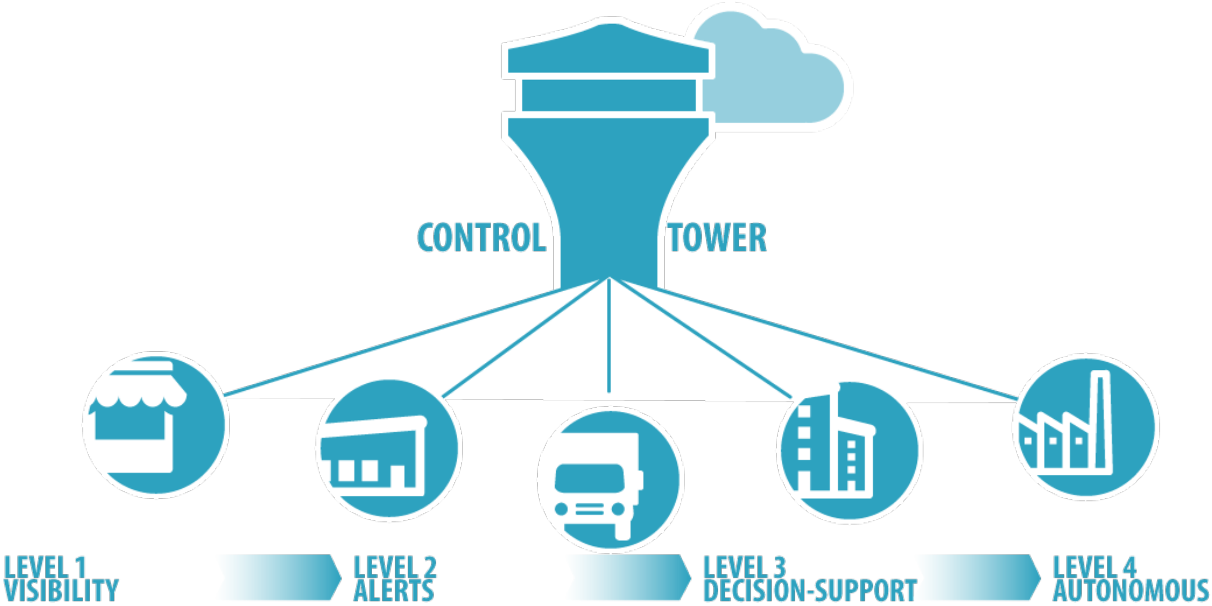

Figure 20: The 4 Stages of Control Tower Deployment [19]

- **Level 1 - Visibility:** the exchange of data between manufacturers and suppliers allows the gain of process visibility along the Supply Chain. Monitoring the stock of finished and semi-finished products, tracking the transports and foreseeing the future supply helps the whole Supply Chain to increase robustness and responsiveness.
- **Level 2 - Alerts:** the Supply Chain control tower sends out alerts regarding bottlenecks or out-of-stock to the logistic stakeholders, who will be able to prioritize their efforts towards the components that bring a high risk to production continuity and collaborate to resolve them in real time. In this way, resource waste is reduced and the Supply Chain becomes more lean.
- **Level 3 - Decision-support:** the Supply Chain has reached digital maturity, processes are fully mapped and all suppliers are integrated. Transactions are executed within the control tower and the users take decisions based on the recommendations of intelligent agents.
- **Level 4 - Autonomous:** the intelligent agents embedded in the execution layer run the supply network without human intervention through high-tech digital solutions such as Artificial Intelligence and Machine Learning.

Most companies using SRM within their Supply chain processes are mostly working within the first two steps of control tower deployment and this is also the boundary where the project undertaken in Ferrari will lay in. However, as the business ambition is to invest in this innovative technology and achieve a high digital level of maturity, the goal of this Master thesis is to design a tool that can support material planners and logistic managers in the decision-making process during daily operations.

2.3 SRM Applications

Supplier Relationship Management can have a wide variety of applications, as many sectors rely much on the strength and effectiveness of their Supply Chains. In fact, beside an extended ranges of industries where logistics is essential in the production process, such as automotive, aerospace or maritime, control towers have shown the potential to bring a major impact also in the healthcare and grocery businesses.

SRM has demonstrated to establish sensible improvements in hospital material management. Indeed, as mentioned by the European Commission [9], although labor costs constitute the major share of the total costs of a medical treatment, there is still a major economic potential in improving expenditure on materials and services. One source to reduce costs and enhance service delivery can therefore be found in the sophisticated management of the relationships with suppliers [32]. A case study conducted in a Swiss hospital [32] explains how the introduction of SRM allowed the automation of 80% of in-house order processing and a better communication between the logistic and purchasing department. Due to better information about the reliability of suppliers, stock management and inventory control was improved and the delivery of the needed goods was accelerated, too [32]. In addition, the European Commission reported that more than 50% of the hospitals which had experience with ICT-supported sourcing had sustainable cost reductions [9].

Food is also an industry subjected to disruptions. Lately, the outburst of war between Russia and Ukraine caused a major shortage of some primary resources such as cereals, sunflower oil and corn, causing supermarkets to set some shopping limits for some products, in order to avoid shelves emptying. The introduction of Supply Chain control towers within the grocery industry would help to manage overwhelming demand and ensure the availability of goods by monitoring and mitigating an ever-increasing range of potential disruptions. Keep shelves stocked with expanded inventory visibility to see beyond warehouses, including in-store locations and supply in-transit [17]. [40] discusses the crucial role of SRM in guaranteeing a more sustainable Food Supply Chain, including food waste reduction and promotion of food security. By introducing RFID systems for example, actions such as animal traceability, access control system, library management, automatic toll collection and counterfeit or theft prevention system can already be initiated. Progressions in sensor technology, communication networks and their integration with RFID technology, are expanding the application domain to intelligent transportation, quality control, real-time monitoring, traceability system, food safety, and online information systems for end-user.

[26] summarizes the findings of an industry panel study evaluating how new smart, autonomous technologies, such as Artificial Intelligence and Machine Learning, impact the system and operational architecture of Supply Chain control tower implementations that serve the pharmaceutical industry. Unsupervised learning algorithms can be used for demand forecasting based on historical data, market trends and leading indicators. AI algorithms could be used to send alerts in anticipation of unexpected events, predict inventory stockouts, modify Material Requirements Planning (MRP) functions with factors such as inventory shelf life, customer shelf life requirements, changes in lead times of suppliers, change in risk levels, human resource changes, or transportation lead time changes. Ultimately, through Machine Learning, algorithms could be trained to act as decision-makers within a control tower environment.

A case study involving the integration of a Supply Chain control tower in the automotive industry is presented in [21], where SRM is applied in Valmet Automotive, a vehicle manufacturing provider that has produced cars for brands such as Saab, PSA Chrysler, Porsche and Mercedes-Benz. In particular, this paper focuses on the management and tracking of the inbound transport operations along the A-class Mercedes-Benz Supply Chain, emphasizing the importance of IT solutions in the visibility of the material flow from suppliers located all over Europe to the production line. In [39], the integration of SRM between OEMs and Tier-1 suppliers has been investigated in the construction equipment industry in Sweden. The authors underwent a qualitative cross-case analysis by interviewing five companies (Engcon, Sandvik, Volvo, Scania and Peab), in order to understand how SRM would integrate through twelve sub-processes involving a strong relationship between manufacturers and suppliers.

An alternative Supply Chain coordination solution is proposed by [13] for maintenance scheduling of an offshore wind turbine park. In this case, the current state consisted of a manual matching, contracting and coordination of suppliers within every maintenance operation, which represented a bottleneck for effectively accommodating the increasing demand and complexity, leading to sub-optimal solutions. The proposed solution comprises the development of a system of connected systems that enables trustworthy processing of private data to automate the final stage of maintenance operation planning. Blockchain assumes a crucial role in this case study, as this technology requires a consistent data exchange between many independently owned ERP systems and secure processing of commercially sensitive information.

2.4 Supply Chain Control Models and Model Predictive Control

Supply Chain control towers are a solution increasingly chosen by OEMs to gain a competitive advantage. The interest of this Master thesis is to investigate how digital tools can add value to the control of the material and information flow, and help the logistic managers in the daily decision-making activities. In particular, while several vendors nowadays propose solutions that aim to cover Levels 1 and 2 of the Supply Chain control tower integration (Figure 20), the aim of this research is to investigate how Big Data, communication networks, digital infrastructures and control strategies can push a SRM system to become a decision-support tool or eventually be able to coordinate autonomously an entire logistic process between tiers or, in large-scale, the entire Supply Chain.

Model Predictive Control (MPC) represents a feasible and popular solution in the industrial world that has been widely used by the literature to design control strategies for Supply Chain models.
MPC is a control methodology that solves a discrete time optimal control problem that aims to determine those actions that optimize the behavior of a system by minimizing or maximizing a specific objective function (Figure 21) [34][37].

In each control cycle, the MPC control agent uses the following information:

- **Objective function:** expresses which system behavior and actions are desired
- **Prediction model:** describes the behavior of the system subject to actions
- **Disturbances:** unexpected perturbations of a system's variables, which are predicted over a predetermined prediction horizon
- **Constraints:** value boundaries that are placed on the states, the inputs, the outputs and the disturbances of the system
- **Measurements:** the measurements of the state of the system at beginning of the current control cycle [34].

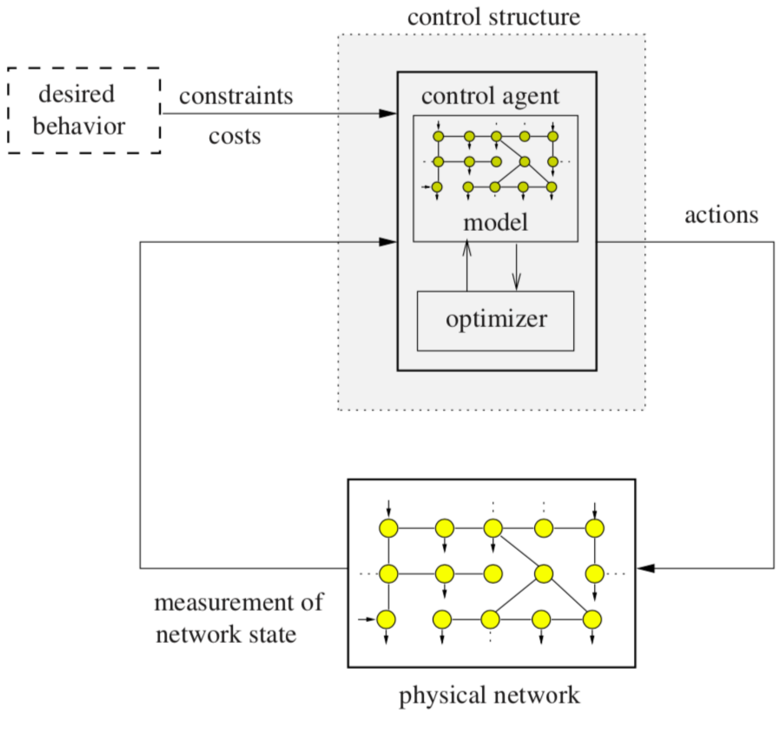

Figure 21: MPC model of a generic system [34]

In order to find the actions that lead to the best performance, the control agent uses the prediction model to predict the behavior of the system over a certain prediction horizon, starting from the state at the beginning of the control cycle. The predicted outputs depend on the known values up to the current instant (past inputs and outputs) and on the future control signals. The set of inputs or control signals (computed over a control horizon) is calculated by optimizing a determined objective function, in order to keep the process as close as possible to the reference trajectory, and by respecting the system constraints. Once the control agent has determined the list of actions that optimize the system performance, only the first control signal is implemented. The cycle is then repeated for every discrete time step [34][37]. Hence, the control agent operates in a receding or rolling horizon fashion to determine its actions, as graphically displayed in Figure 22.

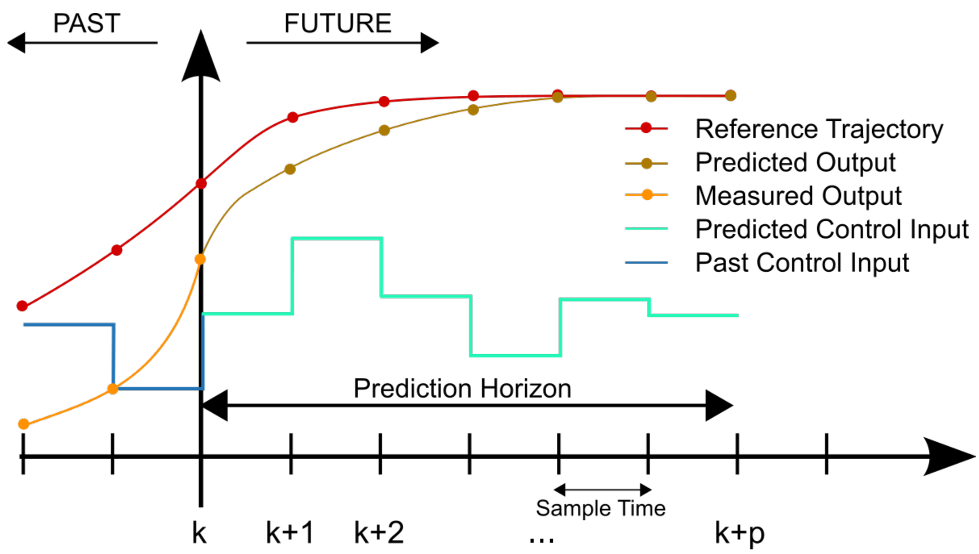

Figure 22: The receding/rolling horizon in Model Predictive Control [5]

2.4.1 Literature review of Supply Chain MPC applications

Over the years, several studies have been conducted over the implementation of Model Predictive Control in Supply Chains, in particular with the experimentation of different algorithms. An overview of all the case studies examined in this paper is presented in Table 3.

Table 3: Literature overview of MPC models applied in Supply Chain case studies

Ref.	Year	Control Strategy	KPIs	SC tiers	Sector	Market Data	Current State	Multiple scenarios
[37]	2003	Centralized MPC Distributed MPC	Profit maximization	4	Generic	×	×	×
[6]	2003	Decentralized MPC	Stock monitoring Order monitoring Min demand variations	3	Semiconductor	×	×	×
[54]	2004	MPC with move suppression	Stock monitoring	-	Semiconductor	×	×	×
[25]	2005	Min Variance Control	Stock monitoring Backlog minimization Min demand variations	-	Generic	×	×	×
[10]	2007	Distributed nonlinear MPC	Stock monitoring Min unfulfilled order Order monitoring Min demand variations	3	Generic	✓	×	✓
[18]	2008	Distributed MPC	Stock monitoring Min demand variations	-	Generic	×	×	×
[28]	2009	Centralized MPC Distributed non-cooperative MPC Distributed cooperative MPC	Stock monitoring Min demand variations	2	Generic	×	×	✓
[29]	2010	Distributed MPC	Stock monitoring Max demand satisfaction	N	Generic	×	×	×
[33]	2011	Decentralized MPC	Stock monitoring Min transport costs Backlog minimization Min demand variations	4	Generic	×	×	×
[53]	2014	Centralized MPC	Stock monitoring Min demand variations	4	Automotive	×	✓	×
[15]	2020	Centralized MPC	Stock monitoring Overdue goods Overproduction Transport minimization	3	Food	×	×	✓

[28] compares the performance of three different MPC strategies (centralized MPC, distributed non-cooperative MPC and distributed cooperative MPC) by applying them on a reduced version of the MIT Beer Game [47], which stands as a popular example of single product Supply Chain control model. The objectives of this algorithm are keeping the stock and the amount of unfulfilled orders closed to a reference value, without varying the orders over a specific threshold. A centralized MPC, characterized by a single controller, solves a single optimization problem to decide the optimal sequences of the inputs with respect to a given performance index based on the full model of the system and on the measurements from all the sensors. While this solution is considered the best in terms of performance, it requires a high computational burden. In a distributed MPC strategy, instead, each control agent solves an MPC problem with regard to the information it receives from other agents in the network. In particular, a non-coordinated MPC scheme the controllers communicate, but do not take a cooperative decision, that aims to optimize a performance function. They iterate exchanging future input sequences until an agreement is obtained, which neither of them can improve, hence reaching a Nash equilibrium [51]. On the other hand, in a coordinated distributed MPC scheme, each agent chooses the solution that optimizes a cost function that depends on both subsystems. Therefore, the decision depends on a global performance index.

The results displayed by this study show that a coordinated distributed MPC, compared to a centralized scheme, reaches an overall optimal performance of the same magnitude, but in a faster time. The iterative Distributed MPC provides a better response that the proposed Distributed MPC, but event in this case only after a certain number of iterations, which determine a higher computational cost and a larger number of communications.

Another distributed MPC solution is proposed in [29]. In this case, since each agent has access only to the model and the state of one of the subsystems, the agents must negotiate, in order to take a cooperative decision. Even this algorithm was tested on a Supply Chain problem, with the goal of monitoring the stock level. Results show that the performances rises with the number of proposals, but this needs to be traded-off with the computational cost, which increases with the number of iterations.

[37] presents a Mixed-Integer Linear Programming (MILP) model for Supply Chains with multiproduct, multiechelon distribution networks, multiproduct batch plants, implemented with an MPC control scheme and a rolling horizon approach, in which the variables that govern the control system are updated every week. In this case study, the model represents the logistic flow as a whole, from the raw material warehouse to the end-consumer, and is tested with three different strategies, with the aim of measuring their performance in profit maximization: a centralized global approach and two decentralized ones, where the objective is to optimize respectively the manufacturing and the distribution costs. The paper underlines how a central coordinator is the best solution for managing a Supply Chain, because the system is able to better coordinate its resources and reduce costs by balancing the distribution network and the plant.

[33] demonstrates how a multi-echelon decentralized MPC control scheme, with real-time update to demand variations, enhances the Supply Chain performance and deals with uncertainty and stochasticity. Also in this case, the introduction of a move suppression term to the cost function, improves the robustness of the systems to changes in costumer demand.

In [54], Model Predictive Control is presented as a tactical decision module for Supply Chain management in semiconductor manufacturing. Since this business is widely characterized by a highly variable market, this paper demonstrates how MPC can have satisfactory performance for systems with high stochasticity and uncertainty, for example considering material reconfiguration and product splits.

[53] examinates how MPC control strategies over an automotive Supply Chain can restrain the bullwhip effect, created by analyzing and controlling the inventory of four nodes: raw material supplier, component supplier, manufacturer and distributor. From the graphs in Figure 23 and 24, it can be observed how MPC reduces over time the bullwhip effect and enhances Supply Chain responsiveness, compared to a traditional strategy.

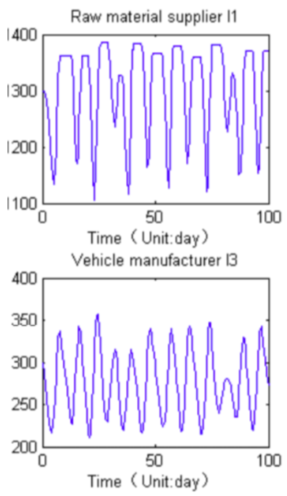

Figure 23: Supply Chain inventory level changes of all nodes with traditional strategy (simulation time: 100 days)[53]

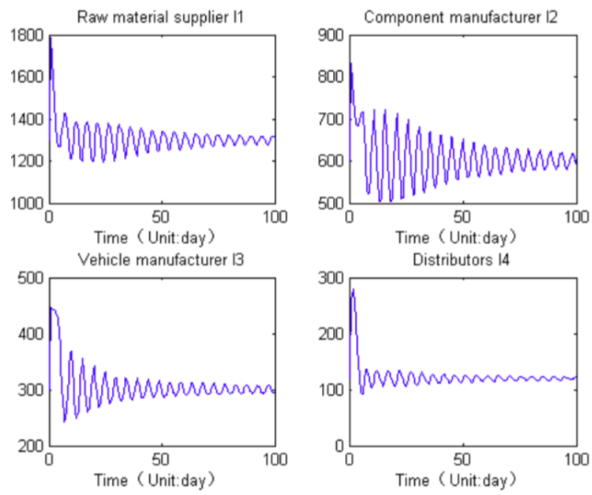

Figure 24: Supply Chain inventory level changes of all nodes with MPC strategy (simulation time: 100 days)[53]

A food Supply Chain case study is displayed in [15], where a centralized Model Predictive Control framework is proposed as a decision-support tool to address the logistics management of perishable goods. The performance of this framework is analysed through the behaviour of a Supply Chain following three distinct management policies, for different prediction horizons and customer demand profiles. The numerical experiments revealed that different management goals lead to different logistical decisions.

A distributed nonlinear Model Predictive Control strategy is presented in [10] for application in a large Supply Chain comprised of cooperative dynamic sub-systems. The implementation consists of different elements (manufacturer, supplier retailer) sharing coupled variables in their models. By communicating at every time step these variables and by using move suppression systems, the MPC controller penalises any "disagreement" between the sub-system on a coupled variable, therefore guaranteeing stabilization and feasibility of the computed solution. The results show an improved performance compared to a nominal feedback controller.

The study presented in [6] is based on the application of a decentralized MPC scheme for a six-node, two-product, three-echelon demand network problem, developed by Intel Corporation, which consists of interconnected assembly, warehouse, and retailer entities and mimics the back end configuration of a semiconductor Supply Chain (Figure 25). The six-node example is of particular interest, because it suggests that the MPC strategy can be readily extended to handle complex systems in a robust manner. Moreover, the results show that a control oriented approach may require significantly lower safety stock levels to be maintained throughout the enterprise system as compared to industry heuristics, while still maintaining high customer satisfaction levels.

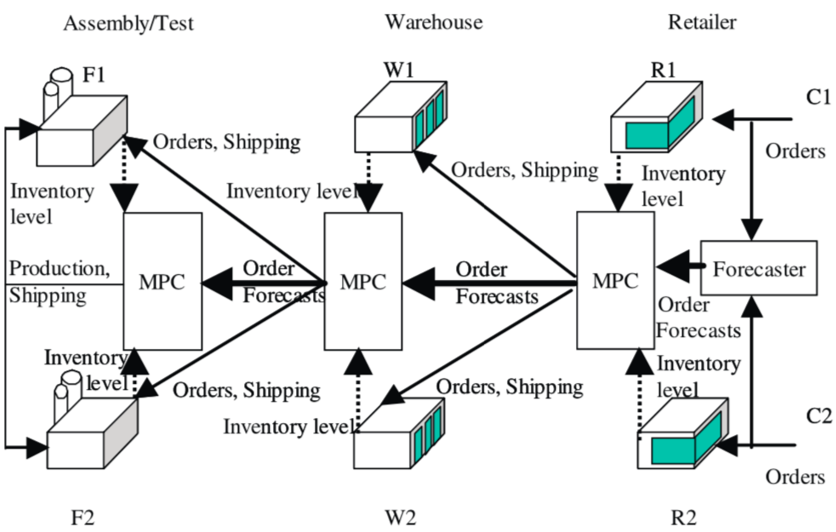

Figure 25: Information flow for control of the six-node Intel demand network [6]

In [18], an optimization-based distributed Model Predictive Control scheme is applied to a dynamic Supply Chain network, with the aim of satisfying the customer orders with the minimum inventory (and therefore the least operating cost) over a specified rolling time horizon. A move suppression term that penalizes the rate of change in the transported quantities through the network increases the robustness of the control system. Simulated results exhibit good dynamic performance under both stochastic and deterministic demand variations.

A Minimum Variance Control (MVC) approach is undertaken in [25] to maintain an inventory level that is just enough to satisfy customer demand, avoiding the formation of the bullwhip effect. Simulation results show that this strategy can be successful with both stationary and variable demand, and shows to have a better performance that other approaches, such as PI control.

2.5 Conclusion

In this chapter, a literature research over the techniques used to improve the efficiency of a Supply Chain was presented, in order to understand what is the current state-of-the-art of Supply Chain digitization in the world of industry and academic research to react to the high instability and uncertainty experienced in today's markets. In particular, in line with the main focus of this thesis, the relationship between buyers and suppliers in terms of data visibility and logistic actions has been put under study with Supplier Relationship Management.

The first section displayed the improvements that a Supply Chain 4.0 could bring, thanks to the introduction of digital technologies enhancing both online communication, but also physical material flows between clients and suppliers. Forecasts and predictive analytics in production planning could extend the visibility over the Supply Chain and definitely increase robustness and responsiveness to material crisis. In line with a complete client's demand overview, digital platforms for order management should be promoted to enhance suppliers to exchange information about their production capacity and ability to satisfy the clients' needs, in order to allow an OEM to have a long-term awareness of material availability. The sharing of real-time data such as stock, Work-In-Progress (WIP), lead times and shortages allows a better collaboration and a work approach based on an early-warning system rather than last-minute urgencies, that foster instability. Finally data gives the possibility to monitor the customer and supplier service level and consequently highlights better the areas of improvement.

Then, Supplier Relationship Management has been introduced both under a theoretical and practical perspective, by presenting the work of several research papers and case studies in the world of industry. Its impact both in the procurement and logistic operations have been displayed. By focusing deeper on Supply Chain control towers, the benefits and the ambitions of these innovations have been presented and compared to a traditional Supply Chain information flow.

Finally, a specific literature study on Supply Chain Model Predictive Control models has been proposed, by collecting academic papers, in order to break down the state-of-the-art in Supply Chain Management and take inspiration for the design of the Ferrari's Supply Chain model, which are presented in the following chapters.

In this Master thesis, Model Predictive Control is applied to an automotive Supply Chain study case and its performance is assessed through different parameters, by analyzing two different control strategies in various scenarios.

This research proposes a solution that investigates the concept of autonomous Supply Chains, and distinguishes itself from previous works by bringing the following inputs:

- Real market data
- Comparison with the simulation of the current state
- Synchronous evaluation of several Supply Chain KPIs
- MPC model assessment over multiple Supply Chain scenarios

Differently from the current literature, where MPC strategies are compared without extracting the current state of the system, in this paper the innovative solution, representing the future state, is compared with a simulation of the "as is" condition, in order to show the benefits of data visibility on Supply Chain operations. In particular, a Supply Chain control tower, governed by a single centralized MPC agent, representing the future solution, is evaluated against a decentralized MPC scheme that is designed to simulate the behaviour of the current state of Ferrari's Supply Chain. The use of real market data allows to analyze a concrete impact of the proposed solution on the logistic KPIs assessed by the OEM. As a further step, additional indices are addressed to evaluate the Supply Chain performance. The model is designed to optimize at the same time stock levels, backlogs, the supplier service level and the order variation over the chain. Finally, for the first time, the MPC models are tested over multiple scenarios: the ability to recover from an initial backlog, the capability to react to a material shortage and a variation of the OEM's production mix are analyzed and compared. The goal is to show how a digital Supply Chain is more robust and efficient to the dynamic behaviour of today's markets.

3 Current State

This chapter discusses the following research sub-question:

- What is the current state of the system and where is the waste in the process?

It presents the current state of Ferrari's Supply Chain, observed under a material planner perspective. By viewing the system with a critical approach, various forms of waste have been found and classified. The non value-adding activities currently run by planners have been measured by conducting a data analysis within the team. The causes of this inefficiency are explained and an analogy with a control behaviour is proposed, in order to simulate it in the following chapters and compare it with the designed innovation.

3.1 Ferrari's Current State

The problem analysis phase conducted in Ferrari was essential to understand the logistic dynamics in an automotive business that presents an extra complexity, caused by a high product customization and therefore the high variable number of components that are ordered and produced along its Supply Chain. The start of a project regarding Supplier Relationship Management demonstrates the necessity to take actions on a process that is yet not standardized and digitized enough to face the complexity of an increasingly dynamic and uncertain market. Indeed, although much effort has been spent on the digitization of the order flow, through for example the introduction of open buying programs, the integration with the production planning and the activation of Electronic Data Interchange (EDI) with several suppliers, yet much needs to be improved in the relationship between Ferrari and its Supply Chain.

In the current state, Ferrari weekly updates its supply program, sending its demand to the suppliers through either the EDI or the Ferrari Supplier portal, in form of both a confirmed quantity in a defined frozen period and a forecast over a long-term horizon, subject to change week by week depending on the production mix. The delivery schedule, depending on the component's demand, logistic batch, world location and other factors or constraints, can be daily, weekly or monthly. An example of a program with a weekly delivery schedule sent by Ferrari to one of its suppliers, is shown in Figure 26.

```
+-----------------------------------------------------------------------------------------------------------------------------+
|Item       |Last receipt data    |Contr.    |      WEEK     48/2022          |             WEEKS     From  49/2022 To 21/2023         |
|           |---------------------|/Pos.     |-----------------------------|   49/     51/     01/     03/     05/     07/     09/     11/|
|           |Qty /N.ddt /ddt Date |/Pat.     |  Mon|  Tue|  Wed|  Thu|  Fri|   50      52      02      04      06      08      10    12-21|
|           |                     |/Rev.     |     |     |     |     |     |                                                                |
|---------------------------------+----------+-----+-----+-----+-----+-----+----------------------------------------------------------------|
|            40/80714882/18-11-202|000117902|    0|    0|   60|    0|    0|     40|     60|      0|     40|     60|     60|     60|     40|
|000949443                        |/    5    |     |     |     |     |     |     60|      0|     60|     80|     40|     40|     60|    500|
|Delivery Cumulative:     1900,0000|/ S2      |     |     |     |     |     |       |       |       |       |       |       |       |       |
|Delay Cumulative   :        0,0000|/  152    |     |     |     |     |     |       |       |       |       |       |       |       |       |
|ALBERO TRASMISSIONE              |Type: Delivery Based                    |       |       |       |       |       |       |       |       |
|Delivery    : MAGAZZINO ESTERNO UBERSETTO                                 |       |       |       |       |       |       |       |       |
|              VIA PERDISA ANG. VIA GIARDINI                               |       |       |       |       |       |       |       |       |
|              41053 MARANELL                                              |       |       |       |       |       |       |       |       |
|              ITALIA                                                      |       |       |       |       |       |       |       |       |
```

Figure 26: Example of a program weekly sent to a supplier for a PN, courtesy of Ferrari

Once the programs are received, it is duty of the supplier to guarantee on-time deliveries respecting the quality standards set by the final client. However, this is not always the case: it is frequent for Ferrari to receive material late or just-in-time for assembly, which not only lowers the supplier's service levels but also puts at risk the company's production flow. The results are clearly visible in the factory: several are the cars stopped at the end of the production line, waiting for the replenishment of one or more components, which may take hours or sometimes even days. This increases the amount of waste in the system, as the cars spend time parked in a buffer, causing loss of time and non-value adding activities on the product. This logistic inefficiency increases the production lead time of the product and causes delays in the delivery to the end costumer and penalties in the company's service level towards the client. A picture of a car parked at the end-of-line due to missing pieces is shown in Figure 27.

Figure 27: Car parked a the end-of-line due to missing components, courtesy of Ferrari

These issues are often caused by the lack of collaboration of suppliers, who'd rather hide issues to the client rather than signaling them and work together to project a plan for a solution. As a consequence, much of the time spent by material planners is to discuss and negotiate by phone or email the quantities needed, giving less importance to the defined programs and creating, through non-value adding activities, other time waste, which could be exploited for projects of Continuous Improvement, strategic tables with the suppliers and collaboration with other company's departments. Another cause of waste may be given by internal problems, such as scrapped pieces, warehouse losses or wrong stock accounting movements. Even in this case, the alarm is given by the material planners to the suppliers only when they either notice or receive the warning, which is left to a manual activity and is therefore highly subject to errors and delays. This also shows a lack of trust and collaboration that does not allow the transparent sharing of information about each other's process, which would certainly improve the efficiency of the operations.

Material Planner Time Analysis

In order to assess the amount of time spent by material planners every day, out of a 8-hour shift, for non-value adding activities, an analysis among 20 material planners working for the inbound logistics of the series vehicle production has been undertaken. In particular, they have been asked to measure, over a 5 days time horizon, their daily occupation (in terms of minutes) for the following recurrent non value-adding operations:

- **Report elaboration:** every day Ferrari material planners print out, organize and share with critical suppliers reports regarding backlog analysis, emergencies in the production line and recovery plans. These files are in most cases necessary for the suppliers, because they base their production on Ferrari's daily requests. After retrieving their internal inputs, the file is turned back to Ferrari with the information about next deliveries and eventual production or supply issues
- **Urgency management (MRP orders):** a high supplier backlog may determine emergencies in the assembly line caused by missing components. Ferrari material planners in average deal with about 4 line issues per day, which inevitably take up much of their time. The activities correlated with this type of operation are analysis of the component's stock, coverage, transfers, etc. on the SCM system, phone calls and emails to the suppliers to solicit the components, management of urgent transports, withdrawals from the spare parts warehouse and management of the arrival of the component on the assembly line

- **Urgency management (PRP orders):** this type of analysis is different from the previous ones, since it needs to be specific on the single PN involved. It consist of both the verification of the daily delivery and the evaluation of the stock coverage.
- **Other activities:** these include the management of extra quantities that some suppliers ship without respecting the programs and the time spent to share general information (e.g, closure days, information about possible disruptions) to the suppliers

The outputs of the 20 measurements have been collected and analyzed, by firstly computing an average of the time wasted by the single material planner over the measured 5 days (working week) and then by extrapolating the mean of the aggregated data. In particular, a boxplot of the data distribution is depicted in Figure 28.

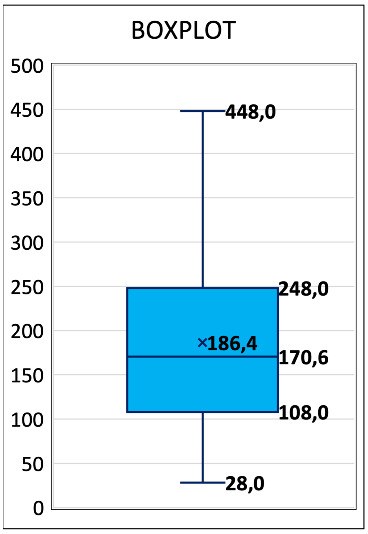

Figure 28: Boxplot of the collected data

Table 4: Data analysis of the collected data

DATA ANALYSIS	
Mean	186.4 min
Std deviation	103.7 min
Median	170.6 min
First quartile	108 min
Third quartile	248 min
Minimum	28 min
Maximum	448 min

The raw data have been elaborated by eliminating the outlier measurement. The final output is given both with the time allocation for every non value-adding activity (Figure 5) and in form of aggregated data (Table 29). The results of these data analysis are displayed below.

