Economic Engineering for Supply Chain Management

Mitigating the Bullwhip Effect Using PID Control

R. M. Dolman

Master of Science Thesis

Delft Center for Systems and Control

Economic Engineering for Supply Chain Management

Mitigating the Bullwhip Effect Using PID Control

Master of Science Thesis

For the degree of Master of Science in Systems and Control at Delft University of Technology

R. M. Dolman

May 9, 2022

Faculty of Mechanical, Maritime and Materials Engineering (3mE) · Delft University of Technology

The work in this thesis was supported by Valtris Specialty Chemicals. Their cooperation is hereby gratefully acknowledged.

Delft University of Technology
Department of
Delft Center for Systems and Control (dcsc)

The undersigned hereby certify that they have read and recommend to the Faculty of Mechanical, Maritime and Materials Engineering (3mE) for acceptance a thesis entitled

Economic Engineering for Supply Chain Management

by

R. M. Dolman

in partial fulfillment of the requirements for the degree of

Master of Science Systems and Control

Dated: May 9, 2022

Supervisor(s):

dr.ir. M.B. Mendel

ir. C. Hutters

Reader(s):

assoc.prof.dr.ir. P.M. Esfahani

ir. J. Mendel

Abstract

The purpose of Supply Chain Management (SCM) is to maximize and stabilize the flow of goods through a supply chain. Disruptions to this flow, such as the Bullwhip Effect (BWE), have become increasingly severe and dynamic, challenging current methods for counteracting these disruptions. This thesis develops a systems and control framework for designing SCM policies to meet this challenge.

The thesis makes use of economic-engineering modeling principles to model the dynamics of the supply chain and calculate the flow of goods. Specifically, the supply chain is considered to be analogous to an electrical circuit, with the flow of goods analogous to the current and price changes analogous to voltage drops. Based on these analogies, the thesis develops the building blocks required for modeling a supply chain, consisting of storage, production and external markets. The building blocks are used to construct a serial supply chain with multiple stages and products. The supply chain is analyzed in both the time and frequency domain, quantifying how disruptions influence the flow of goods.

To regulate the flow of goods through a supply chain, this thesis models the procurement, production and product pricing policies of SCM as individual PID controllers. The PID controllers are shown to regulate the flow of goods in a manner similar to how an actual manager would.

The effectiveness of the framework is demonstrated in a simulation study of the BWE in the supply chain of Valtris Specialty Chemicals (VSC). It is shown how tools in classical control theory, like Bode diagrams, are effective in the analysis of the dynamics and severity of the BWE in terms of the resonance frequency and the amplification, respectively. In addition, this thesis shows how the tuning of the PID controllers relates to specific adjustments in the policies of VSC managers.

Table of Contents

List of Figures

List of Tables

Preface

Starting out my research in supply chains, I had little to no experience in the field. The subject quickly grew on me as I talked to the employees of Valtris Specialty Chemicals, due to their enthusiasm and open-mindedness. It took only a short while before the similarities between supply chains and physical systems became apparent to me and the idea for a thesis arose. The exact subject of this thesis changed a number of times, as I kept learning and seeing new research opportunities. The end result is an application of Systems and Control to a truly relevant problem in supply chains.

I would like to thank my supervisors dr.ir. M.B. Mendel and ir. C. Hutters for their guidance and sharp feedback. Economic engineering has broadened my view of the capabilities of engineering and taught me a great deal more. The most significant improvements I have made during my research have arguably not been made on an academic level, but rather in personal development.

My gratitude goes out to ir. J. Mendel as well for his involvement in my research. It was extremely valuable to be able to talk to the experts at Valtris Specialty Chemicals. The time spent discussing about the intricacies of supply chain management and the connection to Systems and Control was much appreciated.

Finally, I would like to thank the members of the economic engineering research group for the fruitful discussions during both weekly sessions and personal meetings.

Delft, University of Technology R. M. Dolman
May 9, 2022

Chapter 1

Introduction

1-1 Supply Chain Management and the Bullwhip Effect

Supply chains serve as a network to deliver products from raw materials to customers through engineering a flow of goods, which is sensitive to supply chain disruptions [49, 76]. Recent events such as the COVID-19 pandemic [76] and the blockage of the Suez canal [23] have caused disruptions to supply chains that decreased the supply of raw materials, resulted in stock-outs and forced production stops across various industries. A particularly dynamic disruption called the Bullwhip Effect (BWE) ensued these events, causing a prolonged and increased disruption to supply chains of which the effects are currently still noticeable. The BWE is the phenomenon by which small variations in customer demand lead to large fluctuation of suppliers' orders upstream in a supply chain [29, 28, 64]. Some of the negative effects of these fluctuations are: the requirement for high inventory capacity [15, 34], the perpetual excess or shortage of production capacity and the temporary unavailability of products [2, 29, 65, 77]. All of the effects of supply chain disruptions eventually result in high costs for Supply Chain Management (SCM).

The purpose of SCM is to decrease these costs and increase customer service levels by maximizing and stabilizing the flow of goods through the supply chain, which can be achieved by counteracting disruptions like the BWE [55]. This is emphasized by the 'First Manufacturing Law' by George Plossl, which states that "all benefits will be directly related to the speed of flow of information and materials" [50]. SCM has access to a large set of tools that they can commit to minimizing supply chain disruptions such as the BWE and optimizing the flow of goods through the supply chain.

Literature proposes solutions for SCM to mitigate the BWE in the form of managerial insight or through mathematical modeling. The solutions that are listed most often are information sharing, channel alignment and operational efficiency [29]. Previously designed models come in many variations and were created to analyze the BWE in the time [3, 6, 32, 33, 70, 69] or frequency domain [15, 21, 42, 43, 64, 65, 72] and to develop strategies to decrease the BWE [9, 16, 30, 40].

While many of the models incorporate the prices of products [16, 45, 32, 69, 70], none include the dynamics of these prices. This limits the ability of these models to provide solutions for dynamic supply chain disruptions. Specifically, the lack of price dynamics in currently available models implies that the fluctuation of prices, one of the main causes of the BWE [29], can not be taken into account in the analysis and mitigation of the BWE. The amplification of these price fluctuations throughout a supply chain is called the Reversed Bullwhip Effect in Pricing (RBP), which increases the BWE as it grows larger itself [44]. A dynamic model is required for the analysis of dynamic supply chain disruptions like the BWE and for the development of methods to counteract these disruptions.

In this thesis, a systems and control framework is developed for designing SCM policies that counteract dynamic disruptions like the BWE. A dynamic model of a 3-echelon serial supply chain is designed with the use of economic engineering. PID control is then used as management policy for procurement of raw materials, production flow control and product pricing to mitigate the BWE at multiple locations in this supply chain. Managerial insight is derived from the design and tuning of the controllers that SCM can apply to adapt their policies and mitigate the BWE within their supply chain. Alternatively, the controllers can be implemented directly as policies in the supply chain.

1-2 Economic Engineering Model of a Supply Chain

A dynamic 3-echelon serial supply chain is modeled in Chapter 3 with the use of economic engineering [38] principles. The multi-echelon serial supply chain structure is chosen similarly to previously designed supply chain models for simulating the BWE [15, 21, 42, 64, 72]. Each echelon consists of a building block that I design as an electrical circuit, following economic engineering theory. Economic engineering is a new field of research in which engineering methods are applied to economic problems. Economic engineering theory states a set of analogs between the electrical and economic domain that form the basis for constructing economic models as though they are electrical circuits. Known relations in the electrical domain, such as formulas for capacitance and inductance, are seen as analogs of the calculation of convenience and the law of supply and demand, respectively. The economic engineering supply chain model enables calculating the flow of goods through the supply chain and analyzing the influence of dynamic disruptions like the BWE on this flow.

Time- and frequency-domain analysis of the supply chain model is carried out to observe and validate the behaviour of the model and to determine controller design criteria for BWE mitigation. The model's parameter values are first set according to expert knowledge and acquired data, in order to obtain a model that displays realistic supply chain behaviour in simulation. Multiple scenarios are simulated by exciting the model with various inputs that represent either customer demand at the downstream end of the supply chain or materials supply at the upstream end. Additionally, Bode diagrams are used to quantify the BWE in the supply chain as is previously done by [9] and [64]. The inclusion of price dynamics introduces Bode diagrams as a new method for quantifying the RBP as well. The Bode diagrams illustrate the amplification and relative lead times of either flows of goods or price changes between two locations in the supply chain.

1-3 Mitigating the Bullwhip Effect using PID Control

Chapter 3 shows that the BWE is a frequency-domain phenomenon that is quantified with the magnitude plot of a Bode diagram. PID controllers of procurement, production and pricing are therefore developed in Chapter 4 as policies for mitigating the BWE in the supply chain from Chapter 3. The well-established PID control method lends itself for directly shaping the frequency response of the supply chain and its functionality is similar to that of an actual supply chain manager, as is argued in Chapter 4. The three processes of procurement, production and pricing are the main influences that SCM has on their manufacturing plant in the short term [51]. Each of the controllers is tuned to mitigate the BWE at a different location in the supply chain.

1-4 Simulation Study: Valtris Specialty Chemicals

In Chapter 5 a simulation study of the manufacturing plant of Valtris Specialty Chemicals (VSC) in Baleycourt is carried out to demonstrate the effectiveness of the framework. VSC is a chemicals manufacturing company, making a variety products all over the globe. The management of the manufacturing plant of VSC experiences the negative effects of the BWE and seeks an appropriate solution to resolve this issue. The need for an appropriate solution to the BWE makes the manufacturing plant of VSC in Baleycourt a suitable case study to apply the framework presented in this thesis to. A section of the VSC supply chain with its SCM is modeled using the building blocks and PID controllers that I develop in this thesis. While the controlled system is designed based on knowledge from the plant in Baleycourt, the solution is theoretically applicable to any supply chain with any number of different materials, products and echelons.

1-5 Thesis Outline

This thesis is structured as a control systems design process as illustrated in Figure 1-1.

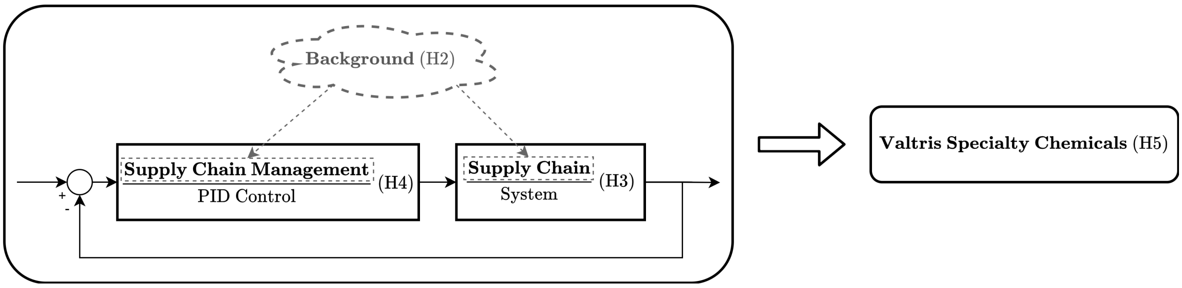


Figure 1-1: This thesis is structured as a control systems design process. Background information is gathered, a model and controller are designed and validated and the solution is demonstrated in a real-world application

Chapter 2 presents background information on SCM and the BWE, required for the design of the model and controllers of the framework and for the subsequent analysis. The methods now used by SCM to influence the manufacturing plant and its surrounding supply chain are presented. Chapter 2 also lists the causes, effects and proposed solutions of the BWE as currently given in literature. Previous BWE modeling research is shown together with its shortcomings and the problem this thesis aims to solve is formulated. The knowledge in this chapter is partly gathered from literature and partly gained through interviews with employees at VSC.

Chapter 3 shows how a model of a supply chain that includes price dynamics is designed. The electrical analog within economic engineering is leveraged to develop electrical circuits that represent the core building blocks of a supply chain. The inclusion of the inductor as the law of supply and demand introduces price dynamics into the model that are essential for quantifying dynamic supply chain disruptions like the BWE and the RBP. The building blocks are connected in series to construct a model of a 3-echelon serial supply chain. The model is then validated in the time- and frequency domain and used to analyze the influence of the BWE on the flow of goods through the supply chain.

Chapter 4 presents a manner in which PID control can be used as SCM policy to mitigate the BWE and regulate the flow of goods through the supply chain. Procurement of raw materials, production of finished products and pricing of these products is controlled by three separate PID controllers. The effect of PID controllers on the supply chain's behaviour is analyzed in scenario analysis and by using Bode diagrams. PID control as management policy is shown to be effective at counteracting the BWE in the serial supply chain from Chapter 3 and to be similar to the behaviour of an actual supply chain manager.

Chapter 5 applies the framework presented in Chapter 3 and Chapter 4 to a section of the supply chain of VSC in a simulation study. A part of the manufacturing plant of VSC is chosen for which a model is designed using the building blocks from Chapter 3. Data from the VSC manufacturing plant is used to tune the parameters of the structured model and the PID controllers. The BWE is quantified by making use of Bode diagrams and the PID controllers' parameter values are adjusted so that the BWE is mitigated. The result of the application of the framework is a quantification of the BWE in a section of the VSC supply chain and a management policy that VSC can use to mitigate the BWE.

Chapter 6 concludes this thesis and discusses the work presented in this thesis. Chapter 7 identifies further research opportunities following this thesis.

Chapter 2

Supply Chain Management and the Bullwhip Effect

2-1 Introduction

This chapter provides background information on Supply Chain Management (SCM) and the Bullwhip Effect (BWE), relevant for understanding the solutions presented in this thesis. Section 2-2 presents how SCM controls the behaviour of a manufacturing plant and the supply chain it is connected to. Section 2-3 describes the BWE, a dynamic supply chain disruption, and lists potential causes, known effects and proposed solutions. Section 2-4 summarizes previous modeling research on analyzing the BWE and developing control methods to solve the issues that result from the BWE. It also lists the shortcomings of the current state-of-the-art, some of which will be resolved in Chapter 3 and Chapter 4 of this thesis. Section 2-5 concludes this chapter by stating the problem this thesis aims to solve in Chapter 3 and Chapter 4 regarding modeling and mitigating the BWE.

2-2 Supply Chain Management

Supply Chain Management (SCM) can be defined as a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize systemwide costs while satisfying service level requirements [55]. In short, it encompasses all tasks that aim to optimize the flow of goods through a supply chain. Any disruption to that flow, such as the BWE described in Section 2-3, results in increased supply chain costs and is to be counteracted by SCM.

SCM tasks span a large spectrum of a firm's activities, in the strategic-, tactical- and operational level [55]. The strategic level is where decisions with a long-lasting effect on the firm are taken, like the placement and capacity of warehouses and the acquisition of new machinery

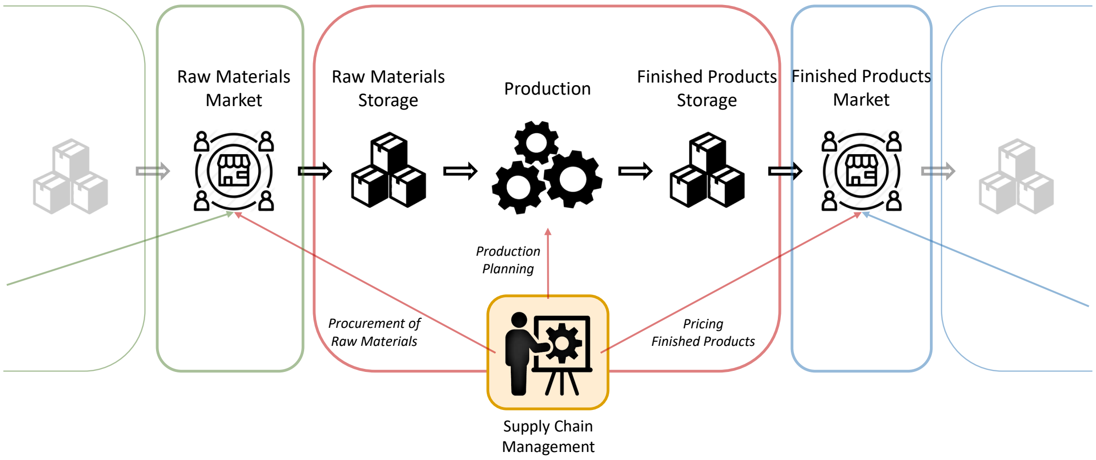


Figure 2-1: The core supply chain structure with the three main operational activities of Supply Chain Management

for production. The tactical level includes the more frequent issues, updated between every quarter and every year, like inventory policy and transportation strategies. The operational level deals with the day-to-day tasks, such as production scheduling, procurement of materials and pricing of products. The control part of the framework presented in Chapter 4 is developed with a scope limited to the operational level of SCM.

The main activities of SCM to influence the manufacturing plant on the operational level are production scheduling, procurement of materials and pricing of products [51, 68]. These three activities are often carried out separately by different entities within the manufacturing plant, even though their individual decisions influence each other greatly [25]. A graphical overview of the core supply chain structure and the three main influences of SCM is displayed in Figure 2-1. The tools used for each of the activities are classically spreadsheets that are updated manually in which the manufacturing plant is represented in a static manner. Chwif et al. argue that a more dynamic (simulation) approach is required to capture the dynamic nature of a supply chain [7]. Specifically, a dynamic approach is required to quantify the effects of dynamic supply chain disruptions to the flow of goods. A vast body of knowledge exists on modeling a supply chain dynamically so that quantifiable managerial advice can be deducted for scheduling, procurement and pricing. The following subsections further explain the main operational activities of SCM, although the reader is referred to the review by Dolman [10] for a more extensive overview of SCM methods and previous modeling approaches to production scheduling, procurement of raw materials and finished product pricing.

Chapter 4 develops PID controllers as management policies for the three main operational activities of SCM.

2-2-1 Procurement of Raw Materials

Procurement of raw materials is the first part of inventory management, focused on re-supplying raw materials inventories with the goal of reaching a high customer service level with low inventory investments. Ivanov et al. [24] state two primary questions that are posed to optimally control the inflow of goods into inventory.

- How much should I replenish?
- When should I replenish?

They argue that inventory management concerns itself mainly with minimizing holding costs, stockout costs, ordering costs and setup costs [24].

A number of methods are used to keep inventories at their desired levels, so that inventory investments are minimized and stockouts are prevented. The two main classes of procurement policies are the re-order point methods and the periodic review methods. Harris [20] introduces the re-order point method, designed to derive the optimal order quantity when inventories reach a certain level. The periodic review method prescribes procurement in fixed time intervals, at which an order is placed to bring the inventory in question back to a pre-determined level. A large range of extensions to the re-order point methods and the periodic review methods have been proposed to improve the calculation of the amount of materials to be procured. The review of recent literature by Williams and Tokar [74] provides a detailed overview of available inventory management methods.

