ANALISI INTRODUTTIVA DELLE TECNICHE DI CONTROLLO DIGITALE APPLICATE ALLA GESTIONE DELLA SUPPLY CHAIN

INTRODUCTORY ANALYSIS OF DIGITAL CONTROL PRACTICES IN SUPPLY CHAIN MANAGEMENT

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SOMMARIO

La ricerca effettuata ha lo scopo di fornire un supporto alla risoluzione del noto problema dell’effetto Frusta nella gestione della Supply Chain, utilizzando un approccio basato sulla teoria dei controlli digitali. La Supply Chain è un sistema dinamico di imprese, caratterizzato da flussi di informazioni, merci e denaro che ha l’obiettivo di soddisfare le richieste del cliente e di produrre profitto. A causa dell’effetto frusta si verifica un aumento della variabilità della domanda man mano che ci si allontana dal consumatore finale e questo comporta l’insorgere di numerosi problemi dal punto di vista gestionale. L’analisi è iniziata presso il KIT, Karlsruhe Institute of Technology e completata presso il Dipartimento di Scienze e Metodi dell'Ingegneria di Reggio Emilia con l’obiettivo di individuare l’applicabilità di modelli matematici a tempo discreto ottenuti introducendo tecniche tipiche dei controlli digitali alla logistica. Essa ha portato a determinare quale modello matematico impiegare ed a definire una metodologia per testarlo. In particolare è stato scelto lo strumento di analisi, creato un indice di performance e verificata l’applicabilità del modello, mediante una attività di simulazione. A tal fine sono state impiegate diverse tipologie di dati di input come i segnali deterministici, i dati random e infine dati reali provenienti da tre Supply Chain diverse.
SINTESI

Negli ultimi anni la complessità dei mercati internazionali è aumentata notevolmente e con essa la competizione tra le imprese. Per tale motivo sempre più aziende si sono unite e hanno creato delle “Supply Chain”. Data la varietà delle richieste dei clienti e la necessità di evaderle nel tempo più breve possibile, si è prodotta una quantità elevatissima di merci, ma le giacenze di magazzino rappresentano una delle problematiche più diffuse a livello internazionale.

La letteratura ha a lungo indagato l’effetto frusta, ne ha riportato le cause, le conseguenze e sono state studiate molte strategie manageriali allo scopo di prevenirlo. Ciò nonostante è ancora molto diffuso e comporta conseguenze negative dal punto di vista economico, manifatturiero e manageriale.

A partire dal 2011 la collaborazione tra il Professore Dr.-Ing. Kai Furmans e il Professore Dr.-Ing. Jürgen Beyer ha portato allo studio di un nuovo metodo per affrontare questo problema. Il professore K. Furmans è il direttore dell’istituto per il trasporto dei materiali e della logistica (IFL) dell’università di Karlsruhe e il Professor J. Beyer è esperto di teorie di Controllo Digitale e lavora presso l’istituto per l’aviazione e i controlli automatici (FSR) dell’università di Darmstadt. L’idea di base della collaborazione è stata quella di introdurre tecniche tipiche dei controlli digitali alla gestione della Supply Chain.

Nel presente elaborato sono stati descritti i risultati del progetto che ho iniziato presso il dipartimento IFL dell’università di Karlsruhe nell’ambito del progetto Erasmus Placement e terminato presso il Dipartimento di Scienze e Metodi dell’Ingegneria dell’università di Reggio Emilia. La redazione dell’elaborato è stata svolta in lingua inglese per permettere una migliore comprensione alle diverse parti coinvolte.

L’obiettivo dell’analisi è stato quello di validare i modelli matematici proposti e indagarne il range di applicabilità. I modelli sono stati creati allo scopo di soddisfare la domanda del cliente, evitare lo Stockout e prevenire la formazione dell’effetto frusta. L’analisi effettuata è stata caratterizzata da vari passaggi.

In particolare è stato necessario svolgere uno studio preliminare di controlli digitali e dei modelli proposti. Si è effettuato, in seguito, un confronto tra di essi fino ad individuarne il più adatto. Una volta scelto il modello da impiegare si è proceduto alla simulazione del suo comportamento con diverse tipologie di dati.
L’analisi dei risultati delle simulazioni ha portato a determinare le regioni di stabilità del modello matematico e a fornire una base di dati utili per il proseguimento della ricerca nel campo. Si è mostrato come l’applicazione dei controlli digitali alla gestione della logistica possa introdurre numerosi vantaggi e possa portare stabilità nel sistema, prevenendo l’insorgere dell’effetto frusta. Questo porta ad una notevole riduzione dei costi lungo tutta la catena di fornitura e ad una migliore gestione del personale, della logistica e quindi ad un incremento generalizzato della performance del sistema.

Approfondendo ulteriormente la struttura dell’elaborato nel primo capitolo vengono richiamati alcuni concetti tipici della logistica come ad esempio la struttura della Supply chain e del Bullwhip effect.

Il secondo capitolo ha lo scopo di introdurre alcune nozioni teoriche di controlli digitali. Vengono inoltre presentate le ipotesi teoriche su cui si basa la formulazione dei modelli ed i concetti relativi ai tre differenti controller impiegati. In particolare è importante sottolineare che il modello è di tipo discreto e quindi non introduce approssimazioni matematiche e permette una grande affidabilità nella pianificazione giornaliera degli ordini. Nella figura 2.3.2 è presentata una schematizzazione semplificata del modello. Si ipotizza di conoscere la domanda attuale del cliente, il tempo necessario per evadere gli ordini chiamato di seguito “delay”, il livello di scorte che si ha attualmente e quello che si vuole mantenere, detto “reference”. Utilizzando questi dati di input il modello fornisce come output il numero di ordini da piazzare lungo la Supply Chain. Nello schema sono rappresentati anche filtro e controller in quanto influenzano il sistema. In particolare il controller considera le informazioni provenienti dalle scorte ed è indicato con il parametro α. È il fattore di ponderazione del residuo tra il “reference” e il valore attuale delle scorte. Il filtro, invece tiene in considerazione la domanda proveniente dal cliente finale, è individuato dal parametro β. Entrambi i parametri variano tra zero e uno e, in particolare, se è assunto uguale a zero significa che il fornitore non tiene in considerazione l’attuale domanda del cliente, se è uguale a uno il fornitore la segue esattamente.

Nel medesimo capitolo si introducono tre diverse tipologie di controller. Il primo detto “Fixed Gain Controller” è semplice da implementare e utilizza un filtro passa basso, ovvero un filtro che limita le variazioni eccessive della domanda. Il secondo chiamato “Deadbeat Approach” considera in parallelo anche gli ordini storici del cliente, rappresenta il controller che fornisce la risposta teoricamente più veloce del sistema, ma
è sensibile alle variazioni della domanda e genera instabilità nel sistema. Il terzo, ovvero l’“Autopilot Controller” combina i due approcci precedenti.

Nel terzo capitolo si mostrano le motivazioni per cui si è deciso di impiegare “l’Autopilot Controller” per effettuare le simulazioni. Tra le altre, si osserva come quest’ultimo non sia sensibile alla variazione del delay time.

Nel quarto si presenta la tecnica di simulazione impiegata per determinare i range di stabilità del sistema utilizzando l’Autopilot Controller. La simulazione è stata svolta utilizzando fogli di calcolo e tabelle Pivot. Una volta individuato lo strumento per effettuare l’analisi si è determinato l’indice di performance più appropriato per confrontare i risultati delle simulazioni. In particolare, dopo avere considerato diverse ipotesi si è scelto di impiegare un indice chiamato ISE tipicamente utilizzato nei controlli digitali. Dalla formulazione matematica riportata nel paragrafo 4.4 si evince che tale criterio è tipicamente adottato nei modelli a tempo continuo. Si è pertanto sostituito il simbolo di integrale a quello di sommatoria e si è utilizzato il nome ASQUID per definirlo.

Nel capitolo 5 sono stati riportati i risultati della simulazione effettuata. Siccome la variabilità della domanda dei clienti è alta, si è deciso di indagare il comportamento del modello, utilizzando diverse tipologie di dati. In primo luogo sono stati introdotti nel sistema segnali deterministici e, in particolare, si è indagata la risposta del sistema utilizzando picchi e gradini, normalmente impiegati nei controlli digitali e andamenti stagionali tipici della logistica. Il modello è stato in seguito testato utilizzando dati random, l’analisi della combinazione tra dati random e deterministici ha portato a individuare il comportamento di dati “mixed”. Si riportano a partire dal paragrafo 5.2.1 gli andamenti di β al variare di α per i casi sopra citati. Analizzando i risultati delle simulazioni, si mostra come, impiegando l’“Autopilot Controller” il sistema risulti stabile per qualsiasi valore di α, mentre è opportuno individuare un range di stabilità per il parametro β a seconda della tipologia di dato di input impiegato. Nelle figure 5.5.1 e 5.5.2 vengono riportate tali regioni. Si mostra come nel caso di richieste di clienti caratterizzate da alta variabilità e quindi rappresentabili con valori random il valore del parametro beta debba essere tenuto basso, mentre nel caso di dati deterministici possono essere impiegati valori più alti di beta e la risposta del sistema possa essere più veloce. Il comportamento nel caso di dati mixed è descritto da una regione di stabilità intermedia rispetto alle precedenti.
L’analisi è stata conclusa utilizzando dati reali, provenienti da tre Supply Chain diverse, in modo da verificare l’affidabilità del modello.

La prima produce caldaie, la seconda componenti elettrici, la terza gestisce magazzini. Per ciascuna di esse sono stati analizzati gli andamenti e la deviazione standard delle domande e delle scorte dei diversi attori per diversi valori di alpha e beta e individuati i valori ottimi dei parametri $\alpha$ e $\beta$. Sono stati impiegati i dati reali per confrontare quanto accade impiegando il Fixed Gain Controller e nell’Autopilot controller variando il delay time.
INTRODUCTION

During the last years the complexity of international markets has increased a lot. Since the competition is high, many firms have worked together and created supply chain. It is a complex dynamic system with the aim to satisfy each customer’s demand and gain profit. In each production system a huge amount of different items have been introduced and therefore also the complexity of the logistic management has increased. In order to answer to the customer’s demand suddenly, companies have produced a huge amount of products, but at the moment unsold goods represent one of the most important and common problem in all the international markets. The inventory costs are huge and, therefore, the study of the phenomena which happen, in the supply chain, has a key role. The good management of orders between the different suppliers make the difference between efficient system and one that is destined to fail. Since the bullwhip effect is well-known, in the last years, several management strategies have been studied to prevent it, but it is still widespread and brings different negative effects from the logistics, economic, manufacturing and management point of views.