Table 5: Data analysis on material planners' non value-adding activities

MATERIAL PLANNER NON VALUE-ADDING ACTIVITIES		Average time (min)
Report elaboration	Critical PNs analysis	27,3
	Ad hoc file elaboration	33,4
Urgency management (MRP)	Missing PN analysis	29,6
	E-mails/phone calls to suppliers	30,9
	Urgent transport management	13,8
	Spare parts retrieval	7,8
	Factory supply managament	18,5
Urgency management (PRP)	Closed orders delivery check	4,2
	Stock coverage	5,8
Other activities	Extra-quantities management	8,6
	Information sharing with suppliers	4,4

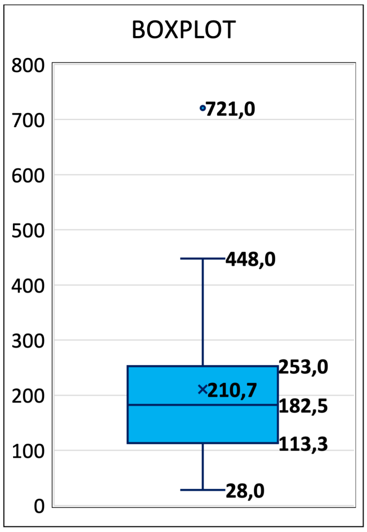

Figure 29: Boxplot of the collected data

Table 6: Analysis of the collected data

DATA ANALYSIS	
Mean	186.4 min
Std deviation	103.7 min
Median	170.6 min
First quartile	108 min
Third quartile	248 min
Minimum	28 min
Maximum	448 min

The data shows that planners spend about 3 hours a day (which corresponds to the 38% of their working time) on non value-adding activities caused by Supply Chain inefficiency. It is clear from this output that there is currently a high waste, as much of the planners' time and competence could be invested in other tactical operations, such as projects of Continuous Improvement and the enhancement of the relationship with the suppliers. Moreover, this time waste often implies a higher burden for the material planner, who may need to spend more hours in the office in order not to neglect other daily duties.
This analysis demonstrates that the margins of improvement in Ferrari's logistic department are high both in the operations and in the work organization. The impact of automation and digitization however would benefit not only the employee, but also the process and the company, as skills would be exploited in a more efficient way.

By observing the current state of the process, it was possible to identify the high amount of waste in Ferrari's logistics, which has an effect on the Supply Chain and on the assembly line. In order to present the observed inefficiencies, wastes have been classified according to the Lean methodology TIMWOODS. TIMWOODS is a tool that identifies 8 areas where waste can be eliminated (Figure 30). This leads to more efficient processes and ultimately results in cost savings [36].
The issues encountered in this system are summarized with the following forms of waste:

- **Transportation:** lack of coordination among Supply Chain tiers often causes high backlogs and increases the probability of missing pieces in the assembly line. As a consequence, milk runs are not always respected and the frequency of urgent transport increases. This makes the Supply Chain less efficient and sustainable.
- **Inventory:** a supplier that does not follow the programs may become uncontrollable also for the delivery of extra quantities, which, if accepted, risk to excessively fill up the warehouse with useless material, increasing the risk of losses and obsolescence for buyers.
- **Waiting:** missing components for the assembly caused by Supply Chain inefficiencies for the production flow. Cars that need to be stopped create a time waste, an increase in costs for extra-work recoveries and may cause delays in the delivery to the customer, which nowadays can take up years.
- **Overprocessing:** the lack of data visibility between buyers and suppliers causes a higher burden of daily activities for logistic employees. Phone calls or emails to ask about stocks and capacity are all overprocessing activities that represent a waste in the system.
- **Skills:** competent resources spending much of the working day on non value-adding activities represent a non-utilized talent for the company and a waste of potential for innovative projects and improvements of Supply Chain operations.

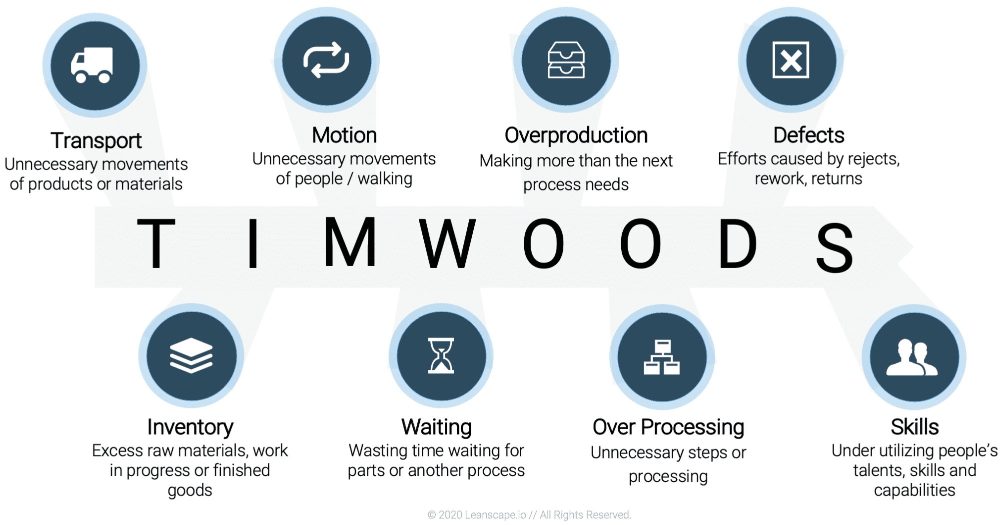

Figure 30: TIMWOODS [36]

The factors causing this reduction of the performances are various. As previously mentioned, much of this inefficiency is due to a unstructured management of the information flow, caused by a low exchange of data along the tiers. This causes a lack of coordination between buyers and suppliers, and usually leads to discover problems too late to solve them in a strategic way, but instead run to recover the emergency. This miscommunication and operative method originates first from a culture where different entities along a Value Chain work by silos: every business tries to make its own interest, without looking at the benefits of their clients or suppliers. Secondly, such a lack of structure inevitably ends up in extra-flux work, which brings wastes in the process. This mentality focused on the resolution of problems on short-term doesn't allow to face the problems with a tactical or strategic perspective and in the long run leads to weaken the Supply Chain and compromise its competitiveness among the market.

3.2 The analogy with Decentralized MPC

In this section, it is explained how businesses that lack of coordination within a Supply Chain can be associated with a specific control strategy. This analogy is made to understand the behaviour of such a network in both a qualitative manner and quantitative manner, simulate the effects of this behaviour on the Supply Chain performance and compare it with the proposed innovation.
As a daily representation of a process is difficult to replicate without an enormous amount of available data, in this paper a representative model of the current state is built with the information collected from the suppliers (that are presented in Chapter 4). In this regard, Decentralized Model Predictive Control (DMPC) can simulate the way businesses currently interact within the network. In this scheme, every company consists of its own MPC control agent, that looks for the optimal system inputs that maximize the company's own objectives. Like businesses operating by silos, in this configuration nodes do not communicate any type of information (states, variables or computed choices) with each other. A graphical representation of a DMPC control structure is displayed in Figure 31.

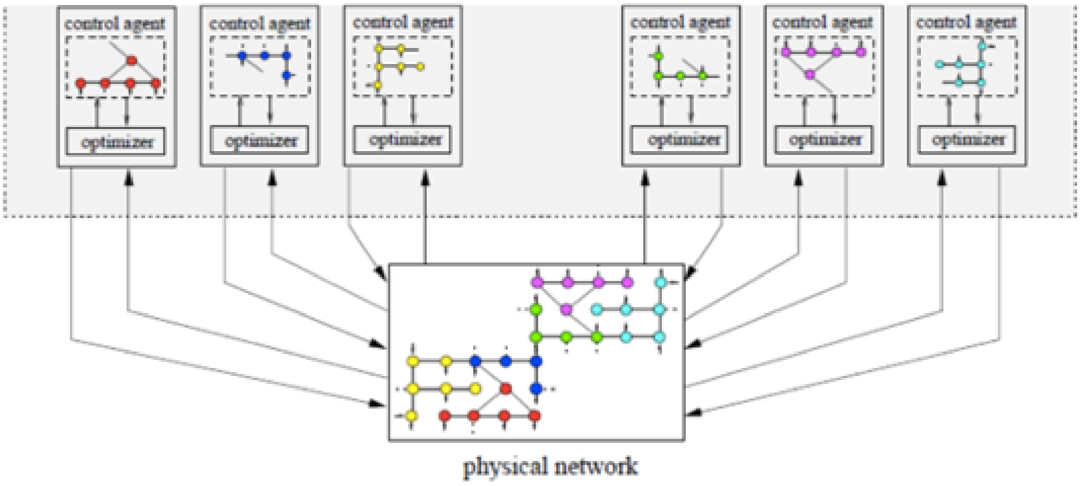

Figure 31: Decentralized MPC scheme

As Decentralized MPC is a control strategy widely chosen in the literature to design Supply Chain controllers, in this research it is used for two main scopes. On one hand, it models the current state of the system in terms of data visibility and interaction among the network and, on the other, it is evaluated as a potential application for automated Supply Chain control and compared with the centralized control strategy. In this way the simulations demonstrate the possible benefits of the future application on the current state of the Supply Chain and give the opportunity to analyze through many KPIs which solution could better govern the material and information flow of the logistic operations and increase the Supply Chain performance.

4 Supply Chain Model & Future State

Supply Chains, especially in the automotive industry, are highly complex systems, as they comprise several elements (the companies) that usually present very different characteristics, depending on their location, economical capital, production capacity and operational organization. Moreover, the variability and uncertainty given by a manufacturer's production system and logistics are of high relevance, especially in today's dynamic and globalized networks.
Therefore, the control of such a system is a difficult and intricate process, that involves not only good management skills, but also a wide perception of the whole chain, in order to get a complete acknowledgement of the logistic operations. This involves the establishment of solid relationships between clients and suppliers based on a reliable communication and exchange of information.
In this Master thesis, the themes of Supply Chain digitization and logistic flow control is undertaken by focusing on the essential role of data visibility in reaching a self-controlled Supply Chain, that could lead the way towards the ultimate goal of autonomous and smart logistic networks.
This chapter aims to give the reader a clear understanding of the control theory chosen for this study case, Model Predictive Control, its different strategies and its applications in a Supply Chain. In particular, the design of the model used to simulate Ferrari's logistic network is presented and the KPIs chosen to assess its performance will be introduced.
These are the research subquestions answered in Chapter 4:

- How can a Supply Chain be modelled and controlled with MPC thanks to process visibility?
  1. What are the variables and the control actions involved?
  2. Which parameters does a Supply Chain control agent try to optimize?
  3. Which control theories can better represent the current and future state of the system?
- How can data visibility and Model Predictive Control make autonomous decisions for Supply Chain Operations?
- What are the KPIs that can help monitor a supplier's logistic performance?

4.1 The Model

Ferrari's Supply Chain is a very wide network, currently composed by about 450 suppliers spread all over the world and producing a wide range of products that are used to assemble an engine or a complete supercar. As a consequence, the number of variables and the uncertainty factors affecting them make the whole system very complex to design and control with a desired accuracy. Moreover, also the computational cost of such a model needs to be taken into account, as the calculations made over such a high-populated network may reach excessive running times, not efficient for a practical application.

For this reason, with the intent of demonstrating accurately the thesis of this work, the focus of the study is on a small part of Ferrari's supplier network and, in particular, the model of the Supply Chain will be designed for a single Part Number (PN) of the Prancing Horse's portfolio. Subsequently, it is also necessary to define the extent to which analyze and simulate a logistic flow: as the SRM project in Ferrari has the short-term goal of achieving visibility of their Tier-1 suppliers, this study aims to go beyond this short-term goal and investigate the potential impact of a Supply Chain visibility reaching Tier-2 suppliers, in order to better predict and quantitatively show the benefits of data exchange on the behaviour of the chain.

The dashboard (or car instrument panel) is the product selected for this thesis to demonstrate the efficiency of an autonomous Supply Chain control agent. This component is characterized by a high logistic complexity, since it is formed by both mechanical and electronic sub-components. In particular, for this study case, a specific version of the product was selected: in fact, as a Ferrari client has a wide optionals choice, the dashboard is sold in different colors and is designed differently for every model. For this simulation, it was taken the dashboard of the Ferrari Portofino, which is characterized by carbon inserts and by the presence of a double Thin Film Transistor (TFT) display. A picture of the component assembled on the car can be seen in Figure 32.

Figure 32: Ferrari's Portofino's Dashboard, courtesy of Ferrari

The Supply Chain of this PN is large and covers multiple countries, as this product mounts many sub-components, produced in different parts of the world. Due to computational constraints and for sake of simplicity, for this simulation the Supply Chain was reduced to a total of 5 companies: Ferrari itself, the dashboard Tier-1 supplier and three Tier-2 suppliers, producing respectively the dashboard's cover, the electronic board and the TFT displays.
The list of the suppliers involved in this simulation is provided below, in order to make the reader acquainted of the logistic process of this dashboard.

- **TAM:** a Tier-1 automotive manufacturer, whose main business involves electronic components. It produces all the dashboards mounted on a Ferrari, which makes it a critical supplier. Especially in this period of time, it is kept under the eyes of Ferrari's management for the issues that may derive from the semiconductor crisis. The production plant is in Emilia Romagna (the same region of Ferrari's headquarters and plant).

- **ProPlastic:** this manufacturer works in the thermoplastic sector and is both a Tier-1 and Tier-2 supplier for Ferrari, producing for the Prancing Horse hundreds of PNs. Indeed, it provides many of the plastic and aesthetic painted components that can be seen on a Ferrari's exterior body and internal furniture. As a Tier-2 supplier it sells TAM the plastic covers that make up the dashboards' body. With this high impact on Ferrari's portfolio, ProPlastic is considered a critical supplier for the high-quality standards required by Ferrari for its components and for the logistics of molds, which it imports from China. Its production plant is located in Piemonte, about 3 hours away (by truck) from Maranello.

- **Mtronic:** this company is a Tier-2 supplier in Ferrari's Supply Chain. It works in the automotive industry and produces electronic components. In particular, is sells TAM the electronic boards, necessary to activate the dashboards. This product is considered a critical supplier for TAM, due to its high dependency on the semiconductor market. Since also this company is located in Emilia Romagna, TAM works with a Just-In-Time philosophy, trying to keep zero stock of electronic boards in its warehouse.

- **EBOVx:** a Tier-2 supplier, specialized in digital displays for the automotive sector. In Ferrari' Supply Chain, this company sells TAM the TFT displays of which modern digital dashboards are built. The company's production plant is in China, which, over the last years, has been a source of logistic issues, such as Covid-19 and port congestions.

The next graph and table show the logistic flux between the companies selected for the simulation and the match between the company and its product.

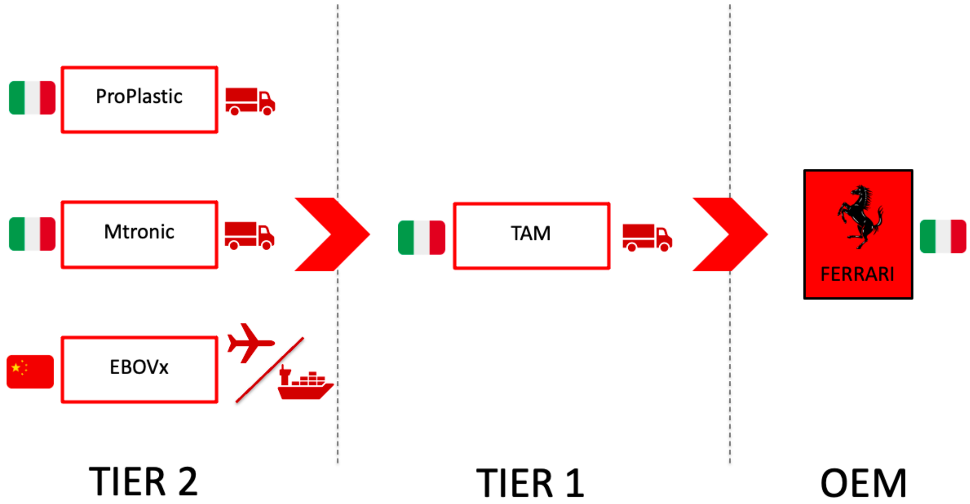

Figure 33: Ferrari's Supply Chain simulation test case

Table 7: Supplier presentation table

Company	**TAM**	**ProPlastic**	**Mtronic**	**EBOVx**
Product	Dashboard	Cover	Electronic Board	TFT display
Tier	1	2	2	2
Plant Location	Italy	Italy	Italy	China
Transport mode	Truck	Truck	Truck	Ship/Airplane

In order to deeply comprehend the scope of this simulation, it is important to focus on the choices made for the design of this model determined to prove the benefits of data visibility along the Supply Chain. For this reason, it is crucial to have a complete vision of the supplier process, from the arrival of inbound material to the shipping of the finished product. Being able to look into the supplier's stocks and production capacity gives a broader perspective of the Supply Chain operations and facilitates a better coordination on the decisions to be made. This takes inspiration from the goals of the SRM project started by Ferrari, but aims to go beyond it, underlining the importance of sharing information along the whole Supply Chain to enhance the forecast of any bottleneck or disruption.
Figure 34 shows the logistic flux and the main constraints that could be relevant in analyzing a supplier's process.

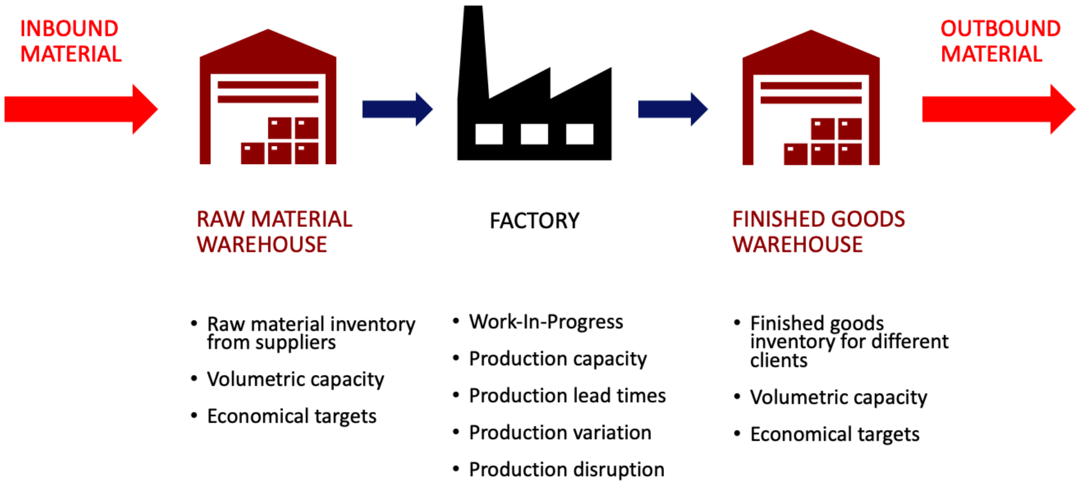

Figure 34: A scheme of a typical logistic flux in a manufacturing business

As a MPC controller is characterized by an optimization algorithm, this chapter shows how Ferrari's Supply Chain has been represented into an optimization model, specifically customized on a logistic application.
First, the sets and parameters of the model will be presented. These data have been directly taken from companies, taking benefit from their partnership with Ferrari, and can be considered reliable and close to reality for this kind of simulation. Following, the model variables will be listed and described. The system equations and constraints will be shown in detail, explaining their impact on the optimization problem. Finally, a list of assumptions made for this model will be displayed.

4.1.1 Model Environment

Indices

i	Index representing the material produced or transported
k	Index representing the Supply Chain node/company
k'	Index representing the Supply Chain node/company upstream of node k
k''	Index representing the Supply Chain node/company downstream of node k
l	Index representing the production line
$n_k = \{0; 1; 2; 3\}$	Index representing the tier level along the Supply Chain
r	Index representing the material consumed
t	Index representing the discrete time instant

Sets

N	Network of companies in the Supply Chain
L_k	Set of production lines at node k
M	Set of products
T^{n_k}	Set of companies at Tier-n of the Supply Chain

Parameters

$$z_{k,k''} = \begin{cases} 1 & \text{if node } k \text{ delivers to node } k'' \\ 0 & \text{otherwise} \end{cases}$$

LT_i^k	Production Lead Time of product i at node k
OF_i^k	Delivery scheme (and therefore frequency of orders in the supplier programs) at node k for product i
$\rho_{r,i}$	Consumption rate of material r for the production of component i
$\tau_{k,k''}$	Transit time between node k and node k''
V_l^k	Production capacity of process unit l at node k
LB_i^k	Logistic batch of product i at node k
PB_i^k	Production batch of product i at node k
FD_i^k	Frozen days of order programs of product i sent by node k

$$e_k^i = \begin{cases} 1 & \text{if product } i \text{ is an inbound material at node } k \\ 0 & \text{otherwise} \end{cases}$$

$$o_k^i = \begin{cases} 1 & \text{if product } i \text{ is an outbound material at node } k \\ 0 & \text{otherwise} \end{cases}$$

$S_{ref,k}^i$	Target stock value of product i for node k

The parameters chosen for the simulation are listed in the Appendix.

4.1.2 System Variables

States

S_k^i	Stock level of product i at node k
B_k^i	Backlog of node k towards the downstream node for product i
Ou_k^i	Unfulfilled order of product i sent by node k
$Q_{i,l}$	Quantity of product i produced by process unit l
P_k^i	Production throughput of product i at node k
C_k^r	Consumption of material r at node k
O_k^i	Order sent by node k to the suppliers of product i
d_k^i	Demand received by node k from clients consuming product i

$$p_{i,l} = \begin{cases} 1 & \text{if product } i \text{ is being processed by process unit } l \text{ at a specific discrete time instant} \\ 0 & \text{otherwise} \end{cases}$$

$x_{k,k''}^i$	Material flow of component i from node k to downstream node k''
$lb_{k,k''}^i$	Logistic batches of component i shipped from node k to downstream node k''
pb_k^i	Production batches of component i produced at node k
Sv_k^i	Floating stock level of product i at node k
$tt_{k,k''}^i$	Quantity of component i in transit from node k to downstream node k''
oo_k^i	Batches of product i ordered by node k

$$f_{i,k} = \begin{cases} 1 & \text{if product } i \text{ is being ordered by node } k \text{ at a specific discrete time instant} \\ 0 & \text{otherwise} \end{cases}$$

4.1.3 System Equations

Stock Balance

This equation indicates, at every node k and at every instant t, the numerical balance of product i between what enters the warehouse from the upstream nodes or is produced at node k and the shipping of the component towards downstream nodes or the material consumption, depending on the company's role in the Supply Chain.

$$\begin{aligned} S_k^i(t+1) =& S_k^i(t) + e_k^i \cdot \left(\sum_{k' \in N} \left(z_{k',k} \cdot x_{k',k}^i(t+1) \right) - C_k^i(t+1) \right) \\ &+ o_k^i \cdot \left(P_k^i(t+1) - \sum_{k'' \in N} \left(z_{k,k''} \cdot x_{k,k''}^i(t+1) \right) \right), \qquad \forall i \in M, l \in L_k, k \in N \end{aligned} \tag{1}$$

In this model, two particular cases are considered:

- When the node considered corresponds to Ferrari, its production part neglected, as it is not part of this case study. Moreover, the material consumption represents the production demand, which in the simulation is directly taken from Ferrari's database. Therefore the stock balance equation at Ferrari node is the following:

$$S_k^i(t+1) = S_k^i(t) + e_k^i \cdot \left(\sum_{k' \in N} \left(z_{k',k} \cdot x_{k',k}^i(t+1) \right) - d_k^i(t+1) \right), \forall i \in M, l \in L_k, k \in \{\text{Ferrari}\}$$

- In this study case, for the Tier-2 suppliers, the inbound received material is not taken into consideration (it is supposed they can produce with infinite raw material, in a standard scenario). Therefore, the stock balance will be defined only for the finished products:

$$S_k^i(t+1) = S_k^i(t) + o_k^i \cdot \left(P_k^i(t+1) - \sum_{k'' \in N} \left(z_{k,k''} \cdot x_{k,k''}^i(t+1) \right) \right), \forall i \in M, l \in L_k, k \in T^2$$

Unfulfilled Order Balance

In this equation is displayed the amount of stacked unfulfilled orders for product i caused by the missing delivery of material from a specific node k'.
In particular, the unfulfilled orders for Tier-2 suppliers are set to zero, as no Tier-3 supplier is considered in this simulation.

$$Ou_k^i(t+1) = Ou_k^i(t) + O_k^i(t+1) - \sum_{k' \in N} x_{k',k}^i(t+1), \qquad \forall i \in M, l \in L_k, k \in N \tag{2}$$

Backlog Balance

In this equation is displayed the backlog amount of product i caused by the missing shipment of material from node k to a specific node k''.

$$B_k^i(t+1) = B_k^i(t) + d_k^i(t+1) - \sum_{k'' \in N} x_{k,k''}^i(t+1), \qquad \forall i \in M, l \in L_k, k \in N \tag{3}$$

Floating Stock Balance

This equation controls the balance of the floating stock, which represents that gray area when the material is in transit between two nodes. Oppositely to the stock balance defined above, that is updated only when a new amount of material is *delivered*, this balance shows the physical finished product availability in the supplier warehouse, which is consumed once the material is *shipped*. In this way, the model can register the shipping date of a certain order, and, through the known transit time, forecast the delivery date to the client.

$$Sv_k^i(t+1) = Sv_k^i(t) + o_k^i \cdot \left(P_k^i(t+1) - \sum_{k'' \in N} z_{k,k''} \cdot tt_{k,k''}^i(t+1) \right), \qquad \forall i \in M, l \in L_k, k \in N \tag{4}$$

4.1.4 Constraints

Non-negative constraints

$$S_k^i, Ou_k^i, B_k^i, Sv_k^i, x_{k,k''}^i, p_{i,k,l}, Q_{i,k,l}, P_k^i, C_k^i, d_k^i, O_k^i, pb_k^i, lb_k^i, tt_{kk''}^i, oo_k^i, f_k^i \geq 0, \qquad \forall i \in M, l \in L_k, k, k'' \in N \tag{5}$$

4.1.4.1 Supplier Production

Production Feasibility

A product can be produced by a company k only if material i is an outbound material for k.

$$p_{i,k,l}(t) \leq o_k^i, \qquad \forall i \in M, \forall k \in N, \forall l \in L_k \tag{6}$$

Work In Progress (WIP) visibility

By considering the company's number of production lines available for the fabrication of the component, this constraint sets a limit to the quantity of components that could be produced on that line at the same time, which coincides with the production lead time.

$$\sum_{i \in M} \sum_{t^*=t-LT_k^i+1}^{t} p_{i,k,l}(t^*) \leq 1, \qquad \forall k \in N \backslash \{\text{Ferrari}\}, \forall l \in L_k \tag{7}$$

Production Capacity

Since every company has a limit in terms of production capacity, with this constraint an upper bound for daily production capacity of a specific component on a company's production line is defined.

$$Q_{i,k,l}(t) \leq p_{i,k,l}(t) \cdot V_l^k, \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\}, \forall l \in L_k \tag{8}$$

Production Throughput

The daily quantity of a specific component that a company produces comprises the throughput of every production line. In particular, this constraint identifies the start of production of a specific component through Q and the time instant in which it is finished and stocked in the warehouse, through the production lead time.

$$P_k^i(t) = \sum_{linL_k} Q_{i,k,l}(t + LT_k^i), \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\} \tag{9}$$

Material Consumption

The daily quantity of a material r that a company consumes is relative to its consumption rate for a finished product i and is therefore defined by the throughput of i in every production line.

$$C_k^i(t) = \rho_i^r \dot{\sum}_{linL_k} Q_{i,k,l}(t + LT_k^i), \qquad \forall i \in M, \forall k \in \{\text{Ferrari, TAM}\} \tag{10}$$

Material Availability

The production of a certain quantity of a component cannot be started if there is not enough material used to assemble it. Therefore, start of production happens only if the quantity of every product of its Bill of Materials (BOM) is available in stock for the quantity required.

$$\rho_i^r \cdot \sum_{linL_k} Q_{i,k,l}(t + LT_k^i) \leq S_k^r(t), \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\}, \forall l \in L_k \tag{11}$$

Production Batches

The quantity of produced components must respect the production batches defined by the company.

$$P_k^i(t) = PB_k^i \cdot pb_k^i(t), \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\} \tag{12}$$

4.1.4.2 Material Flow

Material Flow Feasibility

A quantity of a component can be transported between two nodes only if the upstream node k has k'' as a client, and viceversa, if k is recognized as a supplier of k''. In short, transport is possible if the arc between the two nodes is activated ($z_{kk''} = 1$).

$$x_{kk''}^i(t) \leq M \cdot o_k^i \cdot e_{k''}^i, \qquad \forall i \in M, \forall k, k'' \in N \tag{13}$$

Shipment Feasibility

A quantity of a component can be shipped to the client only if it is available on stock in the finished product warehouse

$$tt^i_{kk''}(t) \leq Sv^i_k(t), \qquad \forall i \in M, \forall k \in N\backslash\{\text{Ferrari}\}, \forall k'' \in N \tag{14}$$

Material delivered/in transit

The material is considered delivered to the client's warehouse after it has been transported there, in the defined transit time τ

$$x^i_{kk''}(t + \tau^{k''}_k) = tt^i_{kk''}(t), \qquad \forall i \in M, \forall k \in N\backslash\{\text{Ferrari}\}, \forall k'' \in N \tag{15}$$

Logistic Batches

The quantity of shipped/received components should respect the logistic batches agreed betwen the client and the supplier.

$$x^i_{kk''}(t) \leq LB^i_k \cdot lb^i_{kk''}(t), \qquad \forall i \in M, \forall k \in N\backslash\{\text{Ferrari}\}, \forall k'' \in N \tag{16}$$

4.1.4.3 Information Flow

Order-Node Association

An order can be sent by a company k to its suppliers only if material i is an inbound material for k.

$$O^i_k(t) \leq M \cdot e^i_k, \qquad \forall i \in M, \forall k \in N \tag{17}$$

Demand-Order Association

With this constraint every supplier's received order for a specific product corresponds to the sum of the demands requested by its clients.

$$d^i_k(t) = \sum_{k'' \in N} z_{kk''} \cdot O^i_{k''}, \qquad \forall i \in M, \forall k \in N\backslash\{\text{Ferrari}\} \tag{18}$$

Order Feasibility

A specific component i can be ordered only by a node k that receives it to manufacture its final product.

$$f^i_k(t) \leq e^i_k, \qquad \forall i \in M, \forall k \in N\backslash\{\text{Ferrari}\} \tag{19}$$

Order Frequency

The frequency of the orders sent by the client must be in line with the chosen delivery schedule.

$$\sum_{t^*=t-OF^i_k+1}^{t} f^i_k(t^*) \leq 1, \qquad \forall i \in M, \forall k \in N\backslash\{\text{Ferrari}\} \tag{20}$$

Order Repetitiveness

An order in the programs sent to the suppliers must follow the delivery schedule defined by the client and the supplier itself.

$$f^i_k(t + OF^i_k) = f^i_k(t), \qquad \forall i \in M, \forall k \in N\backslash\{\text{Ferrari}\} \tag{21}$$

Order Creation

An order appears on a specific day in the client's programs only if it follows the delivery schedule set by Constraint 21.

$$O_k^i(t) \leq M \cdot f_k^i(t), \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\} \tag{22}$$

Order Batches

The quantity of ordered components must respect the logistic batches agreed between the client and the supplier.

$$O_k^i(t) \leq LB_k^i \cdot oo_k^i(t), \qquad \forall i \in M, \forall k \in N \tag{23}$$

4.2 Future State

Ferrari's SRM project aims to improve the information flow between the company and its suppliers, in order to bring more efficiency to the process and avoid any risk of stock-out and possible production stop. This project will first be started with some structured Tier-1 suppliers, and then extended to all the Tier-1 class, with the future goal of potentially include even the Tier-2.
Compared with a current state where collaboration between the OEM with Tier-1 businesses is usually limited to calls, emails, that are often caused by emergencies, Ferrari feels three main Supply Chain needs that it is addressing with this project:

- **Suppliers capacity and bottlenecks:** Real-time monitoring of suppliers' production capacity, in order to improve partner collaboration, make the production planning more efficient and anticipate any risk of backlog and shortages.
- **Order Management:** Complete integration of order management with the suppliers, by gaining information about their ability to absorb Ferrari's demand on a short and long term.
- **Inbound Logistics Management:** Improve suppliers' stock visibility, control the inbound material flow, work through exceptions management and alert generation

In the future state, the focus of the proposed solution is the digital exchange of data between clients and suppliers, which allows them to gain visibility over the process and better coordinate logistic operations. This approach clearly separates from the current state of the system, where companies tend to hide their process information and work by silos, creating misunderstandings, ambiguity and consequently inefficiency over the Supply Chain. A better communication and a stronger collaboration enhances a much better management of the logistics, diminishing the waste in the system. In this sense, the improvement of information flow would help to increase the performance of the material flow operations over tiers.
However, data has much more potential than increasing awareness over the chain. The goal of this Master Thesis is to demonstrate how data visibility could not only improve the efficiency of a complex Supply Chain, but even pave the way for the automation of the logistic operations between clients and suppliers, in terms of both material and information flow. In this way, the role of a Supply Chain control tower gains value, as it becomes a decision-support tool for logistic managers. It enables to identify faster the bottlenecks in the system and intervene promptly to solve issues in their supplier network, reducing the level of risk of production stops.
In particular, in order to analyze the impact of this innovation, here is described how this solution could reduce the inefficiency in the system, by using the TIMWOODS methodology, in analogy with the discussion of the current state in Chapter 3.

- **Transportation:** as the exchange of information could lead to the automation of the decision-making processes of logistics, it is expected that a higher punctuality of suppliers reduces the amount of urgent transports and therefore also the extra costs currently undertaken. Moreover it would also help the Supply Chain to reduce its environmental footprint.

- **Inventory:** a better control of logistic operations can also benefit the warehouse management, as data visibility and automation should also enhance the reduction of extra quantities shipments and extra batch management, which has also an impact on the probability of scrapped pieces and packaging material costs.
- **Waiting:** a better coordination within the Supply Chain has an important impact on the production processes. Data visibility should reduce the amount of missing pieces on production lines and the time wasted by a product to waste along the process. It finally would also increase the service levels towards the end-consumer. Since nowadays Ferrari deliveries take up years to be completed, this innovation would clearly bring a benefit to the company's performance and competitiveness among the market.
- **Overprocessing:** the first stakeholders to benefit from this innovation are certainly material planners and logistic operators. In fact, the increase of transparency ad the automation of decision-making would reduce the non value-adding activities currently taking up most of their daily work. In a future perspective, the operational role of the material planner would be limited to monitor the correct processing of the automated operations.
- **Skills:** as a consequence of the reduction of overprocessing activities, companies could benefit of this innovation to exploit their resources in a more efficient manner, by raising up their work to a tactical or even strategic level. Projects of Continuous Improvement could be promoted, as well as a higher coordination within the company's internal departments and a better management of the Value Chain.