2-2-2 Production Planning

The second part of inventory management is production planning, focused on re-supplying finished products inventories with the purpose of attaining a desired inventory level while keeping to capacity constraints under the influence of uncertain demand. The production scheduler of a manufacturing plant often makes use of the conventional Master Schedule (MS), Master Production Schedule (MPS) and Material Requirements Planning (MRP) to determine what products to make at what time. The MS gives high-level goals for production and contains demand forecasts, orders and the MPS. The MPS contains the anticipated production schedule with dates, quantities and specific manufacturing configurations. The MRP finalizes the production scheduling process with an overview of the available inventories and the Bill of Materials (BOM), which contains the recipes of all products. A more visual manner of production planning is the so-called 'product wheel', popularized by King [27]. The product wheel describes the product mix and relative production flows for each product, as well as the time taken for each process and the total time spent in a production cycle. It provides an easily interpretable overview of the ratios of time spent per month manufacturing each product and the order in which they are most efficiently manufactured. Both the conventional tools and the product wheel are not easily adaptable to change and are not well suited for application to supply chains that are affected by dynamic disruptions. More complex production scheduling approaches make use of mathematical optimization to determine what products to manufacture and when. Sagawa and Nagano [52, 53] and Sarimveis et al. [54] provide extensive overviews of available modeling methods for production scheduling. The available tools for production scheduling are used jointly in industry to regulate the flow of products into finished products inventory.

2-2-3 Finished Products Pricing

Simon and Fassnacht [56] distinguish between three classes of finished product pricing methods that each have the purpose of maximizing the revenue from finished products sales. One-dimensional pricing involves setting the price of a single product, only considering the current moment in time. Multi-dimensional pricing considers demand and prices of multiple products at the same time for setting the price of one of the products. Long-term price optimization does so as well and takes into account the movement in time of the price in question, making it the only dynamic pricing approach. While long-term price optimization is the most sophisticated approach, the majority of the companies uses a one-dimensional pricing method due to its simplicity [19, 56].

An often used pricing policy is to initially carry out cost-plus pricing, followed by price adjustments related to the expected price-response and the prices of competitors. Cost-plus pricing takes the sum of all costs incurred in the production of a finished product and multiplies it with a markup that determines the profit margin made on that product. To avoid pricing the company out of the market by setting a price that is too high, the expected demand as a response to that price is considered. The law of supply and demand [35] is used to predict customer demand for a specific price using knowledge about the price elasticity of demand. Competitor price information may finally give an incentive for further adjusting the price in order to make the most profits. Even though many factors may be taken into account for setting the price of a product, the price of a product is rarely considered as a dynamic variable by looking at the way it changes over time influenced by internal and external supply chain factors.

2-3 The Bullwhip Effect

The BWE is a dynamic supply chain disruption, which is described as the amplification of small variations in downstream customer demand to large fluctuations in upstream manufacturers' orders [28, 29, 64]. An illustration of the BWE is shown in Figure 2-2. The disruption was first identified by J. Forrester [11, 12]. He argued that the amplification is caused by typical supply chain behaviour, inherent to the manufacturing and distribution practices. The BWE has been observed in many industries and was given its name by Procter & Gamble (P&G) logistics executives who discovered the effect in their own supply chain [29]. J. Sterman [60] developed the so-called 'Beer Distribution Game' to experimentally show the fluctuations of production and procurement. The experiment shows oscillations in inventory and orders, amplification of these oscillations further upstream in the virtual supply chain and significant phase lag or delays in the actions of different supply chain members. The existence of the BWE is evident and it has a severe negative effect to the flow of goods through a supply chain. In Chapter 3 a model of a supply chain is constructed with which the BWE is quantified. The model serves as a basis for the development of a control method in Chapter 4 that counteracts the BWE. This section lists the potential causes, negative effects and current solutions to the BWE.

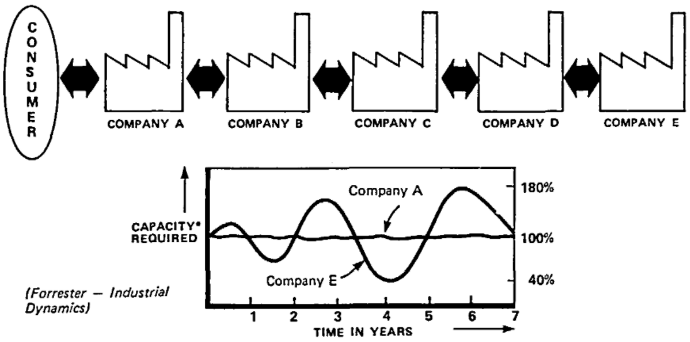


Figure 2-2: The Bullwhip Effect causes demand amplification in a supply chain [12]

2-3-1 Causes

The four main causes of the BWE according to Lee et al. [29] are:

- Price fluctuations
- Demand forecast updating with non-zero lead times
- Order batching
- Rationing and shortage gaming

Others [4, 5] recognize these as the main source of the amplification of demand fluctuations as well. Especially the demand forecast updating is seen as having the largest influence on the BWE [12, 60]. Bhattacharya and Bandyopadhyay [2] categorize these as operational causes and extend the list of potential causes. They also name inventory policy, replenishment policy, improper control system, the number of echelons, misperception of feedback and local optimization without global vision, amongst other things. Furthermore, they identify three behavioral causes related to the previously named causes. For a detailed overview of the causes of the BWE and their respective effects on the supply chain, the reader is referred to the review by Bhattacharya and Bandyopadhyay [2]. Each of the causes on its own can lead to the existence of the BWE in a supply chain and usually multiple causes are present.

The control method designed in Chapter 4, as part of the systems and control framework this thesis develops, focuses on counteracting price fluctuations, adjusting the inventory and replenishment policies and avoiding incorrect demand forecasting. The effects of the number of echelons, the misperception of feedback and local optimization are also shown in Chapter 3 and Chapter 4.

2-3-2 Effects

The amplified fluctuations in orders, production and inventory have a negative impact on the supply chain in a number of ways. The 'First Manufacturing Law' as formulated by George Plossl states that "All benefits will be directly related tot the speed of flow of information and materials" [50]. If the flow is disrupted by fluctuations in the supply chain, this will result in an increase in cost at several parts of the supply chain. Campuzano and Mula [5] identify a number of sources of cost increase as a result of the BWE, among which; insufficient or excessive capacity, employees' contract/dismissal, excess stock, obsolescence, poor suppliers' delivery, poor customer service, poor public image.

The effects of the BWE again have an influence on the amplification of order fluctuations as supply chains are governed by negative feedback [61]. Excessive manufacturing capacity leads to relatively higher fixed costs per sold item, which increases the prices of finished products, resulting in price fluctuation. Excess finished product stock may encourage SCM to present price promotions, also resulting in price fluctuations. Excess raw material stock will reduce the procurement volume for these materials leading directly to the fluctuations in orders. To counteract the BWE, solutions are required that deal with the causes of the BWE directly.

2-3-3 Current Solutions

The solutions for mitigating the BWE are focused on directly counteracting the causes of the amplifications stated in subsection 2-3-1. The main solutions as proposed by Wikner et al. [73] are:

- Tuning existing echelon decision rules
- Removing echelons from the supply chain
- Integrating information flow
- Reducing time delays (procurement/production/pricing)
- Improving individual echelon design rules (taking into account pipeline behaviour)

These solutions stem from principles proposed by Forrester and Burbridge [17, 12] and have been adopted by researchers through the years. The principles were further developed into specific actions that SCM can use on the supply chain.

The actions that SCM can undertake are numerous. A few examples are; Every-Day-Low-Pricing (EDLP) [5, 29, 47], better control of production and procurement [6, 9, 12, 15, 60, 73], using point-of-sale (POS) data for forecasting [5, 29, 39, 73], sharing inventory and manufacturing capacity data with upstream and downstream supply chain members [5, 8, 29, 36], reducing lead times [6, 29, 36, 73, 62], eliminating a redundant link in a supply chain [36, 47, 73]. The reader is referred to the reviews by Bhattacharya and Bandyopadhyay [2] and Wang and Disney [71] for a more extensive summary of possible solutions to the BWE.

Lee et al. [29] categorize the available solutions based on their underlying coordination mechanism, namely, information sharing, channel alignment and operational efficiency. Information sharing encompasses all manners in which downstream information is shared with other supply chain members. Channel alignment means the coordination of transport, pricing and inventory planning, among other things. Operational efficiency refers to performance improving activities, such as reducing lead time. The categories aid SCM in finding the appropriate action for mitigating the BWE [29]. The control solution proposed in Chapter 4 belongs to the operational efficiency category as its purpose is to improve the operational activities of SCM.

The list of available solutions for SCM is lengthy and is growing still as the BWE has not yet been eradicated from supply chains [36]. McCullen and Towill [36] argue that there are ten so-called 'bullwhip clichés' that explain why the BWE still exists in supply chains. The clichés in essence tell us that either SCM does not believe the BWE exists, SCM does not think the BWE affects them negatively, BWE does not accept the available solution methods or SCM feels like there is nothing they can do to decrease the BWE. This thesis develops a systems and control framework for designing SCM policies that can counteract dynamic supply chain disruptions like the BWE.

2-4 Review of Supply Chain Models for Analyzing the Bullwhip Effect

A large quantity of models and control applications have been designed for supply chains in an attempt to quantify and counteract the BWE. The supply chain is classically modeled as a dynamical inventory system [71], that varies in several elements such as type of demand, forecasting method, ordering policy or supply chain structure. A recent detailed overview of the various types of supply chain models and their extensions is given by Wang et al. [71]. While the set of models for the BWE is merely part of the much larger range of supply chain models, this section will restrict itself to listing only the specific BWE models. The underlying structure of the models, the theories on which they are built and the extensions to the models are similar in both general and Bullwhip-specific supply chain research. This section summarizes modeling research and mitigation strategies for the BWE to clarify previous research directions and shortcomings in the state-of-the-art.

2-4-1 Bullwhip Effect Models

To address the different BWE model types structurally, categorization is required. The three so-called "Lenses" for observing the BWE presented by Towill et al. [65] are chosen for classification of previous modeling research. With the "Variance Lens", a cost function is minimized and time-responses of random demand signals are observed, measuring the BWE with the ratio of variances of orders or inventories. The "Shock Lens" uses step responses of simulation models to observe system behaviour, measuring peak response time and overshoot for determining the existence of the BWE. The "Filter Lens" makes use of Filter- and Control Theory, looking at frequency responses of transfer functions to find resonance peaks, measuring the BWE with the gain of the transfer function from downstream demand to upstream supply. An additional paragraph is dedicated to models that specifically feature the prices of goods. The fluctuation of prices is one of the most important BWE causes [77] so the addition of prices in a model is of value for the analysis and control of the BWE. The categorization allows for structural assessment of the strengths and weaknesses of each model type.

The "Shock Lens"

One of the first models of the BWE comes from Jay Forrester [12], who constructs a well-known system dynamics model of a supply chain. System dynamics, or industrial dynamics,

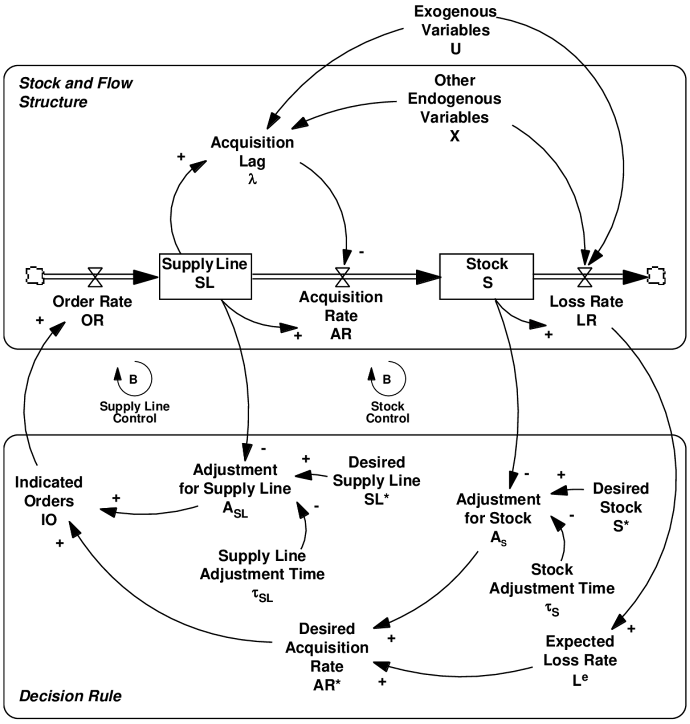


Figure 2-3: System dynamics model of an inventory management system by Sterman [61]

is the investigation of the information-feedback character of industrial systems and the use of models for the design of improved organizational form and guiding policy [12]. It features feedback loops of materials and information that may describe the behaviour of an industrial system visually and with equations. The demand amplification that he observes from his model was initially named the "Forrester Effect" and only later re-branded as the BWE [29]. Paik and Bagchi [47] leverage the system dynamics approach to construct a modular supply chain model. Fractional simulation is carried out to investigate the relative contribution of nine of the main influences on the BWE. They conclude that demand forecast updating, level of echelons and price variations are of the highest influence on the demand amplification. Sterman [61] develops a system dynamics model of an inventory management system for which he provides several customization options. The system dynamics model he constructs can be observed in Figure 2-3. He observes oscillation, amplification and phase lag in a case study of the model and proposes solutions for the BWE. The system dynamics approach is a strong visual modeling method with which the relations between parts of the system are easily observed. It can be used for simulation without much effort, providing possibly unexpected and troublesome results [12]. However, supply chains models constructed with system dynamics do not feature any financial variables and are only concerned with the flows of goods and information through the system, eliminating the option of studying the reciprocal effect of fluctuating prices on the BWE.

Other simulation approaches that fall under the "Shock Lens" label may be based on different model types than system dynamics. Bray et al. [3] have constructed a discrete event simulation model. O'Donnell et al. [40] apply a Genetic Algorithm (GA) to a descriptive behavioural decision model of a 5-stage supply chain, based on the beer game by Sterman

[60]. Holland and Sodhi [22] develop an analytical model of a supply chain and quantify the influences of price fluctuation, order batching and rationing on the BWE. Although the model types are different, the way of measuring the BWE is the same for each model in the "Shock Lens" class and the lack of financial variables limits all of them.

The "Filter Lens"

The frequency domain provides completely different tools that can be applied to modeling and mitigating the BWE. The use of transfer functions and Bode diagrams make it possible to quantify the BWE and determine system stability. Towill and Del Vecchio [64] convert a system dynamics model of a 3-echelon supply chain into a block diagram from which the transfer function of each echelon is derived. These transfer functions are used to show the frequency response of each echelon and show regions of amplification and attenuation in the gain plot of a Bode diagram. The block diagram of Towill and Del Vecchio is shown in Figure 2-4. Ouyang and Li [43] extend a serial supply chain model to a model with multiple customers in different markets, for which they develop a control theory framework for analyzing order stability and the BWE. The influence of different forecasting methods on the BWE is researched by Dejonckheere et al. [9] and Li et al. [30]. The effect of various strategies for sharing information with supply chain members is addressed by Ouyang [42]. Policies for operational activities are analyzed in several papers. Hoberg et al. [21] investigate three common inventory policies. Fu et al. [15] introduce Model Predictive Control (MPC) for the ordering policy. Wang et al. [72] investigate nonlinear ordering policies. The graphical block diagram modeling method used often within the "Filter Lens" class makes the derivation of transfer functions for frequency-domain analysis of the supply chain easy. Bode diagrams then provide a frequency-specific BWE metric with which filter design can be carried out. However, the models within the "Filter Lens" class lack any financial variables and rather focus on the flow of goods and the delays between supply chain elements.

The systems and control framework that is developed in this thesis can be categorized in the "Filter Lens" class, but includes prices as dynamic variables. Bode diagrams are employed to quantify the BWE in the frequency domain and to tune the PID controllers that regulate procurement, production and product pricing.

The "Variance Lens"

The method of analytically modeling a supply chain with difference equations and mathematical optimization has gained interest in recent research. Lee and Padmanabhan [28] popularized the method by designing an analytical model of a supply chain from which managerial insight could directly be derived for different echelons in a supply chain. Luong [31] measures the influence of lead times and autoregressive demand coefficients on the BWE by deriving analytical expressions for the variance of the orders and for the partial derivatives of the BWE to the lead times and demand coefficients. The first analytical models do not include any financial variables though, limiting their applicability.

Later research in the "Variance Lens" class includes the prices of goods in its models of a supply chain. Zhang and Burke [75] first add in price-dependent demand for which both the price and the demand itself are represented by an autoregressive process. Y. Ma et al. [34]

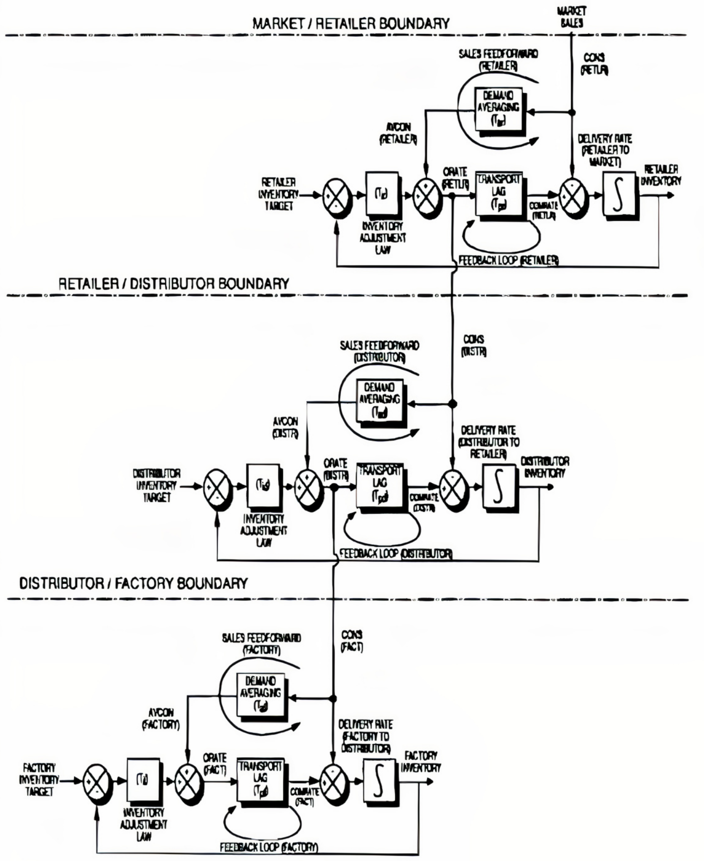


Figure 2-4: Block diagram representation of a three-echelon supply chain [64]

also include price-sensitive demand with an autoregressive pricing process in the model of a supply chain, and examine the order-up-to procurement policy under a mean-squared error forecasting technique specifically. Tai, et al. [63] add the price as a random i.i.d. variable to an autoregressive demand process and analytically derive the influence of several demand parameters on the BWE. Gamasaee and Zarandi [16] use the optimal price found through a pricing-game to forecast demand in order to decrease the BWE. J. Ma et al. [32] construct a supply chain model with an online part where the prices of each echelon are also determined through a price game, which now also considers discount sensitivity. Wang, Lu et al. [69] use this model to investigate the BWE on inventories instead of orders in different information sharing settings. Y. Ma et al. [33] derive a combined measure of the BWE on orders and inventory to study the effect of different demand forecasting methods. Wang, Ma et al. [70] analyze the effect of consumer price forecasting methods on the BWE. Cao et al. [6] construct a supply chain model in which the supply function, demand function and the price adjustment function are introduced simultaneously. Their research is notable as they are the only who assume the price to move in accordance with excess supply or excess demand, creating a feedback loop in the model. The inclusion of prices gives the analytical modeling method of the "Variance Lens" an edge over the other classes as the fluctuation of prices can then be taken into consideration as one of the main causes of the BWE.