Therefore, since 2011, the collaboration between Professor Dr.-Ing. Kai Furmans and Professor Dr.-Ing. Jürgen Beyer have brought a new approach to this problem. Professor Kai Furmans is the director of the Institute for Material Handling and Logistic (IFL) and Professor Beyer is an expert of Digital Control Systems and works at the Institute of Flight Systems and Automatic Control (FSR) of the University of Darmstadt. They have understood that, even though there are different specific technical languages and approaches, the methodology of Digital Control System can be applied to the Supply Chain Management and can guarantee more stability in the system. Beyer, has introduced a new mathematical method with respect to logistics, based on simple notions of a Digital Control System with the aim to prevent the bullwhip effect and fulfill the customer’s demand.

In this work, the results of my training work made at IFL will be described. The purpose of the project has been to test the Beyer’s model and to understand its behavior in different contests, both with theoretical analysis and real data from Germany companies.

The first chapter of this thesis introduces the theoretical references to the Supply chain and the concept of the bullwhip effect, its causes and its consequences. The second one deals with some basic of Digital Control System and describe Professor Beyer’s model.
The third one concerns the description of the controller that is used in the analysis. The fourth describes the methodology used during the test while the fifth collects all the results of the analysis.
CHAPTER 1: Theoretical references to supply chain

In this chapter a short introduction of the concept of the supply chain will be done. It deals with the well-known bullwhip effect, its causes, its consequences and some of the most important management strategy to prevent it.

1.1 Introduction of the concept of supply chain

A typical configuration of supply chain may involve different stages and includes customers, retailers, wholesalers or distributors, manufacturers and component or raw material suppliers. It is linked also with transporters and warehouses. It is dynamic and involves the constant flow of information, funds and products, between the different stages. In the real word, every stage can receive material from different suppliers and distribute to several distributors.

The supply chain became a network of interaction, as the figure below shows:

![Figure 1.1.1 Supply chain as a network of interaction](image)

The principle goal of each supply chain (SC) is to satisfy the customer needs, but also generate profits for itself. The value that a supply chain generates is the difference
between what the final product is worth to the customer and the costs the supply chain incurs in filling the customer’s requests. Supply chain success should be measured in terms of supply chain profitability and not in terms of the profits at individual stages and for this reason, successful supply chain management requires many decisions relating to the flow of information, products and funds. Each decision should be made to raise the supply chain surplus. As competition has shifted from single companies to SC’s supply chain management (SCM) is integrating organizational units and coordinating material, information and financial flows in order to fulfill customer demands with the aim of improving the competitiveness of a SC as a whole. Quality of decision support provided by an Advanced Planning System APS largely depends on an adequate model of the elements of a supply chain, the algorithms used for its solution and the coordination of modules involved. [1]

It is possible to divide decisions in three categories or phases, it depends on the time they take and at the end of all of them and it is useful to consider uncertainty over the decision horizon.

- In the **Supply chain strategy or design**, given the marking and the pricing plans for a product, a company decides how to structure the supply chain over the next few years. It decides the configuration of the supply chain, which resources it needs and what process, each stages will perform. In this phase, the company makes strategic decisions. Typically these are long-term decisions (it takes years) and implies a lot of costs. Consequently, when the company makes this decision, it must take into account uncertainty in anticipated market conditions in a few years.

- In the **supply chain planning**, decisions made in this phase, affect a time window between a quarter to a year and for this reason, the supply chain configuration determined in this strategic phase is fixed. The aim of planning is to maximize the supply chain surplus, that can be generated over the planning horizon given the constraint within which planning must be done. Companies usual start to plan this phase with a forecast for the incoming demand from different markets. Planning includes decision regarding which marked can be supplied from which locations, the subcontracting of manufacturing, the inventory policy to be followed, the time and size from marketing and price promotion. Thus, thanks to this activity, companies which have defined parameters within a supply chain will function, over a specified period of time. As a result of this phase, companies define a set of operating policies that govern short term operation.
- In the supply chain operation, the time horizon is the week or the day, and during this phase company makes decisions regarding individual customer orders. At the operation level, supply configuration is considered fixed and planning policies are already defined. The goal of this phase is to manage the incoming customer’s order in the best way. During this phase companies allocate inventory or production to individual orders, set a data of order to be filled, handle the shipment, set delivery schedules of track and place replenishment orders. The decision are taken in the short time, generally in hours or days and, for this reason, in this phase, the uncertainty is less. Given the constrains of the previous phases, the aim of the supply chain operation is to reduce the uncertainty and optimize performance.

1.2 Coordination in the supply chain and the bullwhip effect.
In the previous paragraph, it has been mentioned that supply chain must generate profit and that its success should be measured in terms of supply chain profitability. From the logistic literature, it is possible to understand how the coordination among the supply chain influenced its performance. It is known that if all stages of the chain take action together the total profit of the system will increase. On the other hand, if in the system there is a lack of coordination, the result could be the decrease of the profit of all the supply chain. It can happen when each supplier has conflictive objective because, at each stage, there are different owners or information moving between stages is delayed and distorted. This distortion is also due to the huge amount of product variety that is possible to find, nowadays in every supply chain.
Many companies are affected by the **bullwhip effect**. It means that fluctuations of orders increase, as they move up among the supply chain, since each stage has a different estimate of what demand looks like. The result is a loss of coordination among the supply chain. It has been observed that, although the final demand of the final product was constant, there was a high variability in the request of raw material. This increased inventory cost and made very difficult to fulfill the demand. From the logistic literature is possible to understand that the bullwhip effect is not due to the specific product, but is linked to how the supply chain is managed\(^1\). Thus, company which works in completely

\(^1\)We will see that the bullwhip effect depends on the method. The refillment is a feedback circuit which compares its reference value and the actual status quo
different areas, has discovered this problem in their supply chain. To mention some of the major ones consider Proctor & Gamble, HP, the grocery industry, Barilla, the factory that produce memory chips. For example HP discovered that the fluctuation in orders increase a lot as they move from the reseller up the supply chain to the printer division to the integrated circuit. One products demand show some variation in demand, order placed in division of integrated circuit are much more variable. [2]

As consequences of the bullwhip effect as mentioned, the inventory costs increases. It is not the only negative effect and indeed also the replenishment lead time and the manufacturing, transportation, labor cost for shipping and receiving increase, while the level of product availability decreases. Furthermore, this problem brings as result a negative relationship among the supplier.

Thus, the bullwhip effect should be prevented and the coordination among the supply chain need to be reached. However, from the logistics’ literature, it is known that there are some obstacles that make this latest objective more difficult to reach.

First of all, the incentives offered in the different stage of the supply chain lead action that increase variability and reduce total supply chain costs. For example if there are personal incentive for the logistic manager to decrease the cost of transportation per unit, it will decrease the transportation cost, even if it will increase inventory cost. Also the sales force incentive brings, as a consequences, jump of request among the supply chain and difficulties in the coordination.

It is also possible to have information obstacles: the demand is distorted and it moves along the different stages of the supply chain and increased the variability of the system. This happened, for example, when different stages within the supply chain make forecast that are based on orders they received. Any variability in the customer demand is magnified as orders move up in the supply chain to manufacturers and suppliers.

The lack of information sharing between the different suppliers increases the bullwhip effect. For example, if the retailer has planned to make a promotion, he may increase the size of the particular order. If the manufacturer is not informed about this promotion, he would think the customer’s demand is increased and, thus, he would produce more. When the retailer finishes his promotion, his order will become less than usual and the manufacturer will increase his stock.

There are also operation that may increase the variability of the system and the lack of coordination. It is happened, for example, when the order are placed in large lot, that the
size in which demand arises, and this choice is made to decrease the cost of placing, transportation and receiving an order. The bullwhip effect is also magnified if the replenishment lead time between stages are long and the order strategy still remains the same as in shorter variants.

Since the bullwhip effect and the obstacles of the coordination in the supply chain are known, there are also some management strategy, in literature, to achieve coordination among the supply chain.

The manager of the supply chain can align goals and incentive in order to improve coordination and make every participant active in order to maximize profit of all the system. All the decision, concerning costs have to be made with particular attention to the profitability of the system.

He can also use lot-sized based quantity discount to achieve the coordination among all the supply chain. In order to prevent lack of information, among the supply chain, he can improve the accuracy of the available one and in some cases, implement collaborative forecast and planning. It is also possible to improve operation performance, reducing a lot sizes and replenishment lead timer. It is possible to build strategic trust and partnership among the different suppliers.
CHAPTER 2:
The introduction of Digital Control Systems in the Supply Chain.

In the previous paragraph, it has been introduced the bullwhip effect in the supply chain, its causes and effect and some of the most important management strategies that can prevent this phenomenon. Nevertheless this problem is well known and the “beer game” is been played in most of the company and management university for several years, most of the supply chain still need a solution, in order to prevent this problem. The complexity of the system is increasing, because every supplier needs to manage a huge amount of different products, the final customer has more possibility to choose than in the past and want to satisfy his requests in the shortest possible time and at the cheapest price. Most of the supply chain need to change all production in a very short time and they need to be flexible in order to be efficient. Nevertheless, management strategies are necessary, and human decisions are needed, in particular when there are unpredictable new situations, tools are useful to understand which is the best solution to solve new problems or can help to make the right decision quickly in the ordinary situation.

In his papers “Die Supply chain als regelungstechnische Aufgabe. The supply chain as a control Engineering Assignment” [3] Professor Jürgen Beyer introduced a model, based on Digital Control of Dynamic Systems that helps to analyze and prevent the Bullwhip effect among the supply chain using control engineering methods. As it is known, the supply chain must guarantee the fulfillment of the customer’s requests and make profit. In order to prevent the bullwhip effect the system should be stable and for this reason would be desirable to have features like predictability and standardization of the system, which are directly correlated to the already mentioned stability. The control engineering approach can easily guarantee both and can increase the quality of the system in parallel.

2.1 Beyer’s approach

The aim of the Beyer work is to approach the Digital Control theory to the logistic. In these subjects, there are lot of similar main concepts, but also still different languages and methods.

In this section it will be explained, in detailed, how Beyer’s model works, its features, the meaning of different parameters and how it is possible to prevent the bullwhip effect in
the supply chain with this approach. In the real life, supply chain are complex dynamic systems, but the decisions are usually made daily and in some special cases, hourly. For this reason Beyer introduces a discrete time-discrete event approach among the supply chain. In this way, also the treatment of delays becomes simpler, because delays are formulated as a number of basic cycles (e.g. hours or days etc.). The paragraph is written for people, who have no background knowledge in Digital control Theory and work within the supply chain.