In order to achieve complete data visibility over Supply Chain processes, it is necessary to have an agent able to keep an eye on the whole network, in order to control and optimize the chain as a whole, changing a traditional company's self-centered mindset and used to work by silos.
Centralized Model Predictive Control (CMPC) is the solution chosen for this study case. A centralized controller has visibility over the whole Supply Chain, measures all variables in the network and determines actions or set-points for all the system's actuators (the supplier's shipments and the clients orders). Oppositely to a decentralized controller, it optimizes at every iteration a single objective function that encloses the goals of all the companies involved.
A representation of a CMPC control scheme is displayed in Figure 35.

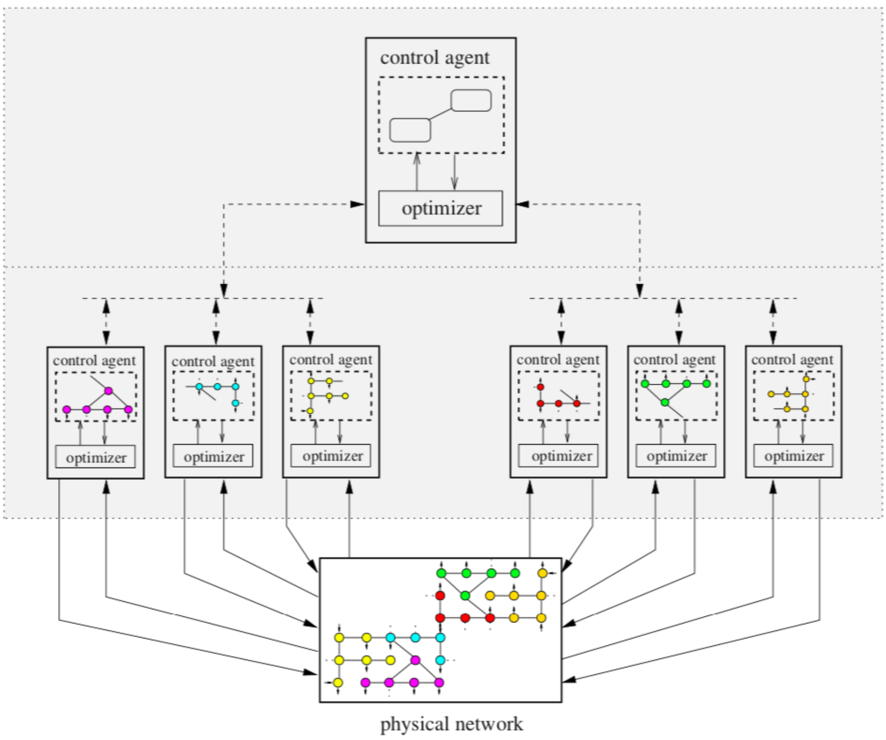

Figure 35: Centralized MPC scheme [34]

With the rapid development of sensor technology and of data collection techniques, the ability to analyze, classify, communicate information and exploit them to make decisions in the Supply Chain, is a strategic advantage for companies who aim to increase their competitiveness among the market and be leaders in the search for innovation and avant-garde solutions.
In the world of Supply Chain, where is required high precision in the information flow and a structured collaboration between partners, process digitization and automation is certainly a crucial step towards a lean transformation of the logistic operations. The potential of a central agent being able to make decision through the ownership of a large amount of data is a clear example of the potential of this transition, as it would not only reduce the workload of material planners, but also remodel their jobs into monitoring activities that could leave more space for new ideas of continuous improvement. In this way, companies can put a base for growth by creating solid Supply Chains, with a robust strategy of management and control.

4.3 Simulation KPIs

Since MPC is an optimization problem, it is also necessary to investigate the goals of the system under study. The main objective of every business is always make the highest money with the lowest costs. Supply Chains are a central part of a business, because they involve production and therefore direct incomes for the businesses involved. In this sense, the relationship and the logistics between clients and suppliers are vital for the production continuity of a factory.

Nowadays, service levels are a widely used KPI used by OEMs to monitor the performance of their suppliers. The main impact on this parameters is certainly given by delivery punctuality: the orders should be satisfied in the times indicated by the programs and backlogs should be minimized. At the same time, the client should guarantee a minimum variation of the ordered quantity over time, in order not to create a bullwhip effect over the Supply Chain and possibly cause disruptions. Another performance parameter is the respect of the quantities, as this guarantees a more standardized logistic flow and a better warehouse management. Additionally, as another issue caused by globalization is the high environmental footprint of logistics, another goal for Supply Chains nowadays should be the reduction of transports causing high emissions. Finally, warehouse stock has also a direct impact on a business' finance. In fact, while having too little stock puts at risk the production, excessive amount of material represents an immobilized capital, that takes liquidity away and is a potential source of obsolescence and therefore waste.

The performance of the MPC models is included in the optimization problem through an objective function, that will be presented in Section 5.1.1. The KPIs extrapolated from the model are the following:

- **Supplier Backlog:** this data is directly taken from the model variable B and is presented by a graph over discrete time steps.
  A normalized index of the backlog over the whole Supply Chain is computed as following:

$$\text{Backlog Index} = \text{mean}\left(\frac{\text{Backlog}}{\text{Logistic Batch}}\right) \tag{24}$$

  The efficiency of the Supply Chain increases when this value is low.

- **Material Stock:** this data is directly taken from the model variable S and is presented by a graph over discrete time steps. The stock trend is compared with the target defined by the company.
  Also in this case a KPI is computed, as shown in the next equation:

$$\text{Stock Index} = \text{mean}\left(\frac{\text{Stock} - \text{Target Stock}}{\text{Logistic Batch}}\right) \tag{25}$$

  The efficiency of the warehouse management over the Supply Chain goes along with the minimization of this value.

- **Order Variation:** this index aims to evaluate how much a client keeps its ordered quantity flat throughout time. This is important not to increase the complexity throughout the chain. This value is represented through a percentage ratio and shows a better efficiency of the Supply Chain with low values.

- **Supplier Punctuality:** this KPI analyses how the model allows a supplier to be on time with its deliveries. It is represented by the percentage ratio of the times an order O at time t is fulfilled with a delivery x of the same exact quantity. This value is higher if a supplier manages to follow the client's program.
- **Number of transports:** as another Supply Chain goal should be minimizing its impact on the environment, the simulation also measures the number of transports that are made over the simulation time, in order to evaluate which option makes the logistic operations more sustainable.
- **Simulation running time:** this performance index is chosen to compute the computational cost given by the two different control strategies, in order to assess their time-efficiency.

5 MPC Simulation

In Chapter 3 and 4 the current and future state of the system were presented, as well as the model designed to simulate the behavior of Ferrari's Supply Chain, to let the reader acknowledge the dynamics of the logistic network and the decision-making process studied for the two MPC controllers.
Simulating the DMPC and CMPC models is necessary to obtain a comparison between them and understand the benefits of the proposed solution. This chapter presents the the MPC objective functions, the simulation parameters and the scenarios in which the two models have been tested, by answering to the following research subquestions:

- What are the simulation parameters chosen for a MPC Supply Chain application?
- What scenarios can put at risk a Supply Chain and should be controlled by an autonomous control agent?

In particular these represent cases in which Supply Chains could deal with, in order to compare the reaction of the two models and prove the validity of the thesis.

5.1 Simulation Strategy & MPC Objectives

In Section 4.1, the general model used to represent a Supply Chain along three tiers, in terms of both material and information flow was presented, in order to display the brain of the MPC control tower.
The other essential part in the design of such a system is the operational perspective of the simulation, which is useful to understand how the computer runs the control task over the Supply Chain model. In this application, the MPC model over which the control tower operates is broken down into a convex Mixed-Integer Quadratic Programming (MIQP) optimization problem. This program has been coded and simulated on Python, in order to create a unique MPC algorithm, customized for a Supply Chain application. The model optimization, instead, has been run by the Gurobi solver.

Since Model Predictive Control consists of optimization cycles based on an objective function (as described in Section 2.4), the temporal dynamics of the model must be defined. First of all, a time unit must be chosen: a reasonable choice is choosing as a discrete time measure unit the working days. Then, it is crucial to define and distinguish three simulation parameters:

- **Prediction Horizon (H_p):** in every iteration of the MPC, it represents the number of discrete time steps along which the model predicts the output states of the model.
- **Control Horizon (H_c):** in every iteration of the MPC, it represents the number of discrete time steps along which the model computes the optimal input actions.
- **Simulation Time (T_{sim}):** the number of iterations chosen to run the MPC control.

In this simulation, the simulation running time T_{sim} has been set to 120 working days (around 6 months), while H_p and H_c (that have the same value) are set to 15 days (around 3 weeks).
The simulation code has been written and structured as an MPC algorithm, characterized by a number of iterations equal to the simulation time. Every iteration corresponds to an optimization cycle of the MPC problem, running with the receding horizon principle over H_p.

5.1.1 Objectives

The performance of a Supply Chain can be assessed by focusing on many aspects that regard both the material and information flow. The common focus is the efficiency of the logistic network, which should consist of minimized waste throughout the process, extra-flow operations and overprocessing.
To summarize, these are the terms included in the MPC model's objective function:

- **Minimization of the backlog B:** every supplier must be committed to avoid any backlog towards their clients or reduce it as much as possible, in order not to compromise their production continuity.
- **Minimization of the unfulfilled orders Ou:** in analogy with the supplier's commitment to minimize the backlog, the aim for the client is to not have any late material to be received from the suppliers. While in this simulation every component is procured through a single-sourcing strategy, the distinction between these two terms could be more relevant in the cases where a company buys a component from two or more suppliers.

- **Minimization of order quantity variation ΔO:** clients should minimize the order quantity variation, finding a compromise between safety stocks and frozen order periods, in order not to create entropy and complexity within the Supply Chain.
- **Supplier punctuality ΔXO:** this term equals to the difference between the received quantity x and the program order O; the aim is to incentive the supplier to deliver the quantity once, and in the times and quantity indicated by program in order to reduce the number of transports to deliver a desired quantity.
- **Minimization of the warehouse capital S:** according to the warehouse's volumetric capacity and the material's or product's price, the model aims to keep the stock close to a chosen target (S_{ref}).

Comparing the terms of the performance function with the KPIs presented in Chapter 4, it can be observed that the unfulfilled order index is not included in the KPIs. Indeed, for this study, client unfulfilled orders are equal to the supplier backlog, as the strategy is single-sourcing. In opposite cases, this term could be included in the KPIs analysis.

Since this terms have a different impact on the validity of the model, they are coupled with a weight w, that will be assigned and tuned according to their importance for the demonstration of the benefits of this innovation. This choice is presented in the following paragraph.

Objective function weights tuning

The objective function's weights are important parameters for the simulation, as they highly influence the behaviour of the MPC model. Therefore their choice determines the output of the simulation and is essential to choose them in an efficient manner. For this reason, it is necessary to tune these factors by understanding the system's priorities and their effect on the final results.

In this regard, the highest focus is put on the supplier backlog (and as a consequence on the client's unfulfilled orders), as this represents the main cause of issues in the client's production due to Supply Chain inefficiencies. Along with this, the delivery punctuality is considered a major topic, too. In fact, backlogs are accumulated when a supplier is not on time and needs to recover its faults. Order variation and the stock levels, instead, are considered extra achievements of the Supply Chain MPC models.
To conclude, the tuned weights are summarized in the following table:

Table 8: Weight factors after parameter tuning

Weight Factor	w_S	$w_{Ferrari}$	w_B	w_{Ou}	w_{DeltaO}	$w_{DeltaXO}$
Value	1	100	100	100	1	100

5.2 DMPC Current State Model

The current state of Ferrari's Supply Chain is a logistic network where there is a lack of communication of data and information between the different nodes. In order to recreate this scenario in terms of mathematical modelling, the focus of the design shifts on the objectives of the system and of the behaviour assumed in the simulation by the different actors involved. For this reason, in the design of a DMPC controller, every company behaves like an independent control agent, who aims to satisfy his own goals, without paying an attention on the efficiency of the entire system.
The objective function for the MPC optimization problem of the current state, as a consequence, is specific for every company, and is here displayed:

$$\begin{aligned} J_k =& \min \Bigg[\sum_{j=1}^{H_p} \sum_{i \in M} (w_k^S \cdot (S_k^i(t+j) - S_{ref,k}^i)^2 + w_k^B \cdot (B_k^i(t+j))^2 + w_k^{Ou} \cdot (Ou_k^i(t+j))^2 + \\ &+ \sum_{k'' \in N} w_k^{\Delta XO} \cdot (\Delta XO_k^i(t+j))^2 \Bigg], \qquad \forall t \in (0, ..., T_{sim} - 1) \end{aligned} \tag{26}$$

This choice increases the computational cost of the simulation, as the number of optimizations at every iteration must be equal to the number of nodes in the logistic network (in this case 5). Since in the current state companies work by silos and focus only on the optimization of their processes, the only data that is shared is of course the physical quantity arriving from the upstream nodes. In fact, in reality, it often happens that the quantity shipped not only does not correspond to the programs, but also it is not communicated to the client, who figures it out either observing the quantity in transit, or notices it only once the material has been received.
In the DMPC model, in order to represent reality as close as possible, a new initialization constraint is defined for every iteration n:

$$x^i_{k'k}(t-n) = x^i_{fin,k'k}(t), \qquad \forall t \in (n, ..., n+\tau^i_k), i \in M, k \in T^{n_k}, k' \in T^{n_k+1} \tag{27}$$

As the simulation starts from the upstream tiers to the OEM (Ferrari), at every time step, every inbound material is set equal to what has been decided by the control agent upstream in the logistic flow.

In detail the algorithm is run through the following steps:

1. An empty array X_{fin} (with length T_{sim}) is defined for every variable; the value in the first position is set to initialize the optimization.
2. The simulation time step is set to zero.
3. The simulation of the DMPC Supply Chain control tower starts with the model optimization of the first node of N.
4. The MPC model is run for a number of cycles equal to the prediction horizon H_p to finally obtain the outbound states and the input states
5. The second value of the obtained vectors is collected and added to the array X_{fin} (the first value was used for the initialization). These values represent the decision variable for the physical actions of the model
6. The simulation goes on with the optimization of the next node of N, with the MPC objective function J_k. The state x representing the inbound material is initialized through Constraint 27.
7. Step 4-6 are repeated for every node of the logistic network. The simulation order goes from the most upstream tier to the OEM.
8. The simulation time goes forward of one discrete time step and the previously optimal variables become the new initialization variables
9. Step 3-8 are repeated for T_{sim} times

A scheme of the DMPC simulation scheme is presented in Figure 36.

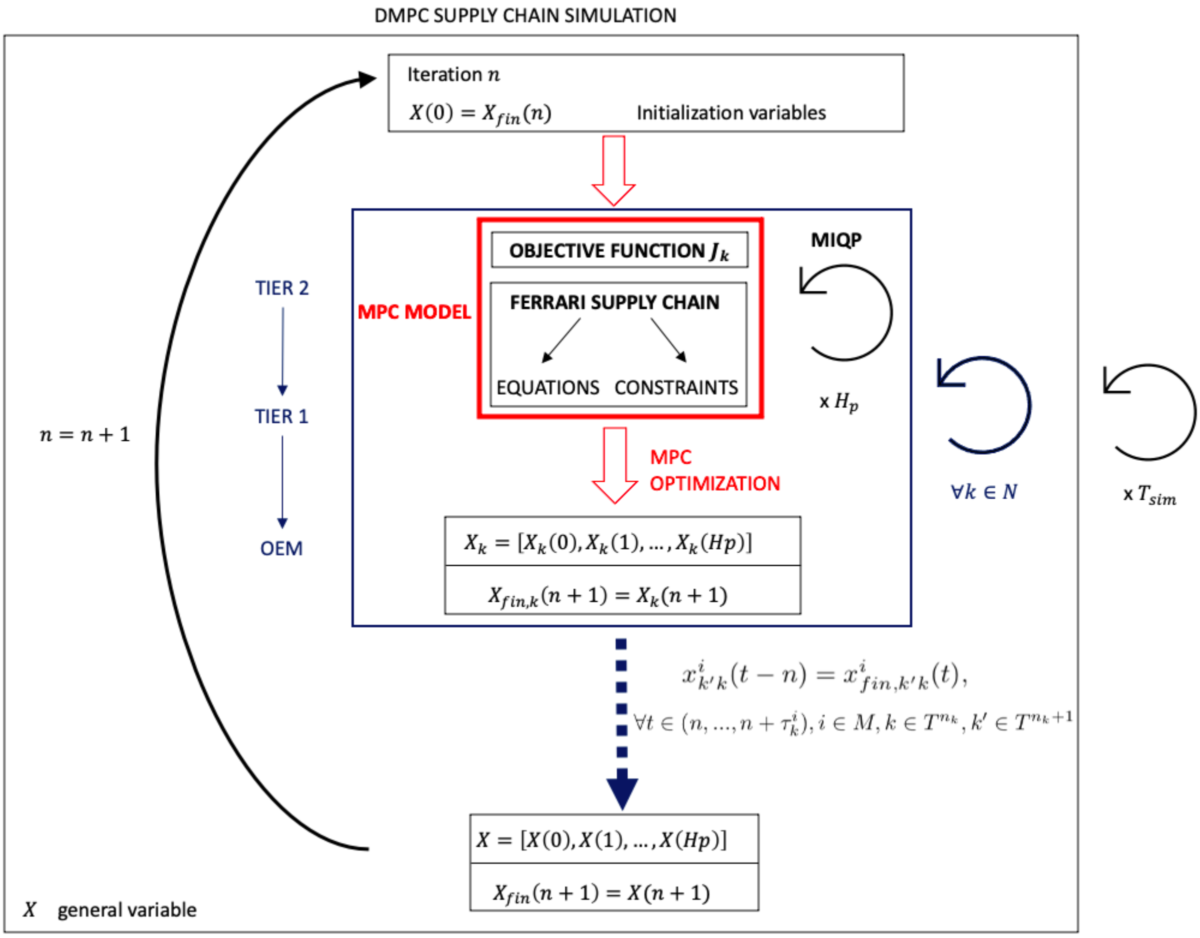

Figure 36: Ferrari's Supply Chain current state simulation algorithm

Another main aspect of the current state of Ferrari's Supply Chain is the decoupling of the orders sent by every company to its suppliers. This means, that, depending on its own strategy (safety stocks, warehouse capacity, material shortage, client production ramp-up etc.) a company sets its programs independently from the state of its client/supplier process state. This in many cases may amplify the bullwhip effect or rise backlogs and sense of urgency among the Supply Chain, that undoubtedly tends to deviate from working in a structured and standardized manner.
To represent this decentralized behaviour of the Supply Chain, the orders requested by every node of the Supply Chain at every iteration n have been collected from reality and reported manually in the algorithm, with the introduction of the following constraint:

$$O^i_k(t) = O_{SC}(n+t), \forall i \in M, k \in N \tag{28}$$

where O_{SC} is the array containing the orders along the Supply Chain.

As a consequence, every state and constraint thought for the optimization of orders along the logistic network, in the DMPC simulation of the current state is not included. These involve states oo, f and Constraints 19-23.
Furthermore, as it can be observed in the DMPC objective function in Equation 26, the optimization of ΔO is not taken in consideration for the current state, as orders are predefined. This has an effect also on the exclusion of Constraint 18, as it is considered redundant for this simulation.

A graphical representation of the DMPC control loop, with the presentation of all the model's states, control variables and disturbances, is displayed in Figure 37

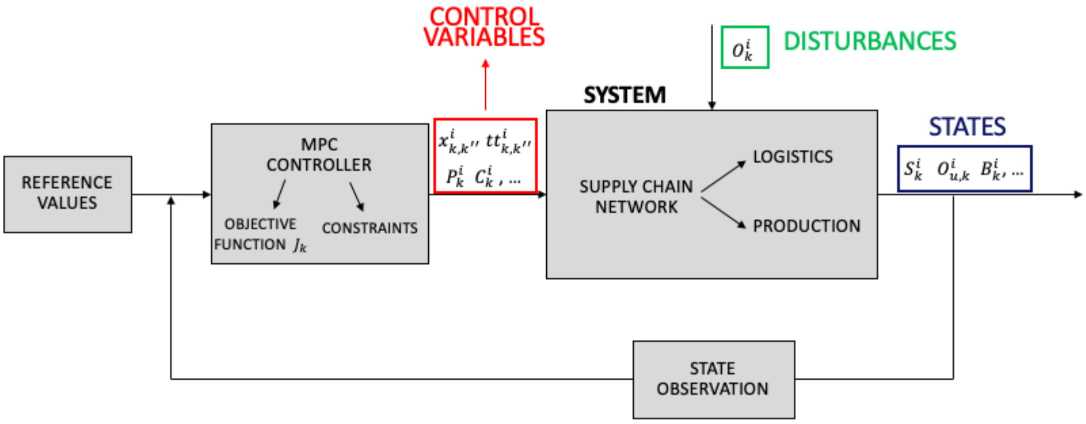

Figure 37: Decentralized MPC control loop

The DMPC model used for the simulation of Ferrari's Supply Chain current state is summarized below:

DECENTRALIZED MODEL PREDICTIVE CONTROL
FERRARI SUPPLY CHAIN
CURRENT STATE

States: S, Ou, B, Sv
Control Variables: $x, p, Q, P, C, lb, pb, tt$
Disturbances: $O = O_{SC}, d$

Objective Function

$$J_k = \min \left[\sum_{j=1}^{H_p} \sum_{i \in M} (w_k^S \cdot (S_k^i(t+j) - S_{ref,k}^i)^2 + w_k^B \cdot (B_k^i(t+j))^2 + w_k^{Ou} \cdot (Ou_k^i(t+j))^2 + \right.$$
$$\left. + \sum_{k'' \in N} w_k^{\Delta XO} \cdot (\Delta XO_k^i(t+j))^2 \right], \qquad \forall t \in (0, ..., T_{sim} - 1)$$

Equations

$$S_k^i(t+1) = S_k^i(t) + e_k^i \cdot \left(\sum_{k' \in N} (z_{k',k} \cdot x_{k',k}^i(t+1)) - C_k^i(t+1) \right)$$
$$+ o_k^i \cdot \left(P_k^i(t+1) - \sum_{k'' \in N} (z_{k,k''} \cdot x_{k,k''}^i(t+1)) \right), \qquad \forall i \in M, l \in L_k, k \in N$$

$$S_k^i(t+1) = S_k^i(t) + e_k^i \cdot \left(\sum_{k' \in N} (z_{k',k} \cdot x_{k',k}^i(t+1)) - d_k^i(t+1) \right), \forall i \in M, l \in L_k, k \in \{\text{Ferrari}\}$$

$$S_k^i(t+1) = S_k^i(t) + o_k^i \cdot \left(P_k^i(t+1) - \sum_{k'' \in N} \left(z_{k,k''} \cdot x_{k,k''}^i(t+1) \right) \right), \forall i \in M, l \in L_k, k \in T^2$$

$$Ou_k^i(t+1) = Ou_k^i(t) + O_k^i(t+1) - \sum_{k' \in N} x_{k',k}^i(t+1), \qquad \forall i \in M, l \in L_k, k \in N$$

$$B_k^i(t+1) = B_k^i(t) + d_k^i(t+1) - \sum_{k'' \in N} x_{k,k''}^i(t+1), \qquad \forall i \in M, l \in L_k, k \in N$$

$$Sv_k^i(t+1) = Sv_k^i(t) + o_k^i \cdot \left(P_k^i(t+1) - \sum_{k'' \in N} z_{k,k''} \cdot tt_{k,k''}^i(t+1) \right), \qquad \forall i \in M, l \in L_k, k \in N$$

Constraints

$$\sum_{i \in M} \sum_{t^*=t-LT_k^i+1}^{t} p_{i,k,l}(t^*) \leq 1, \qquad \forall k \in N \backslash \{\text{Ferrari}\}, \forall l \in L_k$$

$$Q_{i,k,l}(t) \leq p_{i,k,l}(t) \cdot V_l^k, \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\}, \forall l \in L_k$$

$$P_k^i(t) = \sum_{linL_k} Q_{i,k,l}(t + LT_k^i), \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\}$$

$$C_k^i(t) = \rho_i^r \dot{\sum}_{linL_k} Q_{i,k,l}(t + LT_k^i), \qquad \forall i \in M, \forall k \in N$$

$$\rho_i^r \cdot \sum_{linL_k} Q_{i,k,l}(t + LT_k^i) \leq S_k^r(t), \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\}, \forall l \in L_k$$

$$P_k^i(t) = PB_k^i \cdot pb_k^i(t), \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\}$$

$$x_{kk''}^i(t) \leq M \cdot o_k^i \cdot e_{k''}^i, \qquad \forall i \in M, \forall k, k'' \in N$$

$$x_{k'k}^i(t-n) = x_{fin,k'k}^i(t), \qquad \forall t \in (n, ..., n + \tau_k^i), i \in M, k \in T^{n_k}, k' \in T^{n_k+1}$$

$$tt_{kk''}^i(t) \leq Sv_k^i(t), \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\}, \forall k'' \in N$$

$$x_{kk''}^i(t + \tau_k^{k''}) = tt_{kk''}^i(t), \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\}, \forall k'' \in N$$

$$x_{kk''}^i(t) \leq LB_k^i \cdot lb_{kk''}^i(t), \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\}, \forall k'' \in N$$

$$O_k^i(t) = O_{SC}(n+t), \forall i \in M, k \in N$$

$$O_k^i(t) \leq M \cdot e_k^i, \qquad \forall i \in M, \forall k \in N$$

$$S_k^i, Ou_k^i, B_k^i, Sv_k^i, x_{k,k''}^i, p_{i,k,l}, Q_{i,k,l}, P_k^i, C_k^i, d_k^i, O_k^i, pb_k^i, lb_k^i, tt_{kk''}^i \geq 0,$$
$$\forall i \in M, l \in L_k, k, k'' \in N$$

5.3 CMPC Future State Model

Data visibility is the key feature of a centralized MPC controller. By overlooking every company within the chain, the aim of this central agent is to optimize the operations within every node to increase the efficiency of the entire network. In this scheme, the Supply Chain works as a single entity, comprising companies that collaborate together to reach a common goal, while also satisfying their own objectives as much as possible. On a future perspective, this tendency for an OEM to partner up with its suppliers could bring a big boost on the competitiveness of the Supply Chain among the market.
The downside of this solution, on the other hand, is a high computational cost, as the number of variables in the optimization model increases. This cost rises even more with the size and the complexity of the logistic network.

In the definition of the CMPC model, oppositely to a decentralized controller, every system's state will be part of a single objective function, that is defined as following:

$$\begin{aligned} J = &\min \Bigg[\sum_{j=1}^{H_p} \sum_{i \in M} (w^B_{Ferrari} \cdot (B^i_{TAM}(t+j))^2 + \sum_{k \in N} (w^S_k \cdot (S^i_k(t+j) - S^i_{ref,k})^2 + w^B_k \cdot (B^i_k(t+j))^2 + \\ &+ w^{Ou}_k \cdot (Ou^i_k(t+j))^2 + w^{\Delta O}_k \cdot (\Delta O^i_k(t+j))^2 + \sum_{k'' \in N} w^{\Delta XO}_k \cdot (\Delta XO^i_k(t+j))^2)) \Bigg], \\ &\forall t \in (0, ..., T_{sim} - 1) \end{aligned} \tag{29}$$

Thanks to this centralized configuration, the system is governed by a single Supply Chain control tower, that, by keeping an eye on the whole network, is able to constantly record and monitor every state of the process and make decisions on both the material flows between tiers and the information flow, in terms of orders, stock, Work-In-Progress information and transport status.
This new methodology clearly differs from the current state and identifies a potential for creating a more structured, uniform and transparent logistic flow, where non value-adding activities are minimized and more autonomous operations are promoted. In fact, while at the present day, many decisions are made by humans, with agreements that usually differ from the planned supply programs and a mainly unilateral communication (client $\rightarrow$ supplier), the future state introduces a single platform, accessible by all the stakeholders of the chain (with the ability for every company to identify the data that are useful for their operations), where decisions are automatically made by the computer; in this frame, companies, through a simple monitoring activity, can either confirm them or propose new adjustments.

In the CMPC model, it can be observed that also the simulation algorithm slightly changes from the current state. Whereas in the DMPC model the nodes' simulations are in series, in this case, at every iteration, all the system states are optimized at the same time through the single objective function J. When the solver finds the optimum, every optimized variable is stored in a vector X_{fin} (where X is a general variable) and is then used to initialize the following iteration. In detail the algorithm is run through the following steps:

1. An empty array X_{fin} (with length T_{sim}) is defined for every variable; the value in the first position is set to initialize the optimization.

2. The simulation time step is set to zero.

3. The MPC model is run for a number of cycles equal to the prediction horizon H_p to finally obtain the outbound states and the input states

4. The second value of the obtained vectors is collected and added to the array X_{fin} (the first value was used for the initialization). These values represent the decision variable for the physical actions of the model

5. The simulation time goes forward of one discrete time step and the previously optimal variables become the new initialization variables

6. Step 3-5 are repeated for T_{sim} times

A scheme of the algorithm is displayed in Figure 38.

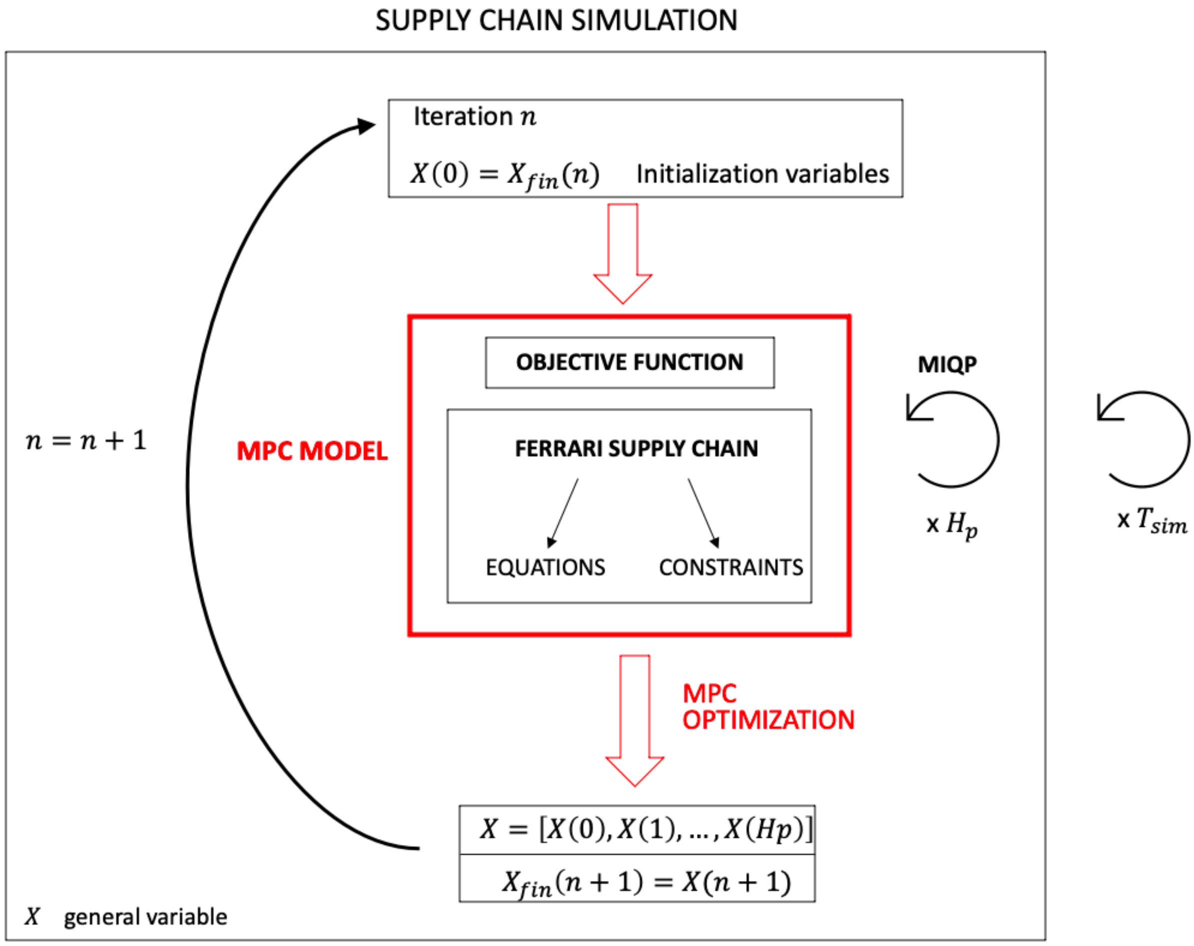

Figure 38: Ferrari's Supply Chain simulation algorithm

The states of the model are even in this case several, the main ones are represented by the stock, the backlog and the unfulfilled orders. The control variables, instead, are not only represented by the material quantities shipped between nodes, the company's production and material consumption, but also include the client orders, that, at every discrete time step, are computed by the centralized control agent, and must respect a frozen day period ($FD_i^k = 10$ days), in which, every time that the orders are updated, they do not change, in order to reduce the variability over the system. It is important to mention that, oppositely to the DMPC simulation where orders are predefined and set by every company, in the future state they are automatically decided based on the Ferrari demand, which represents the only system disturbance.
The constraint determining the demand requested by Ferrari, based on its production order at every iteration n is given below:

$$O_{Ferrari}^{Dashboard}(t) = O_F^{Dashboard}(n + t) \tag{30}$$

where O_F is the array containing the orders sent by Ferrari to its Supply Chain.
In addition, in the CMPC model, Constraint 17 is not included, because of its redundancy with Constraints 19 and 22.

The graphical representation of the MPC control loop for the future state is displayed in Figure 39.