The analytical modeling method has resulted in several direct relations between system parameters and the variance amplification ratio of the BWE. The method is unique in its inclusion of prices in the models, often as an autoregressive process. However, the complexity of the supply chain model is usually limited, due to the inherent complexity of deriving the analytical equations, and the price process is usually not dynamically related to other parts of the model so part of the dynamics of the supply chain are omitted.

The systems and control framework this thesis develops for the development of SCM policies that counteract dynamic supply chain disruptions combines some of the strengths of the "Lenses". Chapter 3 presents a structured graphical model of a supply chain that includes price dynamics, which is analyzed in the frequency domain making use of Bode diagrams. The combination of price dynamics and the frequency domain for a graphical supply chain modeling method is unique to this research, to the best of the author's knowledge.

2-4-2 Bullwhip Effect Measures

To assess the magnitude of the BWE and the influence of an applied solution, a measure of the BWE is required. A limited number of metrics have been presented in literature. First of all there is the demand amplification factor, a ratio of the maximum change in the flow of goods entering the manufacturing plant to the maximum change in end-customer demand [47, 60]. It is calculated by taking the peak values in each signal and subtracting them from the steady-state values, after which the ratio of the results is taken.

$$Amplification\ Factor = \frac{\Delta(Factory\ Orders)}{\Delta(Customer\ Orders)} \tag{2-1}$$

The most used is the ratio of variances of orders, production or inventory [4, 5, 16, 18, 31, 34, 69]. The variance of a signal is first calculated or derived from the model structure, after which the ratio between two variances is taken.

$$Variance\ Ratio = \frac{Var(Material\ Orders)}{Var(Customer\ Demand)} \tag{2-2}$$

The difference between variances is sometimes also used [4].

$$Variance\ Difference = Var(Material\ Orders) - Var(Customer\ Demand) \tag{2-3}$$

If the variance ratio is larger than 1 or the difference is larger than 0, the existence of the BWE is proven according to these measurements. Instead of the variance, the variability can be taken to calculate the magnitude of the BWE, similar to Eq. (2-2) [77]. The variability is linear, compared to the variance that is quadratic, making it better applicable in some situations. In some frequency domain modeling research, the gain plot of a Bode diagram is used to measure the BWE. [9, 64] The gain represents the ratio between the amplitude of the material orders' fluctuations and the amplitude of the oscillations in the customer demand at a specific frequency. An illustration of the regions of amplification and attenuation in the gain plot of a Bode diagram is shown in Figure 2-5. Depending on the type of model used to represent the supply chain, different Bullwhip-measures are available.

Fransoo and Wouters [14] indicate several issues that may hinder a person in correctly measuring the BWE. They firstly argue that levels of data aggregation can lead to different results.

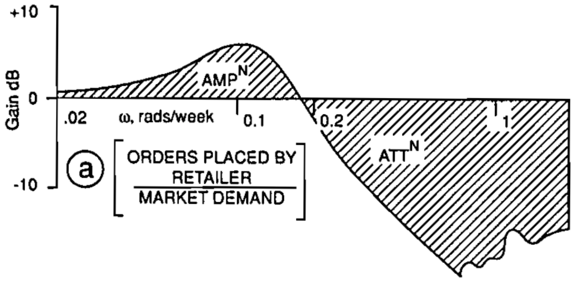


Figure 2-5: Filter characteristics of a retailer (adapted from Towill and Del Vecchio [64])

Secondly, they state that measuring the total BWE does not tell which of the different causes of the BWE has the largest influence. Lastly they argue that manners of disaggregation of demand data can be difficult as demand data may not be easy to split from aggregated data for a particular supplier or supply chain. Caution must be taken when quantitatively comparing BWE research as the data used in the calculation of the amplification may differ on several structural levels.

2-4-3 Reverse Bullwhip Effect in Pricing

A practical mirror version of the BWE has been identified by Özelkan and Çakanyildirim [44] as the Reversed Bullwhip Effect in Pricing (RBP), which describes the amplification of price variation resulting in large downstream price fluctuations. Price variation is one of the root causes of the BWE so any supply chain that displays the RBP needs special attention [45]. Özelkan and Çakayildirim [44] determine whether or not the RBP exists for different demand functions, for which analytical conditions are derived. The research is extended by Özelkan, Lim and Adnan [46] to a supply chain where pricing and replenishment decisions are made simultaneously. Adnan and Özelkan [1] then also examine the existence of the RBP for three different game-structures in the determination of prices. Not much research has been carried out on the RBP, even though the phenomenon may well have a large contribution to the well-studied BWE.

The RBP is measured by the so-called "cost-pass-through coefficient", which is defined as the derivative of the retail price p to the wholesale price w.

$$\textit{Cost-Pass-Through} = \frac{dp}{dw} \tag{2-4}$$

When this coefficient is larger than 1, the existence of the RBP is proven [44]. The potent frequency response measurement tools used in the detection of the BWE have not been used in previous research on the RBP, as prices have not yet been included in frequency-domain models of supply chains.

Chapter 3 quantifies the RBP in the supply chain model designed in this thesis, by making use of Bode diagrams of the transfer functions from upstream to downstream price changes.

2-5 Conclusions

SCM aims to optimize the flow of goods through a supply chain in order to reach a high customer service level and incur minimal costs. SCM requires appropriate management policies to regulate this flow of goods and counteract dynamic supply chain disruptions like the BWE. The current operational activities, for which these policies are sought, are carried out independently and statically in practice, which is ineffective against the inherently dynamic BWE. Current models for analyzing the BWE and developing methods to counteract the BWE omit price dynamics or do not include prices at all. The solutions proposed in previous research therefore fail to take into account the reciprocal effect of price fluctuation on the BWE. A dynamic model of a supply chain is required to quantify the influence of the BWE on the supply chain and develop management policies that mitigate the BWE.

In Chapter 3 a dynamic model of a supply chain is designed with the use of economic engineering. The BWE is analyzed in this supply chain using both time- and frequency-domain methods. Chapter 4 then develops PID controllers as policies for procurement, production and pricing that mitigate the BWE. Managerial insight is obtained from the application of the control policies that can be used by SCM to mitigate the BWE in their supply chain.

Chapter 3

Economic Engineering Model of a Supply Chain

3-1 Introduction

In this chapter I design a structured dynamic model of a 3-echelon serial supply chain to quantify the effect of dynamic disruptions on the flow of goods through a supply chain. The model is constructed as an electrical circuit, using analogs from economic engineering theory [38]. The economic engineering modeling method enables the inclusion of price dynamics in the model of a supply chain so that the reciprocal effect of price fluctuations on the Bullwhip Effect (BWE) can be analyzed. The model of a supply chain is used in Chapter 4 as a basis for developing controllers as Supply Chain Management (SCM) policies that mitigate the BWE.

The remainder of this chapter is structured as follows. Section 3-2 presents analogs between electrical engineering and supply chain management that I use in the design of a supply chain model. In Section 3-3 I develop a building block with which I construct the supply chain model. The locations of possible control inputs, representing supply chain management, are indicated in Section 3-4. Section 3-5 shows how a 3-echelon serial supply chain model is obtained by linking together 3 of the building blocks from Section 3-3. I tune the model's parameters with data from Valtris Specialty Chemicals (VSC) so that it represents part of a realistic supply chain. I then discretize the model for simulation purposes and validate it through time- and frequency-domain analysis in Section 3-6. In Section 3-7 I conclude that the model of a supply chain displays typical supply chain behaviour and can be used to find a solution for mitigating the BWE.

3-2 The Supply Chain as an Economic Engineering Model

Economic engineering theory provides analogs between economics and electrical engineering that I use to model a supply chain as an electrical circuit. The electrical domain is chosen as

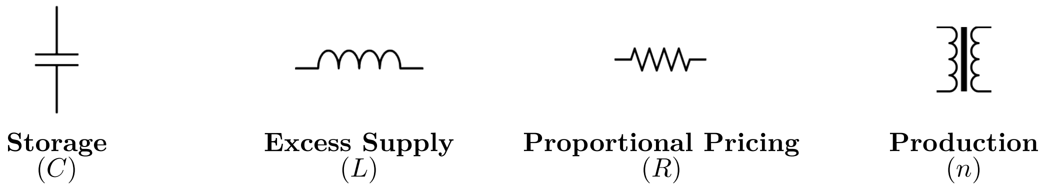


Figure 3-1: Economic processes are translated to electrical elements to enable dynamic modeling of a supply chain. The mathematical relations and detailed interpretation for each element are given in subsections 3-2-1, 3-2-2, 3-2-3 and 3-2-4

Parameter	Interpretation	Unit
$\frac{1}{C}$	Convenience yield	$\frac{\$}{tonne^2 \cdot wk}$
$\frac{1}{L}$	Price elasticity of excess supply	$\frac{tonne^2}{\$ \cdot wk}$
R	Appreciation rate	$\frac{\$}{tonne^2}$
n	Material-Product weight ratio	[-]

Table 3-1: Economic interpretations and units of electrical elements' parameters

analog because the flow of charged particles through wires in a circuit is similar to the flow of goods through a supply chain. As the flow of goods is analogous to the electrical current, the voltage is the analog of an economic force or price change. Each electrical element represents an economic law or phenomenon that matches the physical law contained in the element. These laws define the behaviour of the system and make it possible to design a structured dynamical model of an economic system. The laws are formulated as linear relations so that an LTI model can be designed in Section 3-3. The relations are presented in continuous-time form here, but the full model of a supply chain that the relations are used in is discretized in Section 3-6 for simulation purposes. In this section I present an adaptation of the economic engineering analogs from [38] as I apply them to supply chains and SCM.

An overview of the elements, their supply chain specific interpretation and the corresponding parameters is shown in Figure 3-1. The interpretation of the parameters is listed in Table 3-1.

3-2-1 Storage

Storage is the retention of parts or products for future use or shipment [49], which is modeled with a capacitor in the electrical domain. A capacitor stores charge similar to how goods are stored in inventory. The more goods you have in inventory, the higher the convenience you yield from that inventory. This is similar to the voltage across a capacitor that increases with the charge stored in the capacitor. The formula that relates the convenience of having inventory to the net flow of goods into inventory is:

$$V_{\text{conv}}(t) = \frac{1}{C} \int I_{\text{net}}(t) dt = \frac{1}{C} q(t) \tag{3-1}$$

This formula is a capacitor's voltage-current equation, where the voltage V_{conv} is the convenience of having inventory in $\frac{\$}{tonne \cdot wk}$, $\frac{1}{C}$ is the convenience yield and the current I_{net} is the net flow of goods into inventory in $\frac{tonne}{wk}$. The increase in inventory is the integral of the net flow of goods into inventory over time. q is the relative stock level, which is analogous to the amount of charge stored in the capacitor.

3-2-2 Excess Supply

Excess supply results from the difference between the quantity supplied and the quantity demanded of a good, based on the price level of the good in question. This stems from the law of supply and demand [59] and is modeled with an inductor in the electrical domain. The inductor induces a current based on the magnetic flux that is built up inside of it. This matches the change in excess supply that is induced by a change in the price level. The formula that relates the excess supply to the price change is:

$$I_{\text{sup}}(t) = \frac{1}{L}\int V_{\text{sup}}(t)dt = \frac{1}{L}\lambda(t) \tag{3-2}$$

This formula is an inductor's voltage-current equation, where the current I_{sup} is the excess supply of goods in $\frac{tonne}{wk}$, $\frac{1}{L}$ is the price elasticity of excess supply and the voltage $V_{\text{sup}t}$ is the price change over time of the good in question in $\frac{\$}{tonne \cdot wk}$. λ is the price level, which is the analog of the flux linkage in an inductor.

When used to represent excess demand in a market, the price level is that within the market. When used inside the manufacturing plant to plan production, the price level concerns the internal price or willingness to produce and the inductor represents the internal supply or demand. It is this element that adds price dynamics to an economic engineering model by keeping track of the price as it changes over time due to the influences of other elements.

3-2-3 Proportional Pricing

The proportional pricing phenomenon in a market, also called appreciation, is based on the scarcity principle. In the case of excess supply for a certain product, the price of that product will be driven down by the force of demand, which is proportional to the excess supply. This relation is modeled in the electrical domain by a resistor. The formula that relates the price change to the excess supply is:

$$V_{\text{prop}}(t) = R \cdot I_{\text{sup}}(t) \tag{3-3}$$

This formula is a resistor's voltage-current equation, where the voltage V_{prop} is the proportional price change of a good, R is the appreciation rate and I_{sup} is the excess supply of the good in question.

3-2-4 Production

Production is defined as the conversion of raw materials into finished products [49]. This is modeled in the electrical domain by a transformer. The transformer converts one current into another, with a ratio between the currents equal to the windings ratio of the transformer. This is similar to how the output of finished products is related to the required input of raw materials by a ratio specified in the Bill of Materials (BOM). The voltages on either side of the transformer are related through the inverse of the transformer ratio. This matches the relation between the desirability to produce for products and materials depending on the ratio specified in the BOM. The formulae that relate the flows of goods and the desirabilities on either side of production are:

$$\begin{aligned} I_{\text{rm}}(t) &= n \cdot I_{\text{fp}}(t) \\ V_{\text{rm}}(t) &= \frac{1}{n} \cdot V_{\text{fp}}(t) \end{aligned} \tag{3-4}$$

I_{rm} and I_{fp} are the flows of raw materials and of finished products in $\frac{tonne}{wk}$, respectively, V_{rm} and V_{fp} are the desirability to use raw materials and the desirability to produce finished products in $\frac{\$}{tonne \cdot wk}$, respectively, and n is the weight ratio of raw materials to finished products as specified in the BOM.

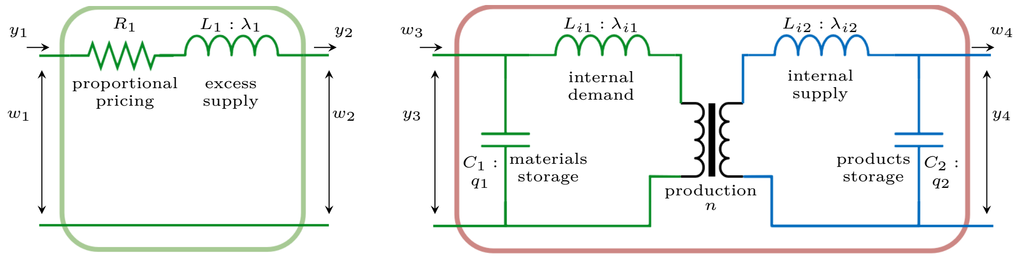
3-3 Model of a Manufacturing Plant and the Surrounding Markets

In this section I combine the electrical elements listed in Section 3-2 into an electrical circuit that serves as a model of a manufacturing plant and its surrounding external markets. A single stage in a supply chain like the manufacturing plant is also referred to as a supply chain 'echelon' [49]. The core supply chain structure as shown in Chapter 2 in Figure 2-1 is taken to match the circuit's structure to. This circuit functions as a building block that I use in Section 3-5 to construct a model of a 3-echelon serial supply chain.

The electrical circuit of a supply chain echelon consists of the circuit of a manufacturing plant and of the circuits of external markets. The flow of goods through these circuits is defined by their core structure. Materials enter a manufacturing plant from the external market for raw materials. These materials either go into storage or are immediately used in production. Production takes the materials and converts them into products with a flow that is controlled by internal supply and demand. The products go into storage or are sold to customers right away by flowing into the external market for finished products. The flow through the market is determined by the prices of the products, which is influenced by proportional pricing and by the finished products stock level. The individual circuits of an external market and of a manufacturing plant are shown in Figure 3-2, for which the state-space representations are given in Eq. (3-5) and Eq. (3-6), respectively.

The time-dependency notation of the variables will be dropped from this point onward for the purpose of readability.

The external market circuit consist of excess supply and proportional pricing, the manufacturing plant consists of storage for materials and products with production linking the two, governed by internal supply and demand. The circuit of a manufacturing plant contains two separate types of flows of goods, of raw materials and of finished products. All green elements and wires correspond to raw materials and all blue elements and wires correspond to finished products. Production is what links the materials and products in the center of the manufacturing plant model. Elements are labeled with their parameters and system states are shown for the elements that store them. The states of the systems are the relative stock levels (q) and price levels (λ).