2.2 Beyer’s model and its theoretical formulation

To understand Beyer’s model, first suppose that the supply chain design and planning phases are just made (please refer to paragraph 1.1) and in the operational one, it is need to define the amount of orders to be placed to fulfill the customer’s request and prevent the occurrence of stock-out. Beyer’s method answer to this question, and keep the system stable, using some parameters.

2.3 The input data of the model:

In the previous chapter, the supply chain is described as a network of interaction between different suppliers. In order to simplify the analysis of the model, let us suppose that the supply chain has the structure shown in in the figure 2.3.1. Suppose also, that you are one of the suppliers and you know the level of the actual stock you have, the demand of your customer and the time you need to manage order and material among the supply chain. This time will be called, in the sequel “delay”.

![Supply chain's structure](image)

To apply Beyer’s model you need to define, which level of stock you want to keep in your warehouse. Using a common notation from Digital Control, it will be called
“references”. The model takes this desired value and calculates the actual value of order that guarantees this target. In doing so, the probability of running out of stock is minimized. In the long term the reference value can be adopted (decreased) to the need within the supply chain, because the variation around the reference value is small since controlled.

For the aim of simplicity, suppose that you have to manage only one type of item further on. The same reasoning of this model can be easily applied to all items you need to manage.

In order to understand Beyer’s model, first the most general representation is introduced in figure 2.3.2, moreover and following definitions are used:

✔ **Reference** $w(t_k)$: is the level of the stock you want to keep

✔ **Order** $b(t_k)$ is the output you want to obtain from the model. It represents the order you will make to the next supplier. With this order you have to guarantee the fullfill of the customer’s demand and prevent stockout. It is the only way to influence the SC.

✔ $z^{-1}$ inside the block represent one cycle (e.g. a week) of delay among the supply chain. The formulation $z^{-1}$ is taken from z-transformation method of digital control theory.

✔ **Inventory** $s(t_k)$ represents the actual inventory

✔ **Inventory** $s(t_k+1)$ represents the inventory in the next period of time

✔ **Demand** $a(t_k)$ represents the actual demand

*Figure 2.3.2 Beyer’s model Block diagram*
In order to explain, the discrete formulation of the model, it is possible to start from the violet part of the block diagram in the figure 2.3.2.

The “new stock” value can be calculated with the following formula:

\[ s(k + 1) = s(k) - a_i(k) + z_i(k) \]

Where \( s_i(0) = s_{io} \)

Please note that in the mathematical formulation, for the aim of simplicity, \( s(k) \) is used to indicate \( s(tk = k \cdot \Delta t) \). The same reasoning is valid also for \( w(tk), b(tk), a(tk), .. \)

Considering the supply line (look at the light blue part of the block diagram in the figure 2.3.2), we have:

\[ z_i(k + n) = b_i(k) \]

Where \( n \) is the number of the cycles (here the delay). Please note that, if \( n \) equals to zero, \( z_i(k) = b_i(k) \). The index \( i \) describes the modul in the supply chain. The demand \( a_i(k) = b_{i-1}(k) \) and \( a_1(k) = r(k) \), where \( r(k) \) is the customer’s demand.

The controller and the filter are both used to influence the system. The first one takes in consideration the information from the inventory, the second one the actual demand, both of them influence orders. In the following sections the behavior of the controller with the alpha parameter and the behavior of the filter with beta parameter is explained. As it has been mentioned before, the aim of Beyer’s work is to approach Digital Control Theory to Logistic and therefore he has chosen the easiest filter and control for his model. However, it is important to mention that, with Digital Control Theory background, his model can be easily modify with different filters and controller to make it even more flexible and efficient.

2.4 Alpha parameter

In order to understand the concept of alpha, beta, the description of the block diagram illustrated in the figure above, will be divided in three areas.

First, it will be introduced the alpha’s concept, after that it will explained how the theory of Digital Control can influence the system (and it will be explained using the green area of figure) introduced before. To understand how alpha works, it is possible to simplify the block diagram of the Beyer’s model, as in the figure 2.4.1.
In the picture, for the aim of simplicity, it is considered only one week of delay (using $z^{-1}$), among the supply line.

From there, with basic notion of Digital System it is possible to find the following formula:

$$b(k) = (w(k) - s(k)) \times \alpha$$

Parameter alpha is a weighting factor of the residual between the stock reference and the actual stock itself. In control theory alpha is called a linear Fixed Gain controller. The stability of the control circuit shown depends heavily on alpha and on the delay of the supply line.

In his study, Beyer has proved that, with the Digital System theory is possible to understand, which value of the parameter $\alpha$ can guarantee the stability of the system and prevent the bullwhip effect, respectively. He has also shown that it is influenced by the delay among the supply chain.

The stability of the closed loop control circuit is calculated via its eigenvalues (or poles). This provides the characteristic polynomial [page 55, Franklin, Powell, Workman [4]] of the system which is

$$P(z) = z^n(z-1) + \alpha = 0$$

Since all eigenvalues (or synonymously all poles) are located within a circle of radius $r=1$ the system is stable. Thus, $\alpha$ of the first pole, which hits this circle, determines the stability limit.

For the chosen delay of one week using $z^{-1}$ and $n=1$ the stability is gained from the equation

$$P(z) = z^1(z-1) + \alpha = 0$$

$$z^2 - z + \alpha = 0$$

$$z_{1,2} = \frac{1}{2} \pm \sqrt{\frac{1}{4} - \alpha}$$
Obviously, selecting $\alpha = 1$ the radius $r^2 = (\text{real part})^2 + (\text{imaginary part})^2 = 1/4 + 3/4$ becomes one. Thus, the stability limit in this case $(n=1)$ equals $\alpha = 1$. In case of $(n=2)$ the critical value becomes $\alpha = (\sqrt{5} - 1) / 2 = 0.6180$ [see page 213, Beyer [3]]. It is out of the scope of this work to explain how all other values $(n>2)$ can be calculated in detail, but in order to understand how to use this information to prevent the bullwhip effect among the supply chain, in the sequel, it is possible to find some of the most important diagrams, taken from his paper, with some comments. Let us consider the picture 2.4.2. It represents the behavior of poles of a discrete supply chain as a function of feedback $\alpha$ and order $n$ (here 1 up to 5) of a transportation delay.

![Poles of a discrete supply chain as a function of feedback and order n of transportation delay](image)

*Figure 2.4.2 Poles of a discrete supply chain as a function of feedback and order n of transportation delay*

To understand the meaning of this picture it is necessary to know that it is possible to describe the supply chain as a Digital System, with a method called Z-transform. It is a mathematical function that converts a time domain, which is a sequence of real or complex numbers into a complex frequency domain representation [page 18, Shen, Chen, TianShuang, [5]]. Usual the Z-transform is expressed with a rational function of a
complex variable. Suppose that we call the numerator polynomial $b(z)$ and the denominator $a(z)$. The place in which $b(z)=0$ are called “zeros of the transfer function” and the place in which $a(z)=0$ are called “poles of the transfer function”. Moreover, from Digital Control Theory, you need to know that a digital system is stable if the poles of the transfer function are inside a unit circle. It is possible to state that in our case it is the alpha parameter (in the future, it will be denoted simply with $\alpha$) that influences the value of poles and, consequently, the stability behavior of the system. If we apply the basic notion of Digital control systems introduced before, we can understand that the system is stable only inside the unit circuit in the figure. Therefore, the intersection between every colored curve and the circle represents, for different $n$, the value in which the system starts to become unstable. It means that, after this point, among the supply chain, it is possible to find that the peak of inventory grows up as well as the probability of having stock out and this situation gets worst day by day. The intersection between the x-axis and the color curves of the graph represents the value in which the system starts to oscillate (the poles becoming conjugated complex). Beyer states that, in order to prevent the bullwhip effect, it is necessary to choose the value of alpha, between the two extremes that are mentioned before. Thus, the supply chain is fast enough to follow customer demands but provides guaranteed stability. It is also necessary to understand, from the picture, how the value of alpha is connected with the delay. Recall that with $n$ it was defined the delay among the supply chain, it is easy to understand that it is necessary to decrease the value of alpha, if the delay increases, in order to guarantee the stability of the system. In fact, from the graph it is possible to see that the intersection between the unit circle and color curves becomes faster, if the delay increases.
In the next figure “damping as a function of feedback and supply line delays” is represented.

![Diagram](image)

*Figure 2.4.3 Damping as a function of feedback and supply line delays*

If the damping is equal to one (please refer to the intersections with x-axis in figure 2.4.2), no oscillation is found in the system, but the system is slow and it can have problem to fulfill the customer’s demand. If the damping is null (please refer to the intersection with the circle) the system oscillates (the dominant poles are becoming unstable). It is necessary to mention that in the diagram above the word “fair” is used to indicate a fast and pretty stable system, while “good” is used to indicate a well damping system. In the last case, the tendency to oscillate will decrease along the supply chain.

From the graph it easy to understand that a good value of the damping could be 0.7. Typically a damping value between 0.4 and 0.8 is chosen in control theory, which is a good compromise between stability and reaction time.

Let us suppose the same hypothesis, mentioned in the section “input data of the model”, are still valid, with the delay of the system, from this graph it is possible to understand which could be the behavior of the system. For example, if we assume that the delay equals to two (n=2), to have damping equal to 0.7 it is necessary to take alpha equal to 0.2. It is important to recall that the stability ends with a value of alpha = 0.6180. In order to confirm this sentence it is possible to look at figure 2.4.3 by taking alpha to have a damping of zero. It has just been mentioned that if the delay equals to one (n=1) the critical value of alpha equals 1. Also this concept can be proved looking at figure 2.4.3.
2.5 Beta parameter

Let us consider also the green area of figure 2.3.2. In this section, a new parameter called $\beta$ will be introduced. This parameter keeps track of how the supplier acts to follow the customer’s demand. It is known that each supplier should fulfill customer’s demand and keep the system stable in parallel. As shown, stability is managed by selecting the parameter alpha. Unfortunately, in real life, every supply chain has to manage several different customer’s demands and each of these can vary in time.

If the customer’s demand is noisy and the supplier decides to follow it directly, also his orders in the supply chain will become noisy. This provides fast and noisy changes in stock and supply lines. We have supposed that in each supply chain, there was only one product to manage, but the reality is more complex and this worsens the effects of non-adequate designed system. Beyer’s model, with the digital theory approach, suggests how it is possible to keep the system stable using the alpha parameter and taking also in consideration the existing noise on the demand side utilizing the beta parameter.