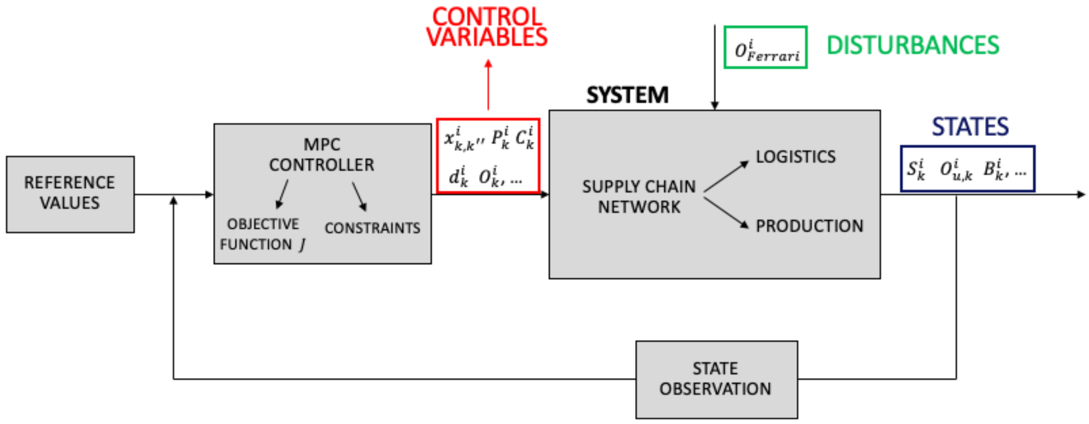

Figure 39: Centralized MPC control loop

As for the current state, a summary of the Centralized Model Predictive Control future state model is supplied below:

CENTRALIZED MODEL PREDICTIVE CONTROL
FERRARI SUPPLY CHAIN
FUTURE STATE

States: S, Ou, B, Sv
Control Variables: $x, O, d, p, Q, P, C, lb, pb, tt, oo, f$
Disturbance: $O_{Ferrari}$

Objective Function

$$J = \min \Bigg[\sum_{j=1}^{H_p} \sum_{i \in M} (w^B_{Ferrari} \cdot (B^i_{TAM}(t+j))^2 + \sum_{k \in N} (w^S_k \cdot (S^i_k(t+j) - S^i_{ref,k})^2 + w^B_k \cdot (B^i_k(t+j))^2 +$$
$$+ w^{Ou}_k \cdot (Ou^i_k(t+j))^2 + w^{\Delta O}_k \cdot (\Delta O^i_k(t+j))^2 + \sum_{k'' \in N} w^{\Delta XO}_k \cdot (\Delta XO^i_k(t+j))^2)) \Bigg],$$
$$\forall t \in (0, ..., T_{sim} - 1)$$

Equations

$$S^i_k(t+1) = S^i_k(t) + e^i_k \cdot \left(\sum_{k' \in N} \left(z_{k',k} \cdot x^i_{k',k}(t+1) \right) - C^i_k(t+1) \right)$$
$$+ o^i_k \cdot \left(P^i_k(t+1) - \sum_{k'' \in N} \left(z_{k,k''} \cdot x^i_{k,k''}(t+1) \right) \right), \qquad \forall i \in M, l \in L_k, k \in N$$

$$S^i_k(t+1) = S^i_k(t) + e^i_k \cdot \left(\sum_{k' \in N} \left(z_{k',k} \cdot x^i_{k',k}(t+1) \right) - d^i_k(t+1) \right), \forall i \in M, l \in L_k, k \in \{\text{Ferrari}\}$$

$$S_k^i(t+1) = S_k^i(t) + o_k^i \cdot \left(P_k^i(t+1) - \sum_{k'' \in N} \left(z_{k,k''} \cdot x_{k,k''}^i(t+1) \right) \right), \forall i \in M, l \in L_k, k \in T^2$$

$$Ou_k^i(t+1) = Ou_k^i(t) + O_k^i(t+1) - \sum_{k' \in N} x_{k',k}^i(t+1), \qquad \forall i \in M, l \in L_k, k \in N$$

$$B_k^i(t+1) = B_k^i(t) + d_k^i(t+1) - \sum_{k'' \in N} x_{k,k''}^i(t+1), \qquad \forall i \in M, l \in L_k, k \in N$$

$$Sv_k^i(t+1) = Sv_k^i(t) + o_k^i \cdot \left(P_k^i(t+1) - \sum_{k'' \in N} z_{k,k''} \cdot tt_{k,k''}^i(t+1) \right), \qquad \forall i \in M, l \in L_k, k \in N$$

Constraints

$$\sum_{i \in M} \sum_{t^*=t-LT_k^i+1}^{t} p_{i,k,l}(t^*) \leq 1, \qquad \forall k \in N \backslash \{\text{Ferrari}\}, \forall l \in L_k$$

$$Q_{i,k,l}(t) \leq p_{i,k,l}(t) \cdot V_l^k, \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\}, \forall l \in L_k$$

$$P_k^i(t) = \sum_{linL_k} Q_{i,k,l}(t + LT_k^i), \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\}$$

$$C_k^i(t) = \rho_i^r \dot{\sum}_{linL_k} Q_{i,k,l}(t + LT_k^i), \qquad \forall i \in M, \forall k \in N$$

$$\rho_i^r \cdot \sum_{linL_k} Q_{i,k,l}(t + LT_k^i) \leq S_k^r(t), \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\}, \forall l \in L_k$$

$$P_k^i(t) = PB_k^i \cdot pb_k^i(t), \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\}$$

$$x_{kk''}^i(t) \leq M \cdot o_k^i \cdot e_{k''}^i, \qquad \forall i \in M, \forall k, k'' \in N$$

$$tt_{kk''}^i(t) \leq Sv_k^i(t), \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\}, \forall k'' \in N$$

$$x_{kk''}^i(t + \tau_k^{k''}) = tt_{kk''}^i(t), \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\}, \forall k'' \in N$$

$$x_{kk''}^i(t) \leq LB_k^i \cdot lb_{kk''}^i(t), \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\}, \forall k'' \in N$$

$$O_{Ferrari}^{Dashboard}(t) = O_F^{Dashboard}(n+t)$$

$$d_k^i(t) = \sum_{k'' \in N} z_{kk''} \cdot O_{k''}^i, \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\}$$

$$\sum_{t^*=t-OF_k^i+1}^{t} f_k^i(t^*) \leq 1, \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\}$$

$$f_k^i(t + OF_k^i) = f_k^i(t), \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\}$$

$$O_k^i(t) \leq M \cdot f_k^i(t), \qquad \forall i \in M, \forall k \in N \backslash \{\text{Ferrari}\}$$

$$O_k^i(t) \leq LB_k^i \cdot oo_k^i(t), \qquad \forall i \in M, \forall k \in N$$

$$S_k^i, Ou_k^i, B_k^i, Sv_k^i, x_{k,k''}^i, p_{i,k,l}, Q_{i,k,l}, P_k^i, C_k^i, d_k^i, O_k^i, pb_k^i, lb_k^i, tt_{kk''}^i, oo_k^i, f_k^i \geq 0,$$
$$\forall i \in M, l \in L_k, k, k'' \in N$$

5.4 Simulation Scenarios

In order to demonstrate the validity of this digital innovation in practical industrial cases, the models described in the previous chapters are tested in different Supply Chain scenarios, where the dynamics of the logistic network are applied in different conditions, both in standard and in critical situations, where the system is pushed to the limit and disruptions put at risk the production continuity of the OEM. In this way, the two models can be compared under different circumstances, by studying how they react to the variation of boundary conditions and to adversities, especially when under pressure and with risk of shortages. This analysis has the goal to prove how an integrated Supply Chain has a better capability and robustness to handle this complexities than the current way of working, where the operations are more decentralized and companies tend to be self-centered.
The scenarios selected for this simulations are four and are all based on real or likely cases in an automotive Supply Chain. They are listed and explained in the following paragraphs.

Scenario 1: Zero Backlog

This scenario can be considered the least complex and represents a standard condition where the Supply Chain is working efficiently and no issues are being faced. Both Tier-1 and Tier-2 suppliers have initially zero backlog towards their clients and therefore there is no unfulfilled order in the system. Furthermore, no production issues or material shortages are experienced on both short- and long-term.
The objective of this simulation is to show how the two MPC models react in a standard and relatively controllable situation. The system is expected to work in a structured manner and maximize its performance.

Scenario 2: Backlog recovery

In this scenario, the system is tested with the first adversity. All suppliers have accumulated an important backlog towards their clients; therefore there is a potential risk of Ferrari to go out-of-stock, due to supplier inefficiencies. This situation creates more urgency in the logistic operations and brings entropy to the system, which is expected to work more extra-flux to make up for the initial issues, in order not to stop Ferrari's production.
The simulation aims to compare the behaviours of the two models while recovering an initial backlog. The recovery speed will be analyzed and the final performances will be assessed through the KPIs.

Scenario 3: Material Shortage

In this simulation, the system is put under stress, with a serious risk of production blockage, due to a semiconductor shortage. This phenomenon is causing Mtronic to partially stop its production, reduce the delivery frequency and accumulate a very high backlog towards its clients. This situation is planned to last for a long-horizon. Since the electronic board supply is scarce, the logistic network needs to handle the situation not only to avoid missing dashboards on Ferrari's cars, but, in case that happens, reduce as much as possible the damages to the production line and the amount of incomplete vehicles.
With this scenario, the two MPC models will be compared in a high risk conditions where the decision-making process is critical and decisive for the companies' business.

Scenario 4: Demand Variation

In this final scenario, Ferrari would like to analyze how its Supply Chain is sensitive to a rapid variation of its production mix, which can cause for some products a reduction in the demand, but for others (as the dashboard here selected) a sudden peak in the orders, which may create a bullwhip effect through the Supply Chain and augment the system complexity. The parameter guiding the simulation in this case are the disturbances $d_{Ferrari}$ and $O_{Ferrari}$ which will be suddenly changed at a time instant along the simulation time.
The ability of the two models to react and adjust their logistic performance will be assessed, to evaluate which MPC technique achieves a higher robustness.

6 Results & Discussion

After discussing the current and future state (Chapter 3 and 4), presenting the Supply Chain model (Chapter 4) and explaining the scenarios chosen for the simulation and comparison of the Centralized MPC and Decentralized MPC agent (Chapter 5), in this chapter the results of the simulations are displayed in detail through the analysis of graphs and KPIs, in order to understand the different outputs of the two control methods and leave space to the discussion of the final thesis.
The research subquestions answered in this chapter are the following:

- How do Centralized MPC and Decentralized MPC perform in a Supply Chain control tower?
  1. How do CMPC and DMPC perform in a standard situation with zero backlog?
  2. How do CMPC and DMPC manage to recover initial backlogs over the Supply Chain tiers?
  3. How do CMPC and DMPC control the Supply Chain in case of disruption?
  4. How much are CMPC and DMPC sensitive to a rapid variation of the OEM's demand?

In the following sections, the outputs of the CMPC and DMPC algorithms applied to Ferrari's Supply Chains are compared through every scenario. The resulting Key Performance Indicators are presented alongside the graphs of components stock and backlog, while the graphs of the produced and ordered quantities can be observed in the Appendix. The stock graphs present the amount of material entering and exiting the warehouse over the simulation time. In the final part, with an overview over all the simulations, the performance of the two control models is compared and discussed.

6.1 Scenario 1: Zero Backlog

As introduced in Chapter 5, the first comparison between the two MPC models is conducted in a standard, ideal situation, where both Tier-1 and Tier-2 suppliers have zero backlog on their client's orders. For this reason every backlog at simulation time step $n = 0$ is set to 0. In this way, the MIQP optimization problem will simulate how DMPC and CMPC behave in this situation and compare their performance. This scenario is meant to show how the models work in an unstressed situation and how well they can keep this condition in the Supply Chain.

Decentralized MPC - Scenario 1

The outputs of the Decentralized MPC simulation for Scenario 1 are displayed below for every company composing the Supply Chain studied.

Dashboard

The results of the dashboard stock at Ferrari and TAM's warehouse over the simulation time are here depicted, alongside the backlog accumulated by TAM:

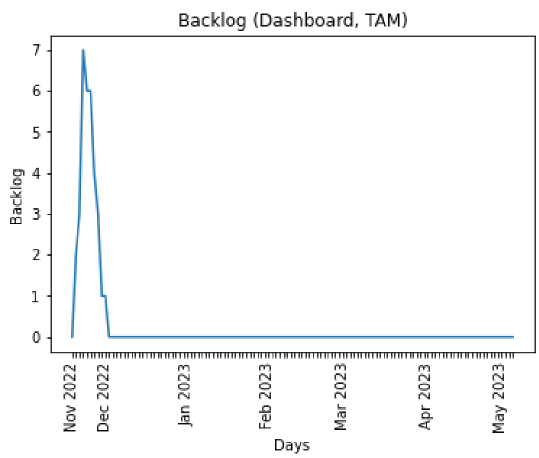

Figure 40: TAM's dashboard backlog, DMPC, Scenario 1

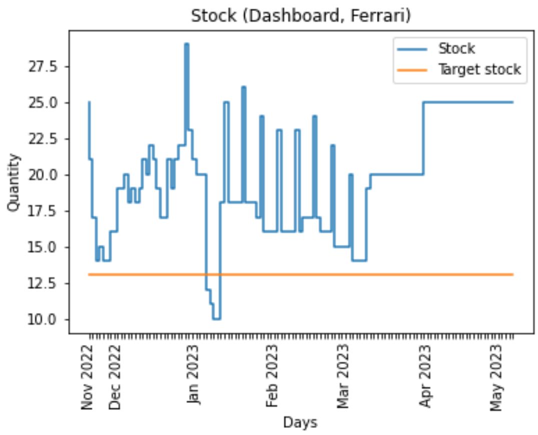

Figure 41: Dashboard stock at Ferrari, DMPC, Scenario 1

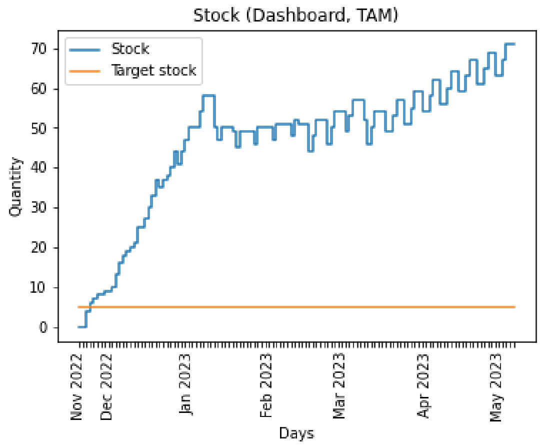

Figure 42: Dashboard stock at TAM, DMPC, Scenario 1

Cover

The results of the cover stock at TAM and ProPlastic's warehouse over the simulation time are here depicted, alongside the backlog accumulated by ProPlastic:

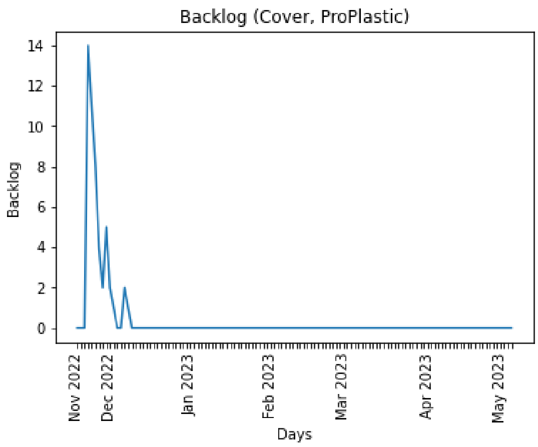

Figure 43: ProPlastic's cover backlog, DMPC, Scenario 1

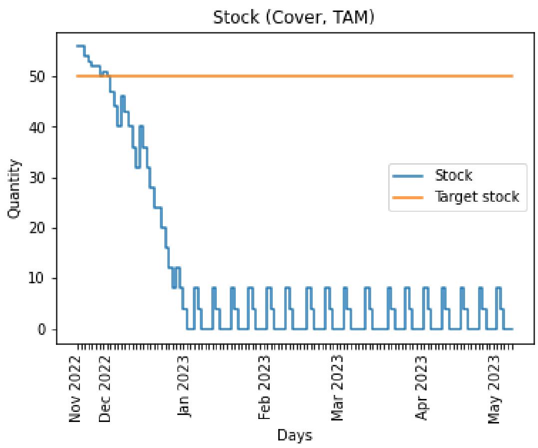

Figure 44: Cover stock at TAM, DMPC, Scenario 1

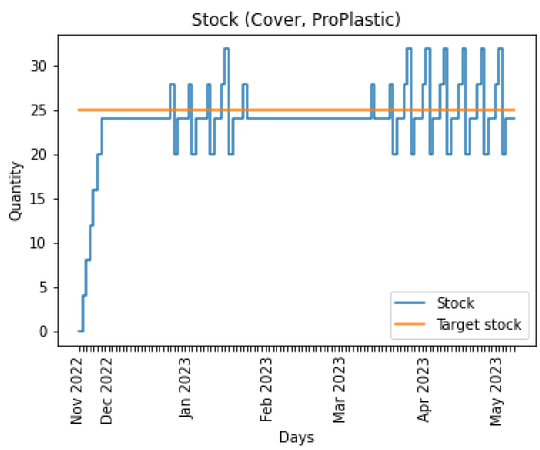

Figure 45: Cover stock at ProPlastic, DMPC, Scenario 1

Electronic Board

The results of the electronic board stock at TAM and Mtronic's warehouse over the simulation time are here depicted, alongside the backlog accumulated by Mtronic:

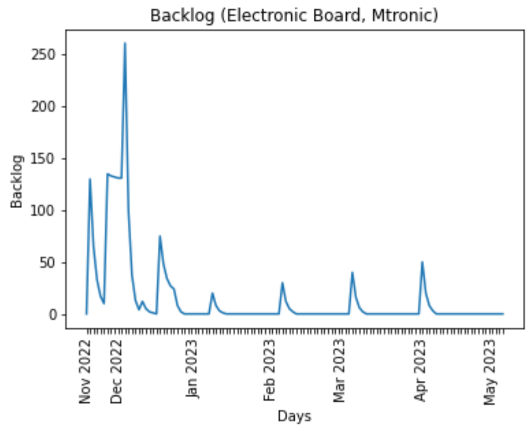

Figure 46: Mtronic's electronic board backlog, DMPC, Scenario 1

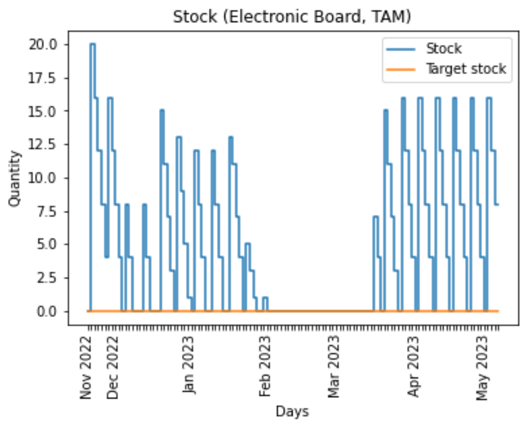

Figure 47: Electronic board stock at TAM, DMPC, Scenario 1

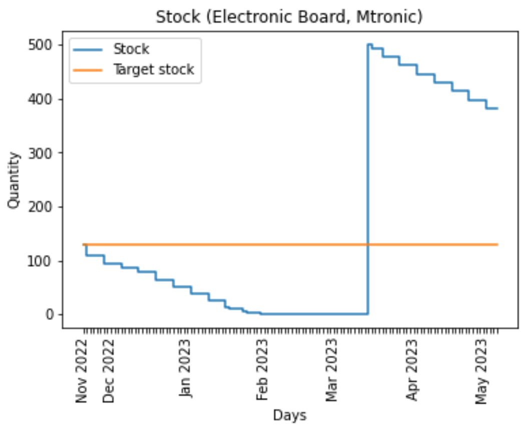

Figure 48: Electronic board stock at Mtronic, DMPC, Scenario 1

TFT Display

The results of the TFT display stock at TAM and EBOVx's warehouse over the simulation time are here depicted, alongside the backlog accumulated by EBOVx:

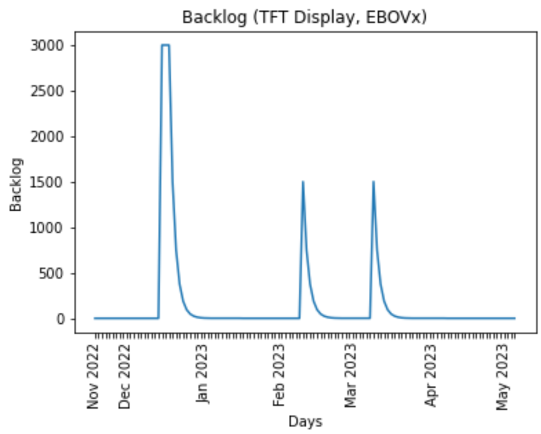

Figure 49: EBOVx's TFT display backlog, DMPC, Scenario 1

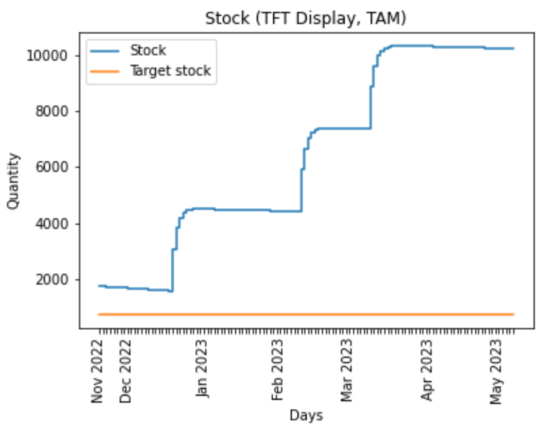

Figure 50: TFT display stock at TAM, DMPC, Scenario 1

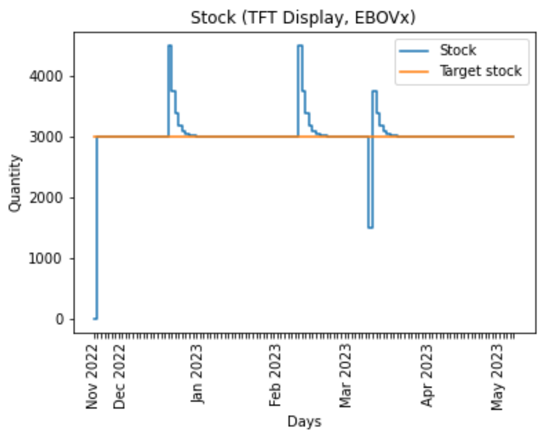

Figure 51: TFT display stock at EBOVx, DMPC, Scenario 1

Centralized MPC - Scenario 1

The outputs of the Centralized MPC simulation for Scenario 1 are displayed below for every company composing the Supply Chain studied.

Dashboard

The results of the dashboard stock at Ferrari and TAM's warehouse over the simulation time are here depicted, alongside the backlog accumulated by TAM:

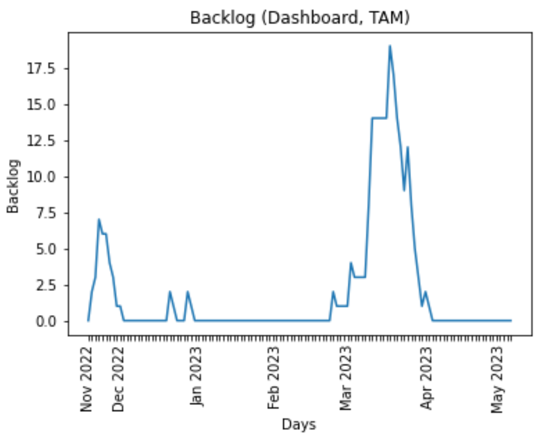

Figure 52: TAM's dashboard backlog, CMPC, Scenario 1

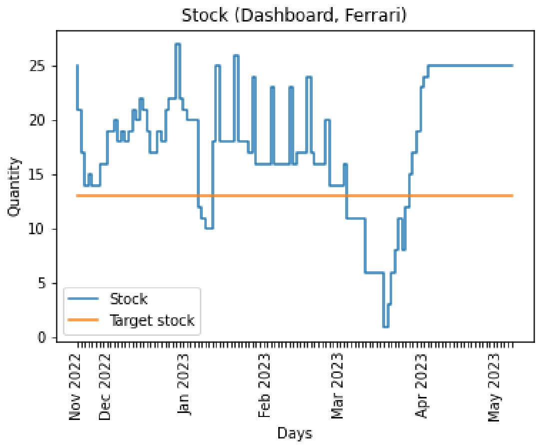

Figure 53: Dashboard stock at Ferrari, CMPC, Scenario 1

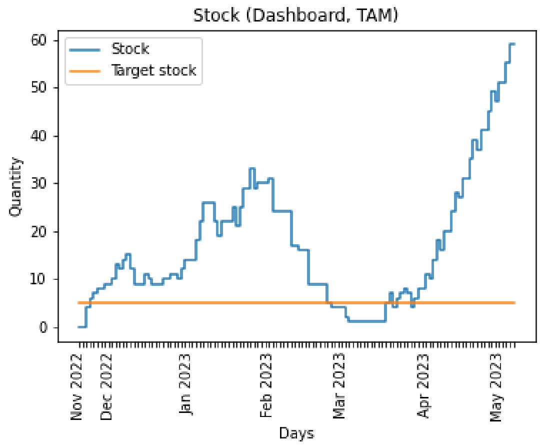

Figure 54: Dashboard stock at TAM, CMPC, Scenario 1

Cover

The results of the cover stock at TAM and ProPlastic's warehouse over the simulation time are here depicted, alongside the backlog accumulated by ProPlastic:

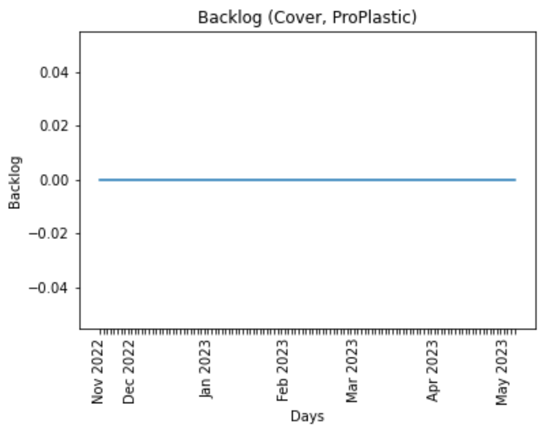

Figure 55: ProPlastic's cover backlog, CMPC, Scenario 1

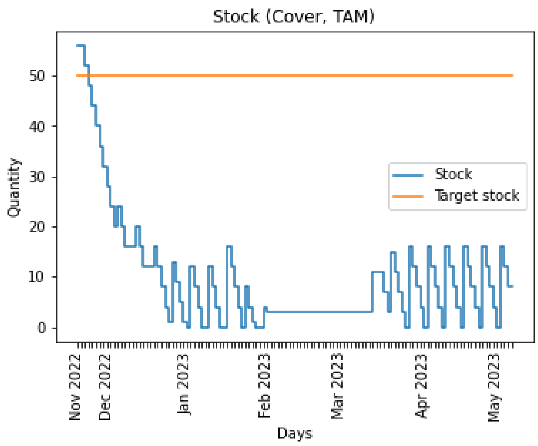

Figure 56: Cover stock at TAM, CMPC, Scenario 1

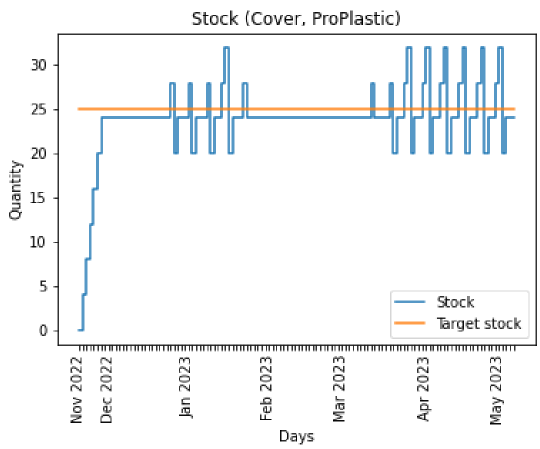

Figure 57: Cover stock at ProPlastic, CMPC, Scenario 1

Electronic Board

The results of the electronic board stock at TAM and Mtronic's warehouse over the simulation time are here depicted, alongside the backlog accumulated by Mtronic:

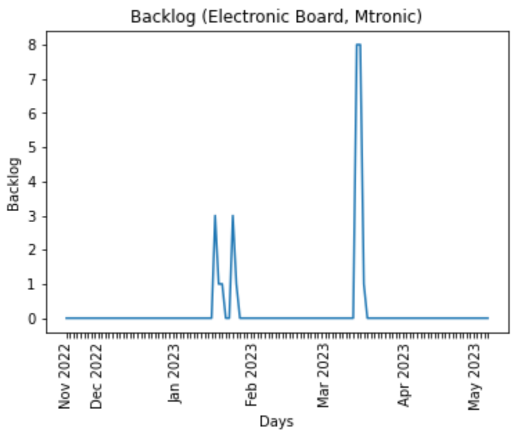

Figure 58: Mtronic's electronic board backlog, CMPC, Scenario 1

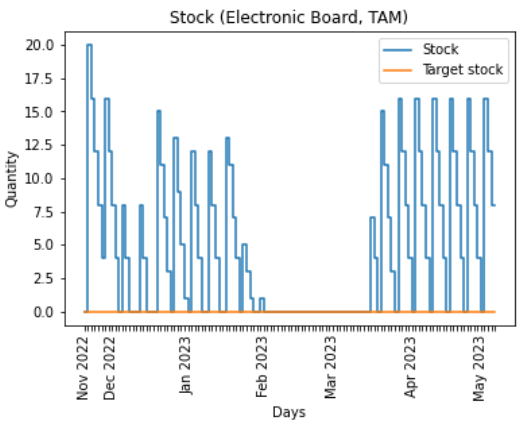

Figure 59: Electronic board stock at TAM, CMPC, Scenario 1

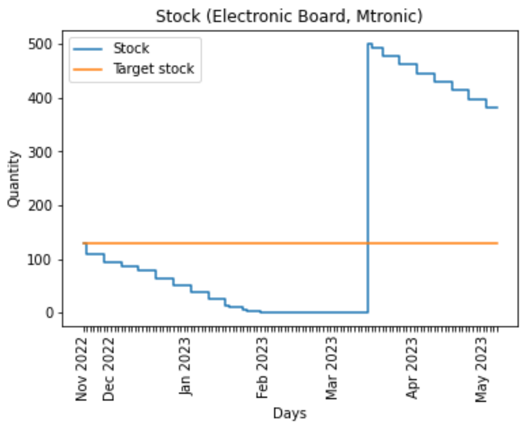

Figure 60: Electronic board stock at Mtronic, CMPC, Scenario 1

TFT Display

The results of the TFT display stock at TAM and EBOVx's warehouse over the simulation time are here depicted, alongside the backlog accumulated by EBOVx:

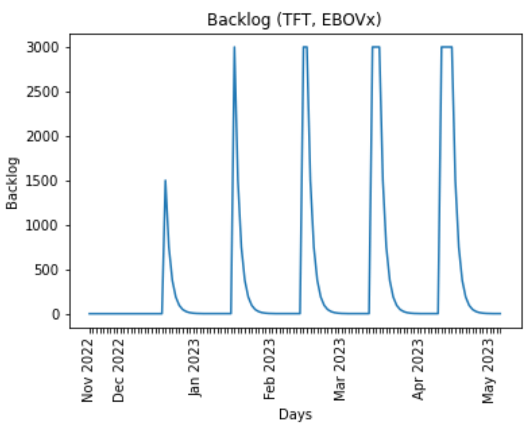

Figure 61: EBOVx's TFT display backlog, CMPC, Scenario 1

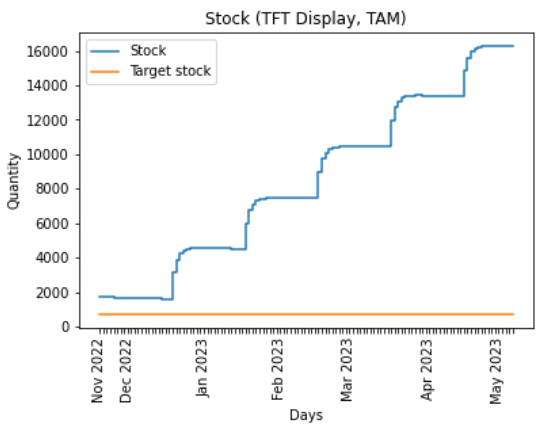

Figure 62: TFT display stock at TAM, CMPC, Scenario 1

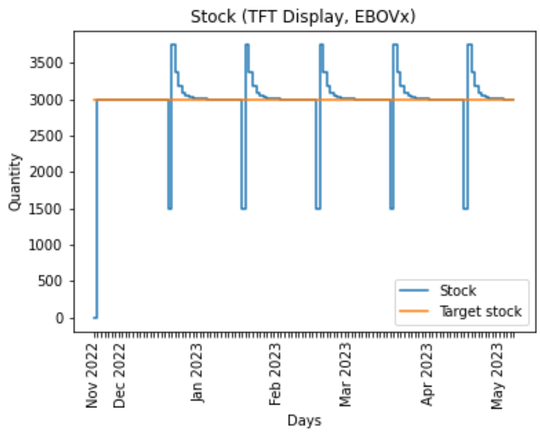

Figure 63: TFT display stock at EBOVx, CMPC, Scenario 1

To summarize the results shown in the graphs and the outputs of Scenario 1's DMPC and CMPC simulations, the KPIs of the two models are displayed in Table 9 and 10.

Table 9: Scenario 1 KPIs, DMPC

DMPC	
Simulation Time	23734 s (6.5 h)
Stock Index	207.0
Backlog Index	3.8
Supplier Punctuality	76%
Number of Transports	175
Order Variation	81%

Table 10: Scenario 1 KPIs, CMPC

CMPC	
Simulation Time	5148 s (1.4 h)
Stock Index	24.6
Backlog Index	0.59
Supplier Punctuality	68%
Number of Transports	156
Order Variation	75%

The KPIs comparison of the two models shows a higher performance of the CMPC model, in terms of both logistic efficiency, computational cost and sustainability.
As a first glimpse, by looking at some graphs it may seem that the decentralized scheme guarantees a lower risk to the production continuity of Ferrari's factory, since, as it can be seen in Figure 40 and 52, in the CMPC output, the Tier-1 backlog reaches a peak of 19 pieces around half of March. However, as the goal of this thesis is to show how the Supply Chain benefits as a whole from a centralized and coordinated control strategy, the KPIs are the most important parameters to analyze to give a final comparison of the two strategies.
By observing in detail the indices, the stock and backlog indices demonstrate that the Supply Chain, performs better in the centralized scheme: backlogs are lower over the whole simulation time and warehouse target stocks are more respected than in the decentralized control output. Furthermore, although order variation is high (75%), the CMPC controller improves the current order distribution. The centralized controller also shows to have a lower environmental footprint, as transports are reduced of 10% with this strategy. Finally, CMPC presents also benefits in the computational cost, as the running time decreases up to 78%.
The only worse parameter is the supplier punctuality, which lowers of 11%: this is due to a delay in the production of electronic boards by Mtronic, which causes the dashboard manufacturer to have zero stock for about half a month. This behaviour is what influences the dashboard backlog peak discussed above. However, this result is considered acceptable, as the dashboard order sent by Ferrari is not a computed input by the controller but is the only disturbance of the system and is a real, fixed data taken from Ferrari's programs. In spite of this, the simulation shows that Ferrari always manages to satisfy its production demand and guarantee its continuous production flow.