External Market

Manufacturing Plant

Figure 3-2: Electrical elements are combined into circuits that represent a manufacturing plant (right) and an external market (left). The state-space representations of the market and plant are given in Eq. (3-5) and Eq. (3-6), respectively

$$\begin{aligned}
\frac{d}{dt}\begin{bmatrix}\lambda_1\end{bmatrix} &= \begin{bmatrix}-\frac{R_1}{L_1}\end{bmatrix}\begin{bmatrix}\lambda_1\end{bmatrix} + \begin{bmatrix}1 & -1\end{bmatrix}\begin{bmatrix}w_1\\ w_2\end{bmatrix}\\
\begin{bmatrix}y_1\\ y_2\end{bmatrix} &= \begin{bmatrix}\frac{1}{L_1}\\ \frac{1}{L_1}\end{bmatrix}\begin{bmatrix}\lambda_1\end{bmatrix}
\end{aligned} \tag{3-5}$$

Here, w_1 and w_2 are price change disturbance inputs (voltages) that may come from manufacturing plants connected to either end of the market. The outputs y_1 and y_2 are the flows in and out of the market on the left and right side, respectively, which are equal as market clearance is assumed.

$$\begin{aligned}
\frac{d}{dt}\begin{bmatrix}q_1\\ q_2\\ \lambda_{i1}\\ \lambda_{i2}\end{bmatrix} &= \begin{bmatrix}0 & 0 & -\frac{1}{L_{i1}} & 0\\ 0 & 0 & 0 & \frac{1}{L_{i2}}\\ \frac{n^2 L_{i1}}{C_1 L_{i2}}\alpha & -\frac{n L_{i1}}{C_2 L_{i2}}\alpha & 0 & 0\\ \frac{n}{C_1}\alpha & -\frac{1}{C_2}\alpha & 0 & 0\end{bmatrix}\begin{bmatrix}q_1\\ q_2\\ \lambda_{i1}\\ \lambda_{i2}\end{bmatrix} + \begin{bmatrix}1 & 0\\ 0 & -1\\ 0 & 0\\ 0 & 0\end{bmatrix}\begin{bmatrix}w_3\\ w_4\end{bmatrix}\\
\begin{bmatrix}y_3\\ y_4\end{bmatrix} &= \begin{bmatrix}\frac{1}{C_1} & 0 & 0 & 0\\ 0 & \frac{1}{C_2} & 0 & 0\end{bmatrix}\begin{bmatrix}q_1\\ q_2\\ \lambda_{i1}\\ \lambda_{i2}\end{bmatrix},
\end{aligned} \tag{3-6}$$

with $\alpha = \frac{1}{1+n^2\frac{L_{i1}}{L_{i2}}}$.

The disturbance inputs w_3 and w_4 are flows of goods entering or leaving the manufacturing plant and the outputs y_3 and y_4 are price changes caused by the conveniences of materials and products storage, respectively.

The open ends on the right and left sides of the circuits indicate the locations that other circuits can be connected to. To construct a serial supply chain, the systems are connected in series through their disturbance inputs (w) and measured outputs (y). The outputs of one circuit become the disturbance inputs to the other and vice versa. The electrical circuit of a single supply chain echelon, consisting of a manufacturing plant connected on either side to an external market, is shown in Figure 3-3, with its state-space representation in Eq. (3-7).

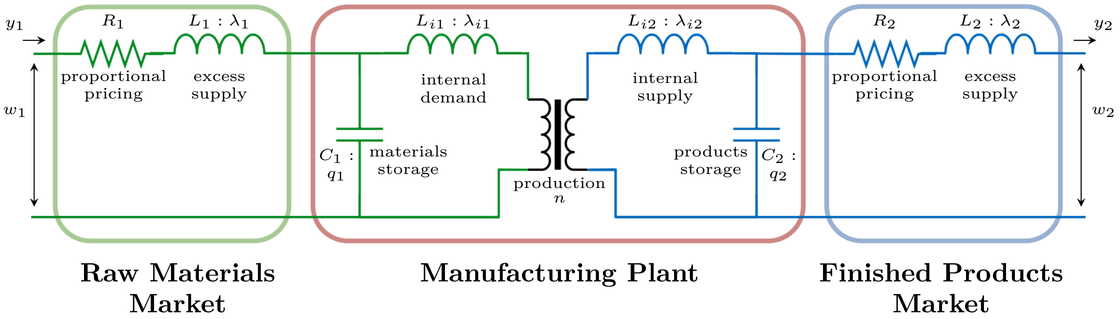


Figure 3-3: The electrical circuits of an external market and manufacturing plant are connected through their inputs and outputs to obtain the model of a supply chain echelon. The state-space representation is given in Eq. (3-7)

$$\frac{d}{dt}\begin{bmatrix} q_1 \\ q_2 \\ \lambda_1 \\ \lambda_2 \\ \lambda_{i1} \\ \lambda_{i2} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{1}{L_1} & 0 & -\frac{1}{L_{i1}} & 0 \\ 0 & 0 & 0 & -\frac{1}{L_2} & 0 & \frac{1}{L_{i2}} \\ -\frac{1}{C_1} & 0 & -\frac{R_1}{L_1} & 0 & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 & -\frac{R_2}{L_2} & 0 & 0 \\ \frac{n^2 L_{i1}}{C_1 L_{i2}}\alpha & -\frac{n L_{i1}}{C_2 L_{i2}}\alpha & 0 & 0 & 0 & 0 \\ \frac{n}{C_1}\alpha & -\frac{1}{C_2}\alpha & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ \lambda_1 \\ \lambda_2 \\ \lambda_{i1} \\ \lambda_{i2} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & -1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \end{bmatrix}$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{1}{L_1} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{L_2} & 0 & 0 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ \lambda_1 \\ \lambda_2 \\ \lambda_{i1} \\ \lambda_{i2} \end{bmatrix}, \tag{3-7}$$

with $\alpha = \frac{1}{1+n^2\frac{L_{i1}}{L_{i2}}}$.

The state-space representation of the dynamics of a single building block shows some of the characteristics of the model. First of all, the behaviour on either side of production is symmetrical. The influence of the stock level on the internal price level and of the resulting production flow on the stock level is the same for raw materials and finished products. Second, the stock levels do not directly influence each other but cause a change in the internal price level and with that a change in production. This in turn does influences the stock levels of both materials and products. Finally, the internal prices both move proportional to one another, only differing by the ratio $n\frac{L_{i1}}{L_{i2}}$. The A matrix is therefore not full rank and can be reduced to obtain a 5-dimensional system. Control and disturbance inputs are not included in this model yet and are added in Section 3-4 and Section 3-5 respectively.

3-4 Controllable Inputs for Supply Chain Management

The supply chain can be influenced through control of three SCM processes. The controllable inputs of the model match the three main influences of SCM on the manufacturing plant and on the surrounding markets as listed in Chapter 2. Figure 3-4 shows the locations of controllable inputs for each building block. The flow of products out of production is influenced by a controller on the products side of production, indicated with '**Prod**'. The flow of materials that is procured from suppliers is influenced by a controller positioned in the market for raw materials, indicated with '**Proc**'. The change in price for the finished products is influenced by a controller in the market for finished products, indicated with '**Pri**'. Flows are controlled in parallel to the circuit and price changes are controlled in series with the elements in the circuit. The continuous-time state-space representation of the controlled building block is shown in Eq. (3-8).

Depending on the type of control chosen for production, procurement and pricing, the control input blocks in Figure 3-4 are replaced with either passive electrical elements that act on local measurements or active components that may take measurements from anywhere in the system. In Chapter 4, I apply PID control to influence the flows of goods with production and procurement and to adjust the product prices in order to mitigate the BWE.

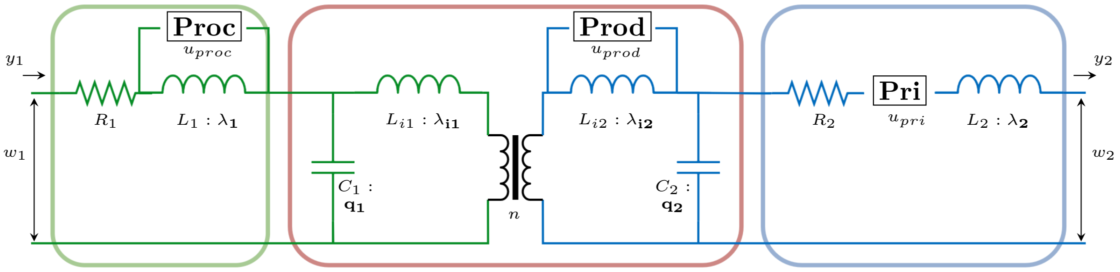


Figure 3-4: The flows of goods and price changes in the supply chain can be controlled with procurement (**Proc**), production (**Prod**) and pricing (**Pri**). The state-space representation is given in Eq. (3-8)

The controlled system is fully controllable under the condition that the system is first reduced to its 5-dimensional form where either λ_{i1} or λ_{i2} is eliminated. Reduction of the system matrix is necessary for controllability as the λ_{i1} and λ_{i2} variables are linearly dependent on one another and can not move independently. Full controllability means that SCM is able to steer the supply chain to any desired state with procurement, production and pricing.

$$
\begin{aligned}
\frac{d}{dt}\begin{bmatrix} q_1 \\ q_2 \\ \lambda_1 \\ \lambda_2 \\ \lambda_{i1} \\ \lambda_{i2} \end{bmatrix} &= \begin{bmatrix} 0 & 0 & \frac{1}{L_1} & 0 & -\frac{1}{L_{i1}} & 0 \\ 0 & 0 & 0 & -\frac{1}{L_2} & 0 & \frac{1}{L_{i2}} \\ -\frac{1}{C_1} & 0 & -\frac{R_1}{L_1} & 0 & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 & -\frac{R_2}{L_2} & 0 & 0 \\ \frac{n_2 L_{i1}}{C_1 L_{i2}}\alpha & -\frac{n L_{i1}}{C_2 L_{i2}}\alpha & 0 & 0 & 0 & 0 \\ \frac{n}{C_1}\alpha & -\frac{1}{C_2}\alpha & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ \lambda_1 \\ \lambda_2 \\ \lambda_{i1} \\ \lambda_{i2} \end{bmatrix} + \begin{bmatrix} 1 & -n & 0 \\ 0 & 1 & 0 \\ -R_1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} u_{proc} \\ u_{prod} \\ u_{pri} \end{bmatrix} \\
&\quad + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & -1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} \\
\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} &= \begin{bmatrix} 0 & 0 & \frac{1}{L_1} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{L_2} & 0 & 0 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ \lambda_1 \\ \lambda_2 \\ \lambda_{i1} \\ \lambda_{i2} \end{bmatrix}
\end{aligned}
\tag{3-8}
$$

3-5 Model of a 3-Echelon Serial Supply Chain

In this thesis I consider a multi-echelon serial supply chain model, similar to what has previously been done in literature [15, 21, 42, 64, 72], to analyze the BWE and to develop SCM policies that mitigate the BWE. The model is constructed by linking together 3 of the building block circuits presented in Section 3-3. Markets and manufacturing plants alternate to create a serial supply chain. The products that flow out of one plant flow into the next plant as its respective raw materials. Each plant has its own production and its inventories for raw materials and finished products. Inputs of flows of goods to one of the manufacturing plants at either the right- or left-hand side of the supply chain are added, resulting in two separate models, to simulate the model behaviour under the influence of disturbances and carry out scenario analysis. These inputs are represented by current sources in the electrical circuit.. The source on the left-hand side represents upstream excess supply and the source on the right-hand side represents downstream excess customer demand. The disturbance to the market at the end of the supply chain without an input is assumed to be 0 for the scenarios that are analyzed in this chapter, illustrated by a wire that closes the circuit on that end. Figure 3-5 shows the models of a 3-echelon serial supply chain with disturbance inputs at either end of the supply chain and Appendix A provides the state-space representations of these models.

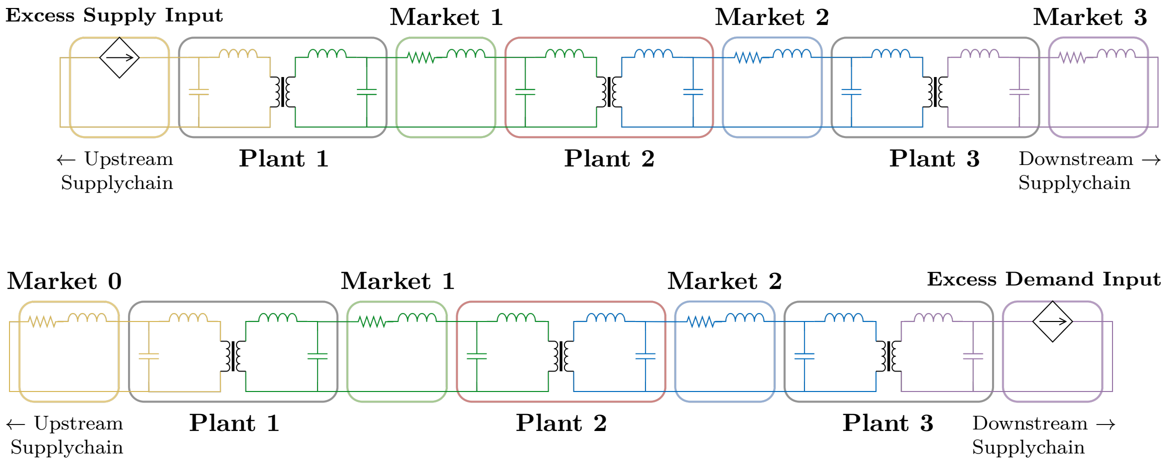


Figure 3-5: Circuits that represent a 3-echelon serial supply chain are constructed by linking together 3 individual echelons and placing a disturbance input for the flow of goods at either end of the supply chain

3-5-1 Tuning the Model

The parameters of the elements in the model of a 3-echelon supply chain must be set such that the model resembles a real supply chain in order to be able to make conclusions about the results the model produces. A supply chain that consists of only a single plant per echelon with only one raw material and one finished product is not found in reality and specific data for this particular setup is therefore not available. The model parameters can instead be set according to expert knowledge and by taking average values of data from the manufacturing plant of VSC in Baleycourt. Through interviews with employees of VSC and by analyzing data from VSC, general knowledge about supply chain behaviour is obtained and the parameter values are tuned so that the model displays realistic supply chain behaviour.

Setting the parameters is done in three steps. First, the weight ratio (n) of raw materials required for the production of finished products is obtained from the BOM. Second, price-volume data from the markets is taken to determine the price elasticity of excess supply ($\frac{1}{L}$) facing the plant. The price elasticity is often not linear in reality [56] and is therefore approximated in order to be able to obtain an LTI model. Third, the parameters for the pricing elements (R), the storage ($\frac{1}{C}$) and the internal excess supply/demand ($\frac{1}{L_i}$) are set so that the stocks and orders fluctuate with a period and amplitude that is similar to the cycles in reality. The result is a model of a 3-echelon serial supply chain that resembles part of a real supply chain and that can be used for validation of the model structure.

Assumptions for Tuning the Model

Various assumptions are made in determining the structure of the supply chain model and for setting the parameter values within the model.

- Electrical elements are linear and time-invariant
- Weight ratios for production (n) are set to 1

- Echelons consist of 1 plant that produce 1 product from 1 material
- Price elasticity ($\frac{1}{L}$) is higher further upstream in the supply chain [56]
- Convenience yield of inventories ($\frac{1}{C}$) is lower further upstream
- Proportional pricing (R) is lower further upstream [56]

Elements behave linearly and are time-invariant in order to obtain an LTI model. Production elements use a ratio (n) of 1, so that fluctuations of flows of goods at different locations in the supply chain can easily be compared with each other without having to take into account a production conversion ratio. For modeling the principle behaviour of a supply chain, a single plant with 1 material and product is sufficient. A case study of a real supply chain, where multiple products and materials are taken into account is presented in Chapter 5. Price elasticity parameters are set according to expert knowledge instead of market data when data is insufficiently available. Simon and Fassnacht [56] list a number of reasons that may increase price elasticity, of which the majority are confirmed by the commercial departments of VSC as having a larger influence further upstream in their supply chain. Similar reasoning is applied to the convenience yield and proportional pricing parameter values at different locations in the supply chain.

Without vertical integration or neighbouring echelons sharing their data, assumptions are necessary for setting the parameters of a supply chain model [36].

The state-space representations of both models and the list of parameter values for these models are found in Appendix A.

3-6 Model Validation

The model of a 3-echelon serial supply chain needs to be validated for the purpose of this thesis so that conclusions can be drawn from the results the model produces. First, I carry out scenario analysis to show the response of the model to various disturbances. Then, I quantify the BWE by analyzing the Bode plots of the transfer functions from excess customer demand to upstream excess supply flows. The results of the scenario analysis and Bode plot are compared to observations on VSC data. If the model shows expected supply chain behaviour and the BWE can be simulated with this configuration, the model is validated for the purpose of this thesis.

State-space representations are derived for the models presented in Section 3-5 and are discretized for simulation purposes. A time step of 1 week is chosen for discretization, as the time period of interest for showing the BWE is in the order of months and SCM generally does not change policies at a higher frequency than weekly, making this sufficiently fast. The zero-order hold discretization method is used, as the control method presented in Chapter 4 supplies only piece-wise constant control inputs, similar to the behaviour of SCM. The continuous-time state-space representation for this 3-echelon serial supply chain model are found in Appendix A.

Subsection 3-6-1 shows the behaviour of the model when subjected to various disturbances in scenario analysis. Subsection 3-6-2 shows the frequency domain characteristics of the model and indicates the existence of the BWE with a Bode diagram.

3-6-1 Scenario Analysis

Scenario analysis is carried out to show the behaviour of the model subjected to disturbances. The model output is compared to expected supply chain behaviour and data from VSC provides a practical reference. Appendix B provides graphs of VSC data used in the validation of the 3-echelon serial supply chain model. Three disturbance types typical to supply chains are chosen to show the principle characteristics of the model under the influence of disruptions.

First, a temporary decrease in the upstream supply of raw materials is simulated by taking an extended pulse as disturbance for the upstream excess supply. This scenario shows the fundamental dynamics of stocks and flows of goods as well as the delays of the responses between echelons. Typical supply chain behaviour to a temporary decrease in upstream supply is a decrease in production due to a lack of raw materials. This is followed by a decrease in supply to downstream echelons when also the product stock levels have dropped. After the upstream supply is back to its original level, the stocks, production and supply volumes eventually return back to their original level.

Second, the model is subjected to equally distributed random downstream excess customer demand. This scenario shows the filter behaviour of the different echelons. The production and procurement of a manufacturing plant behave strictly according to their policies. Production is planned in batches, meaning that the production output fluctuates with a certain frequency [49]. The same behaviour is seen in procurement, where materials are ordered per truckload [74]. The result is that each supply chain echelon filters out the frequencies of their demand that they resonate to as a manufacturing plant.

Third, cyclical demand is used as disturbance for the downstream excess customer demand. This scenario shows the emergence of the BWE for a specific demand cycle. For certain frequencies, a supply chain will amplify demand fluctuations [64, 72]. A delayed response of production and procurement to a change in customer demand results in discrepancies in the stock levels of materials and products. This discrepancy gives rise to a change in the price level and an overreaction of procurement, meaning that the echelon located directly upstream will observe a larger demand change than the original downstream demand change. Each echelon amplifies the fluctuations of demand [2].

The names as given in Figure 3-5 are used to indicate at what echelon in the supply chain a measurement is taken.