It is necessary to know that this beta parameter could vary between zero and one. If beta is equal to zero, it means that the supplier does not take in consideration the customer’s demand and keeps the production flow constant. On the other side, if beta equals to one, the production flow follows the customer’s demand directly. Thus, the stock manager can decide whether to follow a theoretical constant mean flow (since the customers demand is pure noise) or to follow the customer demand exactly, when it is precise and not noisy. In reality, the optimal value lies in between and can be selected using adequate beta.
2.6 The introduction of three different controllers
Concerning the green area of the diagram block, Beyer introduces **three different approaches, to estimate the value of b(tk) using a controller**. The idea behind is to define benchmark figures in order to support the controllers parameter selection. One benchmark is to do nothing but to fulfill customers’ demand. In this case the refilling of inventory is faded out. The other benchmark is the fastest possible refilling of stock. In reality the optimal value lies in between again. Thus, the third approach provides a transfer from one benchmark to the other. This intersection method has been called the supply chain Autopilot by Beyer.

2.6.1 Fixed Gain controller and Low Pass Filter
The first method is called the Fixed Gain controller. It follows the ideas mentioned above about alpha and beta selection. This approach is simple and easy to implement. It is described by using the mathematical equation you will find below:

\[
v(tk) = v(tk - 1) + \beta [a(tk) - v(tk - 1)], \quad v(0) = \bar{a}
\]

\[
b(tk) = v(tk) + \alpha [w(tk) - s(tk)]
\]

In order to understand better this mathematical formulation you will find again, the block diagram of Beyer’s model in the figure below, with some references to what was discussed before.

![Figure 2.6.1 Block diagram of Beyer’s model, - linear Fixed Gain controller](image)

Selecting alpha=0 provides no refilling of the inventory. In this case, parameter beta configures the performance of the supply chain on its own. It is important to note, that alpha=0 guarantees a non-oscillating system since there is no stock refilling feed-back in
the system. The inventory just follows the demand. The green area on the figure above describes a low Pass filter. It is a filter that passes low frequency signals and attenuates signals with frequency higher than the cutoff frequency.

2.6.2 Deadbeat controller
The second controller method is called **Deadbeat approach**. This approach is well known in control theory. It is in general not directly comparable to the linear Fixed Gain controller mentioned before. Deadbeat controllers are using the residuals between references and inventories like the other controllers, but they use the older orders in parallel. The number of how many older orders will become incorporated in the controller depends on the number of delay cycles in the supply line.

Beyer states that it is theoretically the fastest approach, but it is sensitive with respect to noise and model errors. In fact, with the digital control system, it is possible to understand the behavior of the system with the introduction of simple forcing input signals like jump, peak, and sinusoid. It is also possible to use noise to represent all the possible signals, or in other words, all the possible customer’s demands.

Using the noise as input data it is possible to understand that Deadbeat approach guarantees the fastest answer to the customer’s demand, but generates also lot of peak of inventory and makes the system turbulent. To understand better this concept it is possible to refer to the figure 3.2.1, in the following chapter.

Nevertheless, below you will find its mathematical formulation, because it is useful to understand the other approaches:

\[
b(tk) = a(tk) + [w(tk) - s(tk)] + [a(tk) - b(tk - 1)] + [a(tk) - b(tk - 2)] + \ldots
\]

In the figure below it will be recalled the block diagram of Beyer’s model of Diagram 1 from which it is possible to understand the Deadbeat control.

![Figure 2.6.2 Beyer’s model block diagram-recall](image)
2.6.3 Autopilot controller

The Autopilot approach represents a combined approach and enables adaptations. It is described with the following mathematical formulation:

\[
\begin{align*}
v(tk) &= v(tk - 1) + \beta(a(tk) - v(tk - 1)), \quad v(o) = \bar{a} \\
b(tk) &= v(tk) + \alpha[w(tk) - s(tk)] + \gamma[v(tk) - b(tk - 1)] \\
&\quad + \gamma[v(tk) - b(tk - 2)] + ..
\end{align*}
\]

If \(\alpha, \beta, \gamma\) is equal to one, the formula provides Deadbeat approach, while if \(\gamma\) equal to zero, it provides the linear Fixed Gain controller. Gamma takes in consideration historic orders data. In the following chapter this controller and its benefits is discussed more in details. For all the examples, gamma will be taken equal to alpha from now on. Concerning the diagram of the Autopilot controller, it is possible to think about the one that it is shown in the Deadbeat approach.

2.7 The flow of customer’s demand in the system

In the section 2.3, it has been mentioned that Beyer’s model needs customer’s demand as an input data in order to find the correct amount of orders that each supplier should make to keep the system performing appropriate. Thus, it is possible to state that the initialization of the system is also made by the expected customer’s mean demand. After this first step, three different situations can happen. The worst scenery occurs where there is no exchange of information among the supply chain. All the suppliers worked as if there were independent and this fact involves a huge waste of money from each of them, unmet demand and no stability in the system. Thus, we can assume that the information flows among the different stages of the supply line. It is possible to state that, after the initialization with the customer’s demand, all the supplier are promptly informed when any variation occurs in the customer’s demand or that each supplier knows only what has happened in the previous stage.

We assume the first scenery, because with this hypothesis the answer to the customer’s demand is faster in the following stages of the supply chain. In order to confirm what we have just mentioned, it is possible to see the comparison between the columns in the figure.
2.7.1. The only thing that changes between them is the way to exchange information. In the first case all the different stages know the customer’s demand, in the second case they have information only from the previous one. For both columns in the picture below, beta equals to one (the system follows all the variations of the customer’s demand directly, without any filtering), alpha equals to 0.2 and delay equals to two. As it is shown in the picture, from this moment the number one is used to refer to the retailer, two for the wholesaler, three for the manufacturer.

![Customer’s demand- step- no random noise](image1)

![Previous demand](image2)

*Figure 2.7.1 Flow of information in the supply chain*
CHAPTER 3:
The Autopilot controller and its benefit

In the previous section, Beyer’s approach and his model has been theoretically explained and three different controllers used up to now have been introduced.
In this chapter, it is explained why the Autopilot controller has been chosen from the three controllers for the simulations and its benefit for logistics management.
In the following one, the methodology of the simulation analysis, used to test the behavior of the Autopilot controller in the supply chain, also for real data from some Germany companies is introduced.

3.1 The Autopilot controller and the stability of the system

As it has been mentioned in chapter 2.1, the Autopilot approach represents a combined approach and enables adaptions. In the hypothesis of Beyer’s model it has been stated that the delay among the supply chain has been known and that the delay of the system influences the value of critical alpha. For this reason, to keep the system stable, if the delay of the system increases, alpha value needs to be decreased. Although many management efforts and contracts have always been made, between the different stages, to keep the delay time known and constant, in real life unexpected things can always happen.
Supply chain is typically a complex dynamic system and therefore when a shift happens, it can influence negatively the performance of the system during the time. Therefore, after that, many efforts are necessary in order to make it again stable. With digital control theory this goal can be reached easier. In particular, Autopilot controller approach can guarantee the stability of the system even when the delay time between the different stages changes. This behavior is been called "robust" in control theory.
In order to prove this concept, it is possible to see from the table below, that if we take in consideration the Fixed Gain controller and we change the delay of the system, the bullwhip effect occurs, while with the Autopilot controller the system has no importance variations. In both pictures, alpha is taken equal to 0.3 and beta equal to 0.5. In order to understand, in detail, how the controller works, please refer to chapter 5.
Autopilot controller

<table>
<thead>
<tr>
<th>Request</th>
<th>Delay=2 weeks</th>
<th>Delay=4 weeks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customer</td>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
</tr>
<tr>
<td>PT1 Filter</td>
<td><img src="image3.png" alt="Graph" /></td>
<td><img src="image4.png" alt="Graph" /></td>
</tr>
<tr>
<td>Demand 1</td>
<td><img src="image5.png" alt="Graph" /></td>
<td><img src="image6.png" alt="Graph" /></td>
</tr>
<tr>
<td>Demand 2</td>
<td><img src="image7.png" alt="Graph" /></td>
<td><img src="image8.png" alt="Graph" /></td>
</tr>
<tr>
<td>Demand 3</td>
<td><img src="image9.png" alt="Graph" /></td>
<td><img src="image10.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

Fixed Gain controller

<table>
<thead>
<tr>
<th>Request</th>
<th>Delay=2 weeks</th>
<th>Delay=4 weeks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customer</td>
<td><img src="image11.png" alt="Graph" /></td>
<td><img src="image12.png" alt="Graph" /></td>
</tr>
<tr>
<td>PT1 Filter</td>
<td><img src="image13.png" alt="Graph" /></td>
<td><img src="image14.png" alt="Graph" /></td>
</tr>
<tr>
<td>Demand 1</td>
<td><img src="image15.png" alt="Graph" /></td>
<td><img src="image16.png" alt="Graph" /></td>
</tr>
<tr>
<td>Demand 2</td>
<td><img src="image17.png" alt="Graph" /></td>
<td><img src="image18.png" alt="Graph" /></td>
</tr>
<tr>
<td>Demand 3</td>
<td><img src="image19.png" alt="Graph" /></td>
<td><img src="image20.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

Inventory

| Inventory 1 | ![Graph](image21.png) | ![Graph](image22.png) |
| Inventory 2 | ![Graph](image23.png) | ![Graph](image24.png) |
| Inventory 3 | ![Graph](image25.png) | ![Graph](image26.png) |

Figure 3.1.1 The behavior of Fixed Gain controller and Autopilot controller with the delay time
3.2 Autopilot as the most general approach: the extreme cases

It is also important to mention that the Autopilot controller is the most general approach. In this section, it is possible to see how with the extreme case of the Autopilot it is possible to model the other controller. It particular, it is shown what happens if alpha and gamma equals to zero, if alpha, beta and gamma equals to one.