6.2 Scenario 2: Backlog Recovery

With this scenario, the system is for the first time tested in a negative situation: every supplier has initially accumulated a considerable backlog, that needs to be recovered. Through these simulations, it is investigated how the CMPC and DMPC are capable of eliminating the initial deviation and how fast they are able to do it. Oppositely to Scenario 1, where no parameter was touched, in this case it is necessary to set an initial backlog ($B^i_{k,fin}(0) = 0, \forall k \in N \backslash \{\text{Ferrari}\}$). It is important to notice that, as every logistic bridge in this study case is single sourcing, the supplier backlog always equals the client's unfulfilled order. The values chosen in this case are displayed in Table 11.

Table 11: Initial backlog defined for Scenario 2 simulations

	Dashboard	**Cover**	**Electronic Board**	**TFT Display**
TAM	70	-	-	-
ProPlastic	-	102	-	-
Mtronic	-	-	100	-
EBOVx	-	-	-	179

Decentralized MPC - Scenario 2

The outputs of the Decentralized MPC simulation for Scenario 2 are displayed below for every company composing the Supply Chain studied.

Dashboard

The results of the dashboard stock at Ferrari and TAM's warehouse over the simulation time are here depicted, alongside the backlog accumulated by TAM:

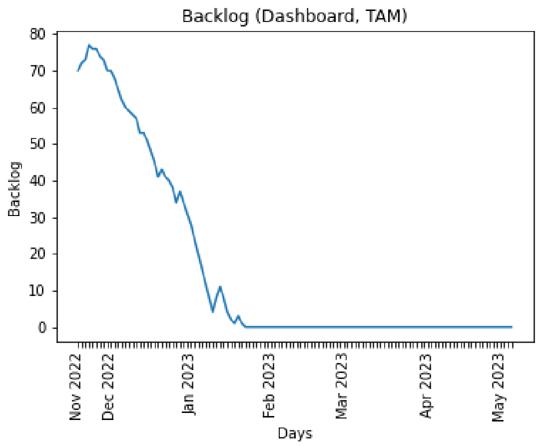

Figure 64: TAM's dashboard backlog, DMPC, Scenario 2

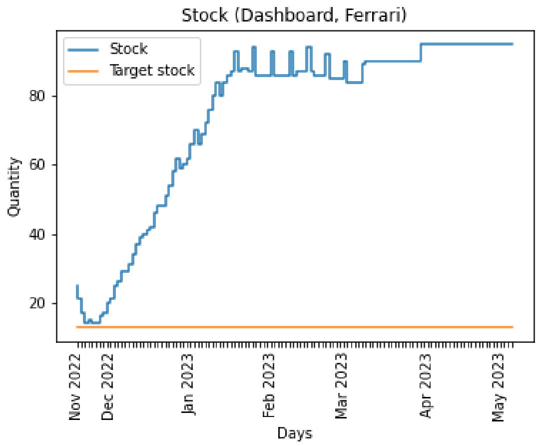

Figure 65: Dashboard stock at Ferrari, DMPC, Scenario 2

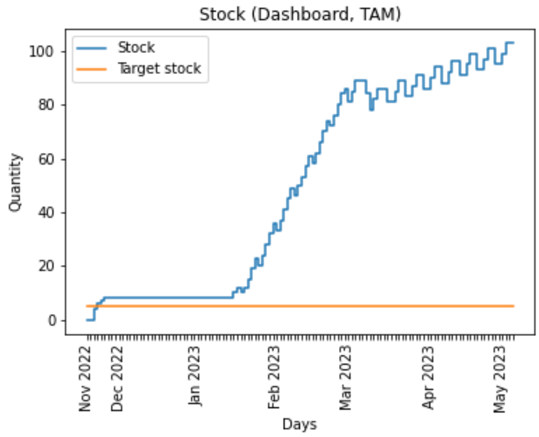

Figure 66: Dashboard stock at TAM, DMPC, Scenario 2

Cover

The results of the cover stock at TAM and ProPlastic's warehouse over the simulation time are here depicted, alongside the backlog accumulated by ProPlastic:

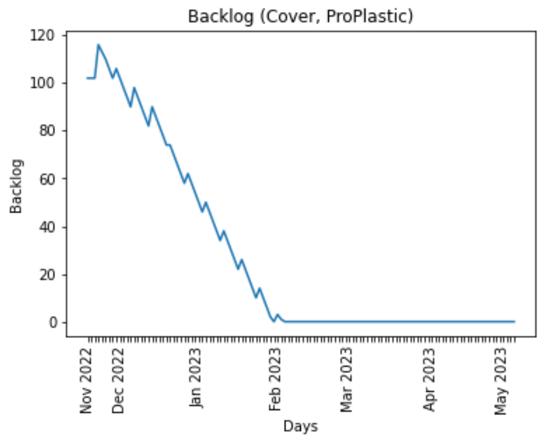

Figure 67: ProPlastic's cover backlog, DMPC, Scenario 2

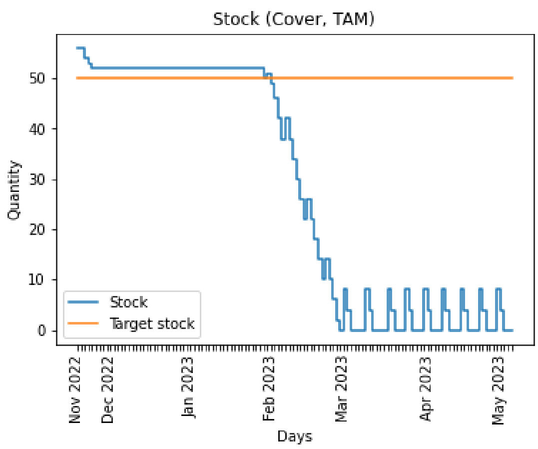

Figure 68: Cover stock at TAM, DMPC, Scenario 2

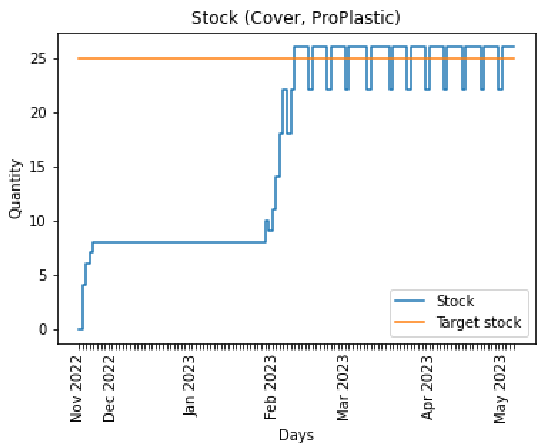

Figure 69: Cover stock at ProPlastic, DMPC, Scenario 2

Electronic Board

The results of the electronic board stock at TAM and Mtronic's warehouse over the simulation time are here depicted, alongside the backlog accumulated by Mtronic:

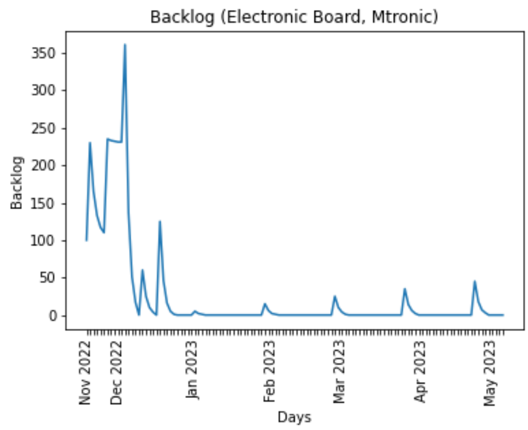

Figure 70: Mtronic's electronic board backlog, DMPC, Scenario 2

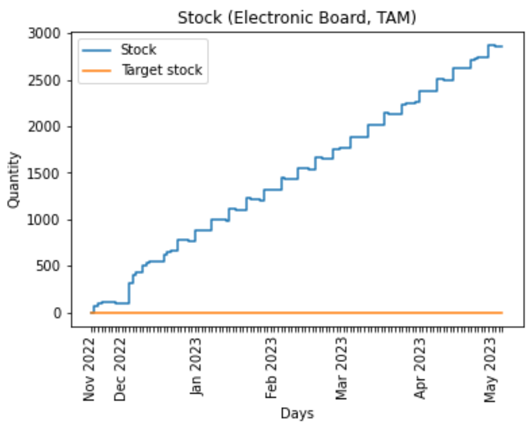

Figure 71: Electronic board stock at TAM, DMPC, Scenario 2

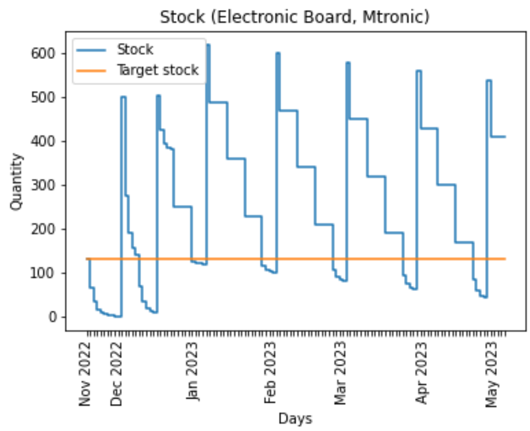

Figure 72: Electronic board stock at Mtronic, DMPC, Scenario 2

TFT Display

The results of the TFT display stock at TAM and EBOVx's warehouse over the simulation time are here depicted, alongside the backlog accumulated by EBOVx:

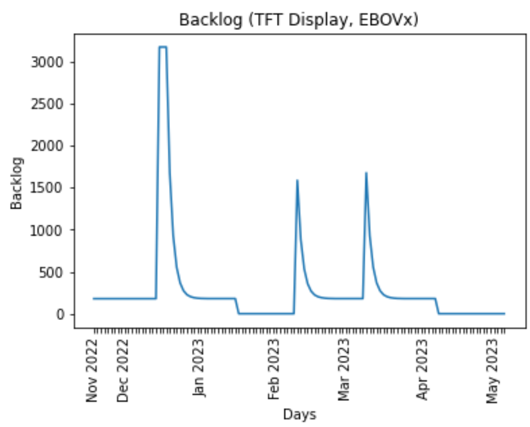

Figure 73: EBOVx's TFT display backlog, DMPC, Scenario 2

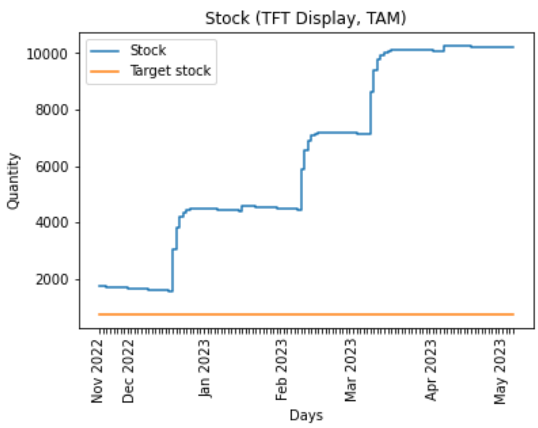

Figure 74: TFT display stock at TAM, DMPC, Scenario 2

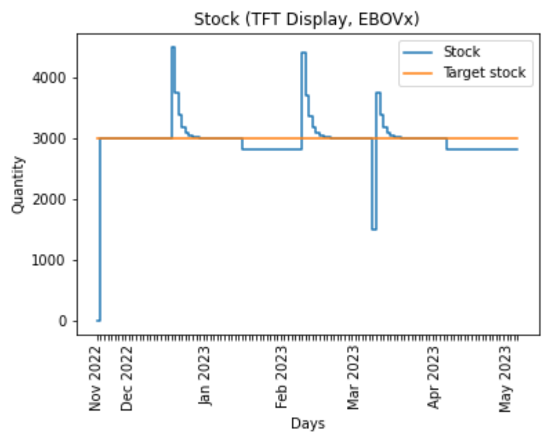

Figure 75: TFT display stock at EBOVx, DMPC, Scenario 2

Centralized MPC - Scenario 2

The outputs of the Centralized MPC simulation for Scenario 2 are displayed below for every company composing the Supply Chain studied.

Dashboard

The results of the dashboard stock at Ferrari and TAM's warehouse over the simulation time are here depicted, alongside the backlog accumulated by TAM:

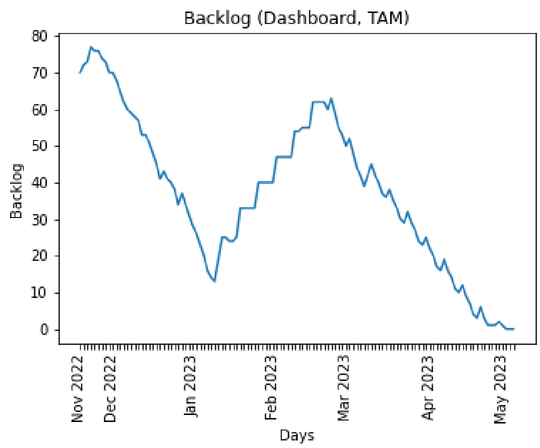

Figure 76: TAM's dashboard backlog, CMPC, Scenario 2

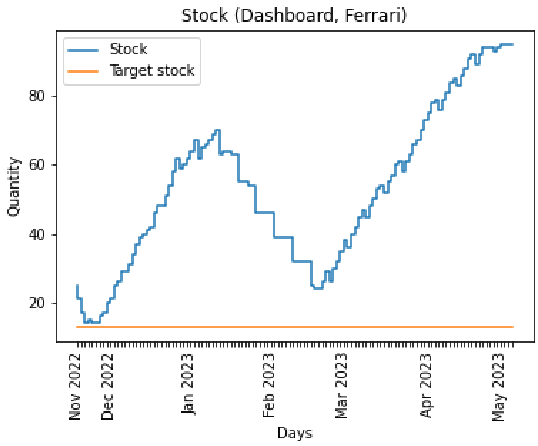

Figure 77: Dashboard stock at Ferrari, CMPC, Scenario 2

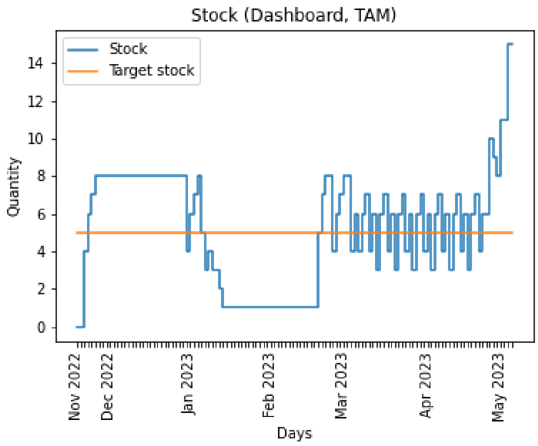

Figure 78: Dashboard stock at TAM, CMPC, Scenario 2

Cover

The results of the cover stock at TAM and ProPlastic's warehouse over the simulation time are here depicted, alongside the backlog accumulated by ProPlastic:

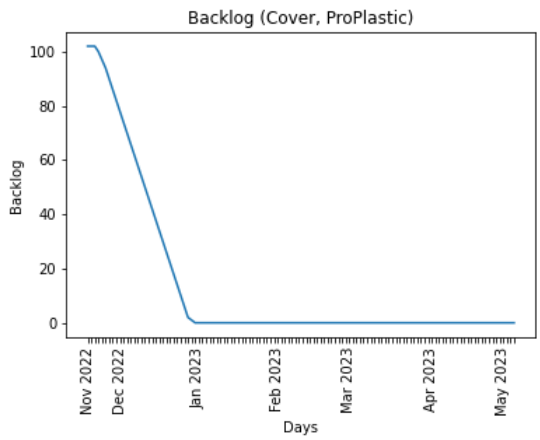

Figure 79: ProPlastic's cover backlog, CMPC, Scenario 2

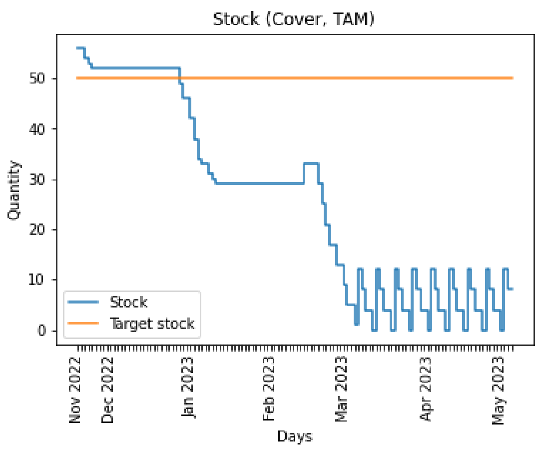

Figure 80: Cover stock at TAM, CMPC, Scenario 2

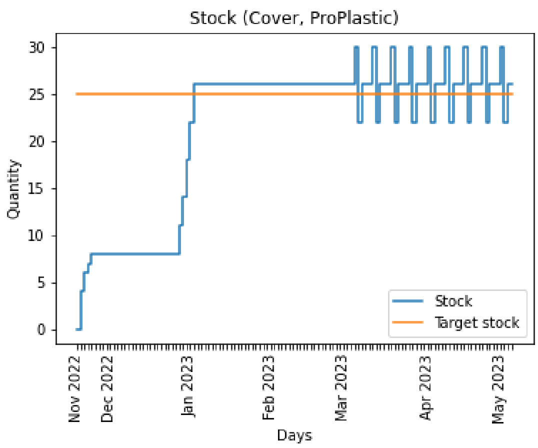

Figure 81: Cover stock at ProPlastic, CMPC, Scenario 2

Electronic Board

The results of the electronic board stock at TAM and Mtronic's warehouse over the simulation time are here depicted, alongside the backlog accumulated by Mtronic:

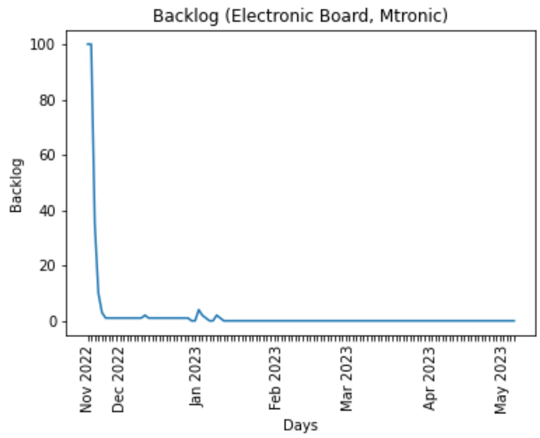

Figure 82: Mtronic's electronic board backlog, CMPC, Scenario 2

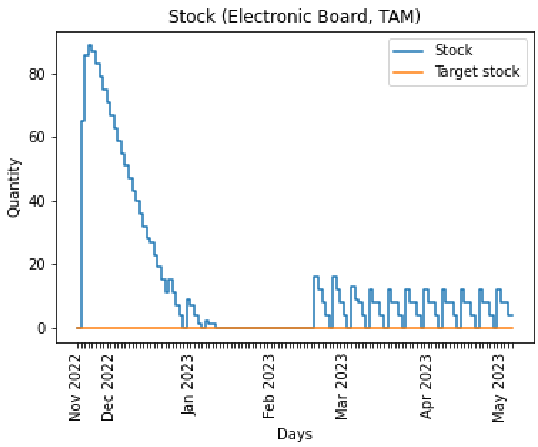

Figure 83: Electronic board stock at TAM, CMPC, Scenario 2

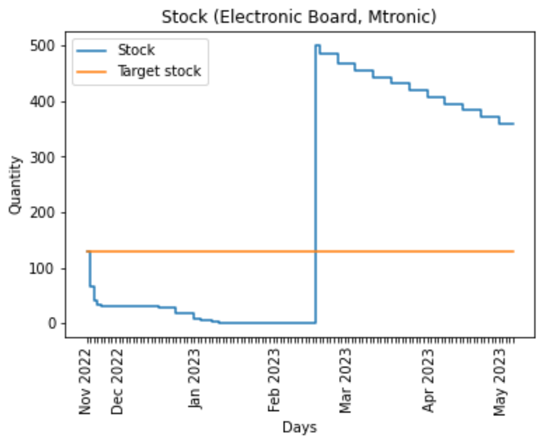

Figure 84: Electronic board stock at Mtronic, CMPC, Scenario 2

TFT Display

The results of the TFT display stock at TAM and EBOVx's warehouse over the simulation time are here depicted, alongside the backlog accumulated by EBOVx:

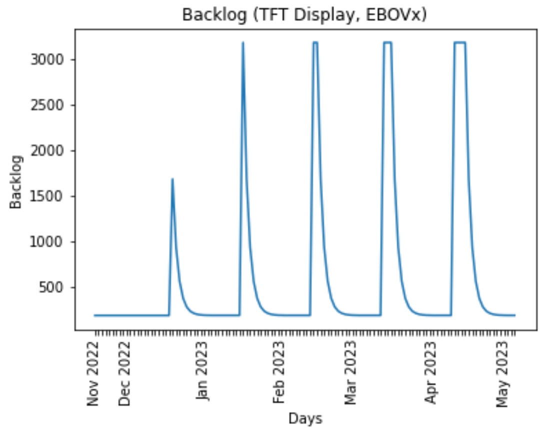

Figure 85: EBOVx's TFT display backlog, CMPC, Scenario 2

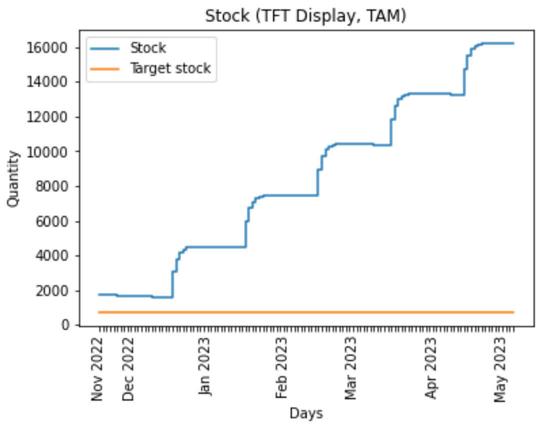

Figure 86: TFT display stock at TAM, CMPC, Scenario 2

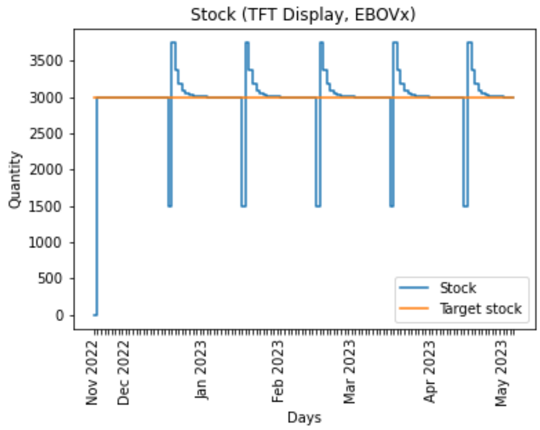

Figure 87: TFT display stock at EBOVx, CMPC, Scenario 2

The results for Scenario 2 displayed in the previous graphs can be summarized in the measured Supply Chain KPIs, presented in Table 12 and 13.

Table 12: Scenario 2 KPIs, DMPC

DMPC	
Simulation Time	26059 s (7.2 h)
Stock Index	219.0
Backlog Index	12.1
Supplier Punctuality	45%
Number of Transports	222
Order Variation	81%

Table 13: Scenario 2 KPIs, CMPC

CMPC	
Simulation Time	4823 s (1.3 h)
Stock Index	32.7
Backlog Index	10.8
Supplier Punctuality	35%
Number of Transports	211
Order Variation	72%

In Scenario 2 the DMPC and CMPC model have been compared not only through their KPIs, but especially in their ability to recover from a high backlog set at the beginning of the simulation. An analysis of the graphs is reported in Table 14, where the backlog recovery dates have been collected for every product.

Table 14: Comparison between the months of complete backlog recovery for DMPC and CMPC model

	DMPC	CMPC
Dashboard - TAM	January 2023	May 2023
Cover - ProPlastic	February 2023	January 2023
Electronic board - Mtronic	December 2022	November 2022
TFT display - EBOVx	Variable	Variable

This table shows that in the CMPC simulation, ProPlastic and Mtronic manage to recover the initial backlogs faster than with DMPC. However, an important struggle is recorded for the recovery of the dashboard backlog by TAM. Even in this case, this is due to a delayed production batch of Mtronic, that, since the dashboard order is a system disturbance and is fixed over time, does not allow a linear backlog recovery, which happens only at the sixth month of simulation. As in Scenario 1, this issue does not compromise the production flow in Ferrari's factory.

On the other hand, by analyzing Scenario 2's KPIs, the overall results favor the management of the centralized controller, as it reduces both the stock (-85%) and backlog index (-11%). As in the previous case also the order variation factor, the number of transports and the computational cost improve in comparison with the DMPC scheme. Supplier punctuality, instead lowers of 23%, for the reasons explained above.

Following this detailed analysis of the performance indices and the models' ability to recover the initial backlog, CMPC can be considered the better solution for the thesis that this research work aims to demonstrate: although it may not perform the best in every logistic operation, the centralized MPC strategy presents a better overall coordination between tiers and enhances a more solid partnership between companies through data visibility.

6.3 Scenario 3: Material Shortage

In the third scenario, the Supply Chain is tested with the most challenging situation: a semiconductor disruption is simulated on the production of the electronic board manufacturer (Mtronic). A shortage of semiconductors does not allow it to produce for the first month, creating a potential risk of blocking Ferrari's production.

The goal of this simulation is to investigate how the two MPC strategies react to such an impacting event and to assess which one results the most robust to market and global uncertainties. This is a crucial case for the determination of the validity of the centralized control application, as it should handle complex scenarios like this one in a coordinated and cooperative way along the Supply Chain tiers, instead of a decentralized strategy more focused on solving the single business' issue. Moreover, since semiconductor shortages are a hot topic in Supply Chains, it is essential to assess this innovative solution on a practical scenario.

To run this simulation, the supplier backlog at the initial discrete time step (and consequently the client unfulfilled order) is initialized as depicted in Table 15, and an initialization constraint blocking the first 20 working days of Mtronic's production is added, in order to represent the effect of the semiconductor shortage.

Table 15: Initial backlog defined for Scenario 3 simulations

	Dashboard	**Cover**	**Electronic Board**	**TFT Display**
TAM	0	-	-	-
ProPlastic	-	102	-	-
Mtronic	-	-	0	-
EBOVx	-	-	-	179

Decentralized MPC - Scenario 3

The outputs of the Decentralized MPC simulation for Scenario 3 are displayed below for every company composing the Supply Chain studied.

Dashboard

The results of the dashboard stock at Ferrari and TAM's warehouse over the simulation time are here depicted, alongside the backlog accumulated by TAM:

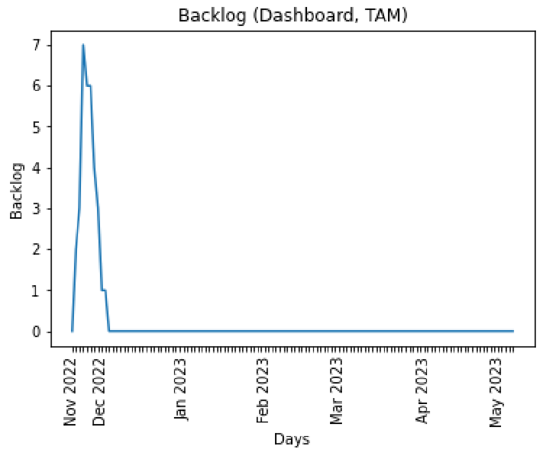

Figure 88: TAM's dashboard backlog, DMPC, Scenario 3

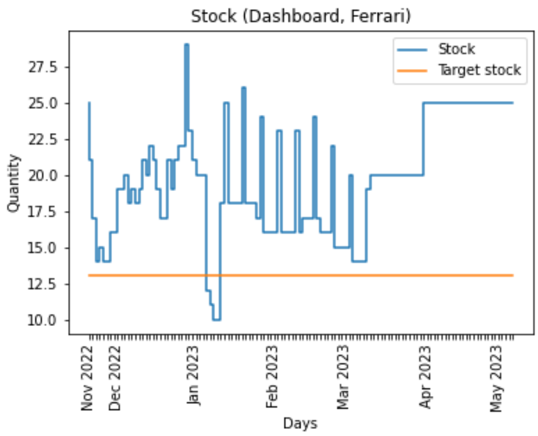

Figure 89: Dashboard stock at Ferrari, DMPC, Scenario 3

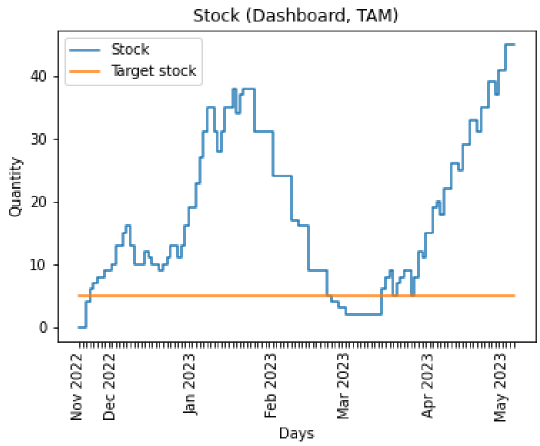

Figure 90: Dashboard stock at TAM, DMPC, Scenario 3

Cover

The results of the cover stock at TAM and ProPlastic's warehouse over the simulation time are here depicted, alongside the backlog accumulated by ProPlastic:

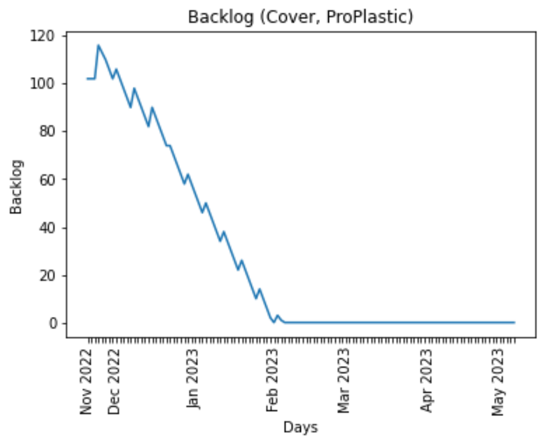

Figure 91: ProPlastic's cover backlog, DMPC, Scenario 3

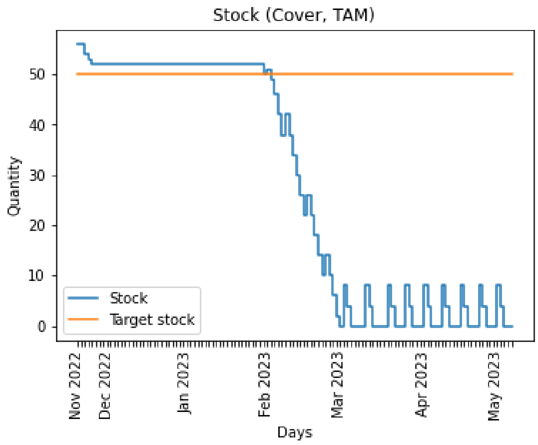

Figure 92: Cover stock at TAM, DMPC, Scenario 3

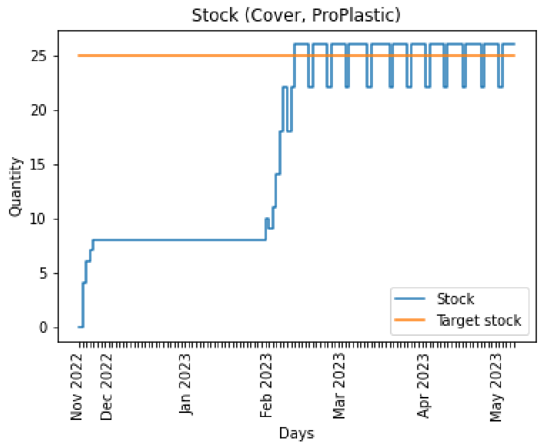

Figure 93: Cover stock at ProPlastic, DMPC, Scenario 3

Electronic Board

The results of the electronic board stock at TAM and Mtronic's warehouse over the simulation time are here depicted, alongside the backlog accumulated by Mtronic:

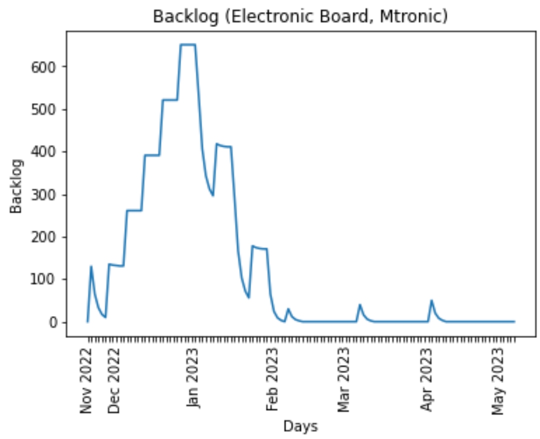

Figure 94: Mtronic's electronic board backlog, DMPC, Scenario 3

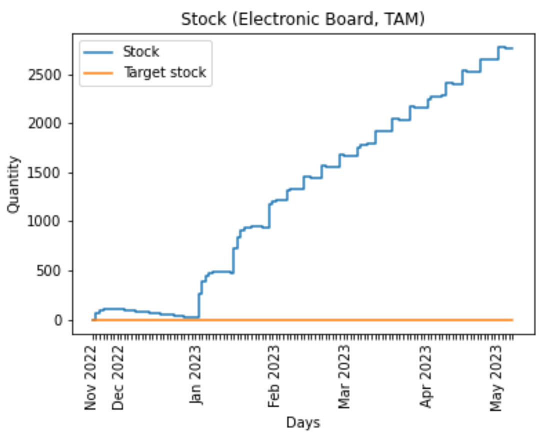

Figure 95: Electronic board stock at TAM, DMPC, Scenario 3

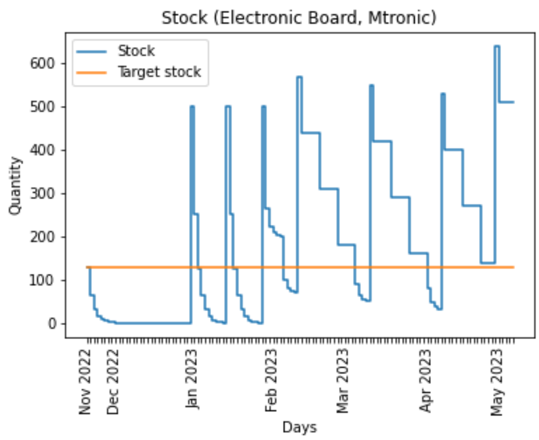

Figure 96: Electronic board stock at Mtronic, DMPC, Scenario 3

TFT Display

The results of the TFT display stock at TAM and EBOVx's warehouse over the simulation time are here depicted, alongside the backlog accumulated by EBOVx:

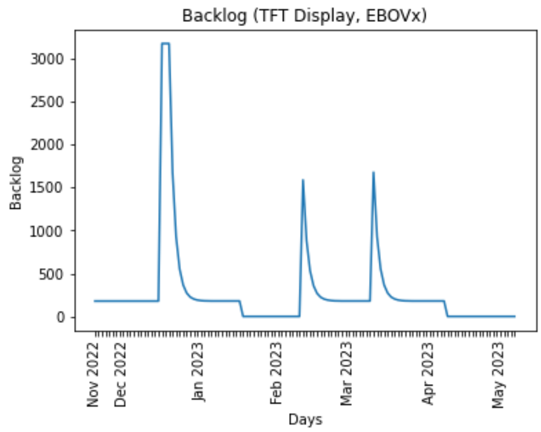

Figure 97: EBOVx's TFT display backlog, DMPC, Scenario 3

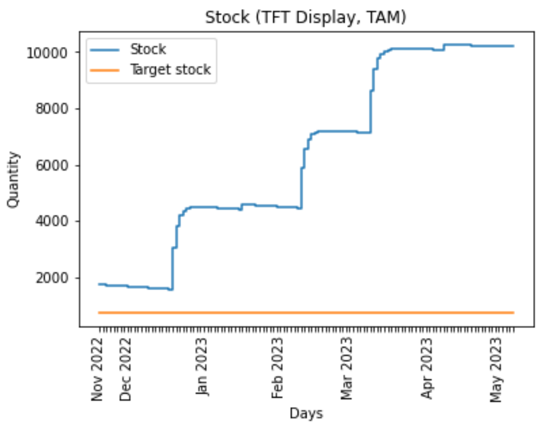

Figure 98: TFT display stock at TAM, DMPC, Scenario 3

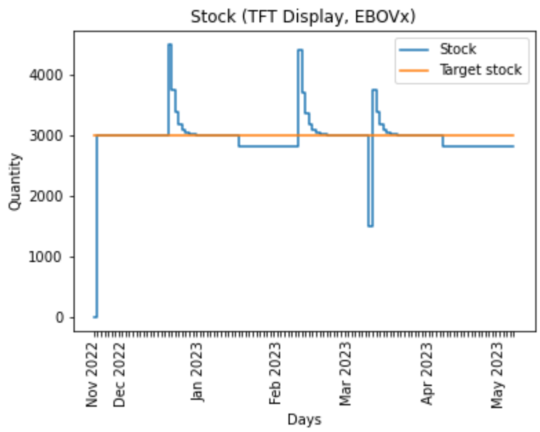

Figure 99: TFT display stock at EBOVx, DMPC, Scenario 3

Centralized MPC - Scenario 3

The outputs of the Centralized MPC simulation for Scenario 3 are displayed below for every company composing the Supply Chain studied.