Scenario 1 - Supply Decrease

Figure 3-6 shows the supply shock input (top left subfigure) and the response of system outputs to the shock. The input to the model is a temporary decrease in the supply of goods to plant 1. As a result of this decrease in supply, the raw material (rm) stock of plant 1 drops as production remains at a steady level at first, shown in the top right subfigure. When raw material stocks decrease, the willingness to produce goes down and production volumes eventually decrease, which can be seen in the middle left subfigure. The result is a decrease in the finished product (fp) stock of plant 1, shown in the top right subfigure. The decrease in finished product stock at plant 1 causes the willingness of plant 1 to supply to decrease, indicated with the relative price level, displayed in the bottom figure. The excess supply to the next echelon, plant 2, therefore drops. This causes the price to increase gradually, due to proportional pricing, as well as leveling out the products stock over time. The process repeats for plant 2 and afterwards plant 3 and the supply chain oscillates as it transitions between excess supply and excess demand. The behaviour of the system, displayed by the response of the outputs, is in line with general supply chain behaviour in the case of a temporary decrease in supply, confirmed by supply chain experts of VSC.

The upstream supply decrease precedes the drop in supply from plant 1 to plant 2 and the supply of plant 2 to plant 3 follows after that. Due to the reactive nature of the elements that make up the model of a supply chain, a delay is added with each element and each echelon. The integral relations of storage and excess supply as seen in Figure 3-1 each add a phase shift of 90 deg. Subsection 3-6-2 also shows the phase shift in Figure 3-9 for each of the echelons. The delay of the response of each echelon is one of the reasons for the existence of the BWE within supply chains [2, 29].

Scenario 2 - Random Demand

Figure 3-7 shows the random demand input (top left subfigure) and the response of system outputs to the random demand. The input signal does not display a specific periodicity as it is an equally distributed random signal. Cyclical behaviour is observed further upstream in the supply chain for plants 1 and 2 in their respective production volumes, relative stock levels and excess supply. This behaviour is caused by the inductor-capacitor pairs that make up the model of a supply chain. Each pair has a resonance frequency, meaning incoming signals with that frequency are amplified by the inductor-capacitor pair relative to incoming signals with a different frequency. The natural frequency of the inductor-capacitor pair is $\omega = \frac{1}{\sqrt{L \cdot C}}$. The cyclical behaviour of each echelon displayed in the scenario of random demand is typical to SCM policies and matches the filter characteristics of a real supply chain.

Scenario 3 - Cyclical Demand

Figure 3-8 shows the cyclical demand input (top left subfigure) and the response of system to the cyclical demand. As demand fluctuates, each echelon attempts to follow the demand with their production and orders. The top right subfigure shows that finished product stocks initially drop due to an increase in customer demand. To counteract the decreased stock level, production is increased and the materials stock drops as well. This drop in materials stock decreases the convenience of raw materials, causing increased prices for these raw materials and an increased supply. When the materials stock is back to its original level, the price and supply are still causing the stock to rise, making it fluctuate over time. Procurement and production are overreacting to the changes in stocks in order to get these back to their desired levels. The result of this overreaction is the amplification of customer demand fluctuations to oscillations in the supply to the plant. It is the effect of price fluctuation on supply and stock oscillations and the return effect of excess supply and stock levels on the price that amplify the BWE even further. Taking this reciprocal effect into account in modeling the BWE is unique to the economic engineering modeling approach I present in this thesis. The oscillations with increased amplitude relative to the amplitude of the downstream demand fluctuations indicate the existence of the BWE. The model displays the BWE in simulation for multiple echelons in the serial supply chain and the response to fluctuating demand matches the expected behaviour under this specific disturbance.

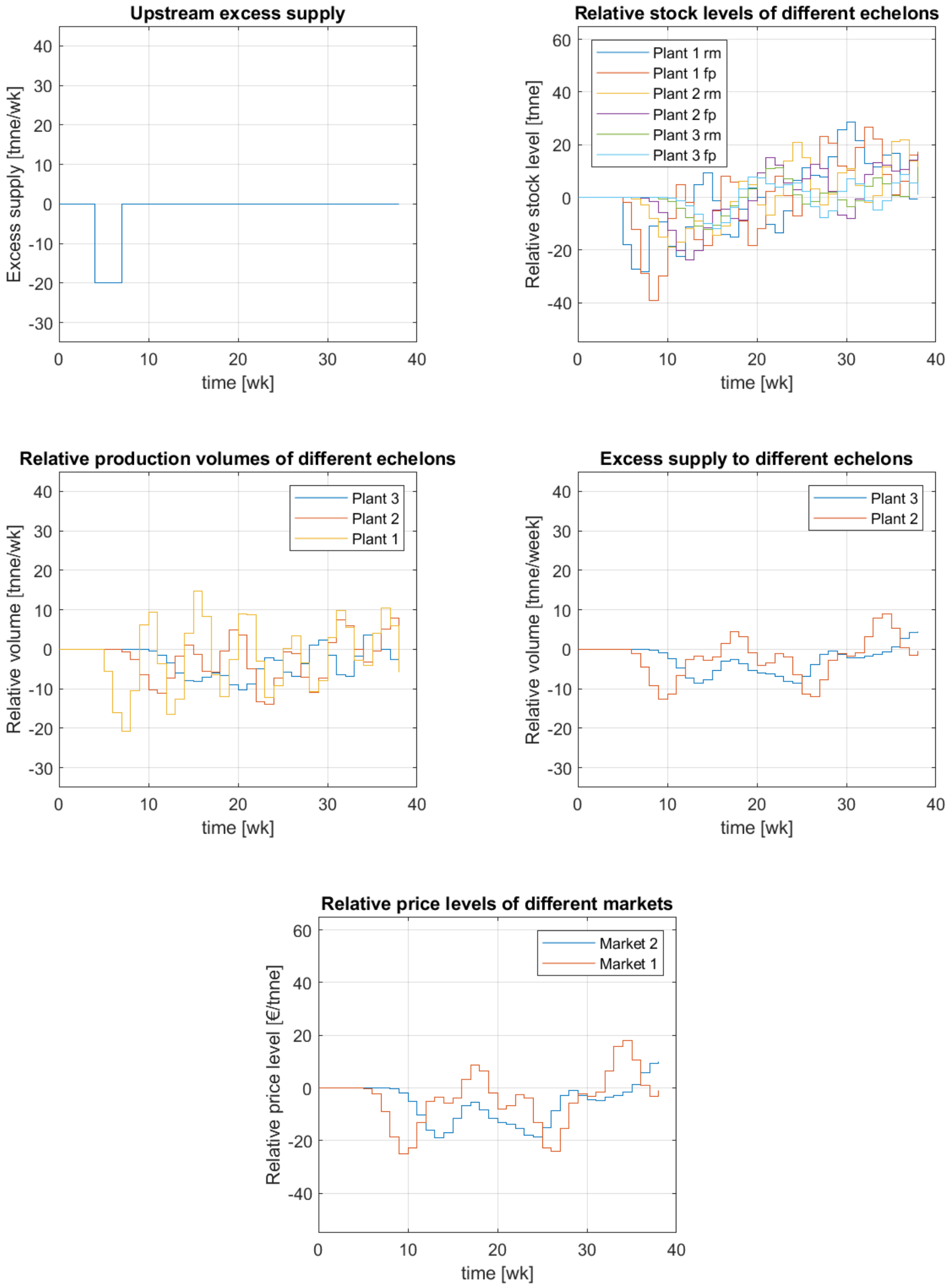


Figure 3-6: Simulation of a supply decrease shows the principle behaviour of the 3-echelon serial supply chain model. Stock levels (top right) initially decrease and eventually return to normal, production volumes (middle left) and supply volumes (middle right) aim to restore the inventory imbalances and relative price levels (bottom) move with the excess supply in the market in question. The indications 'rm' and 'fp' refer to raw material and finished product, respectively

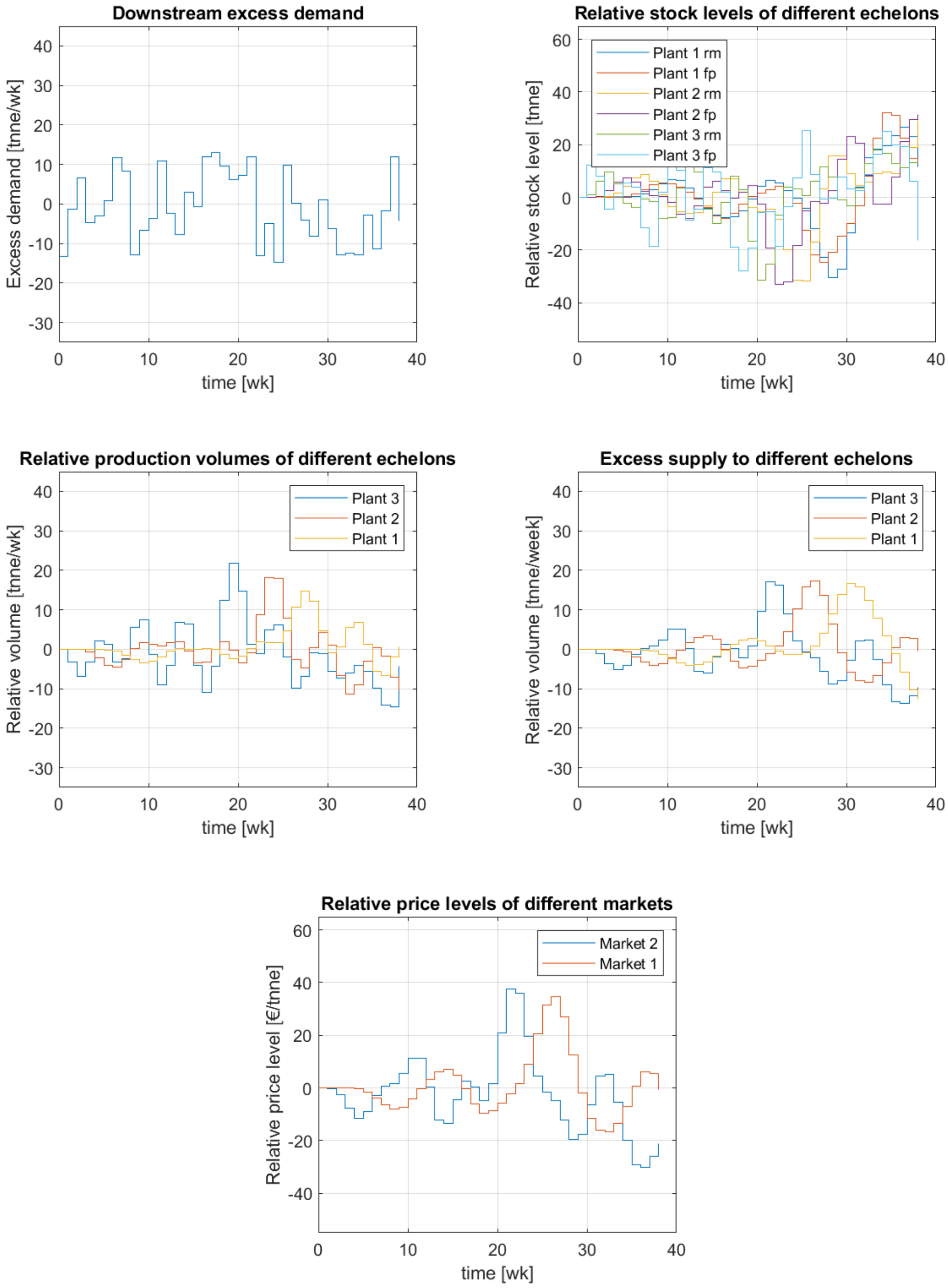


Figure 3-7: Simulation of equally distributed random downstream customer demand demonstrates the filter behaviour of the 3-echelon serial supply chain model. Production volumes (middle left) and supply volumes (middle right) oscillate at specific resonance frequencies filtered out from the random demand signal. The indications 'rm' and 'fp' refer to raw material and finished product, respectively

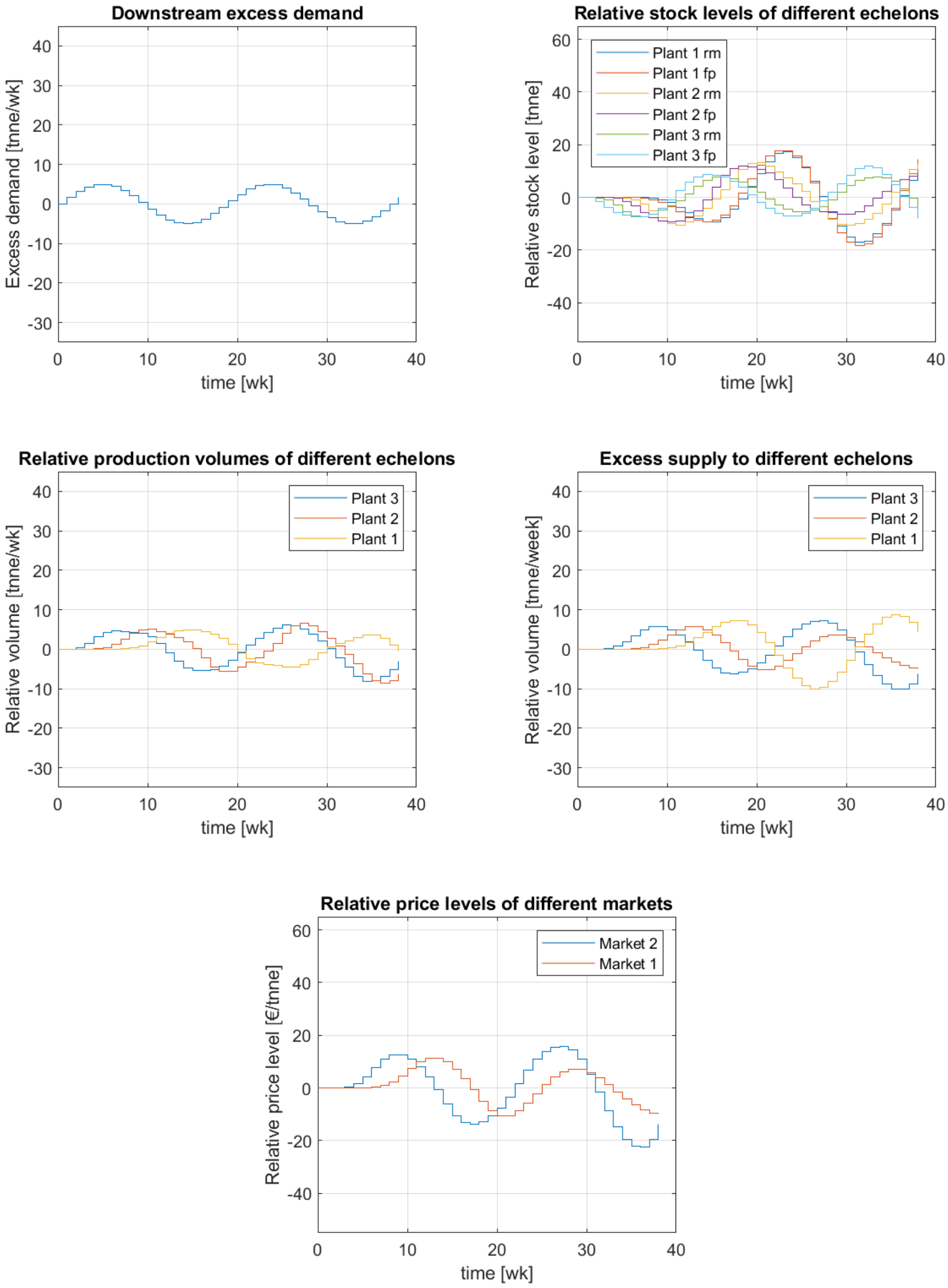


Figure 3-8: Simulation of cyclical downstream customer demand shows the existence of the Bullwhip Effect in the 3-echelon serial supply chain model. The oscillations of production (middle left) and supply (middle right) volumes have larger amplitude than the incoming demand signal, indicating amplification of demand fluctuations at this particular frequency. The indications 'rm' and 'fp' refer to raw material and finished product, respectively

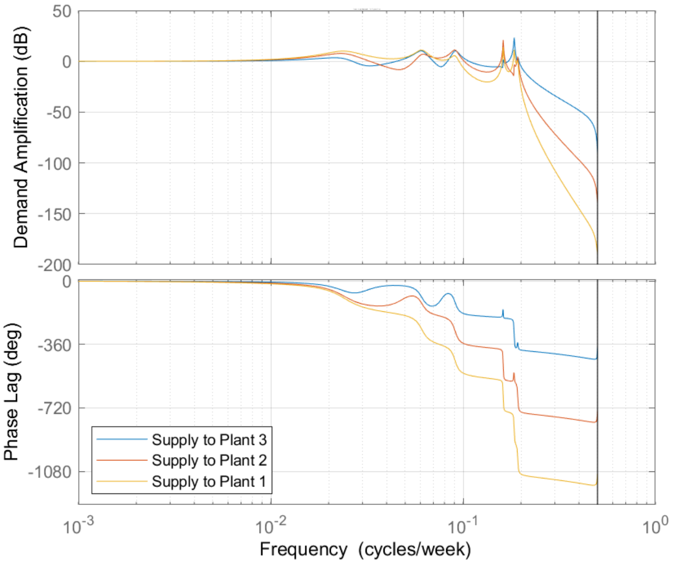


Figure 3-9: The Bode diagram of transfer functions from downstream excess demand to upstream excess supply quantifies the magnitude of the Bullwhip Effect for each resonance frequency. The Bullwhip Effect exists in ranges where the gain reaches above the 0 dB level, most noticeably at the resonance frequency peaks. The phase quantifies the relative lead time, with plants further away from the downstream demand having longer lead times than those closer to it

3-6-2 Frequency-Domain Analysis

The frequency response of the 3-echelon serial supply chain model is analyzed to validate the model's ability to produce the BWE. The Bode diagram for the transfer functions from excess customer demand to excess supply for several upstream supply chain members is chosen to observe the existence and effect of the BWE. This method is also used by [9] and [64] to analyze the BWE in their supply chain models. The gain plot of a Bode diagram enables quantifying the BWE so that the model can be validated for the purpose of this thesis.

Figure 3-9 displays the amplification of oscillations for each demand cycle in the upstream excess supply in the top subfigure and the relative lead times or phase lag in the bottom subfigure. Six peaks are observed in the top subfigure for the supply to each of the plants in the 3-echelon supply chain model. Each peak indicates a demand cycle frequency at which one of the plants or markets resonate. This resonance is the result of a excess supply-storage pair, or inductor-capacitor pair, and causes amplification of the oscillations of demand at a specific frequency range. The three peaks in the lower frequency range correspond to the resonance frequencies in the market. The three peaks in the higher frequency range correspond to the resonance frequencies of the production of the plant. The higher the peaks in the top subfigure, the larger the BWE for the plant in question.