3.2.1 Autopilot becomes Deadbeat controller

Let us consider Autopilot controller and suppose that alpha, beta and gamma equals to one. As in this case, Autopilot becomes a Deadbeat controller. In the section 2.6.1 it has been said that it is theoretically the fastest approach, but it is sensitive with respect to noise and model errors. To understand this concept it is possible to observe the behavior of the system in the two different examples of the table 3.2.1. In the first, it is assumed that the customer’s demand changes, in the period of three, with a peak, from the value of 10 to the value of 30. In the second one, a random input data is used. For both, a delay of two weeks is hypothesized.
## Random noise-Deadbeat controller

<table>
<thead>
<tr>
<th>Customer</th>
<th>PT1 Filter</th>
<th>Demand 1</th>
<th>Demand 2</th>
<th>Demand 3</th>
</tr>
</thead>
</table>

![Graph 1](image1.png)

<table>
<thead>
<tr>
<th>Inventory 1</th>
<th>Inventory 2</th>
<th>Inventory 3</th>
</tr>
</thead>
</table>

![Graph 2](image2.png)

### Figure 3.2.1 The Autopilot becomes Deadbeat controller

### 3.2.2 Autopilot becomes Fixed Gain controller

In the following table it is possible to see what happens if gamma equals to zero. The Autopilot controller becomes a special Fixed Gain controller without inventory feedback. In control theory this case is called an open loop configuration. The behavior of the system with alpha equal to 0.2 is shown in the picture below.
Fixed Gain controller

<table>
<thead>
<tr>
<th>Beta=0</th>
<th>Beta=0.5</th>
<th>Beta=1</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Graph for Beta=0]</td>
<td>![Graph for Beta=0.5]</td>
<td>![Graph for Beta=1]</td>
</tr>
<tr>
<td>![Graph for Inventory 1]</td>
<td>![Graph for Inventory 0.5]</td>
<td>![Graph for Inventory 1]</td>
</tr>
</tbody>
</table>
CHAPTER 4:  
The simulation with the Autopilot approach

In this chapter the methodology used to make the analysis of the Autopilot behavior in the supply chain system is described. In the following the simulation analysis’ results are discussed.

4.1 The simulation approach with spreadsheet file: advantages, aims and methodology

The aim of the simulation’s analysis is to define under which conditions the Autopilot controller can guarantee the proper performance of the system and if can be an useful tool in the real context to manage the amount of order between the different stages of the supply chain and prevent the bullwhip effect. In the theoretical explanation of the Autopilot controller three parameters have been introduced: alpha, beta and gamma. It has been mentioned in the paragraph 2.4 that alpha is a weighting factor of the residual between the stock reference and the actual stock itself and in paragraph 2.5 that beta parameter keeps track of how the supplier acts to follow the customer’s demand. It is also important to recall that gamma takes into consideration the historical data and that it is hypothesized equal to alpha in all the simulations made here. Therefore, from this moment, all the comment refer only to alpha and beta. In order to review the mathematical formulation of the Autopilot controller please review paragraph 2.6.1.

It has been stated that alpha and beta parameters of the Autopilot can vary between 0 and 1. For this reason, in order to find the range of applicability of the system, lot of different results need to be compared and collected and the simulation approach has been chosen to make the analysis.

The simulation analysis has been made with Excel spreadsheet, because this software is much more widespread that other available on the market for the simulation of the supply chain. Moreover, since Beyer’s model is in discrete time, discrete events condition, the customer’s input data can be updated day by day, without any mathematical approximation. This causes a greater reliability of the model itself. In particular, it has been chosen to make the analysis with some different tools of Excel simulation like the scenario management, pivot tables, filters and graphs. Different input data and different
criteria have been also selected. In the following paragraph, this topic is explained more in detail.

4.2 The composition of signal and the analysis of customer’s data
First of all, let us suppose that all the hypotheses described in the chapter 2.3 are still valid. We have assumed that each supplier knows his actual level of stock, his references, the customer’s demand and the delay time of his order. It has also mentioned that, in order to apply Beyer’s model, it is possible to refer to final customer’s demand one at a time and apply the same reason to the others. When any variation occurs in the final customer’s demand all the suppliers are promptly informed.

The customer’s demand are described with a signal. In particular, in order to make the analysis more efficient, it is possible to use a well-known approach of Digital Control System called “composition of signals”. It means that the behavior of complex signal can be described easily studying first different simple signal, and after that by adding, in the system, more complex one.

For this reason, in order to study the behavior of customer’s demand, that could vary a lot, first simple signals like peaks, jumps have been introduced. Peaks have been chosen because in the real life occurs very often for example when a new product from an important brand is introduced in the market. For example, it is possible to think about what happens when a new Smartphone starts to be available. Steps have been chosen because it is the most common signal used in the Digital Control Theory to analyze the behavior of the system. Seasonal trends are useful from the logistic point of view, in order to understand what happens with some particular products. In the following chapter, the results of the analysis are described and it is also used the terminology “force 0” in order to refer to peaks, “force 1” for steps and “force 3” for seasonal trends. In order to study more complex signal, after the simple one, random input data have been introduced. These values are called in the sequel “noise”. Finally deterministic simple signal like peak, jumps and seasonal trend and random noise have been combined.

4.3 The analysis of real data from Germany Companies
Once that the theoretical analysis has been made, real data from Companies have been chosen and in particular three different ones have been selected. The first one, for reasons
of privacy, will be called “Company A”. It works in the field of heating system. The production’s logic is, in general, Make to stock, but for a big amount of orders from the same customers change in Make to Orders. The second one, “Company B” works in the field of the electronics components. The logic of the production system is in general Make to stock and change in Make to order for the most important customer. The third, “Company C” has a huge warehouse of spare parts and tries to answer as soon as possible the customer’s demand.

Different data from different companies have been selected in order to understand if the Autopilot controller could be an efficient and flexible tool in the logistics management. Before that the simulation analysis, all the real data need to be reorganized and studied in order to define which of them are more useful for the analysis itself. For example, for the “Company B”, more than one hundred data of real products were available and, from the picture 4.1 it is possible to see the different behavior of the different customer’s demand during the period of time. From all these products, first the one with only some little and sporadic orders have been neglected. After that the most critical products have been analyzed and two of them have been selected. The first one, is called in the sequel, product M1 and it has been chosen because different products have a quite similar behavior during the time, in this company. The second one is called M17, and it has been chosen because it represents the worst situation, because it has the highest peaks. In the picture 4.2 the behavior in the time of this products is shown.
Also for the other companies, some set of real data have been selected from the available ones. Since the analysis first has been made with theoretical approach and different signals have been studied, it has not been considered necessary to study the behavior of the system with a huge amount of real data, but it has been decided to take some products of different company and compare this result with the theoretical ones.

For this reason, in addition to the products M1 and M17 mentioned before, the product V1 has been taken from the company A and the product N1 from Company C. The behavior of the customer’s demand in the time of these products it is shown in the picture 4.3.2.
<table>
<thead>
<tr>
<th>Product</th>
<th>Figure 4.3.2 Customer’s demand in the time for different products</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td><img src="image1" alt="Graph M1" /></td>
</tr>
<tr>
<td>M17</td>
<td><img src="image2" alt="Graph M17" /></td>
</tr>
<tr>
<td>V1</td>
<td><img src="image3" alt="Graph V1" /></td>
</tr>
<tr>
<td>N1</td>
<td><img src="image4" alt="Graph N1" /></td>
</tr>
</tbody>
</table>

*Figure 4.3.2 Customer’s demand in the time for different products*
4.4 The different criteria used to define the stability of the system

In order to guarantee the stability of the system and to define which value of parameter should be taken, it is necessary to choose the right criteria to test the model. Therefore, first of all, different criteria has been tried and tested with different signals.

In particular, the behavior of the system has been studied taking into account the value of sigma demand and sigma inventory in the different stages of the supply chain and their Aggregate value. It has been tried to use also a criteria which will be called in the sequel “Aggregate of Maximum Deviation Criteria”. In order to compute this value, it has been defined, for each supplier, the deviation between the difference of the initial level of inventory and its minimum value in the time and the difference between the maximum level of the inventory in the time and the its level at the beginning. After that, this deviation has been added in order to define the aggregate value. In chapter 5.1, it is explained why this criteria has been considered not satisfactory and therefore a new one has been searched to analyze the system. In particular, it generally happens that also in the control system design it is necessary to select a performance index in order to define the best performance of the system. A performance index, to be useful, must have a number that have a value always bigger than zero. It is necessary to mention that it would be desirable to have a criteria based only on a factor. In particular, for example if it is taken this expression:

\[
I = k_1 t_{an} + k_2 t_\xi + k_3 e_{max}
\]

Where

- \( k_i \) ( \( i = 1,2,3 \)) are weighting factors characterizing the relative importance of each of the individual performance specifications;
- \( t_{an} \) is the time in which the response reach, for the first time the desired final value;
- \( t_\xi \) is the setting time and represent the time after which the response remain within a band of \( \pm \varepsilon \% \) about the desired final value, where \( \varepsilon \) is selected between 2 and 5%;
- \( e_{max} \) represents the maximum value of the response at the time \( t_{max} \) in relation to its desired final value. It can be considered the measure of the relative stability of the system. It increases as the ratio damping decreases.
The individual selection of the $k_i$-factors and the analytical evaluation of the equation usually causes difficulties. Therefore the performance indices based on various functions $f_k[e(t)]$ of the errors

$$e(t) = r(t) - y(t)$$

between the reference input $r(t)$ and the controller plant output $y(t)$ are preferred. The performance index generally covering an error function in $[0,\infty)$ have been introduced as an integral

$$l_k = \int_0^\infty f_k e(t)dt$$

where $f_k e(t)$ take different various forms. In particular, the formulation called Integral of Squared Errors (ISE) has been chosen. It is considered a good analytical treatment and it highly penalizing large control errors more than small ones. [6]

The mathematical formulation of ISE is:

$$l_k = \int_0^\infty e^2(t)dt$$

In the literature, it is proved that for different examples this integral can be solved analytically. [7]. Therefore it is used in different industrial applications [8] and it has been considered also useful for the analysis of the Autopilot controller behavior.

Since Beyer's model is based on discrete time and discrete events, in this work the integral is replaced by the Sum and this criteria is called, in the sequel, "Aggregate Sum of Squared Inventory Deviations" (ASQID). Even though lot of simulations have been made in order to test all the different criteria, in the next section only the results, achieved with this last criteria, are explained.
CHAPTER 5:
Analysis of the results of the simulations

In the previous chapter, the methodology has been described, used in the simulation’s analysis, in order to understand when the Autopilot controller can be useful in the logistics management of the supply chain.

In this chapter the most important results of some of the simulations test are collected. In particular, it is discussed the behavior of the system with simple signals like peaks, jumps and seasonal trends, with mix of data (simple and random ones) and with real data from German companies. Moreover is made a comparison between the behavior of the system in which the Autopilot controller has been used and the same one with no controller.

5.1 The comparison between the different criteria used in the analysis

The first step of the simulation analysis is to define the right criteria that can allow a good comparison between all the results. As it has been mentioned in paragraph 4.4, Aggregate of Maximum Deviations Criteria has been considered not satisfactory for the analysis, while it was defined reliable the one called Aggregate Sum of Squared Inventory Deviations. The difference between them is the fact that the first one selects only one value of the stock time behavior from the time function. The second one values the deviation, from time equals to zero till the end of the time period. This means that, with the first criteria, if there is a permanent deviation in the index it takes into consideration only the maximum value; instead with the second one, all the deviations between references and stocks are considered.