Dashboard

The results of the dashboard stock at Ferrari and TAM's warehouse over the simulation time are here depicted, alongside the backlog accumulated by TAM:

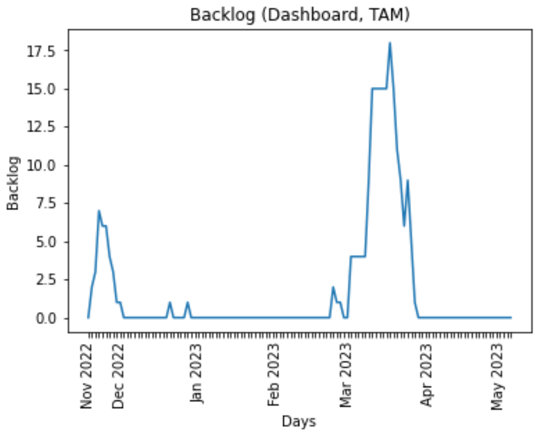

Figure 100: TAM's dashboard backlog, CMPC, Scenario 3

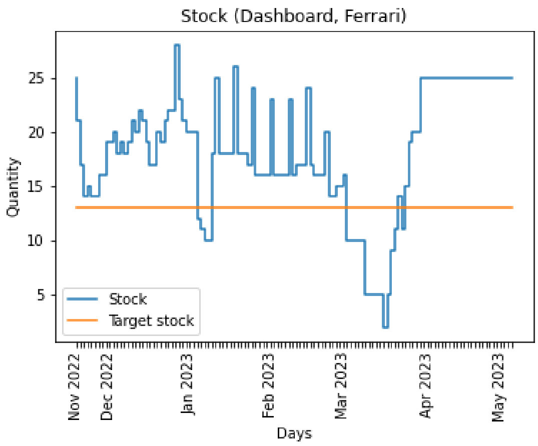

Figure 101: Dashboard stock at Ferrari, CMPC, Scenario 3

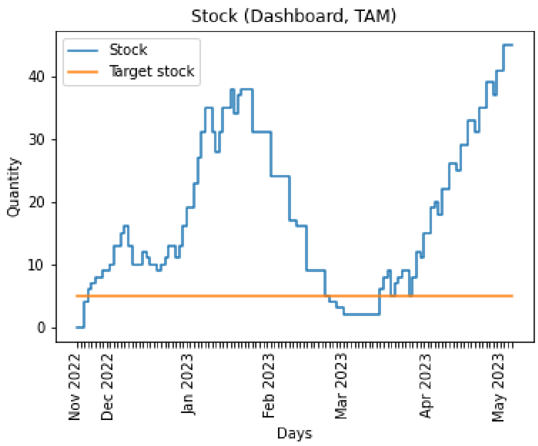

Figure 102: Dashboard stock at TAM, CMPC, Scenario 3

Cover

The results of the cover stock at TAM and ProPlastic's warehouse over the simulation time are here depicted, alongside the backlog accumulated by ProPlastic:

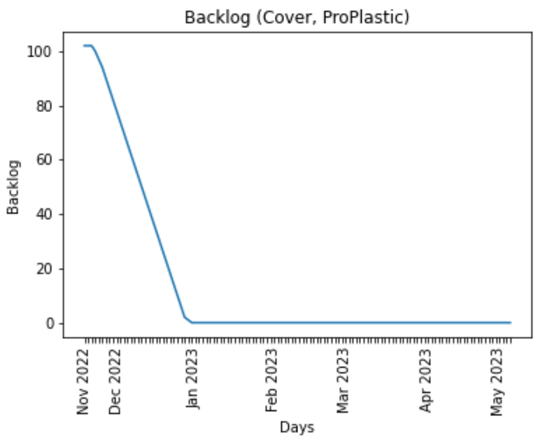

Figure 103: ProPlastic's cover backlog, CMPC, Scenario 3

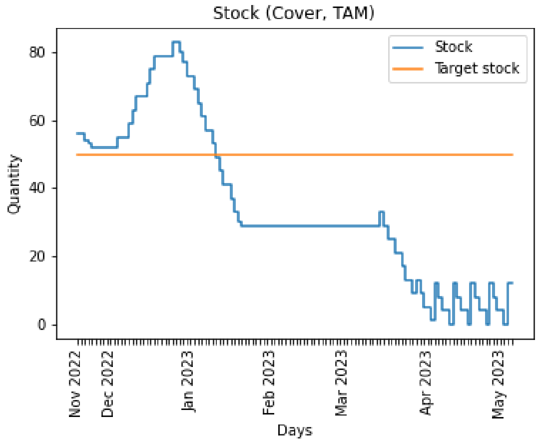

Figure 104: Cover stock at TAM, CMPC, Scenario 3

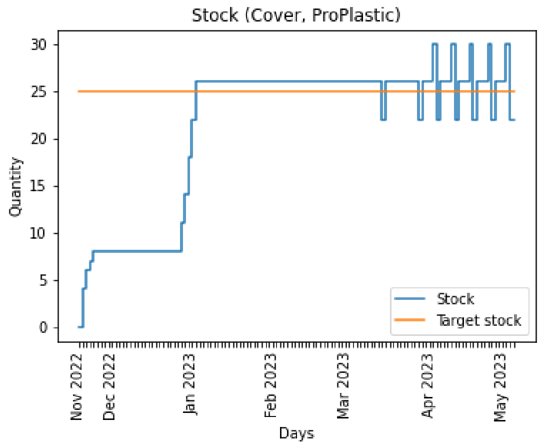

Figure 105: Cover stock at ProPlastic, CMPC, Scenario 3

Electronic Board

The results of the electronic board stock at TAM and Mtronic's warehouse over the simulation time are here depicted, alongside the backlog accumulated by Mtronic:

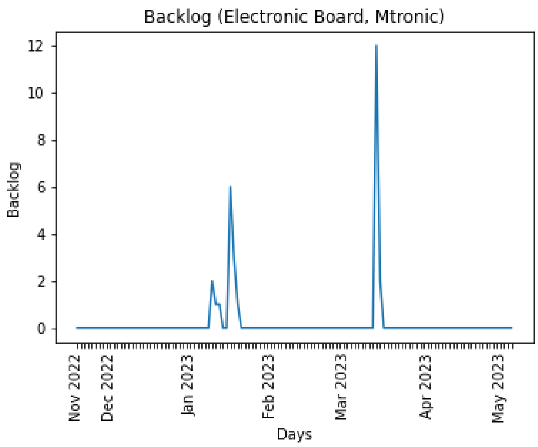

Figure 106: Mtronic's electronic board backlog, CMPC, Scenario 3

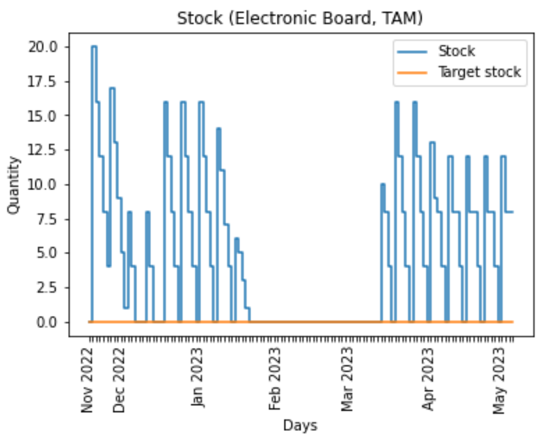

Figure 107: Electronic board stock at TAM, CMPC, Scenario 3

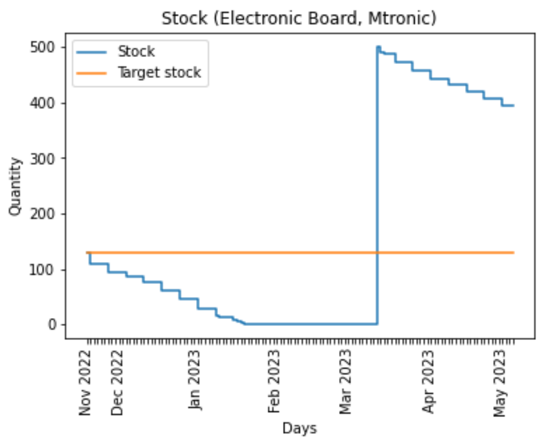

Figure 108: Electronic board stock at Mtronic, CMPC, Scenario 3

TFT Display

The results of the TFT display stock at TAM and EBOVx's warehouse over the simulation time are here depicted, alongside the backlog accumulated by EBOVx:

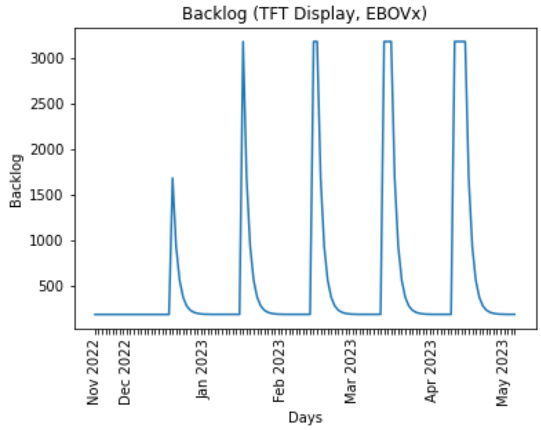

Figure 109: EBOVx's TFT display backlog, CMPC, Scenario 3

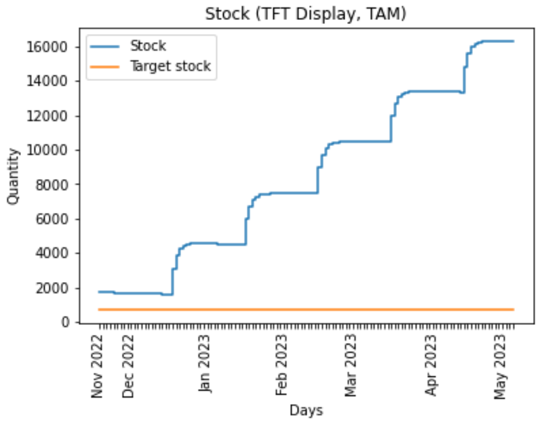

Figure 110: TFT display stock at TAM, CMPC, Scenario 3

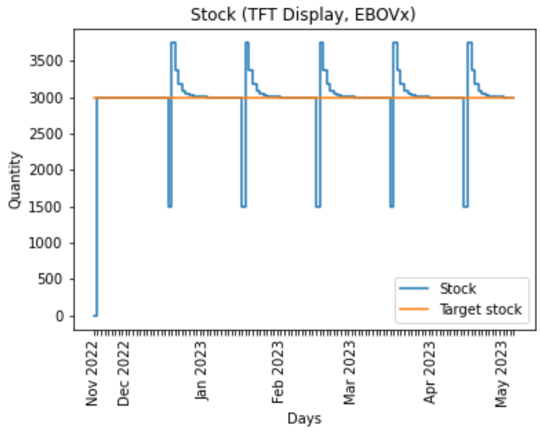

Figure 111: TFT display stock at EBOVx, CMPC, Scenario 3

The KPIs of Scenario 3, that summarize the performance of the Supply Chain graphically represented above, are presented in Table 16 and 17.

Table 16: Scenario 3 KPIs, DMPC

DMPC	
Simulation Time	25285 s (7 h)
Stock Index	190.8
Backlog Index	34.8
Supplier Punctuality	65%
Number of Transports	205
Order Variation	81%

Table 17: Scenario 3 KPIs, CMPC

CMPC	
Simulation Time	6585 s (1.8 h)
Stock Index	24.8
Backlog Index	1.4
Supplier Punctuality	67%
Number of Transports	172
Order Variation	76%

In this scenario, the MPC models have been tested with a critical Supply Chain issue, consisting in the shortage of a semiconductor, that is causing trouble to the electronic board Tier-2 supplier. As this is a hot topic in today's logistic networks, it is interesting to compare the robustness of the two models to this market uncertainty.
From the results, it is clear how the centralized MPC controller performs much better under all the indices measured. Stock targets are much more respected in the CMPC scheme, as the stock index decreases by 87%. This infers that, in spite of the shock caused by the shortage, the Supply Chain is

not hit by a bullwhip effect and manages the stocks efficiently. An important difference is certainly the output of the backlog index, which is reduced by 96%, mostly due to the different reaction of the model to the semiconductor disruption: in fact, while in the DMPC simulation the backlog initially reaches a maximum value of about 650 pieces, the CMPC controller distributes the orders in a more efficient way, incurring in maximum peak of only 12 pieces further on in the simulation. CMPC shows to be better also on the client's side, as order variation lowers for a 5% delta, and to be the most sustainable solution, because of the 16% reduction of transport and hypothetically CO_2 emissions. In this case, even the supplier punctuality benefits from the centralized strategy, raising of about 3%, demonstrating how this control tower performs better than the decentralized scheme in this critical scenario. Finally, also in this simulation, CMPC results the most cost-efficient solution in terms of computational time since the DMPC running time of 7 hours lowers down to less than 2 hours.

6.4 Scenario 4: Demand Variation

The last scenario for the evaluation of the Supply Chain control towers studies the models' sensitivity to sudden variations of the system disturbance: Ferrari's production demand. This simulation is interesting under a strategic point of view, as it represents a likely scenario in a production process characterized by high production mix variations (especially in this historical times) and that may experience changes in the assembly line takt time. In the current state, this is certainly a case where the Supply Chain gets highly stressed, and suppliers may not be able to react to this change, especially if acknowledged under lead time. Through this scenario, it is possible to observe how the MPC models react to this event, if they are able to guarantee the continuity of the production flow and assess their robustness to system uncertainties.

The boundary conditions for this simulations have been set up with the introduction of a new parameter indicating the day in the simulated period corresponding to Ferrari's demand increase. In this case, it was chosen to double the production demand on the 30th working day till the end of the simulation time. In the DMPC, in order to keep the simulation as realistic as possible, it was chosen to double all the orders sent by the suppliers, while in the CMPC only the demand and order relative to Ferrari were doubled, as the others are variables automatically computed by the control agent.

The optimization runs of both the DMPC and CMPC simulations don't show any final result, as the models return an infeasible solution (respectively at time step 21 and 18). This result is expected, as the demand increases without a parallel rise of the suppliers' production capacity. It shows how even a Supply Chain control tower is not able react in an efficient manner to this sudden variation. The infeasibility of the models, in fact, infers that Ferrari goes out-of-stock with the dashboard, which may cause the stop of the car assembly line.
However, this can still be considered a valuable result for the proposed innovation. In fact, Supply Chain control towers can be an innovative solution not only in the monitoring of supplier performance and in the early intervention in case of any production issue, but it could also be used by clients to evaluate the impact of a planned decision over the Supply Chain. As demonstrated in this example, the control tower can be used to predict the capacity of the logistic network to absorb an eventual change in the production mix, a reduction of takt-time or even a rise of the projected volumes, and make decisions based on robust information supplied by the simulation. This allows to improve the strategic management of the Supply Chain and make decisions by analyzing at an early stage their potential impact on the overall process. By gaining this large perspective over a logistic network through the access to supplier data, these analyses may determine significant strategic decisions such as the supplier substitution or the activation of an additional supplier for a specific component that can guarantee the complete satisfaction of the demand. Therefore it can be considered a step forward in the support of Supply Chain Management activities ad may acquire a major role in the future to increase the competitiveness of the Supply Chain on the market.

6.5 Model Verification

When designing a model it is always essential to conduct a verification and validation, in order to assess the accuracy and reliability of the design. In this section, a few test will be run to verify if the model works in several extreme situations and satisfies the expected output. In the model verification phase, the question to be answered is:

Is the model right?

In this section a few verifications of the DMPC and CMPC models will be conducted, in order to prove the correctness of the design and the variation of their results in proportion to the forecast range of the model. First, the models will be tested with a change of the Supply Chain parameters, in particular the supplier lead times and their production capacity. Following, an analysis on the effect of the model prediction horizon on the simulation output will be undertaken. The verifications will be checked on Scenario 1's model for both DMPC and CMPC.

Lead Time Test

In the first verification test, the suppliers' lead times are all raised to 10 days. Considering that the current orders are calibrated on lower lead time values, it is expected that such a high variation can cause issues for Ferrari's production flow, as the suppliers may not be able to follow Ferrari's demand and especially react to the variations in a short period of time.
The results of the CMPC and DMPC simulations respect the predictions, as both models are infeasible under these conditions. The variation of the lead times causes the complete consumption of the initial dahsboard stock at Ferrari and major delays in the Tier-2 components delivery to TAM, which is not able to replenish Ferrari's warehouse in time. This causes a stock-out at Ferrari's warehouse, and therefore the model infeasibility.
Therefore the simulation results impossible to solve, which is consistent with the initial expectations.

Supplier Capacity Test

In the second test, the models are tested with a reduction of all suppliers' production capacity to only 1 piece per day. With this modification, it is expected that the suppliers are not able to follow Ferrari's demand, which definitely overcomes this value. As a consequence, this will lead to a rise of backlogs along the Supply Chain and can potentially compromise Ferrari's production continuity.
Also in this case the simulation output does not contradict the initial predictions. The model outcomes are in both cases unfeasible solutions: the initial stock at Ferrari's warehouse is entirely consumed at the beginning of the simulation and the highly reduced production capacity does not let suppliers keep pace with Ferrari's production. This raises the backlogs between tiers and causes Ferrari to miss the assembly of the dashboard on the cars, which cannot be considered an acceptable solution. In this case, Ferrari would need to think about alternative sourcing strategies to guarantee a continuous production flow.

Prediction Horizon Analysis

After verifying the model through the capacity of Supply Chain, an analysis regarding the impact of the MPC prediction horizon on the final results is undertaken. This comparison has the aim to show how the centralized MPC architecture can show even better results with a higher availability of data along the process. In fact, by augmenting the visibility on the demand forecasts, it is expected that the MPC model could compute optimal solutions in a more efficient way, as it has a more complete long-term view on the process.
In this section, the impact of the simulation parameters on the Key Performance Indicators will be assessed by running the CMPC and DMPC model with six different Hp values: 15 (already displayed in Section 6.1), 20, 25, 30, 35, 40.
The KPIs trends for the DMPC and CMPC scheme in function of the varying prediction horizon presented and discussed below.

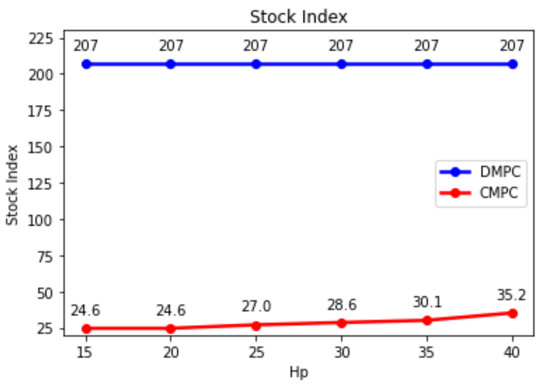

Figure 112: Stock Index in function of Hp

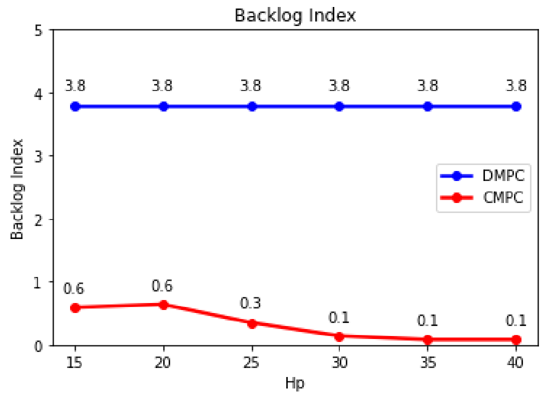

Figure 113: Backlog Index in function of Hp

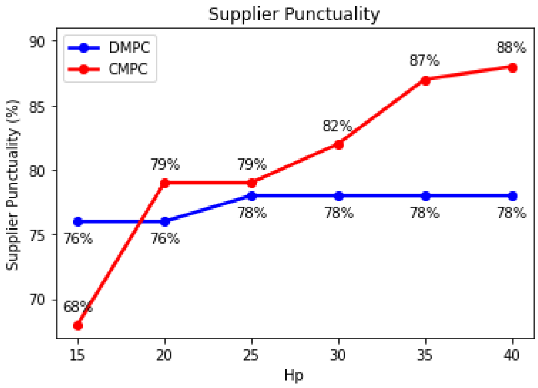

Figure 114: Supplier Punctuality in function of Hp

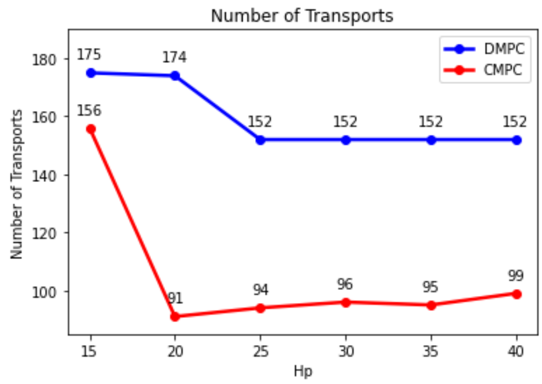

Figure 115: Number of transports in function of Hp

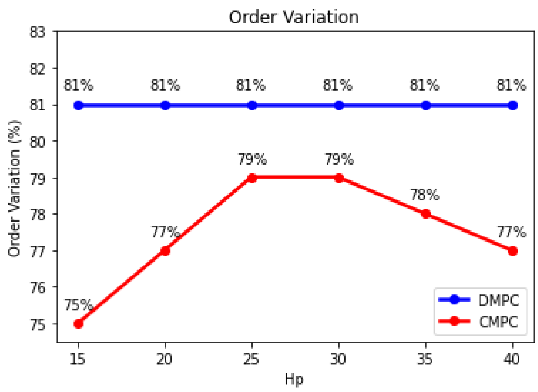

Figure 116: Order variation in function of Hp

The results from this verification test show that overall, the ability of the MPC models to foresee the system disturbances (in this case the demands) over a longer horizon enhances even more the different performance between the DMPC and CMPC solutions.
In fact, while with the DMPC architecture there is no major change in the Supply Chain performance (there is only a slight improvement in supplier punctuality and a 13% reduction of transports with $Hp >= 25$), a more significant impact of the prediction horizon on the final output can be observed in the CMPC scheme. The backlog index, with a 30-days prediction horizon lowers down to 0.08, reducing by 86% compared to the 15-days parameter set for Scenario 1. Moreover supplier punctuality raises by 20% and the number of transports drops down of 38%, always keeping a lower environmental footprint than the decentralized architecture.
Therefore it can be concluded that, with a longer-term visibility over the process, the centralized agent

constantly increases its logistic performance compare to DMPC, which matches the initial expectations.
However, it is also important to observe that, although their value is always lower (and therefore better) than in the decentralized scheme, the stock index and the order variation tend to rise with the increase of the prediction horizon. This can be considered another verification of the model correctness. In fact, since these two KPIs have been associated with lower objective function weights, it can be expected that with a higher visibility the models tend to satisfy the primary goals and oversee these two performance indices.

6.6 Model Validation

After conducting the model verification and making sure that the model works properly and supplies the expected outputs, the validation of the model must be assessed. Validating a model means answering to the following question:

Is this the right model?

The centralized MPC strategy represents the future state envisioned for this process: a coordinated Supply Chain, where a single agent has a complete visibility over the entire processes. This allows the control agent to compute at every time step the optimal inputs for every company of the system. In this way, the logistic network is constantly updated in a synchronous manner and decisions can be taken by always observing the whole process data. Therefore, for this research purpose, it can be considered a valid application.
However, much of the logistic complexity characterizing a Supply Chain has been neglected in this paper, but could be integrated and tested in different case studies. In fact, the model here presented is a small representation of a very large automotive Supply Chain like Ferrari's. Furthermore, as this works represents a prototypical digital tool used for research purposes, it cannot be considered complete, due to computational constraints. As a consequence, it was necessary to design the system by considering several assumptions that at the moment separate this model from practical and industrializable applications and are addressed for future research:

- **Stochasticity:** every variable in the system in real life is subject to a stochastic uncertainty (e.g, production capacity, warehouse stock, transport delays). In this study, for computational cost reasons, it was not possible to include the statistics in the simulation.
- **Safety Stocks:** this model does not consider the safety stock days set by every company for its suppliers.
- **Sourcing Strategy:** in this model every client-supplier relationship is based on single-sourcing. This model could eventually be adapted to alternative sourcing strategies.
- **Production mix:** The suppliers' production mix and therefore the factory operational constraints are not considered in this simulation as only one product for company is considered for this simulation.

Moreover, in perspective of an extension of the model to the entire Supply Chain, it should be considered that the amount of variables and the complexity would raise exponentially. In this case, a CMPC architecture may experience some limitations, especially in terms of robustness and responsiveness. In fact, it is known from theory that a centralized control system does not respond well to sudden changes in the network and it requires a high computational time for optimization in larger systems, such as a complete automotive Supply Chain. Therefore, it can be concluded that CMPC is valid control strategy in small systems, but is not cost-efficient in large-scale applications.

6.7 Discussion of the results

By analyzing the four scenarios simulated in this chapter and observing their final outputs, many conclusions can be deduced.
First, it is clear how the role of data visibility and information exchange between Supply Chain partners is a significant step in the reduction of the seamless split between clients and suppliers. A higher acknowledgement of the processes implies a better ownership of the system and enhances the quality of the decisions made by managers and executives to manage the Supply Chain. Through control towers, companies are able to constantly monitor the supplier's production capacity, their ability to follow the

client's demand and their service level. Alerts generation can help to anticipate any risk of shortage and have the time to react and proceed with alternative solutions in a smarter and more strategic way, rather than having to make quick decisions under stress in emergency situations. Furthermore, the control tower's role as a decision support tool can reduce the waste in the system: in fact, controlling supplier's backlog and preventing disruptions would definitely reduce extra costs caused by urgent transport, missing components on the assembly line (and therefore Lead Time losses) and would allow a better use of resource skills, by reducing the non value-adding activities currently led by material planners.

A second conclusion can be inferred regarding the optimal control strategy. Model Predictive Control shows to be effective in determining the optimal control inputs on both a short- and long-term, thanks to the rolling horizon approach. By comparing the current and future state and the Supply Chain performances in the four cases, MPC has a better impact with a centralized strategy, in terms of logistic efficiency, robustness to uncertainties, computational cost and environmental sustainability. This result is underlined even more with the ability of the models to foresee the system states over a longer horizon, as demonstrated in Section 6.5. In terms of process efficiency, it is interesting to observe the different interpretation of the results based on the stakeholder perspective. In fact, in all scenarios, by comparing only the dashboard backlog graphs of the Tier-1 towards Ferrari (Figures 42-52, 66-76, 88-100), it could be concluded that the DMPC strategy works in a much better way, as the backlog trend doesn't reach any peak during its simulation. However, the goal of this thesis is to change the perspective from a traditional way of thinking by silos and looking at the own objectives, to envisioning the Supply Chain as a single entity that must increase its competitiveness on the market. Under this point of view, the centralized MPC presents better KPIs in all the first three scenarios, thanks to a better coordination between the information and material flows, that minimize the resulting backlog and allow to keep the warehouse stocks closer to the prefixed targets. In Scenario 3, for example, it is clear how in the future state, buyers and suppliers considerably change their cooperating method in case of a material shortage. By observing the figures below, in the DMPC method, the controller prefers to adopt a Just-In-Case strategy, letting the buyer (TAM) receive as much electronic boards as possible, while the CMPC model prefers to keep the stock low for the Tier-1 (in order to stay closer to the target stock) and work on a Just-In-Time fashion, which increases the performance indices.

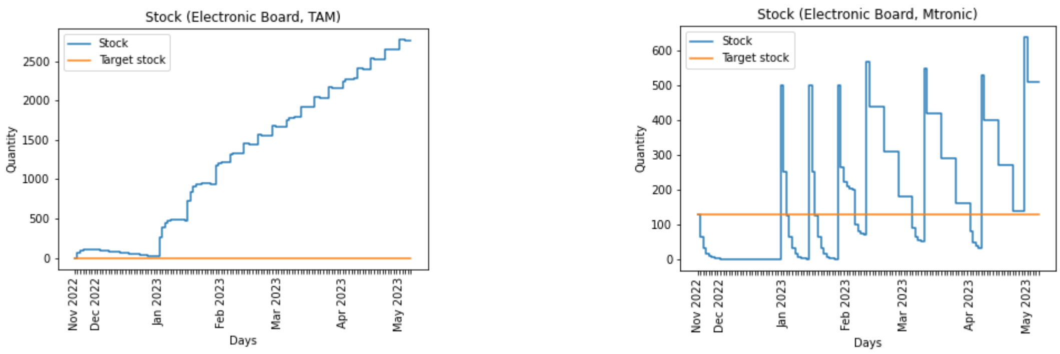

Figure 117: Electronic board stock at TAM and Mtronic, DMPC, Scenario 3

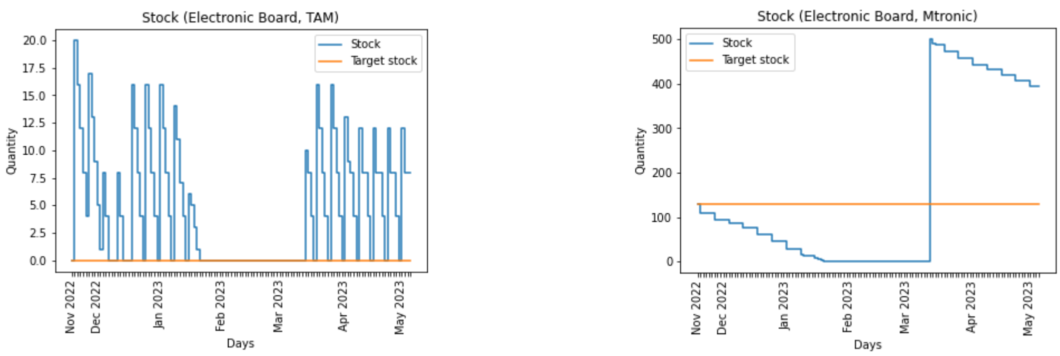

Figure 118: Electronic board stock at TAM and Mtronic, CMPC, Scenario 3

Moreover, the CMPC model demonstrates to be overall a better solution also in terms of computational cost and CO_2 emissions. Compared to the DMPC scheme, simulation running times are much shorter and guarantee a higher time-efficiency in case of extension to a larger part of Ferrari's Supply Chain. Another improving aspect is the number of transports, that are always reduced, thanks to a lower frequency of emergencies and extra-flux operations.

After the complete analysis of the final outputs and the comparison between the two MOC models, SRM and in particular Supply Chain control towers definitely represent a high-value innovation and a crucial technology in the digital transformation of logistic operations. The centralized scheme is concluded to be optimal solution of a Supply Chain application, as it guarantees a better decision-making support than a decentralized strategy in terms of performance, cost and environmental sustainability, and represents the most avant-garde solutions in the path towards autonomous Supply Chain Management.

7 Conclusion & Future Research

Rising complexities and uncertainties in today's Supply Chains nowadays require buyers and suppliers to reduce the split in their logistic processes and build solid partnership to gain a higher competitiveness among the market. In this research paper, the role of digitization and data visibility within Supply Chains is investigated by designing a centralized Model Predictive Control agent, able to automatically make optimal decisions regarding the material and information flow over the logistic network.
This research work, in comparison with the state-of-the-art, contributes to the scientific knowledge by adding a study case where, through the use of real data, it presents the impact of a centralized Supply Chain control tower on the current state of Ferrari's Supply Chain and compares the proposed CMPC scheme with a DMPC simulation representing the behaviour of today's system. The models are compared in different scenarios that stress the system and recreate potential risks of disruption and production stop.