The bottom subfigure shows larger relative lead times for the plants further upstream in the supply chain with respect to the downstream customer demand. The lower the line, the longer the relative lead time. To obtain the actual delay, the phase lag is divided by the frequency at which it is measured. An upstream supply chain member will always take a longer time

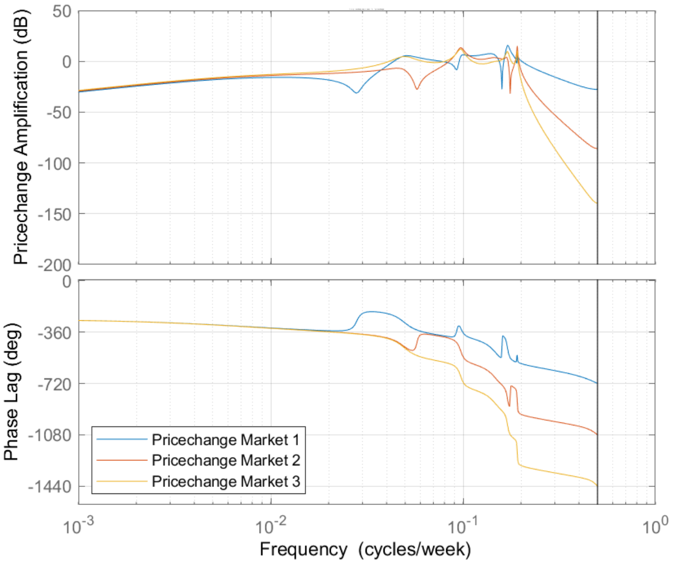


Figure 3-10: The Bode diagram quantifies the magnitude of the Reversed Bullwhip Effect in Pricing in the 3-echelon serial supply chain. The Reversed Bullwhip Effect in Pricing exists for the range of frequencies where the gain in the magnitude plot is larger than 0 dB. The phase quantifies the relative lead time, with plants further away from the upstream price change having longer lead times than those closer to it

to respond to changes in downstream customer demand than a supply chain member that is part of an echelon closer to the origin of the demand. This reactive nature is due to policies only acting locally and the lack of information sharing between supply chain members. This inherent order of response to changes in downstream customer demand is displayed by the lines in the bottom subfigure that do not cross and are stacked in order of closeness to the downstream demand from top to bottom. Plant 3 is closest to the downstream customer demand and is therefore the first to react to it.

In Chapter 4 a control method is developed to decrease the peaks in the gain plot of the Bode diagram from Figure 3-9 so that the BWE is mitigated.

Additionally, I quantify the Reversed Bullwhip Effect in Pricing (RBP) with the use of a Bode diagram. Similar to how the regular BWE is measured in the magnitude plot of a Bode diagram, the RBP can be measured using the transfer functions from upstream price changes to downstream price changes. Figure 3-10 shows the amplification of upstream price changes to downstream price changes for the 3 markets in the supply chain. The peaks in the magnitude plot of the Bode diagram indicate the RBP in a frequency range that is similar to the range that the regular BWE is largest in. The amplification of price changes may result in larger amplification of the BWE as price fluctuations are one of the main causes of the BWE [29, 45]. The Bode diagram is a new method for quantifying the RBP and can now be used because of the inclusion of price dynamics in the supply chain model.

3-7 Conclusions

The economic engineering model of a supply chain is effective at quantifying the effects of dynamic supply chain disruptions on the flow of goods through a supply chain. The building blocks of a manufacturing plant and an external market allow for easy construction of complex supply chain configurations. Economic engineering enables the inclusion of price dynamics in the supply chain model. This means that the reciprocal effect of fluctuating prices on the BWE can be taken into account in the analysis of the BWE. The outputs of the model display typical supply chain behaviour under the influence of disturbances and Bode diagrams quantify the BWE for each echelon. The results of the scenario analysis and frequency-domain analysis prove the validity of the supply chain model for the purpose of this thesis.

The model of a 3-echelon serial supply chain designed in this chapter is used in Chapter 4 as a basis for the development of a control method that mitigates the BWE. In Chapter 5 a simulation study is carried out for the BWE in the supply chain of VSC, demonstrating the effectiveness of the modeling method presented in this chapter and the control method from Chapter 4. The building blocks designed in Section 3-3 are used to construct a model of a part of the VSC supply chain and controllers are developed to mitigate the BWE in that specific part.

Chapter 4

Mitigating the Bullwhip Effect using PID Control

4-1 Introduction

In this chapter I show how the Bullwhip Effect (BWE) is mitigated in the 3-echelon serial supply chain from Chapter 3 using PID control. The control method serves as Supply Chain Management (SCM) policy, acting locally as procurement, production planning and pricing. PID control is chosen specifically because of its interpretability, its close match with a manager's behaviour and its ability to lower the peaks in the Bode diagram shown in Chapter 3 in Figure 3-9, mitigating the BWE. By tuning the controllers' parameters, the amplification of demand oscillations is decreased. The PID policies can be applied in the actual supply chain after they have been tuned to a satisfactory level in order to counteract the BWE in real life.

The remainder of this chapter is structured as follows. Section 4-2 shows the application of PID control as SCM policy to the 3-echelon serial supply chain from Chapter 3. Sections 4-3, 4-4 and 4-5 elaborate on the three PID controllers that I use to mitigate the BWE in the 3-echelon serial supply chain. I provide interpretation of the controllers' elements and explain the influence of the control action on the BWE. In Section 4-6 I tune the controllers' parameters so that the oscillations throughout the supply chain are decreased. Section 4-7 shows the results of using PID control for the serial supply chain in the time- and frequency domain. I provide managerial insight based on these results in Section 4-8. The results and insights are discussed in Section 4-9. In Section 4-10 I conclude that PID control can be used to mitigate the BWE in a multi-echelon serial supply chain by applying it as policies for procurement of raw materials, production planning and finished product pricing.

4-2 Supply Chain Management as PID Controllers

In this chapter, I introduce PID control as representation of SCM. Procurement of raw materials, production planning and finished product pricing are chosen as controlled processes,

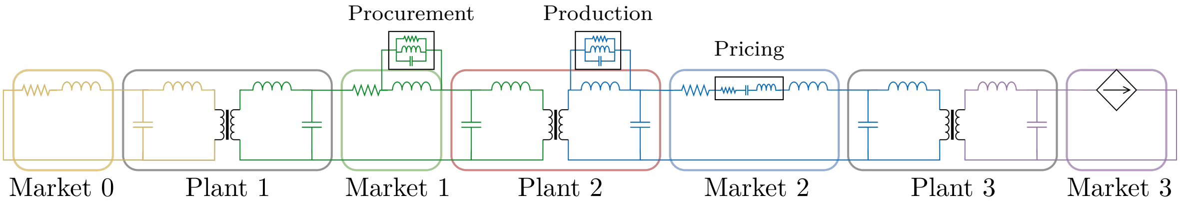


Figure 4-1: Procurement, production planning and pricing are modeled as individual PID controllers in the 3-echelon serial supply chain

as explained in Chapter 3. The three elements of PID control each represent different aspects of management policies. The proportional element acts on the current state of the system, while the integral action looks at the past and the derivative action anticipates on the future states of the system [13]. In real supply chains, management often take into account more than these three aspects, as supply chains are heavily constrained, time-variant and nonlinear. However, the LTI model designed in Chapter 3 allows for the use of interpretable PID control, which is effective at reducing oscillations and therefore fits the goal of mitigating the BWE. This section explains the general functionality of the PID control as applied to the supply chain.

Figure 4-1 shows the labelled electrical elements for the three locations at which PID control is applied to the supply chain. Procurement and Production control the flow of goods into Plant 2 and out of the production of Plant 2, respectively. Pricing controls the price change of finished products of Plant 2. Only the flows and price changes of Plant 2 are controlled in this scenario.

The structure and placement of the controller elements define its effect and functionality. In case the flow of goods is controlled, the controller elements are placed in parallel, while they are placed in series when the price change is controlled. The elements in parallel all receive the same voltage, which corresponds to a price change, and outputs a current, which translates to a flow of goods. The elements in series function precisely the other way around and output a voltage as a reaction to the current they receive. The interpretation and effect on the BWE are presented in Sections 4-3, 4-4 and 4-5.

PID control bases its controller output on the current, historic and expected measurement [13]. The P-action takes the current value of the measured input and multiplies it with the corresponding element's parameter to obtain the control output. The I-action takes the sum of all past values of the measured input and multiplies it with the corresponding element's parameter. The D-action takes the first time-derivative of the measured input, based on the current and previous measurement, and multiplies it with the corresponding element's parameter. The functionality of the three elements matches a manager's behaviour, taking into account past, present and future system states to determine its actions. What element fulfills what function is dependent on the purpose of the controller, whether it controls a flow of goods or a price change.

The PID controllers mentioned in this chapter are formulated in discrete-time as the model from Chapter 3 and the simulations in this thesis are also in discrete-time.

4-3 Procurement of Raw Materials

Procurement of raw materials concerns controlling the flow of goods into Plant 2. The controller outputs a flow of goods based on the price change in Market 1. This price change is the cause of the finished product inventory levels of Plant 1, the raw materials inventory of Plant 2 and the excess supply in Market 1, so if these measurements are available they can be used instead. The P, I and D elements of the procurement controller each give separate outputs that are summed up to obtain the total control output. The sum of the excess supply and the procurement output is the total flow of goods that enters Plant 2.

The PID controller for procurement is interpreted as the policy that dictates the desired flow of goods into the manufacturing plant. The controller is depicted in Figure 4-2 with the controller elements labelled. The elements that make up the controller are listed in Table 4-1 together with their interpretation.

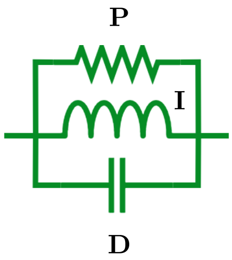


Figure 4-2: PID controller for raw materials procurement

Element	Interpretation
P	Price anticipation
I	Demand for raw materials
D	Price change anticipation

Table 4-1: Interpretation of the PID procurement controller elements

The controller output is calculated as

$$I_{\text{proc}} = k_P V_{\text{sup}} + k_I \sum V_{\text{sup}} T + k_D \frac{\Delta V_{\text{sup}}}{T} \tag{4-1}$$

I_{proc} is the relative flow of goods from procurement, V_{sup} the price change in the market for raw materials, T the sampling time (1 week in the case of this thesis) and k_P, k_I, k_D are the controller parameters.

All three elements of the PID procurement policy take the price change of raw materials in the market as their input to determine the procurement flow of goods. The P-action takes this price change directly and decides how much to order proportional to this price change. As the price change is determined partially by the inventory level of raw materials, the P-action is related to the order-up-to policy that is common in inventory management. The I-action sums up the price changes of all past periods, resulting in the price in the market relative to some initial price. The desired flow of materials is obtained by multiplying this relative price with the integral gain. The calculation of the procurement flow of goods based on the price level follows the demand curve [66], similar to excess supply in Section 3-2. The D-action divides the difference in price change over the last period by the sampling time. The anticipated price change is then obtained and multiplied with the derivative gain. In practice such behaviour is not observed often for procurement in supply chains, although speculations on system states could speed up the system's response [13]. Together with the excess supply in the market, the three elements output the desired flow into the manufacturing plant.

The PID procurement controller aims to smooth out the flow of goods into the manufacturing plant and improve the response to fluctuations in the stock levels. Due to the added proportional control action, the flow into the plant is returned to its original equilibrium level more quickly. This also means that supply fluctuations are damped out more quickly and thus the BWE is decreased. The integral action ensures that procurement eventually ends up at this equilibrium level with no steady-state error. The I-action is unsuccessful at smoothing out fluctuations however and therefore does not serve well for mitigating the BWE. However, the resonance frequency of the excess supply-storage pair at the procurement side of the plant can be altered by tuning the integral gain so that it is located at a frequency that is less common in the incoming demand signal. The speed of the response is improved with the derivative action. The D-action also aids in adding stability to the system, but makes the system more sensitive to noise in the market. For this thesis, no noise is added so this side-effect does not have to be taken into account although it might be important for further studies. The purpose of the elements together is to decrease the fluctuations of supply to the manufacturing plant and thus mitigate the BWE.

4-4 Production of Finished Products

Production is controlled so that the inventories of finished products and raw materials are balanced and at a desired level. The controller decides the flow of goods that comes out of production based on the inventory levels of materials and products. The sum of the internal supply of finished products and the output from the PID production controller is the total flow of goods that comes out of production.

The PID controller for production is interpreted as the policy that plans the desired flow of goods out of production. The controller is depicted in Figure 4-3 with the controller elements labelled. The elements that make up the controller are listed in Table 4-2 together with their interpretation.

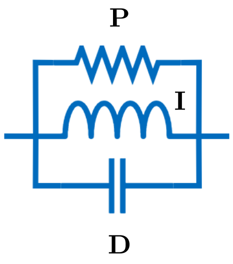


Figure 4-3: PID controller for finished products production

Element	Interpretation
P	Inventory balancing
I	Long-term inventory balancing
D	Inventory change anticipation

Table 4-2: Interpretation of the PID production controller elements

The controller output is calculated similarly to that of the procurement PID controller as

$$I_{\text{prod}} = k_P V_{\text{fp}} + k_I \sum V_{\text{fp}} T + k_D \frac{\Delta V_{\text{fp}}}{T} \tag{4-2}$$

I_{prod} is the relative flow of goods out of production, $V_{\text{fp}} = nC_{\text{rm}}q_{\text{rm}} - C_{\text{fp}}q_{\text{fp}}$ is the internal price change of finished products, calculated from the inventory levels of finished products and raw materials, n is the weight ratio of raw materials to finished products from the Bill of Materials (BOM), C is the convenience yield of holding goods in storage, T is the sampling time and k_P, k_I, k_D are the controller parameters.

The three elements of the PID production policy take the internal price change as their input to determine the desired flow of goods out of production. The internal price will be non-zero when the inventories are out of balance, meaning their conveniences are unequal. The P-action takes the imbalance directly and multiplies it with the proportional gain to obtain the desired flow of products that balances inventories directly. The I-action sums up the imbalance over time to know if a longer-term imbalance has existed. The sum is multiplied with the integral gain to determine the flow of goods out of production that counteracts the long-term imbalance. The D-action takes the change in imbalance over the past period and divides it by the sampling time to obtain an approximation of the time derivative of the inventory balance. This time derivative is then multiplied with the derivative gain to get the flow of products that balances inventories through anticipation of inventory changes. Summed with the internal supply, the outputs of the PID controller elements determine the flow of finished products out of production.

The PID production controller aims to smooth out the production inside the manufacturing plant to decrease the fluctuations of the stock levels and keep them close to their desired level. The proportional action added by the PID controller makes the stock levels return to their desired levels more quickly instead of letting them oscillate. In case the inventories are out of balance, the P-action immediately steers production so that the imbalance is resolved. This way, the fluctuations of stock levels are directly reduced. The integral element of the controller may change the resonance frequency of production inside the plant so that it is at a frequency that does not coincide with that of the supply or demand of the plant. Besides this change, the I-action does not decrease the fluctuations and is not successful at counteracting the BWE. The derivative action increases the response of production to changes in the inventory levels. Similar to the D-action for procurement, this does make the system more sensitive to noise. The three controller elements together decrease the oscillations inside the manufacturing plant and mitigate the BWE for inventories.

4-5 Finished Product Pricing

Pricing of finished products involves changing the price of a product to be sold to a customer. The controller outputs a price change based on the demand in Market 2. The sum of proportional pricing, the conveniences of the inventories connected to the markets and the controller output is the total price change for finished products. Reducing the fluctuations of prices is essential for mitigating the BWE as it is listed as one of the main causes of the BWE [29].

The PID pricing controller is interpreted as the policy that adjusts the prices of finished goods. The controller is depicted in Figure 4-4 with the controller elements labelled. The elements that make up the controller are listed in Table 4-3 together with their interpretation.

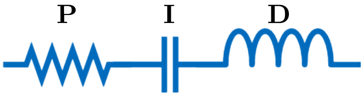


Figure 4-4: PID controller for finished product pricing

Element	Interpretation
P	Proportional pricing
I	Long-term pricing
D	Anticipatory pricing

Table 4-3: Interpretation of the PID pricing controller elements

The controller output is calculated as

$$V_{\text{pri}} = k_P I_{\text{dem}} + k_I \sum I_{\text{dem}} T + k_D \frac{\Delta I_{\text{dem}}}{T} \tag{4-3}$$

V_{pri} is the price change, I_{dem} the excess customer demand, T the sampling time and k_P, k_I, k_D are the controller parameters.

The pricing controller elements take the excess customer demand as input to calculate the price change for the finished products. This excess demand is how much the customer demand deviates from the demand in the case the market is in equilibrium. The P-action attempts to bring the market back to this equilibrium directly. Any fluctuations in the customer demand are steered back towards the equilibrium by pricing proportionally to the excess demand. This functions the same as the proportional pricing presented in Chapter 3 in Section 3-2. The I-action steers the demand back to equilibrium in the long term and makes sure there is no steady-state error. This phenomenon is uncommon in real supply chains as often the production is adjusted to cope with a long-term change in demand instead of attempting to influence demand itself. I refer to it as long-term pricing because it acts to influence the long-term state of the market. The excess demand is summed over time to obtain a virtual backlog and multiplied with the integral gain to get the price change to counteract long-term market imbalance. The D-action changes the price based on the change in demand. It anticipates change in demand and adjusts the price of the finished product to decrease the deviation of demand from market equilibrium. The approximated first time-derivative of the demand is taken and multiplied with the derivative gain to obtain the price change that anticipates customer demand changes. The sum of the outputs of the controller elements, together with the conveniences of surrounding storage and the original proportional pricing determine the total price change for finished products.

The PID pricing controller aims to decrease the fluctuations in customer demand by reducing price changes in the finished products market. The proportional action of the controller directly decreases excess demand oscillations by adjusting the price opposite to the change in demand. As the BWE starts with fluctuations in demand, the P-action acts on the source of the BWE. The excess demand is controlled towards 0 in the long run due to the integral action. The I-action is unsuccessful at reducing oscillations themselves, but may alter the resonance frequency of the market for finished goods. This way, the resonance frequency does not coincide with a dominant customer demand cycle and the BWE can be avoided. The derivative action improves the speed of the pricing response to changes in the customer demand but makes the pricing process more sensitive to noise in the customer demand signal. The three elements of the pricing controller together try to take away the cause of the BWE by reducing the oscillations of customer demand.

4-6 Tuning the PID Controllers

I tune the controller parameters for the three PID controllers manually with the use of a Bode diagram that shows the amplification from downstream customer demand to upstream supply. Each controller acts on a different part of the supply chain and therefore has a different effect on the frequency response of the system. The goal is to find controller parameters that decrease the peaks in the magnitude plot to just below the 0 dB line, while keeping the phase lag as small as possible.