In the following pictures, it is shown the behavior of the two different criteria. In the first one, the maximum value of deviation is represented, in the second one the area of deviation.
It has been mentioned that alpha and beta parameters can vary between zero and one and that the simulation analysis has been made with identical interval of 0.1 increments. During the analysis, the first criteria hasn’t been able to handle alpha equals to zero and beta equals to zero and it has been necessary to delete these values manually, while with the second one (ASQUID), these particular values of alpha and beta have returned very high index value. This result is due to the fact that the permanent deviations are summed up.

Since it has been decided to select the value of beta in such a way that can guarantee the minimum of ASQUID, with this second criteria each value of alpha and beta can be taken in consideration, without any problem in the result.
5.2 The analysis of the behavior of the system with simple signal as customer’s data

In this section, the behavior of the system is discussed, when simple and deterministic signals are introduced. This analysis is useful in order to understand better the behavior of real supply chains. For all the examples, it has been chosen a delay time between each supplier equals to two. In order to analyze the influence of the Autopilot controller in the system, it has been decided to compare the results of the simulation obtained with the Autopilot controller and the Fixed Gain feedback approach. The last one shows the behavior of the system when in the supply chain any theory from Digital Control System is used. In the sequel, it will be called the Autopilot controller with the expression “Mode 14” and the Fixed Gain controller with “Mode 11”.

All the graphs and the results concerning the ASQUID criteria. The same analysis is described, in the next section, also with random noise and real data.

5.2.1 Introduction of “Force 0: peak”, “Force 1: step” and “Force 3 seasonal trends”

In the figure 5.2.1 it is possible to see the behavior of the system, with different alpha and different beta. It has been mentioned, in the previous chapters, that alpha is a weighting factor of the residual between the stock reference and the actual stock itself and beta parameter keeps track of how the supplier acts to follow his customer’s demand. In this example, from alpha equals to 0.3, for each beta, Mode 14 can guarantee better performance of the system than Mode 11. In particular, it decreases a lot the value of the Aggregate Sum of Squared Inventory Deviations and make the supply chain more stable. For graphic simplicity, it is not shown the behavior of the system for alpha equals to one. Anyway, this fact does not influence the analysis, because it will not chose alpha equal to one as a good value for the stability of the system. In the figure 5.2.2, it is possible to see the comparison between what happens in the system with Mode 11 and Mode 14, if the step signal has been taken as customer’ input data, while in figure 5.2.3 it has been introduced the seasonal trend. For all these examples, all the considerations made for the force 0 are still valid.

From the figures 5.2.1, 5.2.2 and 5.2.3, it is easy to observe that for alpha equals to zero, there is no difference between Mode 11 and Mode 14, but as soon as the value of alpha increases, the Autopilot controller brings several advantages.
Figure 5.2.1 The behavior of the system with peaks as customers' demand.
Figure 5.2.2 The behavior of the system with step as customers' demand.
Figure 5.2.3 The behavior of the system with seasonal trends as customers’ demand.
5.2.2 Introduction of noise as customer’s input data

In the previous paragraph the behavior of the system with only some simple deterministic has been shown. Since in the real supply chain the complexity of the customer’s demand is higher, random input data has been introduced in the Excel spreadsheet and the simulation analysis has been made also with these new input data.

The table 5.2.4 shows the comparison between the behavior of the system, characterized only by the force 0 and the one in which is also introduced a random noise that it will be called, in the sequel, “Random 10”, because one sigma equals 10. The picture also shows what happens if other random data are introduced and it will be denoted with the expression “Random 20” with one sigma equals 20.

It is possible to observe that generally the value of ASQUID increases both for the deterministic signals and random noise if the value of alpha parameter increases. When random noise is introduced, it is possible to observe the same behavior.

Comparing the behavior of the system for Random 10 and Random 20 it is possible to observe that the value of the ASQUID increases for more “noisy” input data. These considerations are correct both for the Mode 11 and the Mode 14, but with the introduction of the controller all the value of ASQUID decrease.

In particular, it is possible to states that the Autopilot controller, from alpha equals to 0.4, can guarantee, for each beta, a smaller value of the ASQUID than the feedback approach, even when Random 20 has been introduced in the supply chain as input data. This result is very important, because it shows the real benefits of the Autopilot controller. Since the customer’s demand could vary a lot, it is very important to guarantee a good performance of the model also with random data. This involves several advantage also from the economic point of view and they are discussed further. In the picture 5.2.5, the same comparison between Mode 11 and Mode 14 has been made with Force 1 and Random 10, and in the picture 5.2.6 for Force 3 and Random 10. Since with Random 10 and Random 20 the behavior of the controller is the same, it has been decided to take in consideration only the first one. In the example of the peaks, starting from alpha equals to 0.3 the Autopilot controller can guarantee a better performance than the feedback approach for each value of beta. In the example of the seasonal trends this reasons can be apply from alpha equals to 0.5. The Fixed Gain feedback approach brings irregular in the trend of the curves, while the Autopilot controller provides as a result a smoother ones. As much as the value of alpha increases as more this phenomena can be observed.
Force 0 and random noise

Figure 5.2.4 The behavior of the system with peak and different random data
Figure 5.2.5 The behavior of the system with force and different random data
Figure 5.2.6 The behavior of the system with seasonal trend and different random data
5.3 The delay time and the Autopilot controller

It has been mentioned in paragraph 3.1, that the Autopilot controller can guarantee the stability of the system, even when the delay time changes and it has been stated that this characteristic has a significant importance for the supply chain management, because it is very difficult to have in the real life constant delay time.

In the pictures 5.3.1, 5.3.2 and 5.3.3 it is shown the comparison between Mode 11 and Mode 14, with and without random data and with different delay time. It is shown what happens in the system with a delay time equals to two and with a variable delay time. In particular in this last case, it has been assumed equals to two for the retailer, three for the wholesaler and four for the manufacturer.

In these examples, only some value of alpha have been taken in order to simply the graphic representation, but the analysis with the simulation spread sheet has been made for each value of alpha. From alpha equals to 0.1, for each signal, it is possible to observe that the Autopilot controller, as has been mentioned before, decreases the value of the “Aggregate Sum of Squared Inventory Deviations (ASQID)” and keeps the curve smoothed. Concerning Force 0, it is possible to observe that, if there is no noise in the system, the behavior of the system with a constant delay of two weeks is the same as of the one with variable delay among the supplier and the two curves overlap.

If Random 10 has been introduced as input data and the delay time is variable, for each beta, the value of ASQID is bigger than when there is a constant delay time. For low value of the beta parameter, this value is small and it increases for high value of beta and alpha. However, this differences in minimum, compared of what happens in the example with the Mode 11. Concerning Force 1 and Force 3, the reasons can be repeated, but if we consider only the deterministic signals, there are no curves overlapped.

It is also important to observe that, if the delay time equals to two, as it has been mentioned in chapter 2.4 and as it can be observed in the previous tables, Mode 11 provides instability for alpha approximately equals to 0.6. With the Autopilot controller the system, as it can be observed in the previous pictures, is stable for each value of alpha parameter and the answer of the system to the customer’s demand will be faster as soon as alpha increases. If the delay time is more than two weeks, the critical value of alpha for the Mode 11 decreases, while it is not possible to observe this phenomenon with the Autopilot controller. Therefore, when the delay time is variable, the benefits introduced from the Autopilot controller are even more important.
Force 0 and random noise – comparison between constant and different delay

Alpha = 0

Alpha = 0.2

Alpha = 0.4

Alpha = 0.6

Alpha = 0.8

Figure 5.3.1 Comparison between force 0 and random noise with different delays
Force 1 and random noise – comparison between constant and different delay

**Alpha = 0**

**Alpha = 0.2**

**Alpha = 0.4**

**Alpha = 0.6**

**Alpha = 0.8**

*Figure 5.3.2 Comparison between force 1 and random noise with different delays*
Force 3 and random noise – comparison between constant and different delay

Alpha = 0

Alpha = 0.2

Alpha = 0.4

Alpha = 0.6

Alpha = 0.8

Figure 5.3.3 Comparison between force 3 and random noise with different delays
5.4 The Autopilot controller and the possibility to be more efficient and more flexible

In the previous paragraph of this chapter it has been assumed a constant value of alpha between each module of the supply chain and it has been studied the behavior of the system in different situations. In the real life, the supply chain is a complex dynamic system and it could be difficult to define the same value of the parameter alpha for each supplier. Therefore, after this simulation analysis, it has been tried to understand if the Autopilot controller can have good performance, even when there is a different value of alpha among each supplier.

It has been proved, that the choice to have different value of this parameter let the suppliers not only to be more flexible, but also to be more efficient. In particular, it has been noticed that if the supplier is close to the customer, the value of alpha should be smaller and it can increase as more as the module of the supply chain is far from it.

As it has been discussed, customer’s demand can vary a lot. For this reasons, it can be described in the system with random data. For the suppliers who are far away from the final customer, the behavior of the demand is smoother and it can be described theoretically with a deterministic function.

In particular, for the simulation analysis it has been considered as good value for alpha = 0.08 for the stage between the retailer to the wholesaler, 0.18 between the wholesaler to the manufacturer and 0.80 between the manufacturer and the company that produce raw materials.

In order to understand what happens with these different value of alpha among the supplier, the simulation analysis has been made again, for all the deterministic forces that have been introduced before and for Random 10 noise.

For all the simulation, have been taken the same values of references and inventories. With the criteria of Aggregate Sum of Squared Inventory Deviations, it has been taken the minimum value and it has been found the optimum value of beta parameter. The results for the Autopilot controller are shown in the table below:
From this table it is possible to observe that for Jumps and seasonal trends, if there is no noise, the delay time doesn’t influence in any way the supply chain behavior.

In general, if random noise has been introduced, the optimum value of beta decreases in comparison to the case in which there is only the deterministic function. If the peak’s column and random noise it seem that this rule of thumbs is not right, but it depends on the particular set of the random data. It is also important to observe that it is shown in the table the value of beta that can guarantee the minimum value of ASQID.

In this section, different values of alpha have been assumed among the supply chain and since, in the Beyer’s model the filter signal is valid for all the suppliers and it depends only on the final customer, for each beta the value of the ASQID stays constant. In the previous paragraph, with the same alpha among all the module of the supply chain, the value of ASQUID changed with alpha and beta, and in particular in this case a range of value of alpha and beta parameters are defined, instead of only the minimum one.