First, in Chapter 2, through an extensive literature review, the state-of-the-art technologies leading the transition towards a digital management of the Supply Chain have been presented, especially regarding Supplier Relationship Management and Supply Chain control towers. Moreover, a research over the literature's applications of MPC models in logistic operations has been conducted.
Since the project has been undertaken in collaboration with Ferrari, the designed model of the proposed innovation has been adapted to a small part of its Supply Chain, relative to the supply of the car dashboard. The problems regarding the current state of the process have been explained and measured with an analysis on the non value-adding activities coordinated by material planners. Then, in order to evaluate the performance of the future state, two MIQP optimization problems have been designed to run MPC control over the past and future solution. In particular, Decentralized MPC has been chosen to represent the current state of the process, while Centralized MPC represents the future innovative solution. In Chapter 6, the models have been run over 4 scenarios, representing different and recurrent situations characterizing modern Supply Chains. In Scenario 1 a standard situation with zero initial backlog is simulated, where the system is not stressed with the boundary conditions. Scenario 2 tests the system by including an accumulated backlog at the beginning of the simulation for every supplier, in order to study how fast the models are able to recover. Scenario 3 sets the most critical challenge for the models, as they deal with a semiconductor shortage affecting the electronic board manufacturer, which is unable to produce for an entire month. Finally, in Scenario 4, a reduction of the takt-time and a Ferrari production ramp-up for the chosen Part Number is simulated, in order to evaluate the sensitivity of the MPC models to variations in the system disturbances.
The results show that the CMPC solution has the best performance in the first three simulations, as it manages to coordinate better the information and material flow within tiers, thanks to its ability to overlook the production and logistic processes of the whole Supply Chain. With this innovations, the controller is able to distribute the client's orders in a tactical way, depending on the boundary conditions affecting the system. In this way, suppliers do not work under the pressure of emergencies, but are able to organize their activity in a smarter and optimized way. This has a much added value in case of shortages, as the Supply Chain is structured to automatically understand weeks before when and where there could be a risk of material stock-out and to intervene faster to mitigate or solve the problem. Furthermore, businesses are able to control their stock levels in a much more efficient way, since the model tends to adjust the orders and shipments to the target stocks set by companies.
As shown in the simulation conducted for Scenario 4, the Supply Chain control tower can support managerial decision-making processes not only in the monitoring of logistic operations and supplier performance, but also in the choices regarding the production scheduling and strategies. Changes in production mix, or sudden volume ramp-ups could be investigated with the control tower and with the suppliers, in order to understand how it would impact the logistic network and evaluate the choice feasibility.
The verification and validity of the model have been assessed at the end of Chapter 6 through different tests. Results confirm that the centralized MPC architecture gains an increasing performance with a longer-term visibility over the Supply Chain processes, which strengthens the validity of the thesis here proposed.
Therefore, it is clear how digital transition could bring a much stronger partnership between buyers and suppliers. A shared and interconnected flow of information enhances trust and sense of responsibility as businesses are less free to hide their processes, but work with a more open spirit of collaboration.

The aim of this research work is to show how the exchange of data can largely improve the efficiency and the coordination of logistic operations and strengthen the relationship and the communication between buyers and suppliers. A centralized Supply Chain control tower represents a decision support tool for logistic managers and can be a base for a further step in the path towards Supply Chain 4.0, consisting in the complete automation of the information and material flow between companies.
In order to achieve this, many are still the challenges that could be integrated in the solution proposed in this paper. First, this simulation has been built for a single component of Ferrari's Supply Chain. The extension to other PNs, in a complex logistic scenario like the automotive industry, is a big challenge in terms of data availability, storage and controllability, as it would require an advanced data management system, a robust and wide network that can connect companies' management systems in real-time, and an IT structure able to withstand a high computational load. As centralized MPC is not robust and has a low responsiveness on a large scale, future research should evaluate the application of distributed MPC on this Supply Chain study case. The advantage of this architecture stands in the fact that every single agent, by gathering a limited amount of information and by having limited action capabilities, can execute a more effective control on its specific subsystem both in terms of responsiveness to change and low computational costs. Therefore, distributed MPC is a suggested solution for the extension of the model to the entire Supply Chain and for an eventual future industrialization, as it could guarantee high performance with a lower computational cost. Furthermore, additional logistic aspects should be included and tested in the model, to increase its complexity: safety stocks, multi-product production lines, competitive supplier sourcing strategies are points that can be integrated in this centralized MPC model. Stochasticity is another crucial theme in this regard, since it is normal to experience a high variability of the system's states. In this paper, the sensitivity of the model has been tested through small variations of the disturbances and parameters. In a real application, every variable needs to be elaborated with a range of uncertainty based on historical data and future predictions. The use of AI and Machine Learning techniques could really help to increase the accuracy and reliability of the computed actions in the near and long future. On the other hand, though, it would inevitably raise the computational cost of the simulation.
Finally, in this paper MPC control has been run through a MIPQ optimization problem, which is designed to find global or local optimum. Since the results displayed in Chapter 6 have certainly margins of further improvement, other optimization techniques, such as heuristic methods, may be investigated in future research.

References

[1] M. Akamp and M. Müller. "Supplier management in developing countries". In: *Journal of Cleaner Production* 56 (Oct. 2013), pp. 54–62. DOI: 10.1016/j.jclepro.2011.11.069.

[2] K. Alicke, J. Rachor, and A. Seyfert. "Supply Chain 4.0 – the next-generation digital supply chain". In: (Oct. 2016).

[3] A. T. Bahill and C. Briggs. "The Systems Engineering Started in the Middle Process: A Consensus of Systems Engineers and Project Managers". In: *Systems Engineering* 4 (Jan. 2001), pp. 156–167. DOI: 10.1002/sys.1013.

[4] W. Beelarts van Blokland. "Lecture Module 1 B: Theory Road Map I". In: *Advanced Operations and Production Management* (2021).

[5] M. Behrendt. *A basic working principle of Model Predictive Control.* 2009. URL: https://commons.wikimedia.org/wiki/File:MPC_scheme_basic.svg.

[6] M. Braun et al. "A Model Predictive Control Framework for Robust Management of Multi-Product Multi-Echelon Demand Networks". In: *Annual Reviews in Control* 27 (Dec. 2003), pp. 229–245. DOI: 10.1016/j.arcontrol.2003.09.006.

[7] J. Busch et al. "The Impact of Disruptive Technologies and Solutions on Strategic Procurement Technologies (Analytics, Sourcing, Supplier and Contract Management)". In: (Mar. 2017).

[8] T. Choi and D. Krause. "The Supply Base and Its Complexity: Implications for Transaction Costs, Risks, Responsiveness, and Innovation". In: *Journal of Operations Management* 24 (Sept. 2006), pp. 637–652. DOI: 10.1016/j.jom.2005.07.002.

[9] European Commission. "ICT and e-Business in Hospital Activities: ICT Adoption and e-Business Activity in 2006". In: *eBusiness Watch* 10/2006 (2006).

[10] W. Dunbar and S. Desa. "Distributed MPC for Dynamic Supply Chain Management". In: vol. 358. Sept. 2007, pp. 607–615. ISBN: 978-3-540-72698-2. DOI: 10.1007/978-3-540-72699-9_51.

[11] Ferrari. *Sito ufficiale del marchio Ferrari.* 2021. URL: https://www.ferrari.com (visited on 02/04/2022).

[12] Brand Finance. *Brand Finance Global 500 2021.* 2021. URL: https://brandfinance.com/press-releases/brand-finance-global-500-2021-sber-becomes-worlds-third-strongest-brand (visited on 02/04/2022).

[13] G.J. Freijters. "Design of a Supply Chain Coordination System-of-Systems applied to offshore wind power park maintenance". In: *TU Delft Master Theses* (Dec. 2021).

[14] Gartner. *Gartner Official Website.* 2022. URL: https://www.gartner.com/home/feed.

[15] T. Hipólito et al. "A centralised model predictive control framework for logistics management of coordinated supply chains of perishable goods". In: *International Journal of Systems Science: Operations Logistics* (July 2020), pp. 1–21. DOI: 10.1080/23302674.2020.1781953.

[16] R. van Hoek. "Supplier Relationship Management: How Key Suppliers Drive Competitive Advantage". In: (2013).

[17] IBM. *What is a supply chain control tower?* 2022. URL: https://www.ibm.com/topics/control-towers.

[18] F. Jingshuang et al. "Applications of Distributed Model Predictive Control in Supply Chain Management". In: *2008 International Conference on Information Management, Innovation Management and Industrial Engineering.* Vol. 2. 2008, pp. 63–67. DOI: 10.1109/ICIII.2008.235.

[19] M. Jones. *How networks and control towers enable risk management during disasters.* 2018. URL: https://supplychainbeyond.com/supply-chain-resilience-in-disasters/ (visited on 05/06/2022).

[20] D. Kaparis. *Driving Innovation for Automotive Suppliers.* 2022. URL: https://www.engusa.com/en/posts/driving-innovation-for-automotive-suppliers (visited on 03/07/2022).

[21] K. Kolehmainen. "Automotive Supply Chain through the "Control Tower" model". In: (2013).

[22] M. Lerma. *Ferrari and Armani Are Going to Start Making Clothes Together.* 2019. URL: https://robbreport.com/style/menswear/ferrari-and-armani-clothing-collaboration-2878136/ (visited on 02/04/2022).

[23] J. Liker and T. Choi. "Building Deep Supplier Relationships". In: *Harvard Bus. Rev.* 82 (Dec. 2004).

[24] J. K. Liker. *The Toyota Way : 14 Management Principles from the World's Greatest Manufacturer.* New York: McGraw-Hill, 2004.

[25] P.-H. Lin, S.-S. Jang, and D. Shan-Hill Wong. "Predictive Control of a Decentralized Supply Chain Unit". In: *Industrial Engineering Chemistry Research* (2005), pp. 9120–9128. DOI: 10.1021/ie0489610.

[26] M. Liotine. "Shaping the Next Generation Pharmaceutical Supply Chain Control Tower with Autonomous Intelligence". In: *Journal of Autonomous Intelligence* 2 (May 2019), p. 56. DOI: 10.32629/jai.v2i1.34.

[27] Luxottica. *Ray-Ban and Ferrari strengthen their collaboration.* 2017. URL: https://www.luxottica.com/en/ray-ban-and-ferrari-strengthen-their-collaboration (visited on 02/04/2022).

[28] J. M. Maestre, D. Muñoz de la Peña, and E. F. Camacho. "Distributed MPC: a supply chain case study". In: *Proceedings of the 48h IEEE Conference on Decision and Control (CDC) held jointly with 2009 28th Chinese Control Conference.* 2009, pp. 7099–7104. DOI: 10.1109/CDC.2009.5400590.

[29] J.M. Maestre et al. "Distributed model predictive control based on agent negotiation". In: *Journal of Process Control* 21 (June 2011), pp. 685–697. DOI: 10.1016/j.jprocont.2010.12.006.

[30] W. McNeill, M. Keck, and K. Kose. *How to Navigate the Fragmented Supplier Management Solutions Market.* 2021. URL: https://www.gartner.com/document/3997324?ref=solrAll&refval=325145850 (visited on 08/05/2022).

[31] J. Mentzer et al. "Defining Supply Chain Management". In: *Journal of Business Logistics* 22 (Sept. 2001). DOI: 10.1002/j.2158-1592.2001.tb00001.x.

[32] T. Mettler and P. Rohner. "Supplier Relationship Management: A Case Study in the Context of Health Care". In: *Journal of Theoretical and Applied Electronic Commerce Research* 4 (Dec. 2009), pp. 58–71. DOI: 10.4067/S0718-18762009000300006.

[33] M. Miranbeigi and A. Jalali. "Supply Chain Management Systems Advanced Control: MPC on SCM". In: Sept. 2011, pp. 17–34. ISBN: 978-953-307-250-0. DOI: http://www.intechopen.com/books/supply-chain-management-applications-and-simulations/supply-chain-management-systems-advanced-control-mpc-on-scm.

[34] Rudy R Negenborn, Hans Hellendoorn, and Zofia Lukszo. *Intelligent infrastructures.* Vol. 2. Springer, 2010.

[35] P. Oghazi et al. "Unity is strength: A study of supplier relationship management integration". In: *Journal of Business Research* 69 (May 2016). DOI: 10.1016/j.jbusres.2016.04.034.

[36] R. Pannel. *How "TIMWOODS" and the 8 Wastes of Lean drive efficiencies in business process.* 2020. URL: https://leanscape.io/8-wastes-of-lean/.

[37] E. Perea Lopez, B.E. Ydstie, and I. Grossmann. "A Model Predictive Control Strategy for Supply Chain Optimization". In: *Computers Chemical Engineering* 27 (Sept. 2003), pp. 1201–1218. DOI: 10.1016/S0098-1354(03)00047-4.

[38] L. Piana. *Ferrari rafforza la squadra di vertice. Parole d'ordine: eccellenza, Dna sportivo e attenzione all'ambienten.* 2022. URL: https://www.repubblica.it/economia/finanza/2022/01/10/news/ferrari_riorganizzazione-333280829/ (visited on 02/04/2022).

[39] F.F. Rad, B. Lebel, and B. Wu. "Limited upstream dyadic integration of the Supplier Relationship Management process within the construction equipment industry in Sweden". In: (2015).

[40] M. Raźniewska. "Meeting the Challenges of Food Sector using Supplier Relationship Management". In: Dec. 2018. DOI: 10.33422/8icmeh.2018.12.47.

[41] A. Rebelo, H. Nobre, and N. Szczygiel. "Managing Relationships With Suppliers: The Case of a Local Subsidiary of a Global Company of Components for the Automotive Industry". In: Jan. 2019, pp. 50–69. ISBN: 9781522581581. DOI: 10.4018/978-1-5225-8157-4.ch003.

[42] A. Rejeb, J. Keogh, and S. Edit. "Exploring New Technologies in Procurement". In: (Dec. 2018).

[43] L. Rysman. *Ferrari Is Racing Into Fashion.* 2021. URL: https://www.nytimes.com/2021/06/16/style/ferrari-fashion-collection.html (visited on 02/04/2022).

[44] S. Schrauf and P. Berttram. "Industry 4.0 - How digitization makes the supply chain more efficient, agile, and customer-focused". In: (2016).

[45] I. Sillanpää, K. Shahzad, and E. Sillanpää. "Supplier development and buyer-supplier relationship strategies - a literature review". In: *International Journal of Procurement Management* 8 (Jan. 2015), pp. 227–250. DOI: `10.1504/IJPM.2015.066283`.

[46] P. Singh et al. "Supplier Relationship Management and Selection Strategies – A Literature Review". In: Dec. 2017.

[47] J. Sterman. "Business Dynamics, System Thinking and Modeling for a Complex World". In: *http://lst-iiep.iiep-unesco.org/cgi-bin/wwwi32.exe/[in=epidoc1.in]/?t2000=013598/(100)* 19 (Jan. 2000).

[48] P. Stevens. *The ship that blocked the Suez Canal may be free, but experts warn the supply chain impact could last months.* 2021. URL: `https://www.cnbc.com/2021/03/29/suez-canal-is-moving-but-the-supply-chain-impact-could-last-months.html`.

[49] C. Titze and B. De Muynck. *How to Choose the Right Supply Chain Operational Visibility Software for Your Organization.* 2017. URL: `https://www.gartner.com/document/3668617`.

[50] S.-M. Tseng. "The Impact of Knowledge Management Capabilities and Supplier Relationship Management on Corporate Performance". In: *International Journal of Production Economics* 154 (Aug. 2014). DOI: `10.1016/j.ijpe.2014.04.009`.

[51] A.N. Venkat, J.B. Rawlings, and S.J. Wright. "Stability and optimality of distributed model predictive control". In: *Proceedings of the 44th IEEE Conference on Decision and Control.* 2005, pp. 6680–6685. DOI: `10.1109/CDC.2005.1583235`.

[52] M. Verwijmeren. *3 Types of Supply Chain Control Towers.* 2017. URL: `https://www.mpo.com/blog/3-types-of-supply-chain-control-towers`.

[53] D. Wang, J. Dou, and Y. Chen. "Automobile Industry Supply Chain Inventory Modeling and Optimization Based on MPC". In: *Advanced Materials Research* 945-949 (June 2014), pp. 3241–3245. DOI: `10.4028/www.scientific.net/AMR.945-949.3241`.

[54] W. Wang et al. "A model predictive control strategy for supply chain management in semiconductor manufacturing under uncertainty". In: vol. 5. Jan. 2004, 4577–4582 vol.5. ISBN: 0-7803-8335-4. DOI: `10.1109/ACC.2004.182673`.

[55] J. Webb. *What Is The Kraljic Matrix?* 2017. URL: `https://www.forbes.com/sites/jwebb/2017/02/28/what-is-the-kraljic-matrix/?sh=1e832f00675f`.

[56] L. Yang et al. "The impact of digitalization and inter-organizational technological activities on supplier opportunism: the moderating role of relational ties". In: *International Journal of Operations Production Management* 41 (2021), pp. 1085–1118. DOI: `https://doi.org/10.1108/IJOPM-09-2020-0664`.

Appendix

Appendix A: Simulation Parameters

Lead Time

		Component			
		Dashboard	Cover	Electronic Board	TFT Display
Client	TAM	1	-	-	-
	ProPlastic	-	1	-	-
	Mtronic	-	-	10	-
	EBOVx	-	-	-	1

Order Frequency

		Producer/Component			
		TAM	ProPlastic	Mtronic	EBOVx
		Dashboard	Cover	Electronic Board	TFT Display
Client	Ferrari	1	-	-	-
	TAM	-	5	5	20

Consumption Rate

	Dashboard	Cover	Electronic Board	TFT Display
Dashboard	-	1	1	2

Transit Time

		Client				
		Ferrari	TAM	ProPlastic	Mtronic	EBOVx
Producer	Ferrari	-	-	-	-	-
	TAM	1	-	-	-	-
	ProPlastic	-	1	-	-	-
	Mtronic	-	1	-	-	-
	EBOVx	-	20	-	-	-

Production Capacity

		Component			
		Dashboard	Cover	Electronic Board	TFT Display
Producer	TAM	4	-	-	-
	ProPlastic	-	4	-	-
	Mtronic	-	-	500	-
	EBOVx	-	-	-	3000

Logistic Batches

		Producer/Component			
		TAM	ProPlastic	Mtronic	EBOVx
		Dashboard	Cover	Electronic Board	TFT Display
Client	Ferrari	1	-	-	-
	TAM	-	4	1	3000
	Mtronic	-	-	-	-
	EBOVx	-	-	-	-

Production Batches

		Component			
		Dashboard	Cover	Electronic Board	TFT Display
Producer	TAM	1	-	-	-
	ProPlastic	-	4	-	-
	Mtronic	-	-	500	-
	EBOVx	-	-	-	3000

Target Stock

	Dashboard	Cover	Electronic Board	TFT Display
Ferrari	13	-	-	-
TAM	5	50	0	750
ProPlastic	-	25	-	-
Mtronic	-	-	130	-
EBOVx	-	-	-	3000