The order that I tune the controller parameters in is: Pricing → Procurement → Production. However, the tuning process is iterative as the parameters of each controller influence the behaviour of the supply chain as a whole and therefore also the complete frequency response.

4-6-1 Finished Product Pricing

First I tune the pricing controller's parameters, as the pricing controller is concerned with reducing the origin of the BWE and is therefore most effective for the supply chain as a whole. The proportional gain has the largest effect on the gain, while the derivative gain aids slightly in keeping the phase lag small for the higher frequency range. The parameter values that I found are listed in Table 4-4.

Parameter	Parameter Value
k_P	4.4
k_I	$3.7 \cdot 10^{-4}$
k_D	$2.1 \cdot 10^{-2}$

Table 4-4: Pricing controller parameter values

Parameter	Parameter Value
k_P	$6.1 \cdot 10^3$
k_I	30
k_D	$1.0 \cdot 10^{-10}$

Table 4-5: Procurement controller parameter values

Parameter	Parameter Value
k_P	97
k_I	1.9
k_D	$1.0 \cdot 10^{-10}$

Table 4-6: Production controller parameter values

It must be noted that the integral gain of the controller is tuned so that is has nearly negligible influence. This means that PD control is essentially used instead of PID control. Increasing the integral gain of this specific controller results in a non-zero negative steady-state gain in the transfer function from downstream demand to supply volumes further upstream in the supply chain, undesirable for the overall supply chain behaviour.

4-6-2 Procurement of Raw Materials

Second I tune the procurement controller's parameters, as the procurement controller acts on the critical symptom of the BWE, namely the oscillations in supply to the manufacturing plant. The effect of the procurement controller is mostly noticeable for the resonance peaks that correspond to the raw materials market, as expected. The proportional gain directly decreases the peak in the magnitude plot, while the integral gain increases the resonance frequency of the market. The parameter values that I found are listed in Table 4-5.

It must be noted that the derivative action is tuned to have a negligible effect on the system. PI control is therefore essentially used instead of PID control. Increasing the derivative gain results in a similar non-zero negative steady-state gain as with the pricing controller, although now as a result of the derivative action instead of the integral action of the controller.

4-6-3 Production of Finished Products

Finally I tune the production controller's parameters. The effect of the production controller is on the higher frequency range, where the resonance frequency of the production of the plant is located. The proportional gain decreases the peak in the magnitude plot directly and the integral gain increases the resonance frequency. The parameter values that I found are listed in Table 4-6.

Similar to the procurement controller, the derivative action is tuned to have negligible effect on the system as it results in a non-zero steady-steady state gain for the transfer function from downstream demand to supply volumes further upstream in the supply chain.

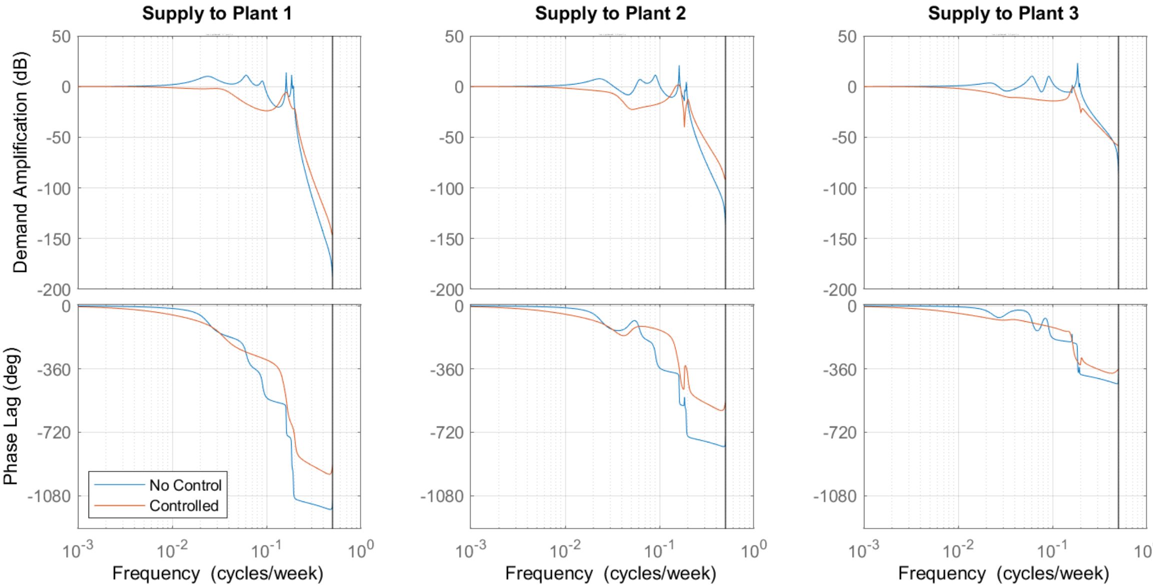


Figure 4-5: Bode diagrams show the frequency response comparison for the Bullwhip Effect between the controlled and uncontrolled system. The controlled system (orange) has a lower gain for the largest part of the relevant frequency range, indicating Bullwhip Effect mitigation

4-7 Results of Implementing PID Control as Management Policies

The results of using PID control for mitigating the BWE are analyzed in the frequency-domain and the time-domain. First, Bode diagrams are taken to observe the decrease in amplification for the resonance frequencies of the manufacturing plant that I apply control to. Then, the scenario of fluctuating demand from Chapter 3 Section 3-6 is simulated again to demonstrate the effect of the controllers on the outputs of the system.

4-7-1 Frequency-Domain Analysis

The effect of the PID controllers on the BWE over the complete frequency range is observed in Bode diagrams for the transfer functions from downstream excess customer demand to upstream supply for each plant. The Bode diagrams in Figure 4-5 show the comparison between the uncontrolled system and the system with PID control policies.

The magnitude plots of the Bode diagrams clearly display the difference in demand amplification between the uncontrolled and the controlled system. The amplification for all three plants in the controlled case is at or below the 0 dB level at all frequencies. The peaks that are still visible in the magnitude plots are the result of resonance frequencies in the other plants that have not been resolved or moved by applying a PID policy to the relevant process. As all supply chain members contribute to the BWE, they all need to work together to mitigate it [47]. Appendix C shows the effect on the frequency-response when all 3 plants implement PID policies for their SCM actions. The attenuation of demand oscillations in the frequency range of $4 \cdot 10^{-2}$ to $1.5 \cdot 10^{-1}$ cycles per week means that there is only a very small response to demand within that specific range. This might cause issues with the stock levels for raw materials and finished products in Plant 3, as they are not restocked at a rate that is in line with the customer demand and the production volume. Appendix D shows the frequency response from customer demand to Plant 3 stock levels to demonstrate this issue. Subsection 4-7-2 shows the response of the stock levels and other outputs of the system in the case of cyclical demand at a chosen frequency. The policies used for Plant 2 are able to sufficiently decrease the amplification of demand so that the peaks caused by resonance frequencies in other markets are of lower influence to the supply chain as a whole. The result of using PID control for procurement, production and pricing is that the BWE is no longer present in the serial supply chain.

The phase plots of the Bode diagrams indicate minor differences in phase for the largest part of the frequency range between the controlled and uncontrolled system. The controlled system shows a higher phase lag in the lower frequency range and a lower phase lag in the higher frequency range. The difference in phase is smallest for the supply to Plant 3 as no control influence is directly acting on the processes between customer demand and supply to Plant 3 and Plant 3 is only indirectly influenced by the added controllers. The supply to Plant 1 and 2 on the other hand do show larger differences especially in the higher frequency range, caused by the added phase from the derivative element of the PID controller. This indicates that the use of PID policies improves the supply response of Plant 2 to fast changing demand. The use of PID control results in better lead times for customer demand at higher frequencies and has only minor negative effect on the lead times at low frequencies.

Additionally, I compare the Reversed Bullwhip Effect in Pricing (RBP) of the controlled system with that of the uncontrolled system with the use of Bode diagrams. Figure 4-6 shows the amplification of upstream price changes to the price changes in markets throughout the supply chain. The leftmost subfigure shows the largest attenuation of price changes for the prices in Market 1. This means that the prices in Market 1 will remain nearly constant, ignoring the price changes in the upstream market for the largest part. The price changes in the other markets are amplified less and even attenuated with control for the largest part of the relevant frequency range. The phase lag of the price changes in the controlled system are similar to or slightly smaller than those in the uncontrolled system. The application of PID control to the serial supply chain results in near complete elimination of the RBP, which in turn reduces the BWE as the fluctuation of prices is one of its main causes [29, 46].

4-7-2 Scenario Analysis

The effect of using PID control on the supply chain is shown by simulating the scenario of cyclical demand from Chapter 3 Section 3-6 for the controlled system. Figure 4-7 displays the outputs of the system and the cyclical demand input.

The subfigures of the system outputs all show low amplitude oscillations and no amplification of the downstream excess customer demand. The fluctuations of excess demand are even attenuated to result in nearly constant supply volumes, as can be seen in the middle right subfigure. The relative prices are kept nearly constant in Market 2, shown in the bottom subfigure, resulting in a steady supply to Plant 3. This steady supply means a steady demand for Plant 2 and so the origin of the BWE is taken away from this part of the supply chain. The relative production volume of Plant 2, shown in the middle left subfigure, follows the demand

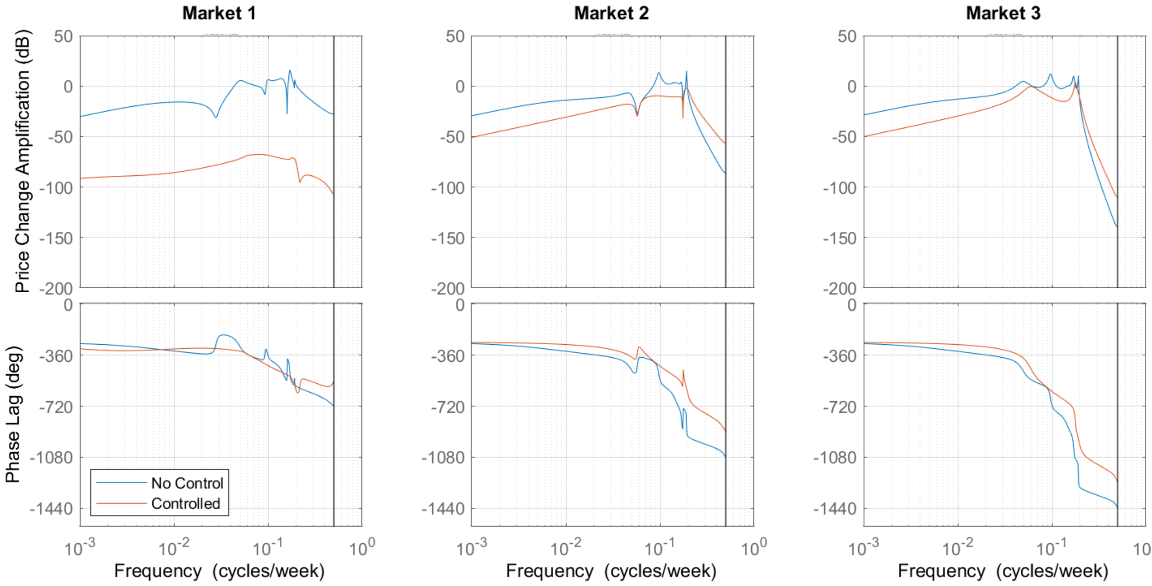


Figure 4-6: The Bode diagrams show the comparison between the controlled and uncontrolled system in terms of the Reversed Bullwhip Effect in Pricing. The lower gain in the magnitude plot indicates a decrease in the Reversed Bullwhip Effect in Pricing for the largest part of the relevant frequency range

to Plant 2 and Plant 1 follows in its supply and production levels after a delay as well. As the supply and the production of Plant 2 are steady, the finished products stock level of Plant 2 also oscillates very little. This in turn decreases the fluctuations of the prices of finished products, attenuating the BWE even further. The attenuation (instead of amplification) of oscillations clearly indicates that there is no BWE in the supply chain for this specific demand cycle, where without control there was.

The stock levels and production volume of Plant 3 still oscillate with the excess downstream demand. In order to further decrease these oscillations, PID control needs to be used for the policies of Plant 3 as well. The effect of using PID control for all echelons in the supply chain is presented in Appendix C.

4-8 Managerial Insight for Mitigating the Bullwhip Effect

The use of PID control for mitigating the BWE leads to quantifiable policies that SCM can use in a real supply chain to decrease the amplification of demand fluctuations. After obtaining a viable policy that counteracts the BWE by experimenting with the controller parameter values, SCM can take the policies to directly calculate the optimal procurement and production volumes as well as the optimal finished products price change for the upcoming period. The measurements of stock levels and prices required for the calculation of these optimal values are readily available in a real supply chain. The outputs of the policies, as in Eq. (4-1), Eq. (4-2) and Eq. (4-3), should be used as weekly setpoints for SCM to steer their daily procurement, production and pricing to.

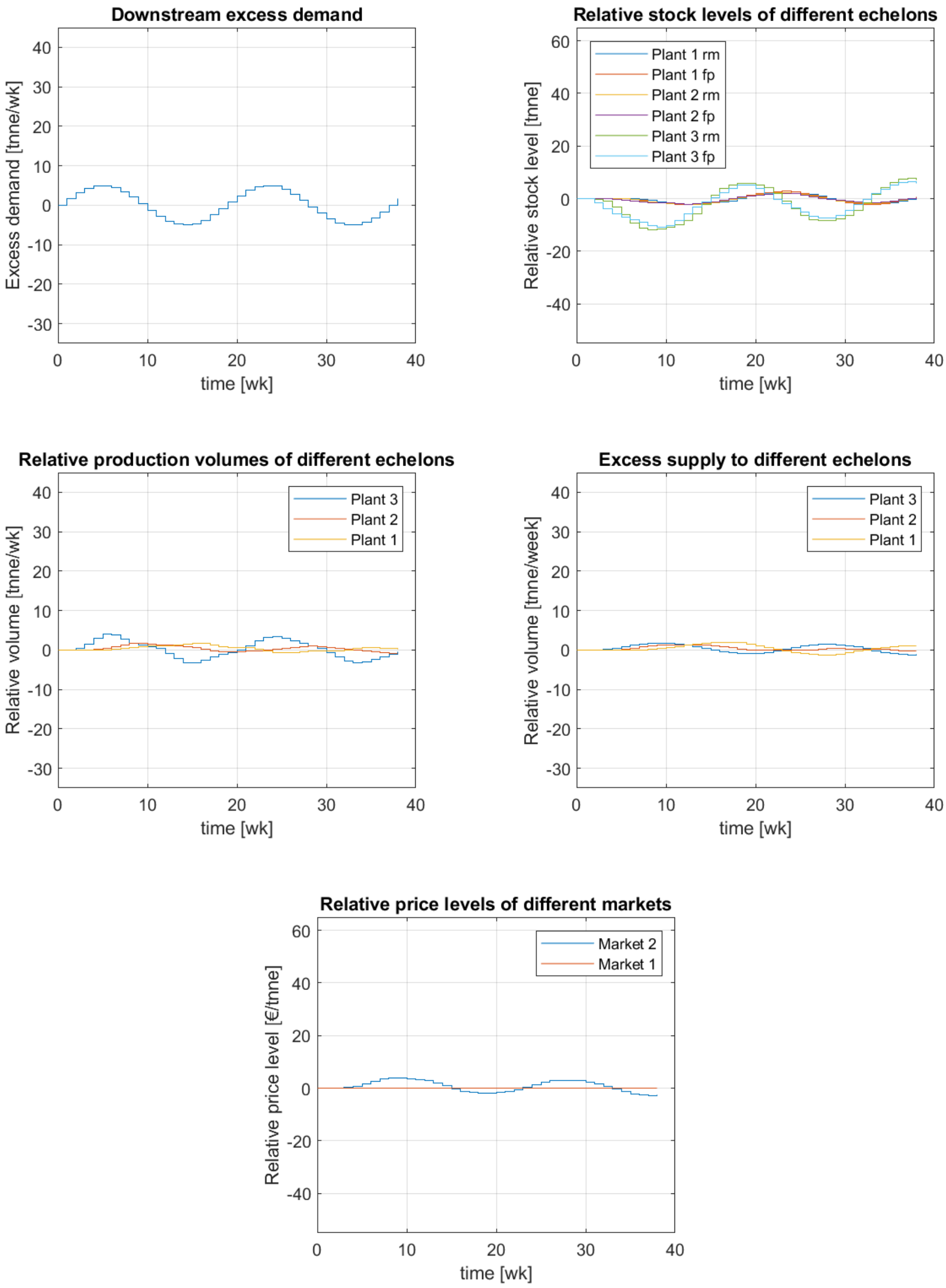


Figure 4-7: Simulation of cyclical downstream customer demand for the controlled supply chain shows attenuation of oscillations for all outputs as a result of applying PID control as management policies to the supply chain. The indications 'rm' and 'fp' refer to raw material and finished product, respectively

The proportional action is most effective in decreasing the amplification of demand fluctuations in all policies. Each part of the supply chain benefits from acting directly on the deviations from desired stock levels and prices or from equilibrium customer demand. Taking direct actions for procurement, production and pricing reduces the time delays to respond to changes in customer demand, as is also presented by [73].

SCM generally increases the BWE by delaying their reaction to changes in customer demand and overcompensating to the resulting discrepancy. This is shown by the parameter value of the integral action in the pricing policy that is tuned so that the effect of long-term pricing is negligible in the total policy. Chapter 5 also shows that decreasing the integral gain of the controllers reduces the BWE. SCM should therefore take into account the pipeline behaviour of a supply chain and not overcompensate to past imbalances, as is also suggested by [73].

In the context of raw materials procurement, the integral action is closely related to shortage gaming. When suppliers ration their supplies for a prolonged period of time, customers tend to inflate their orders to receive what they desire [49]. Their orders only return to their actual demand when the supply imbalance is resolved. Shortage gaming is seen as one of the key sources of the BWE [14, 29, 31, 39] and should therefore be avoided.

The PID pricing policy resembles the every-day-low-pricing policy that is recommended by [5, 25, 47]. By keeping the prices close to the market equilibrium, the demand for finished products is kept at a steady level. The low fluctuations of finished product prices decrease the BWE significantly.

The PID procurement policy outputs volume setpoints that may violate general order batching procedures, in order to mitigate the BWE. The policy does not take into account specific fixed order costs that may lead to order batching. Instead, it outputs simply the volume that should be ordered to avoid the amplification of excess demand. The policy's output can be interpreted as advising against order batching, which is listed by [29] as one of the main causes of the BWE.