Nevertheless, from the graphs of the previous paragraphs, it is possible to state that it is better to speak about a region of parameters in which the Autopilot controller could guarantee optimum performance and not only a single value of the beta parameter. Since the simulation analysis with the Autopilot controller has shown that this controller is stable for each value of alpha, in the real application, it could be interesting to define a range of beta values. From the paragraph 5.6.1, these ones are defined for each real data analysis.
5.5 The region of performance of the Autopilot controller with the ASQUID criteria

In the previous paragraph, it has been mentioned that it has been proved from the simulation analysis that the Autopilot controller guarantees the stability of the system for each value of alpha parameter and there isn’t only an optimum value of the beta parameter, but a region of performance for each simulation test.

For this reason, the behavior of the system with different signal has been simulated. It has been taken different random noise and the deterministic force step. The simulation test has been made with the combination of this signal and it has been found which values of alpha and beta parameter can guarantee the best performance of the system and the minimum value of ASQUID. In all these simulations it has been supposed the same value of alpha parameter in each module of the supply chain, and for these reason for each beta and each alpha the value of ASQUID is different. For each signal, that has been tested, the optimum value of alpha and beta are shown in the graph below. In particular, three different regions have been defined. One for only random noise, one for the signal that is obtained with the combination of random noise and deterministic function (it will be called Mixed) and one only for the deterministic function.

In the graph 5.5.1, it is also shown the behavior of the demand and the inventory for some particular signals. It's also illustrated that for alpha equals to one and beta equals to one, the result could be described as the behavior of a Deadbeat controller. It has been mentioned that this controller is theoretically the fastest approach, but it is sensitive with respect to noise and model errors. If the system is influenced with a noisy signal, the answer to the customer's demand should be slower, while if there is only a deterministic function, it can be very faster.

In the picture 5.5.2, the behavior of the system with noisy and deterministic signals is shown. In particular, if we take into consideration noisy signals and we take beta equals to one, it is possible to say that the system have a harsh behavior. This definition means that the selected order is directly linked to the customer’s demand. If we take beta equals to zero, it is possible to say that the behavior of the system is smooth. It means that only the mean flow in the supply chain is taken in consideration and, that only static numbers for orders are used.

In the case of deterministic signal, for beta equals to one the behavior of system is dynamic, while if it is equal to zero it is static.
5.6 The analysis of the system's behavior with real data from companies

As it has been mentioned in chapter 4.3, in order to understand if the Autopilot controller could be a good tool in the real productivity context, real data from different companies have been taken to test the model.
5.6.1 Introduction of real data from a company that produce heating system.

First, it has been analyzed, the behavior of the Autopilot controller, with the real data, from a Company that has been called, for reason of privacy “Company A”. In particular, it has been compared the behavior of the system with Mode 11 and Mode 14 with the same delay time and with variable delay time. In this last case, it has been assumed that the delay time equals to two from the retailer to the wholesaler, three from the wholesaler and the manufacturer and four from the manufacturer to the raw material’s producer.

In the table 5.6.1, it is shown the comparison between what happens with a constant delay time of two weeks and a variable delay time. For the delay equals to two the minimum value of ASQUID is alpha equals to 0.1 and beta equals to 0.5. In this example it has been taken a constant value of alpha among each supplier.

If the delay time is variable, the optimum value of alpha is the same, but beta needs to be decreased: in particular, from this example it is equals to 0. It means that real customer’s demand is very noisy.
Product V1 – comparison between constant and different delay

Alpha = 0.1

Alpha = 0.3

Alpha = 0.5

Alpha = 0.7

Alpha = 0.9

Figure 5.6.1 The comparison between constant and variable delay time for product V1
In the following pictures, the behavior of sigma demand and sigma inventory among the different suppliers in the supply chain will be shown. In the picture 5.6.2 customer’s demand is been called “sigma demand”, the incoming demand of the wholesaler “sigmademand1”, the one of the manufacturer “sigmademand2” and with “sigmademand3” we refer to the input data of the raw material distributor.

In order to guarantee the stability of the system the sigma demand of each supplier should be smaller than the customer’s one and must not increase along the supply chain, otherwise the bullwhip effect can appear.

This condition is true up to beta equals to 0.6 for alpha equals to 0.2, beta equals to 0.4 for alpha equals to 0.4, beta equals to 0.6 for alpha equal to 0.6 and 0.8 and equal to 0 for alpha equals to one. In general, this picture shows that if alpha increases, beta needs to be decreased.

In the picture 5.6.3 it is shown the behavior of the sigma inventory. The inventory of the retailer has been called “sigma inventory 1”, the one of the wholesaler “sigma inventory 2” and it is used the word “sigma inventory 3” for the producer of raw material.

In the picture 5.6.4, it is shown the increasing percentage of sigma compared with sigma demand. It is important to observe that for some values of the beta parameter this percentage becomes negative. This result is very important, because it shows that the Autopilot controller guarantees the stability of the system. In the picture 5.6.5 the behavior of the different sigma inventory for different alpha and different beta is shown. It possible to observe that each supplier keeps the same trend of the sigma inventory, but if alpha increases, for each beta, the value of sigma also increases. In the previous paragraph, it has been stated that with the ASQUID criteria, the optimum value of beta has been alpha equals to 0.1 and beta equals to 0.5. Even if it is not shown in the following graphs, the analysis with the criteria of sigma inventory and sigma demand confirms that in order to keep alpha beta bigger than 0.5, alpha needs to be kept small. This result can be explained if the graph of the customer’s demand has been recalled.

This picture on the right shows that the behavior of the input data changes a lot during the time, and it can be described theoretically with a noise function and random input data. Please refer to chapter 5.2.
<table>
<thead>
<tr>
<th>Alpha</th>
<th>Product V1 Sigma demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td><img src="image1" alt="Graph for Alpha = 0.2" /></td>
</tr>
<tr>
<td>0.4</td>
<td><img src="image2" alt="Graph for Alpha = 0.4" /></td>
</tr>
<tr>
<td>0.6</td>
<td><img src="image3" alt="Graph for Alpha = 0.6" /></td>
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<tr>
<td>0.8</td>
<td><img src="image4" alt="Graph for Alpha = 0.8" /></td>
</tr>
<tr>
<td>1</td>
<td><img src="image5" alt="Graph for Alpha = 1" /></td>
</tr>
</tbody>
</table>

*Figure 5.6.2 The behavior of Sigma demand for the product V1*
### Product V1 Sigma inventory

<table>
<thead>
<tr>
<th>Alpha</th>
<th>Graph</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td><img src="image" alt="Graph for Alpha = 0.2" /></td>
</tr>
<tr>
<td>0.4</td>
<td><img src="image" alt="Graph for Alpha = 0.4" /></td>
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<tr>
<td>0.8</td>
<td><img src="image" alt="Graph for Alpha = 0.8" /></td>
</tr>
<tr>
<td>1</td>
<td><img src="image" alt="Graph for Alpha = 1" /></td>
</tr>
</tbody>
</table>

*Figure 5.6.3 The behavior of sigma inventory for the product V1*
The analysis of the behavior of the system has been made also with different values of alpha between the different suppliers, and in particular, it has been taken alpha equal to
0.08 between the retailer and the wholesaler, 0.18 between the wholesaler and the manufacturer and equal to 0.80 between the manufacturer and the raw material producer. It has been compared the result with the ASQUID criteria and it has been proved that, taking different alpha among the supply chain, the value of Aggregate Sum of Squared Deviation for alpha equal to 0.1 and beta equal to 0.5 is smaller than 16%.

In the picture 5.6.6, it is shown the behavior of the demand and the inventory during the time for the product V1, if the value of alpha parameter between the different suppliers is different. In the column of the left it is shown what happens with the feedback approach, in the one of the right with the Autopilot controller. In the following picture, the legend of the graph is introduced.

<table>
<thead>
<tr>
<th>Demand</th>
<th>Customer</th>
<th>PT1 Filter</th>
<th>Demand 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand 2</td>
<td>Demand 3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inventory</th>
<th>Inventory 1</th>
<th>Inventory 2</th>
<th>Inventory 3</th>
</tr>
</thead>
</table>
Beta 0

Beta 0.2
Figure 5.6.6 The behavior of demand and inventory in the time for $V1$
5.6.2 Introduction of real data from a company that produce electronics components

In this section it is analyzed the behavior of the supply chain with the real data from a company, introduced in chapter 4.2, that produces electronics components. As it has been mentioned, from all the different customer’s demand, two products have been selected in order to test Beyer’s model.

The first one, M1, has been chosen because there were some products that have the same behavior in this company while M17 it has been taken since it represented the worst scenario with the highest peaks. These two products and the product from the company C, called N1, have been tested both with the same value of alpha parameter among all the supplier and with the different values introduced in chapter 5.4. Since, it has been founded that, with the last criteria, for the optimum beta, the values of ASQUID are smaller, it is shown only the results with different value of alpha.

In the picture 5.6.7, it is shown the comparison between the Mode 11 and Mode 14 with ASQUID. As it has been mentioned before, taking different alpha among the suppliers, since the filter is only one and it is linked with the customer’s demand, the value of Aggregate Sum of Squared Inventory Deviations is unique for each beta and it doesn’t change with alpha. The same reason is still valid also for sigma demand and sigma inventory.

In this example, the value of beta than can guarantee the highest difference percentage between Mode 11 and Mode 14 is for beta equals to 0.3 (102%). It is also important to observe, that the Autopilot controller can reduce the value of ASQUID, but can also guarantee a faster answer than the Mode 11. It has been founded that the optimum value of beta without the controller is equal to 0.2.
Once, it has been found the optimum value of beta, with the ASQUID criteria it has been studied what happens in the supply chain taking this value. In particular, taking beta equals to 0.3, it is possible to guarantee a smaller level of the minimum inventory with the Autopilot controller (8% for inventory1, 16% for inventory2, 67% for inventory3). This result is very important, because it shows how this controller can help to decrease the level of inventories and all the costs and the problem that are linked with them. Moreover, with the same value of beta, it has been found that the maximum level of inventory also decreased. (4% for inventory1, 7% for inventory2, 104% for inventory3).

It has been studied also what happens for the Aggregate Sigma Demand and Inventory. In particular, the value of the first one is 46% smaller with the Autopilot, the second one is 3% smaller. All the comparison have been made between Mode 11 and Mode 14.