Appendix B: Simulation Results

Scenario 1: Zero Backlog

Decentralized MPC - Scenario 1

Dashboard

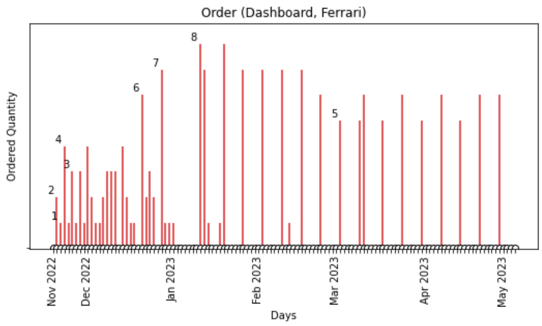

Figure 119: Ferrari dashboard order, DMPC, Scenario 1

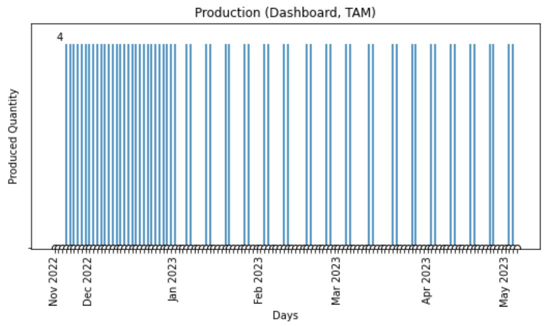

Figure 120: Dashboard production at TAM, DMPC, Scenario 1

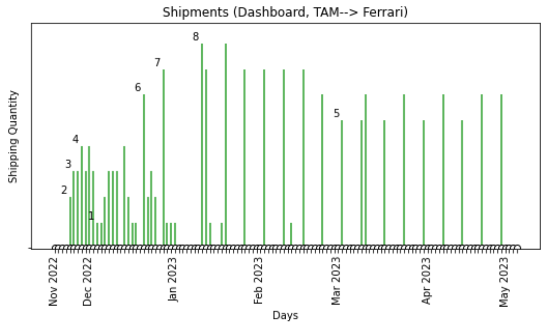

Figure 121: Dashboard shipments from TAM to Ferrari, DMPC, Scenario 1

Cover

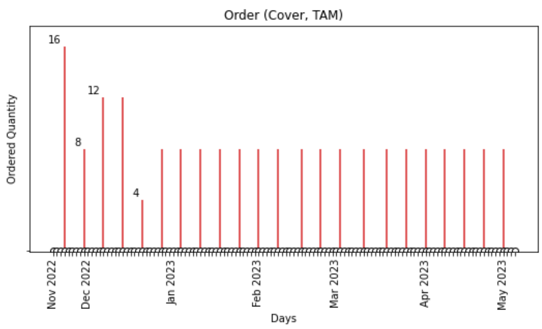

Figure 122: TAM cover order, DMPC, Scenario 1

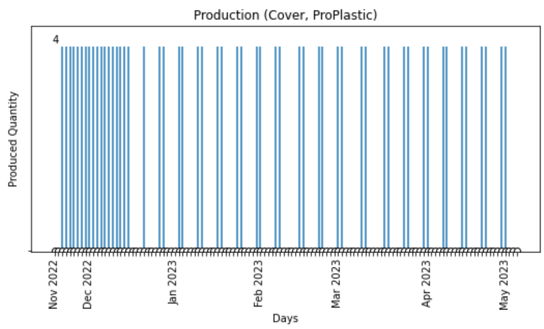

Figure 123: Cover production at ProPlastic, DMPC, Scenario 1

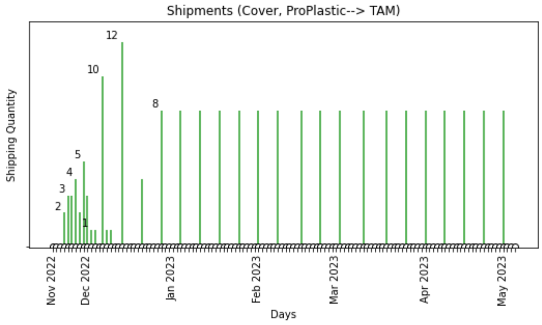

Figure 124: Cover shipments from ProPlastic to TAM, DMPC, Scenario 1

Electronic Board

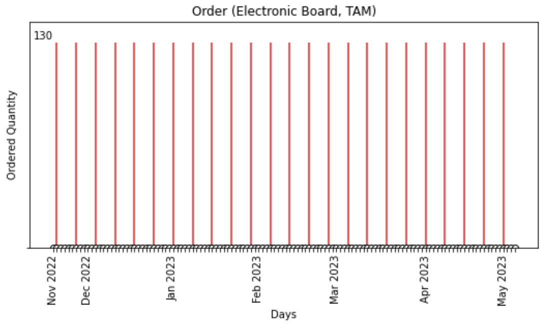

Figure 125: TAM electronic board order, DMPC, Scenario 1

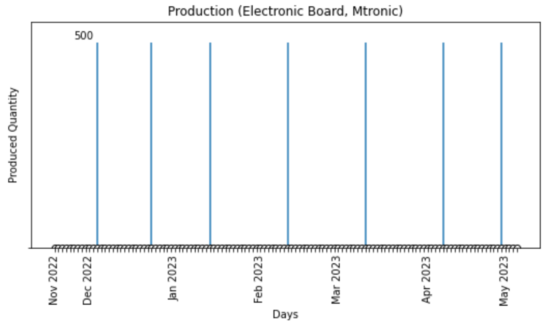

Figure 126: Electronic board production at Mtronic, DMPC, Scenario 1

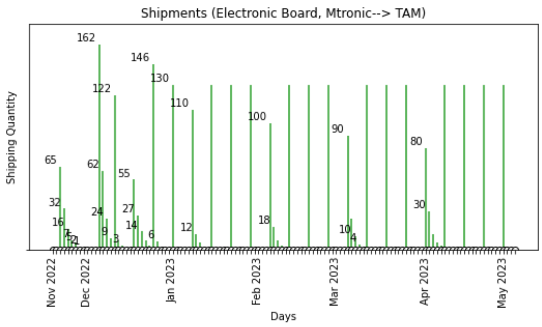

Figure 127: Electronic board shipments from Mtronic to TAM, DMPC, Scenario 1

TFT Display

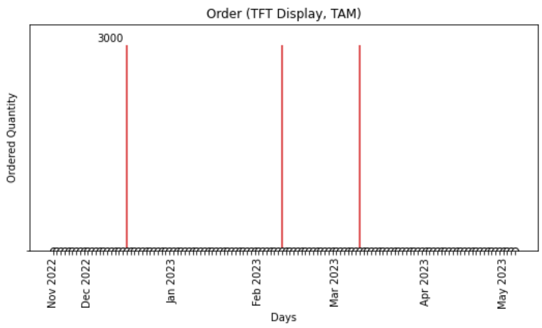

Figure 128: TAM TFT display order, DMPC, Scenario 1

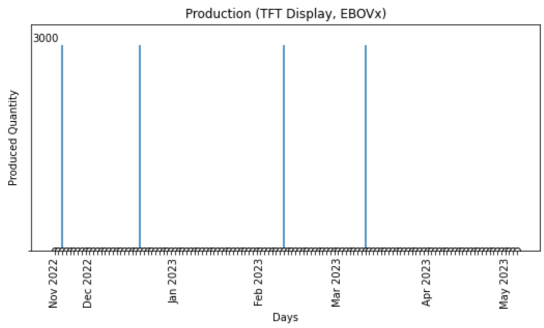

Figure 129: TFT display production at EBOVx, DMPC, Scenario 1

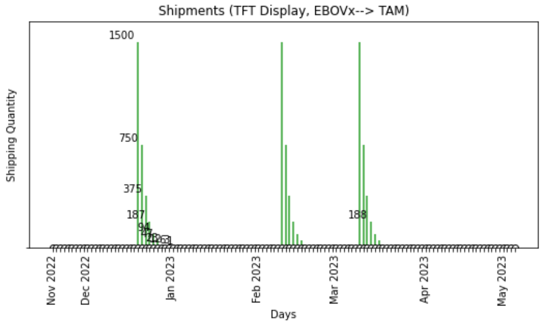

Figure 130: TFT display shipments from EBOVx to TAM, DMPC, Scenario 1

Centralized MPC - Scenario 1

Dashboard

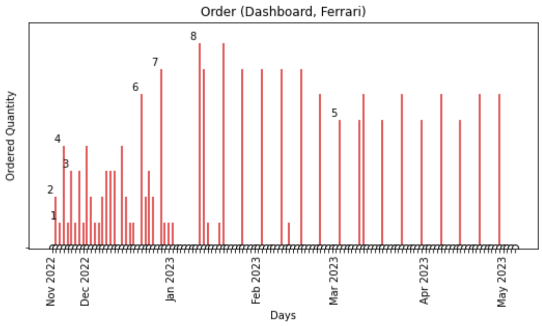

Figure 131: Ferrari dashboard order, CMPC, Scenario 1

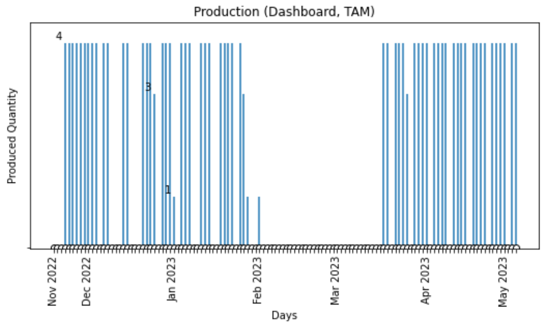

Figure 132: Dashboard production at TAM, CMPC, Scenario 1

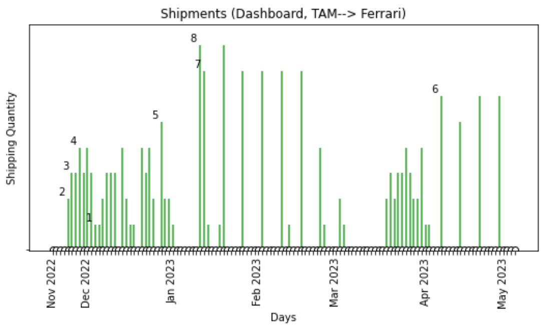

Figure 133: Dashboards shipments from TAM to Ferrari, CMPC, Scenario 1

Cover

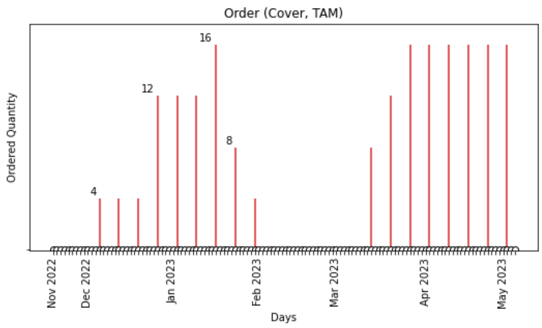

Figure 134: TAM cover order, CMPC, Scenario 1

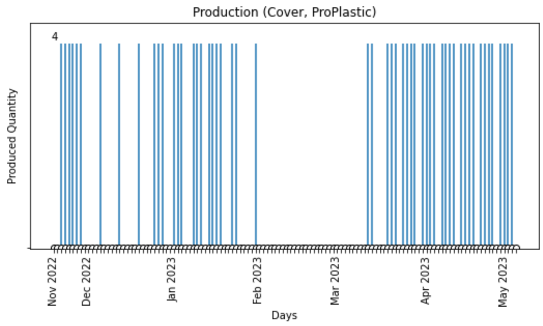

Figure 135: Cover production at ProPlastic, CMPC, Scenario 1

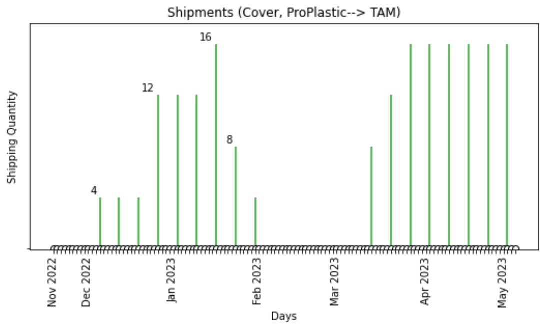

Figure 136: Cover shipments from ProPlastic to TAM, CMPC, Scenario 1

Electronic Board

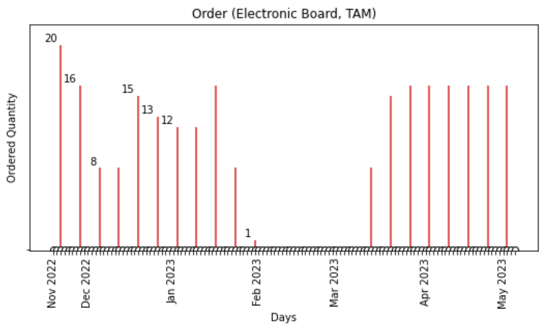

Figure 137: TAM electronic board order, CMPC, Scenario 1

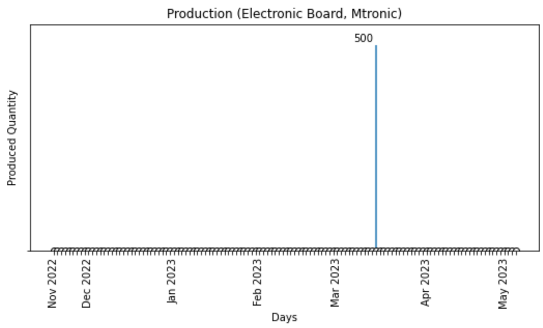

Figure 138: Electronic board production at Mtronic, CMPC, Scenario 1

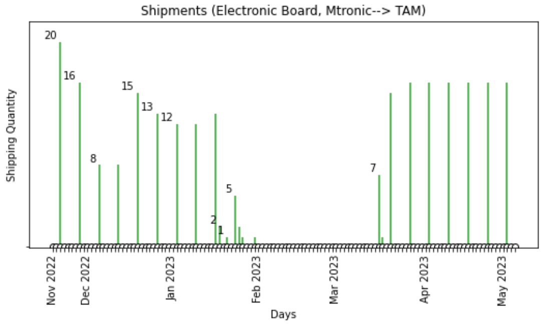

Figure 139: Electronic board shipments from Mtronic to TAM, CMPC, Scenario 1

TFT Display

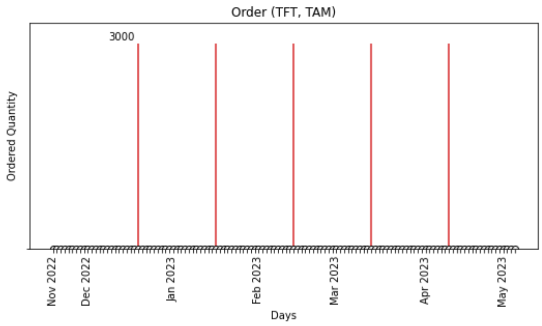

Figure 140: TAM TFT display order, CMPC, Scenario 1

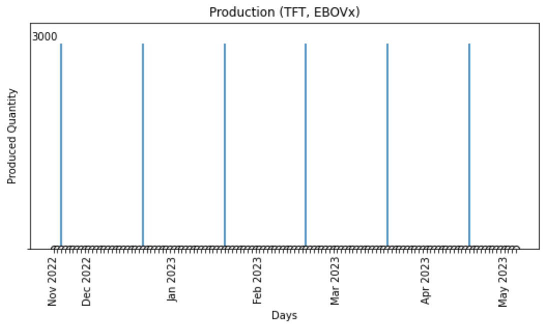

Figure 141: TFT display production at EBOVx, CMPC, Scenario 1

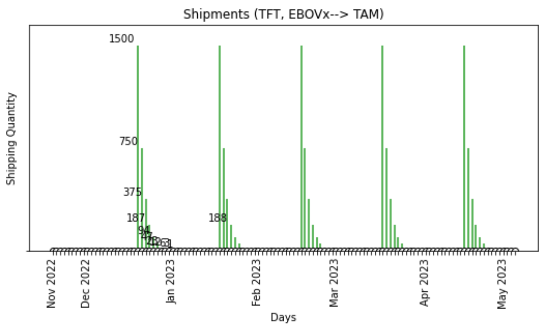

Figure 142: TFT display shipments from EBOVx to TAM, CMPC, Scenario 1

Scenario 2: Backlog Recovery

Decentralized MPC - Scenario 2

Dashboard

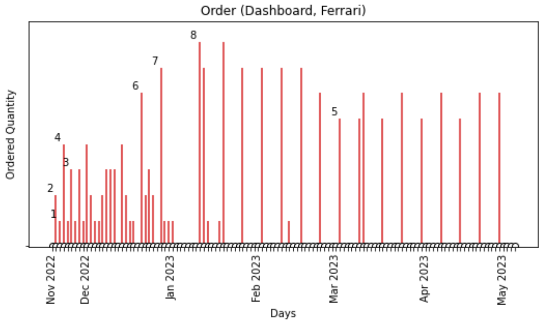

Figure 143: Ferrari dashboard order, DMPC, Scenario 2

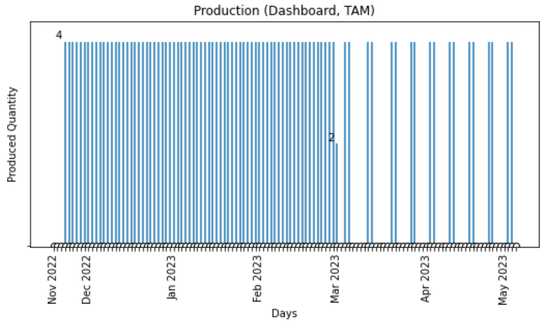

Figure 144: Dashboard production at TAM, DMPC, Scenario 2

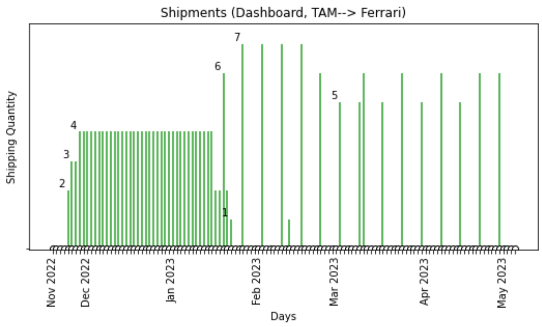

Figure 145: Dashboard shipments from TAM to Ferrari, DMPC, Scenario 2

Cover

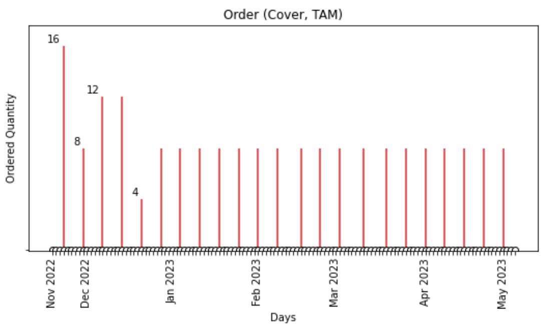

Figure 146: TAM cover order, DMPC, Scenario 2

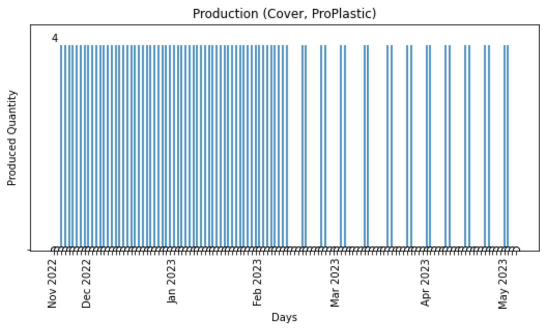

Figure 147: Cover production at ProPlastic, DMPC, Scenario 2

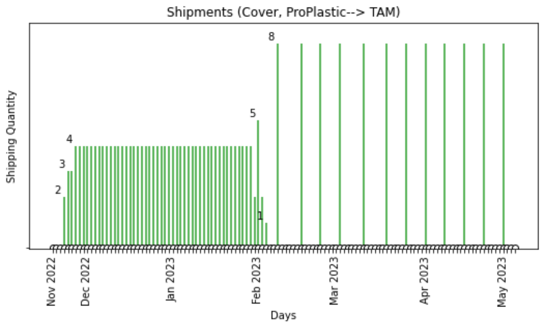

Figure 148: Cover shipments from ProPlastic to TAM, DMPC, Scenario 2

Electronic Board

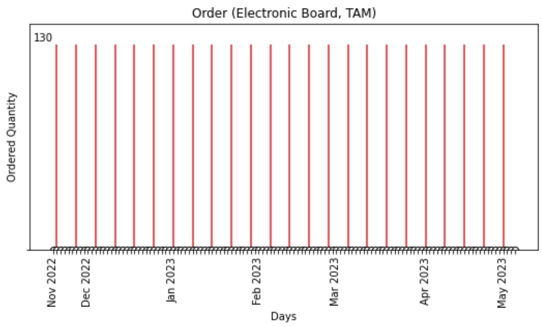

Figure 149: TAM electronic board order, DMPC, Scenario 2

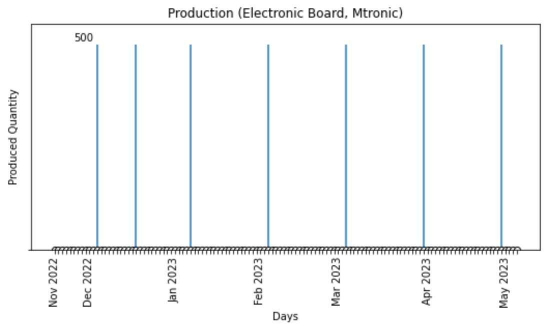

Figure 150: Electronic board production at Mtronic, DMPC, Scenario 2

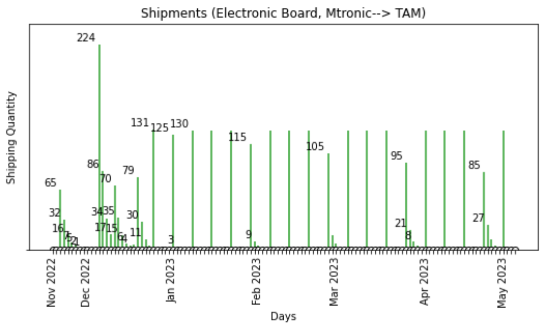

Figure 151: Electronic board shipments from Mtronic to TAM, DMPC, Scenario 2

TFT Display

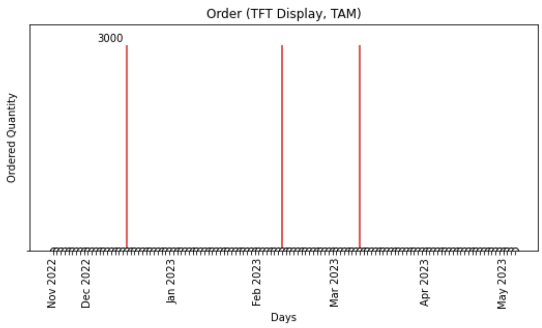

Figure 152: TAM TFT display order, DMPC, Scenario 2

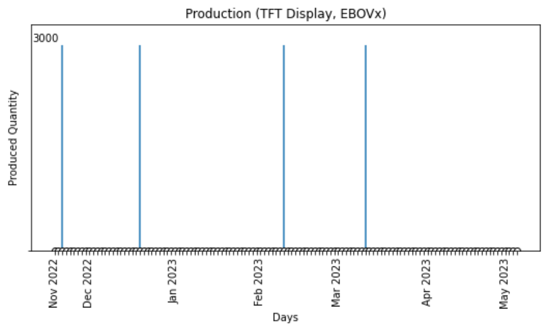

Figure 153: TFT display production at EBOVx, DMPC, Scenario 2

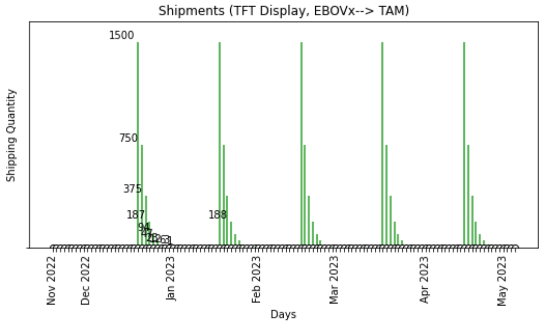

Figure 154: TFT display shipments from EBOVx to TAM, DMPC, Scenario 2

Centralized MPC - Scenario 2

Dashboard

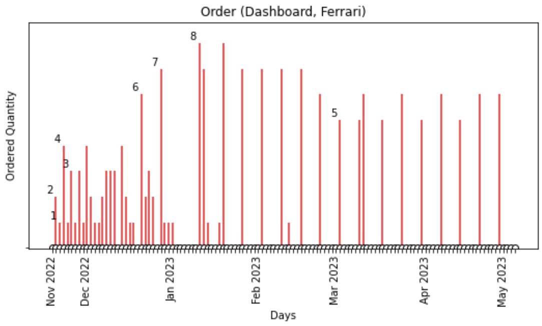

Figure 155: Ferrari dashboard order, CMPC, Scenario 2

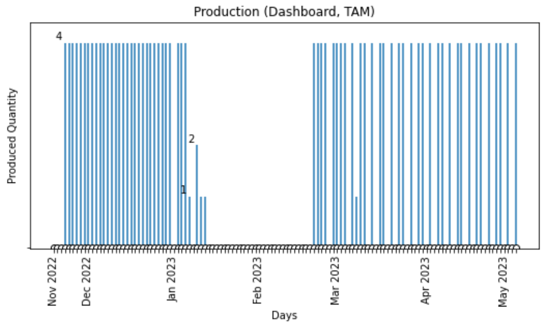

Figure 156: Dashboard production at TAM, CMPC, Scenario 2

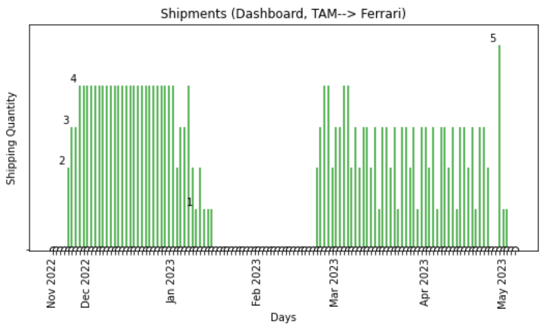

Figure 157: Dashboards shipments from TAM to Ferrari, CMPC, Scenario 2

Cover

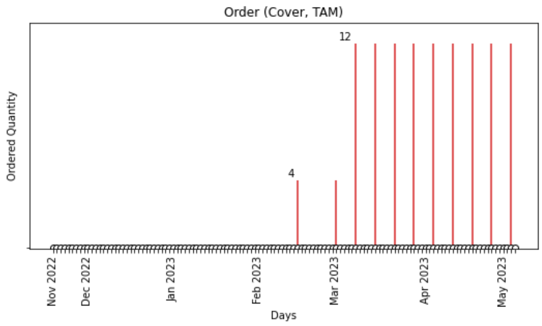

Figure 158: TAM cover order, CMPC, Scenario 2

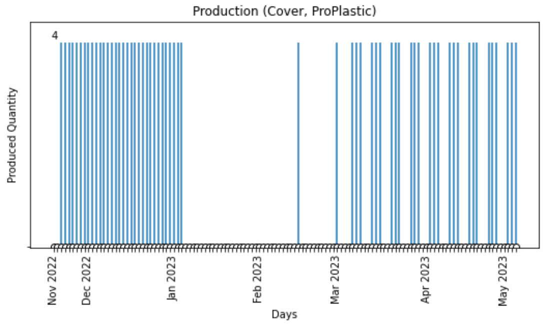

Figure 159: Cover production at ProPlastic, CMPC, Scenario 2

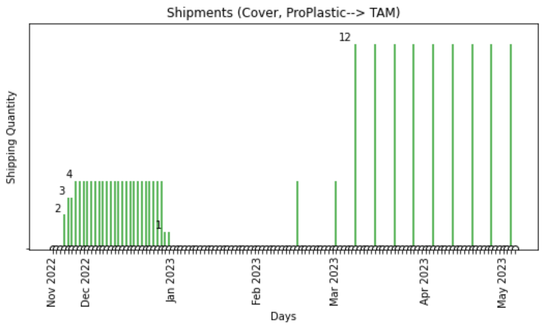

Figure 160: Cover shipments from ProPlastic to TAM, CMPC, Scenario 2

Electronic Board

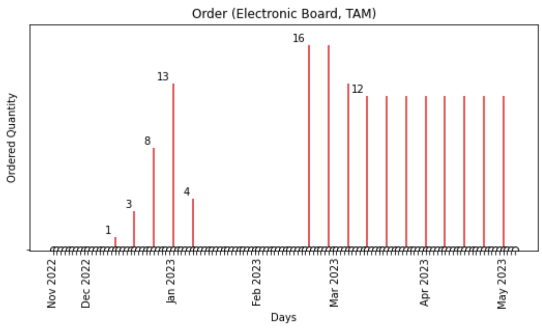

Figure 161: TAM electronic board order, CMPC, Scenario 2

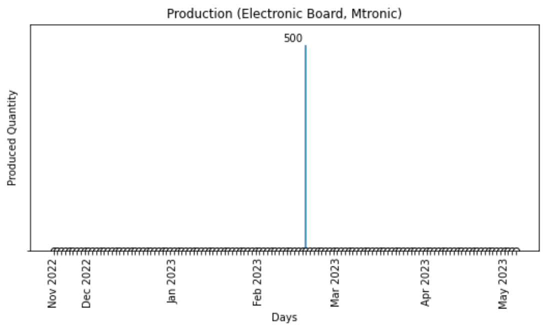

Figure 162: Electronic board production at Mtronic, CMPC, Scenario 2

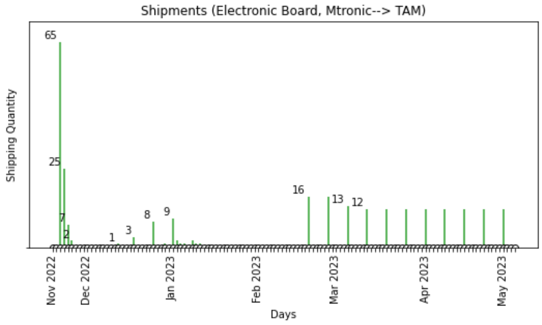

Figure 163: Electronic board shipments from Mtronic to TAM, CMPC, Scenario 2

TFT Display

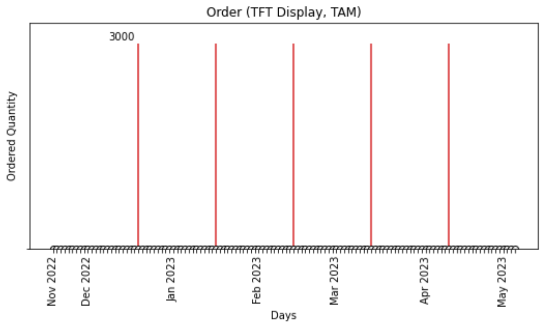

Figure 164: TAM TFT display order, CMPC, Scenario 2

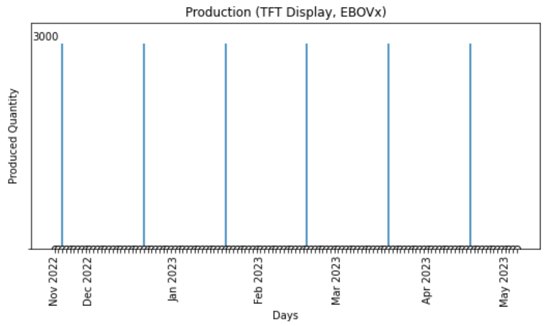

Figure 165: TFT display production at EBOVx, CMPC, Scenario 2

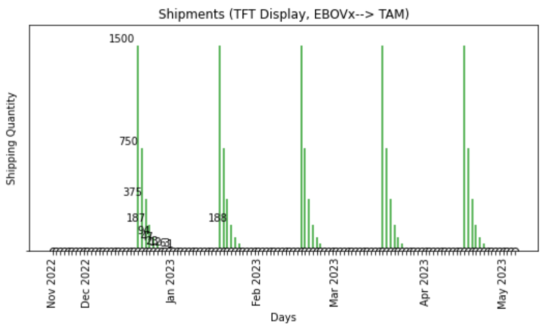

Figure 166: TFT display shipments from EBOVx to TAM, CMPC, Scenario 2

Scenario 3: Material Shortage

Decentralized MPC - Scenario 3

Dashboard

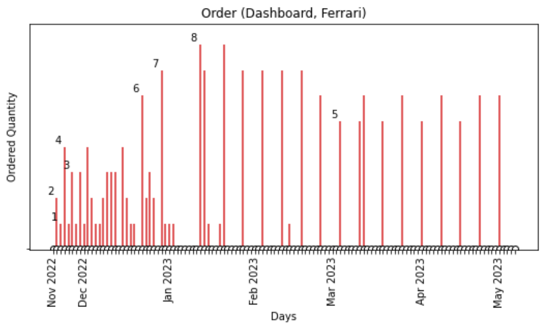

Figure 167: Ferrari dashboard order, DMPC, Scenario 3

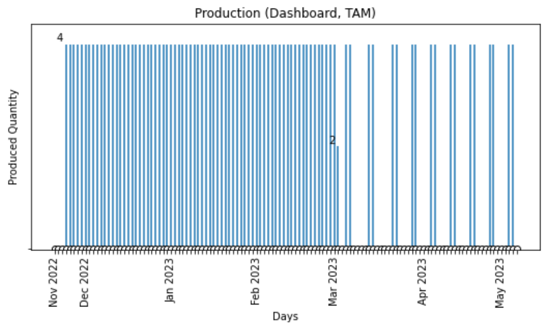

Figure 168: Dashboard production at TAM, DMPC, Scenario 3

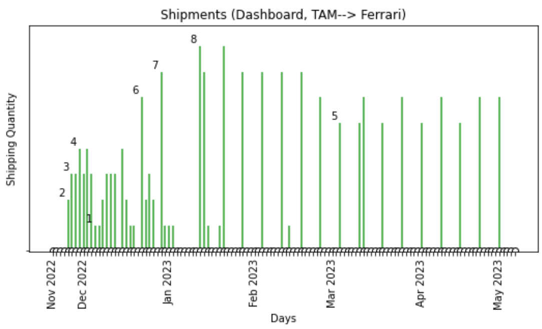

Figure 169: Dashboard shipments from TAM to Ferrari, DMPC, Scenario 3

Cover

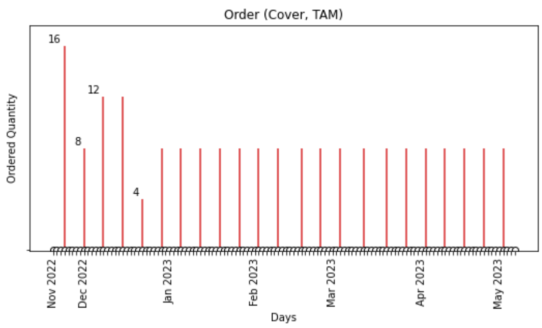

Figure 170: TAM cover order, DMPC, Scenario 3

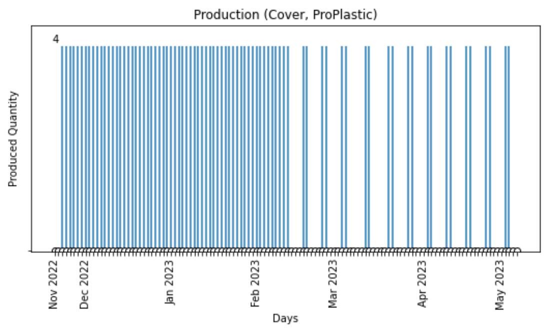

Figure 171: Cover production at ProPlastic, DMPC, Scenario 3

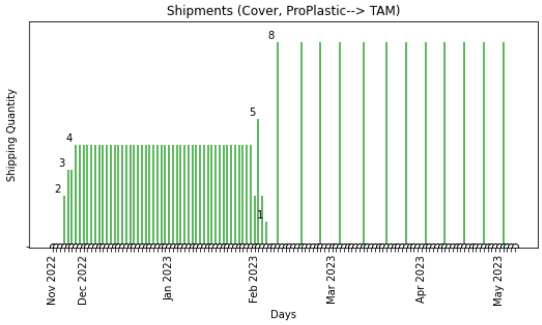

Figure 172: Cover shipments from ProPlastic to TAM, DMPC, Scenario 3

Electronic Board

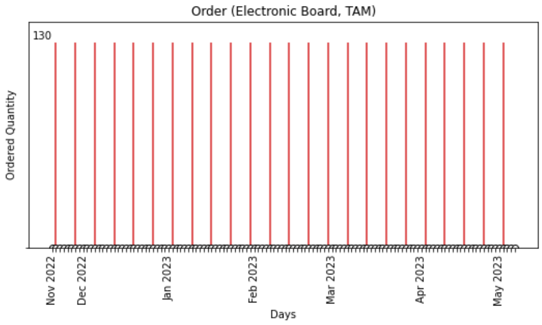

Figure 173: TAM electronic board order, DMPC, Scenario 3

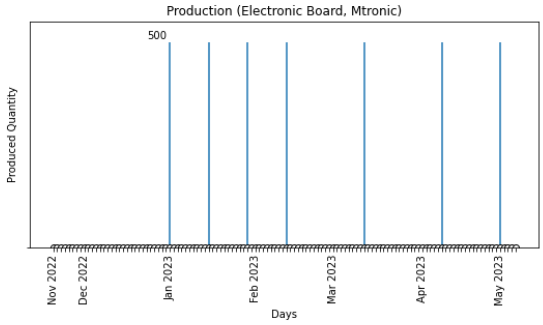

Figure 174: Electronic board production at Mtronic, DMPC, Scenario 3

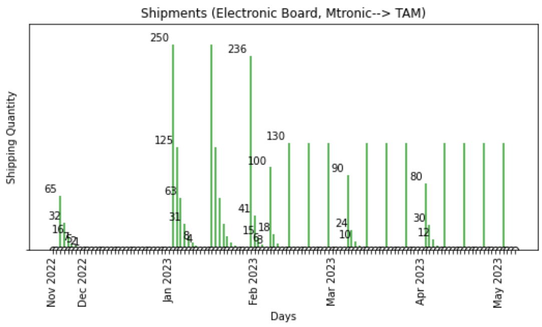

Figure 175: Electronic board shipments from Mtronic to TAM, DMPC, Scenario 3

TFT Display

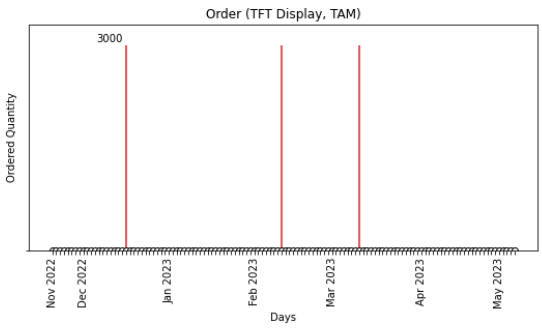

Figure 176: TAM TFT display order, DMPC, Scenario 3

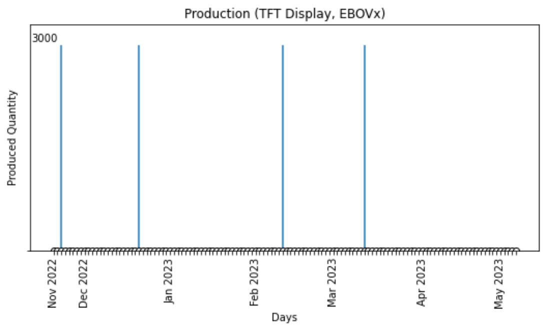

Figure 177: TFT display production at EBOVx, DMPC, Scenario 3

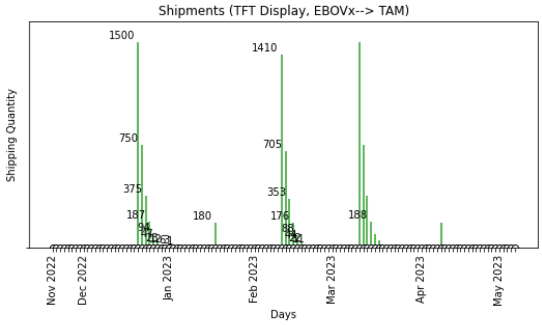

Figure 178: TFT display shipments from EBOVx to TAM, DMPC, Scenario 3

Centralized MPC - Scenario 3

Dashboard

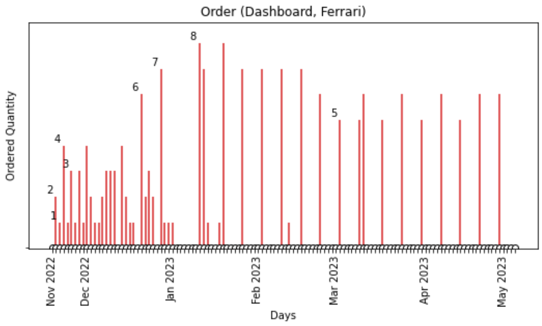

Figure 179: Ferrari dashboard order, CMPC, Scenario 3

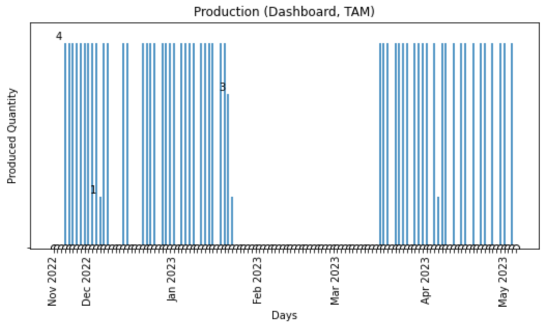

Figure 180: Dashboard production at TAM, CMPC, Scenario 3

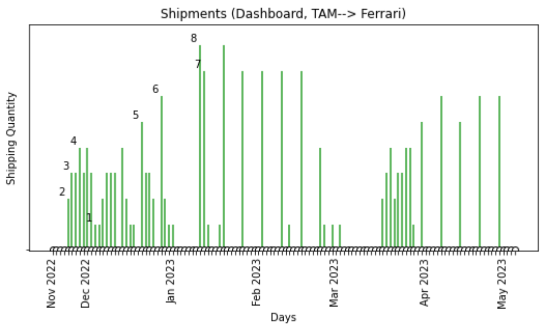

Figure 181: Dashboards shipments from TAM to Ferrari, CMPC, Scenario 3

Cover

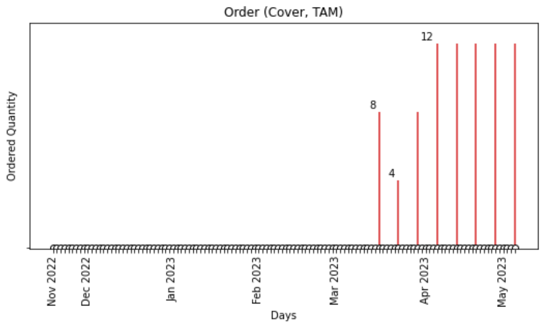

Figure 182: TAM cover order, CMPC, Scenario 3

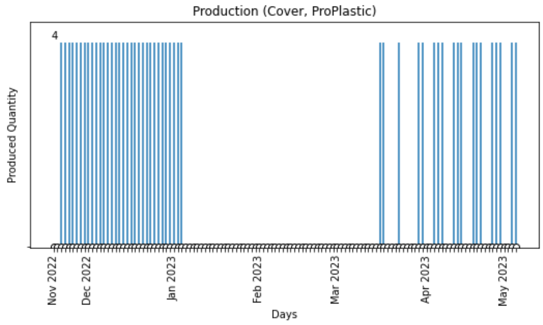

Figure 183: Cover production at ProPlastic, CMPC, Scenario 3

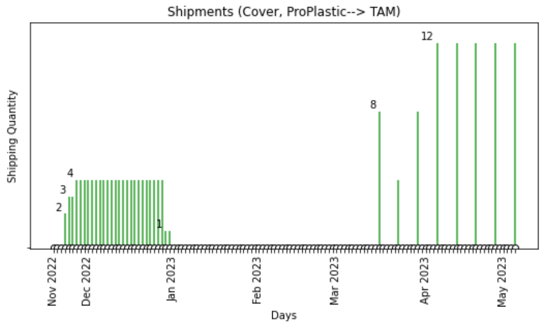

Figure 184: Cover shipments from ProPlastic to TAM, CMPC, Scenario 3

Electronic Board

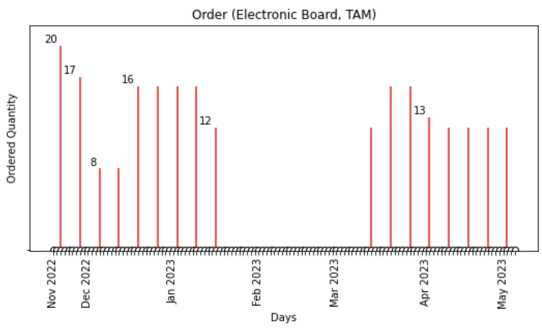

Figure 185: TAM electronic board order, CMPC, Scenario 3

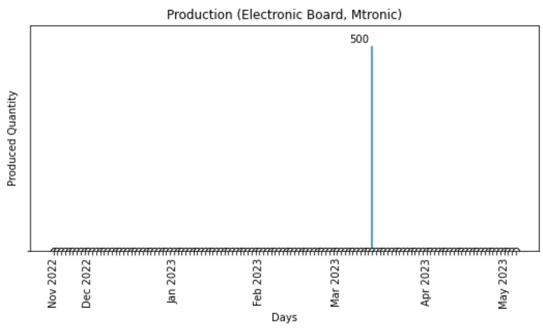

Figure 186: Electronic board production at Mtronic, CMPC, Scenario 3

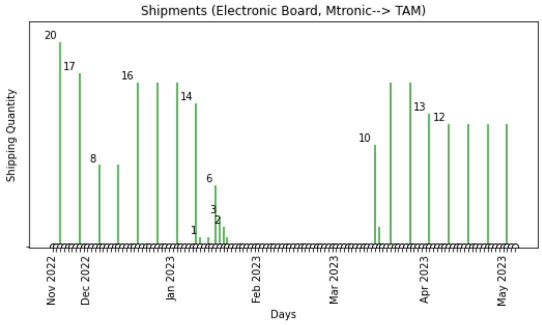

Figure 187: Electronic board shipments from Mtronic to TAM, CMPC, Scenario 3

TFT Display

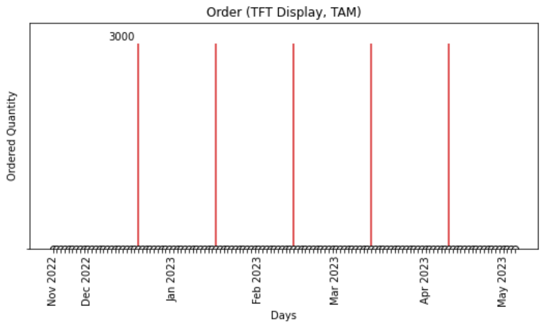

Figure 188: TAM TFT display order, CMPC, Scenario 3

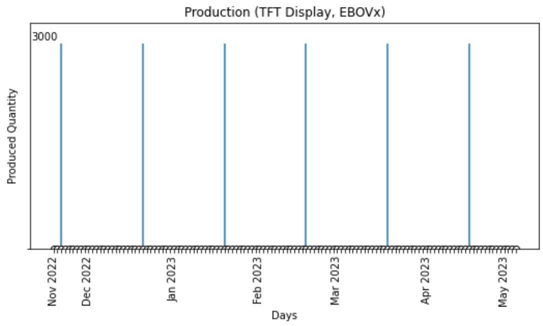

Figure 189: TFT display production at EBOVx, CMPC, Scenario 3

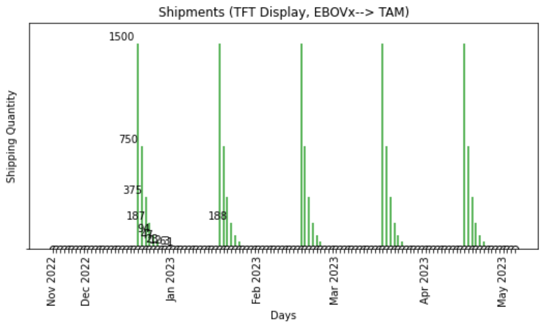

Figure 190: TFT display shipments from EBOVx to TAM, CMPC, Scenario 3

Model Verification

$Hp = 20$

DMPC	
Simulation Time	31776 s (8.8 h)
Stock Index	207.0
Backlog Index	3.8
Supplier Punctuality	76%
Number of Transports	174
Order Variation	81%

Figure 191: DMPC, Scenario 1, $Hp = 20$

CMPC	
Simulation Time	5373 s (1.5 h)
Stock Index	24.6
Backlog Index	0.64
Supplier Punctuality	79%
Number of Transports	91
Order Variation	77%

Figure 192: CMPC, Scenario 1, $Hp = 20$

$Hp = 25$

DMPC	
Simulation Time	38324 s (10.6 h)
Stock Index	207.0
Backlog Index	3.8
Supplier Punctuality	78%
Number of Transports	152
Order Variation	81%

Figure 193: DMPC, Scenario 1, $Hp = 25$

CMPC	
Simulation Time	6986 s (1.9 h)
Stock Index	27.0
Backlog Index	0.35
Supplier Punctuality	79%
Number of Transports	94
Order Variation	79%

Figure 194: CMPC, Scenario 1, $Hp = 25$

$Hp = 30$

DMPC	
Simulation Time	43856 s (12.2 h)
Stock Index	207.0
Backlog Index	3.8
Supplier Punctuality	78%
Number of Transports	152
Order Variation	81%

Figure 195: DMPC, Scenario 1, $Hp = 30$

CMPC	
Simulation Time	8536 s (2.4 h)
Stock Index	28.6
Backlog Index	0.14
Supplier Punctuality	82%
Number of Transports	96
Order Variation	79%

Figure 196: CMPC, Scenario 1, $Hp = 30$

$Hp = 35$

DMPC	
Simulation Time	61186 s (17 h)
Stock Index	207.0
Backlog Index	3.8
Supplier Punctuality	78%
Number of Transports	152
Order Variation	81%

Figure 197: DMPC, Scenario 1, $Hp = 35$

CMPC	
Simulation Time	11604 s (3.2 h)
Stock Index	30.1
Backlog Index	0.08
Supplier Punctuality	87%
Number of Transports	95
Order Variation	78%

Figure 198: CMPC, Scenario 1, $Hp = 35$

$Hp = 40$

DMPC	
Simulation Time	65075 s (18 h)
Stock Index	207.0
Backlog Index	3.8
Supplier Punctuality	78%
Number of Transports	152
Order Variation	81%

Figure 199: DMPC, Scenario 1, $Hp = 40$

CMPC	
Simulation Time	13543 s (3.8 h)
Stock Index	35.2
Backlog Index	0.08
Supplier Punctuality	88%
Number of Transports	99
Order Variation	77%

Figure 200: CMPC, Scenario 1, $Hp = 40$