As it has been described before, with the simulation analysis it also been made the comparison of what happens with constant delay time of two weeks and variable delay of time among suppliers. Also in the last case, it has been found that the optimum value of beta with the ASQUID is bigger with the Mode 14 and it is equals to 0.2, while the feedback approach it is equal to 0.1. In order to understand the real benefits of the Autopilot controller when a change in the delay time occurs, it is possible to observe the figure 5.6.8.

For the optimum value of beta parameter, the percentage difference among the two values with the ASQUID is equal to 514%. Moreover, the Autopilot can guarantee a smaller value of Aggregate Sigma Demand (15%) and a smaller value of Aggregate Sigma Demand.
Inventory (109%). It also allows to decrease about 188% the maximum level for the manufacturer inventory.

In the picture 5.6.9, it is shown the behavior of demand and inventory for the product M1. In the left it is shown what happens with the feedback approach, in the right with the Autopilot controller. The legend of the graph is the one shown in the following picture:

![Aggregate Sum of Squared Inventory Deviations](image)

*Figure 5.6.8 Comparison with ASQUID with different delay time for product M1*
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Beta 0

Beta 0.2
Figure 5.6.9 The behavior of demand and inventory in the time for product M1
Concerning product M17, the same analysis have been made and it has been found that the optimum value of the beta parameters for the Autopilot controller is equal to 0.4, while for the feedback controller it is equal to 0.3.

It has been taken alpha equal to 0.07 between the retailer and the wholesaler, 0.20 between the wholesaler and the manufacturer and equal to 1 between the manufacturer and the raw material producer.

In the picture 5.6.10, it is shown the comparison between them with the criteria of ASQUID.

Moreover, the optimum value of beta decreases the Aggregate of Sigma Inventory value of 47%, and the value of the Aggregate of sigma value of 5%. It also decreases the minimum level of the inventory for the wholesaler and the manufacturer (9% for inventory2, 181% for inventory3) and decreases the maximum level of inventory in all the supply chain (3% for inventory1, 10% for inventory2, 88% for inventory 3).

In the picture 5.6.11, it is possible to observe the behavior of the system, with different values of beta. On the left, it is represented the behavior with the feedback approach, on the right with the Autopilot controller. In the following picture it is represented the legend of all the graphs.
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Beta 0.4

Beta 0.6
Beta 0.8

Figure 5.6.11 The behavior of demand and inventory in the time for product M17

Beta 1
5.6.3 Introduction of real data from a company that has a huge warehouse of spare parts

Up to this paragraph, it has been analyzed the behavior of the system, when real customer demands are introduced in the system, and in particular, it has been selected only suppliers that produce items. Since, the Autopilot controller has to be tested in different contexts in order to prove its flexibility, it has been decided to take also real data from a huge warehouse of spare parts. In particular, as it has been mentioned in chapter 4.3, it will be shown the result for the product N1. In this example, it has been taken different value of the alpha parameter among the supply chain, and in particular, they are equal to 0.7 between the retailer and the wholesaler, 0.20 between the wholesaler and the manufacturer and 1 between the manufacturer to the raw material producer.

In the picture 5.6.12, it is shown the comparison between the Autopilot controller and the feedback approach with the Aggregate Sum of Squared Inventory Deviations criteria. It is possible to observe, that for each value of beta bigger than zero Mode 14, can guarantee a better performance than Mode 11. The optimum value of beta with this criteria is equal to 0.4. With this value of the beta parameter, it is possible, with the Autopilot controller, to decrease the Aggregate value of Sigma Inventory of the 58%, and the Aggregate value of Sigma Demand of 10%, while the value of the ASQUID of the 227%.

Figure 5.6.12 Comparison between mode 11 and mode 14 with ASQUID criteria for product N1
In picture 5.6.13, it is shown the comparison between the maximum level of the inventory of the retailer (Inventory 1) with the feedback approach and the Autopilot controller, in picture 5.6.14 it is represented what happens in the inventory of the wholesaler (Inventory 2) and in figure 5.6.15 in the manufacturer one (Inventory 3).

**Figure 5.6.13 Comparison between the maximum levels of the inventory of the retailer**

**Figure 5.6.14 Comparison between the maximum levels of the inventory for the wholesaler**
The comparison between the three pictures above shows that with the Autopilot controller the manufacturer has the maximum benefit, and in particular, for beta equal to 0.4 it can decreased the maximum level of the inventory of 58%. There are some values of beta for which the level of the maximum level of the inventory of the wholesaler are bigger with Mode 14, but the percentage difference is very little, and with the optimum value of beta parameter all the suppliers have advantage with the introduction of the Autopilot controller. In picture 5.6.16 it is shown the behavior of the demand and the inventory in the time using different beta. In particular, on the left column it is shown what happens with the feedback approach, in the right one the behavior of the system with the Autopilot controller. The legend of the graph is the same that has been introduced before. In the following picture, it will be recalled.

It has been stated that, in this example, different values of alpha among each supplier have been taken. Therefore, since the filter is only linked with the customer’s demand, the behavior of the system is influenced only from the beta value.
Figure 5.6.16 The behavior of the demand and inventory of product N1 in the time
5.7 Covariance analysis

In this section the results of the covariance analysis made by Professor J. Beyer are shown, in order to test the validity of the results that I have obtained with the simulation analysis. He has used a tool called “Steady-state covariance analysis” that provides the exact covariance calculation, and therefore is not based on Monte Carlo runs. The tool calculates the steady state variance of the supply lines and the inventories if the customer's demand is pure noise (here with sigma equals to one). \( K_{\text{Covariance}} \) is the gain of sigma inventories in comparison to sigma of the forcing function. The analysis has been made with the Autopilot controller for the delay time equal to two. The results of these analysis are shown in the picture 5.7.1 and 5.7.2.

![K_Covariance Inventory](image)

*Figure 5.7.1 Covariance analysis of inventory*

In the picture 5.7.1 it is shown the behavior of the covariance of the inventory, for each value of alpha parameter. It is possible to observe that the variance of the inventory decreases while increasing beta as long as alpha is smaller than 0.5, while if alpha is bigger than this value it increases. In the picture 5.7.2 it is shown the behavior of the covariance of the supply line. It is possible to observe, that for each value of alpha parameter, the variance of the supply line increases with beta. The comparison between the two pictures above shows, that the best choice for the sigma inventory is to keep alpha...
small and beta high, while if you take in consideration all the supply line is better to take both alpha and beta parameter small.

Figure 5.7.2 The behavior of the covariance in the supply line and of the sum of covariance
The diagram called “K_Covariance Sum” shows the behavior of the sum of these two variances, which is calculated by multiplying the delay time (here equal to two) for the supply line covariance and adding the inventory variance. Nevertheless, this figure shows that there is a minimum for beta equal to 0.5 and alpha equal to 0.1 and for beta equal to 0.4 and alpha equal to 0.2, respectively. The smallest value of the total variance is for alpha equal to 0.1. From alpha bigger than 0.3, the variance sum increase with increasing alpha and beta.

The results provided by J. Beyer concerning only the random noise, but identify a good basis for comparison. Therefore, in the following table, it will be collected the values of alpha and beta parameter, that provided the minimum value of the Aggregate Sum of Squared Inventory Deviations, for each set of data that has been used as customer’s input. In this table, it is stated that the alpha value is the same, among all the suppliers. It has just been discussed that, in order to have a better performance of the system, this value should vary. In order to recall this concept, please refer to chapters 5.4 and 5.6.1.
From this table, it is possible to observe that with different deterministic forces the behavior of the system changes a lot and in particular it is possible to observe that Steps and Seasonal trends the value of the beta parameter could be bigger than for peaks. The value of alpha parameter of seasonal trend is between the one of Step and Peak. Concerning the combination of random and deterministic data, it is possible to state that, if there are peaks, the value of alpha parameter should be smaller. Concerning the real data simulation analysis, it is possible to observe that for product V1 and N1 the optimum value of alpha and beta parameter are the same identified by J. Beyer in his covariance analysis. Since, as it has been mentioned before, this analysis is valid only for forcing random noise data, it is possible to state that the customer demand of these products varies a lot and it can be described theoretically closed to random data. The other real data’s analysis confirms that the value of alpha should be taken small, and for all these example equal to 0.1. Concerning the value of the beta parameter, it is
possible to state that its optimum is between 0.3 and 0.6. It is important to recall that Autopilot controller guarantees stability and has a region of performance, not only an optimum value.
Conclusion

The results of the simulation analysis mentioned in chapter 5, show that the application of some notion of Digital Control Systems can help the logistics management in the difficult task of taking the right decisions in order to satisfy the customer’s demand and create profit for all the supply chain. The introduction of the Autopilot controller let the system reach efficiency and flexibility which are the most important performance indexes. Concerning the first one, it has been mentioned that it can satisfy the customer’s demand and prevent the origin of the bullwhip phenomenon and therefore its negative effects. In one word it brings stability in the system. The consequences are not only in the brief period, but also in the long one. Additionally it decreases indeed not only the inventory costs and the ones linked to the work forces, but it also enables the manager to optimize transports and all the aspects linked with the supply chain. If the system is stable, are also incentivized the cooperation between the different suppliers and the agreement between them in the system. It has been proved with the analysis of the simulation results in chapter 5, that with the Autopilot controller and without any problem it is possible to change the delay time among the different suppliers. It has also been shown that different values of alpha among them can increase the performance of the total system. Therefore the Autopilot controller can guarantee the flexibility of the system.

Since the customer's demand can vary a lot and the supply chain is and will stay a complex dynamic system, the introduction of the Autopilot controller will not involve the logistic management’s lay off. But this tool simplifies the day by day business and enables the human mind to focus on unexpected situations and in addition to take decisions more quickly. Therefore, the name Autopilot controller has been chosen wittingly since an Autopilot in an aircraft supports the pilot in a similar manner.
Future developments

In the chapter 2, it has been discussed that the goal of Beyer’s model was to approach the theory of Digital Control Systems to the logistics one, and since the two subjects are characterized by different languages and methodologies he has tried to make this mathematical tool initially as simple as possible.

The results provided from this simulation analysis have shown that the intuitions of Prof. Dr. Beyer and Prof. Dr. Furmans were correct and the introduction of Digital Control theory in the supply chain works and brings several advantages. Therefore, the digital model can be developed with different and more sophisticated filters and controllers and it can include more information such as the forecast prevision.

In this work, different examples have been tested, and a theoretical approach as well as real data have been used. The results of the simulation analysis have defined the region of stability of the Autopilot controller for these data and have defined some basis for comparison for other ones.

In the future, Beyer's model and its development should be developed further on and tested again with other real data, from other companies with the aim to find more general results.

Moreover, other concepts of Digital Control theory can be applied to other problems of logistic management, for example in the optimization of transports.
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Bibliography