The production policy's output recommends to balance inventories as quickly as possible to keep the stock levels close to their desired level. By keeping the stock levels relatively constant, the reaction of the procurement and pricing department is decreased. These departments tend to overreact to near stock-outs or when stocks are completely full. By avoiding these scenarios, the amplification of excess demand oscillations is decreased. The improvement of a plant's inventory policy is also named by [2] as a solution to the BWE.

4-9 Discussion

The current PID control approach for finding SCM policies to mitigate the BWE is limited in a number of ways. This section lists the shortcomings of the current approach in its applicability to a real supply chain.

PID control does not take into account constraints

One of the downsides of using PID control as policy for SCM is that it can not take into account constraints on the system. Constraints on storage and production capacity dictate the planning of production. A plant can only produce a maximum (or even fixed) volume of products per period and cannot produce multiple different products on the same line at the same time. Procurement also suffers from similar constraints, such as the need to order a fixed amount like a full truckload at a time. The result of such constraints is order batching and batch process manufacturing. Chapter 7 recommends the use of Model Predictive Control (MPC) to include constraints in the controlled system and resolve this issue.

PID control does not minimize costs or maximize profits

While decreasing the BWE generally results in lower costs for SCM [5], the goal of implementing the PID policies is not to minimize costs or maximize profits itself. SCM aims to reduce systemwide costs [55], which may be the result of the BWE but do not necessarily have to be. PID control can only aim to optimize the flow in the supply chain and does not 'know' whether it maximizes the profits of the manufacturing plant. Decreasing order batching, as the PID policies' outputs recommend, increases the direct costs of procurement and by keeping the prices constant the opportunity to make extra profit is possible missed out. MPC is again recommended to maximize the profits of the manufacturing plant, which is described in Chapter 7.

A real supply chain structure is larger and more complex

The structure of a real supply chain is more complex than the 3-echelon serial structure of the model that is used in this chapter. Multiple products and materials are generally used in a manufacturing plant and there are usually multiple suppliers and customers per material and product, respectively. The serial supply chain model does not take these multidimensional effects into account. Furthermore, a supply chain may be much longer than 3 echelons, with each echelon amplifying their respective incoming demand signal. An increased number of suppliers, customers, echelons and types of goods will result in a higher dimensional system, more resonance frequencies of markets and production that may give rise to the BWE, more overall amplification of demand fluctuations and the need for more data or estimations to fit the model's parameter values. Chapter 5 presents a case study of a section of the Valtris Specialty Chemicals (VSC) supply chain that contains multiple products and materials and shows the BWE.

4-10 Conclusions

The PID control policies for raw materials procurement, production of finished products and finished products pricing together mitigate the BWE in the serial supply chain. Taking direct action on deviations from desired system states is most effective for decreasing the amplification of demand fluctuations. The policies' outputs recommend every-day-low-pricing and advise against order batching or batch manufacturing. Tuned controllers can directly be used by SCM as setpoints for their procurement, production and pricing processes to mitigate the BWE in the real supply chain.

Care should be taken with the direct implementation of the policies' outputs as PID control does not optimize for profits and does not take into account specific supply chain constraints. It is therefore advised to use the outputs as guidelines instead of exact prescriptions.

Chapter 5

Simulation Study: A Section of the Valtris Specialty Chemicals Supply Chain

5-1 Introduction

In this chapter I apply the systems and control framework developed in Chapters 3 and 4 to a section of the Valtris Specialty Chemicals (VSC) supply chain in order to find management policies that mitigate the Bullwhip Effect (BWE) in their supply chain. VSC experiences negative effects of the BWE at several locations in their supply chain and desires method to counteract the BWE. I model 2 finished products and the 3 materials that they are manufactured with, with their respective storage, production and markets, using PID controllers for procurement and production. The names of the products and materials will not be displayed due to confidentiality obligations, rather 'material 1' or 'product 1' is used as naming convention. The model shows the existence of the BWE after the model is tuned to VSC data. By adjusting the controllers' parameter values, a policy is obtained that mitigates the BWE in a section of the VSC supply chain.

The rest of this chapter is structured as follows. Section 5-2 provides background information on the section of the VSC supply chain that I apply the developed framework to. In Section 5-3 I design a model of this section of the supply chain using the building blocks introduced in Chapter 3, include PID control as proposed in Chapter 4 and tune the model and controller parameter values to VSC data. Section 5-4 shows how to adjust the controllers' parameter values to obtain a policy that mitigates the BWE and presents the results of the new policy on the controlled system. I conclude in Section 5-5 that PID control is effective at mitigating the BWE in a real supply chain.

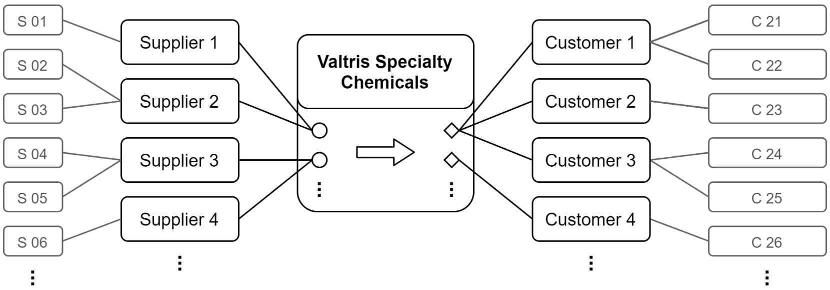


Figure 5-1: Schematic of the Valtris Specialty Chemicals supply chain, which consists of multiple echelons that each contain multiple supply chain members

5-2 The Valtris Specialty Chemicals Supply Chain

The VSC supply chain consists of multiple echelons with multiple supply chain members in each echelon. VSC manufactures esters, which are commodity goods used in the production of lubricants and plastics. Their raw materials consist mainly of alcohols and acids, although some additives and utilities are also required to manufacture the esters. As is the case in most supply chains, the VSC manufacturing plant obtains its raw materials from different suppliers and sells its products to different customers. These suppliers and customers are not the first supplier in the chain or the end customer, meaning that the supply chain that VSC is a member of is at least 5 echelons long. The fact that for each material there are multiple suppliers and for each product multiple customers means that the supply chain is not strictly serial, but rather a complex network. The structure of the VSC supply chain is illustrated in Figure 5-1.

Different products of the VSC plant are manufactured from the same set of materials. To produce an ester, an alcohol and an acid are required. The same alcohol can be mixed with different acids and vice versa to get different esters. As the production of an ester requires both the alcohol and acid in a fixed ratio, the stock-out of a specific acid may result in stopping the production of the ester it is used in and therefore also stopping the procurement of the alcohol for that ester. This means that the products and materials are connected through production and influence each other's procurement, production and pricing.

The management of the VSC manufacturing plant influences the behaviour of the supply chain through procurement, production and pricing. Supply Chain Management (SCM) carries out these management processes separately from each other, with different policies for each one. Every product and material is procured, produced and sold according to a separate policy. The management actions that result from the policies are based on measurements taken from several locations in the supply chain. These measurements include but are not limited to stock levels, prices, expected supply/demand and the costs of processes within the plant. The policies are often not a linear relationship between the measurements and the actions, but rather a non-linear, constrained, time-varying process that also partially depends on the professional opinion of the supply chain manager in question.

A section of the VSC supply chain in which the BWE exists is chosen as a case study. The case is limited to 3 materials and 2 products that VSC have used for a period that is sufficiently long that data is available to perform simulations with and tune the model to. In this period, the chosen section of the VSC supply chain shows signs of the BWE. Data of the weekly sales and orders volumes is taken for a period of 39 weeks and the variance ratio is calculated as in [4, 5]. Table 5-1 lists the variances of the supply and demand data and the ratio of variances for each pair. The existence of the BWE is indicated by variance ratios larger than 1 for a material-product pair.

Material-Product Pair	Variance Ratio
Product 1 - Material 1	$\frac{Var(\mathrm{rm}_1)}{Var(\mathrm{fp}_1)} = \frac{1558.2}{687.5} = 2.27$
Product 1 - Material 2	$\frac{Var(\mathrm{rm}_2)}{Var(\mathrm{fp}_1)} = \frac{614.6}{687.5} = 0.89$
Product 2 - Material 2	$\frac{Var(\mathrm{rm}_2)}{Var(\mathrm{fp}_2)} = \frac{614.6}{157.5} = 3.90$
Product 2 - Material 3	$\frac{Var(\mathrm{rm}_3)}{Var(\mathrm{fp}_2)} = \frac{191.9}{157.5} = 1.22$

Table 5-1: The variance ratios larger than 1 indicate the existence of the Bullwhip Effect in the section of the Valtris Specialty Chemicals supply chain

The variance ratios with material 2 are less relevant for the purpose of detecting the BWE. Material 2 is used for both the products in this case study and for a few other products that are outside of the scope of this case study. The calculation of the aggregated BWE would require the use of data outside of this scope [14]. The variance ratios for materials 1 and 3 are relevant and accurate as these materials are used solely in the production of products 1 and 2, respectively.

The variance ratio for the pairs with the materials 1 and 3 are both larger than 1, indicating the existence of the BWE. The weight ratio used for production is not accounted for in these variance ratios. As this weight ratio is smaller than 1, the variance ratio will be even larger when the supply volume variance is compensated with this weight ratio.

5-3 Model and Controllers of a Section of the Valtris Specialty Chemicals Supply Chain

In this section I design a model and controllers for the chosen section of the VSC supply chain with its SCM. The model structure is obtained by connecting several of the building blocks from Chapter 3 and replacing the finished products markets with excess customer demand inputs. The supply side is cut off at the production of the suppliers, meaning that constant production volumes are assumed for these suppliers. Furthermore, each material is supplied by a single supplier. I add SCM as PID controllers of procurement and production, similar to the approach taken in Chapter 4. I tune the parameter values of the model and controller elements to VSC data so that the supply volumes, stock levels, production volumes and raw material prices display behaviour that matches the behaviour of the VSC supply chain.

5-3-1 Structure of the Model and Controllers

The model and PID controllers are constructed from the building block designed in Chapter 3 and the PID control presented in Chapter 4. The model represents the section of the VSC supply chain mentioned in Section 5-2. The PID controllers are used as raw materials procurement and production planning policies for each material and product. Figure 5-2 shows

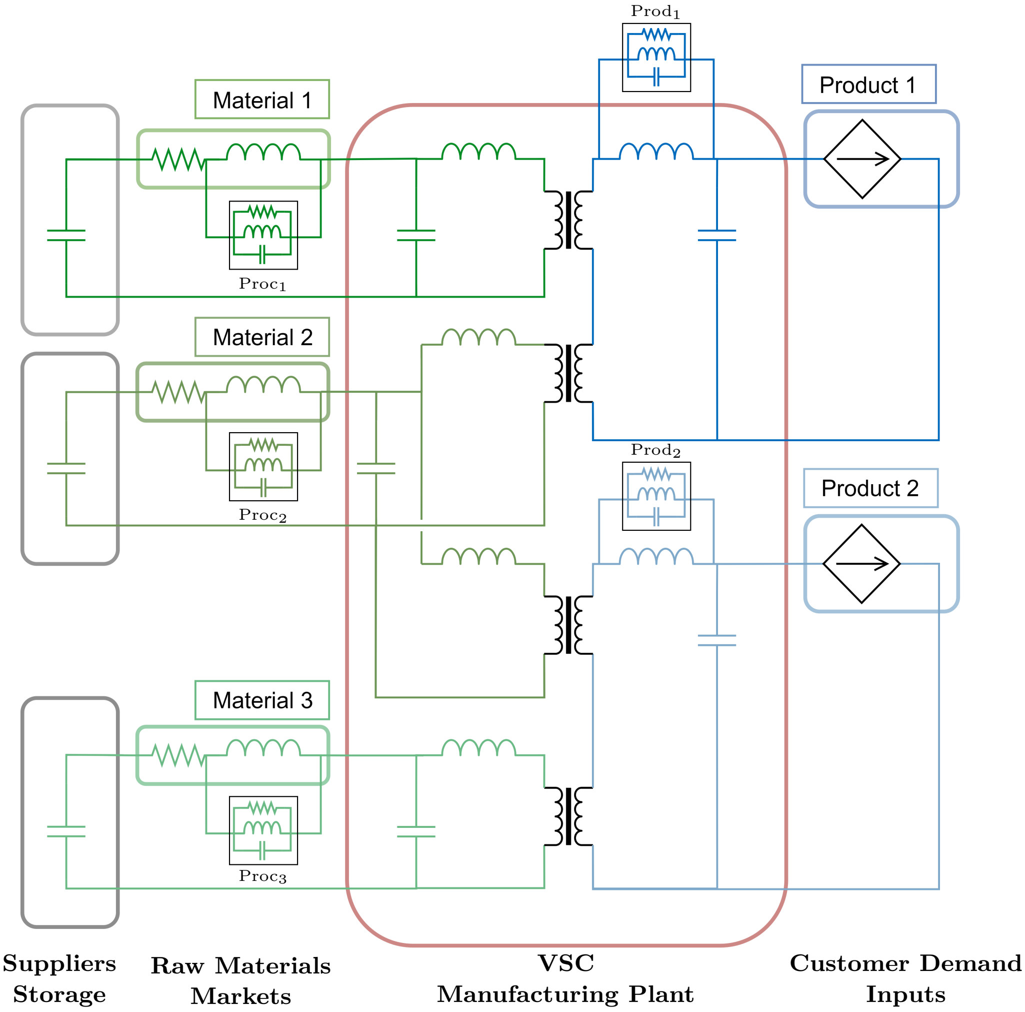


Figure 5-2: The electrical circuit of a section of the Valtris Specialty Chemicals supply chain with PID control as Supply Chain Management. The state-space representation is given in Appendix E together with the parameter values for the model and the controllers

the model and controllers, of which the state-space representation and parameter values are given in Appendix E.

The parts of the model that concern raw materials are colored green, while those of the finished products are colored blue. The controllers are surrounded by black rectangular frames and labeled 'Proc' or 'Prod', for procurement and production respectively, with a number corresponding to the material or product they belong to. The structure of these controllers is as shown in Chapter 4. The state-space representation for this model is given in continuous-time form in Appendix E and is discretized for simulation purposes using the zero-order hold method.

5-3-2 Tuning the Parameter Values

I tune the parameters of the discretized model and controllers so that the controlled system represents the chosen section of the VSC supply chain. The model and controllers are discretized using the zero-order-hold method. Weekly data of sales (demand), orders (supply), stock levels, production volumes and prices for a period of 39 weeks is used to tune the parameters. The sales data is used as input, while the other data is used as reference for the outputs of the controlled system. The data is detrended by subtracting the mean from it [67]. The parameter values of production can be set directly with the weight ratios of raw materials required for the production of a finished product, which can be read from the Bill of Materials (BOM). The other parameters are tuned manually, following the steps from Chapter 3, adjusting the controllers' parameter values simultaneously. I stop tuning the parameters when the outputs show behaviour that resembles the behaviour observed in the data of VSC. The resemblance is sought in the frequency-domain behaviour of the supply chain, as that is where the BWE is best quantified. This means that I try to match the amplitudes and cycle frequencies of the model outputs with those observed in the data. The outputs of the tuned model and controllers are shown alongside the VSC data in Figure 5-3 and Figure 5-4.

The model and controller parameters are tuned manually instead of performing system-identification for several reasons that are related to specific modeling choices.

- The PID control policy for procurement and production differs significantly from the type of policy implemented in the VSC supply chain in the period the data was taken from. The week-to-week behaviour of the model therefore does not match the week-to-week behaviour of the section of the VSC supply chain studied in this case.
- The number of data points available for identification is small, relative to the number of parameters to fit. A period of 39 weeks is chosen specifically, for in that period no significant changes were made to the local structure of the VSC supply chain. In the time before this 39 week period, new products were introduced, manufacturing lines were changed and new suppliers were acquired. Such changes can not be modeled with the LTI system that I designed. A rule of thumb is that the duration of an identification period should be 10 times longer than the longest time-constant of the system [67]. This would imply that data of several years is required for proper system identification, which is not available. Another result of the low amount of available data is that no separate validation dataset is constructed to validate the tuned model and controllers with. The behaviour of the system is therefore validated with the same data that it is tuned to.
- Part of the behaviour of the supply chain is omitted from the model by modeling only a section of the supply chain. The material 2 is for instance also used in the production of other products, besides the ones modeled in this thesis, meaning that its stock level does not exclusively depend on the dynamics of the two products modeled in this thesis. System identification would require an additional disturbance input or modeling the other products to take these influences into account.

The goal of tuning manually is to get close to the real supply chain's behaviour so that the BWE can be quantified and later mitigated for this section of the supply chain. The week-to-week behaviour of the controlled system will be different from that of the real supply chain, but the cycles in supply and production should be of similar amplitude and frequency.

The outputs of the controlled system for the real VSC sales input scenario are shown in Figures 5-3 and 5-4. The behaviour that can be observed in the plots is similar to that of the VSC data, although there are differences.

- The supply volumes of material 1 and material 3 match the amplitude and cycle frequency of the reference supply data relatively well. The amplitude for the first few weeks does not fluctuate as much due to the initial value setting of the simulation. After a few weeks, the fluctuations start reaching amplitudes similar to that of the real supply. The supply of material 2 is however slightly more constant than what the data shows, which is due to some products not being modeled that also use material 2 in their production process.

- The production volume and supply volume both show smoother behaviour in the model outputs than in the VSC data. While the real supply and production volumes often alternate between 0 and a fixed multiple of certain standard order or production batch, the model output does not show such behaviour. This is due to the constraints on the real supply chain inherent to ordering in fixed truckloads or producing in fixed batch sizes, which are not taken into account in the controlled system.

- The production in simulation reacts quickly to changes in the finished product stock level. In a real manufacturing plant, batch-production is often planned to stick to a fixed schedule that is designed to be able to cope with customer demand [55]. The PID policy that I developed in this thesis recommends production volumes that move more flexibly with customer demand than such a rigid schedule. The result is that the finished product stock levels in simulation show much smaller changes than those in reality. The raw material stock levels display similar, smooth behaviour.

- The raw material prices display a rising trend in the VSC data, which is not simulated in the controlled system. The influences that act on the raw materials price in the simulation are limited to the stock levels of the manufacturing plant and the supplier and to the excess supply in the raw materials market. In real supply chains the prices are also subject to, i.e., inflation, changes in the suppliers' competition, negotiations, expectations of upstream or downstream changes in supply or demand, suppliers' costs of production. Such additional effects are not taken into account in the controlled system approach.

The variances ratios for the product 1 - material 1 and product 2 - material 3 pairs in simulation show similar values to the variance ratios calculated from the VSC data. The fluctuations of the supply volumes are similar in amplitude and frequency, which is also reflected in the variance of these volumes. The material 2 variance in simulation is significantly different from that in the VSC due to the causes listed in the bullet list above. The ratios are listed in Table 5-2.

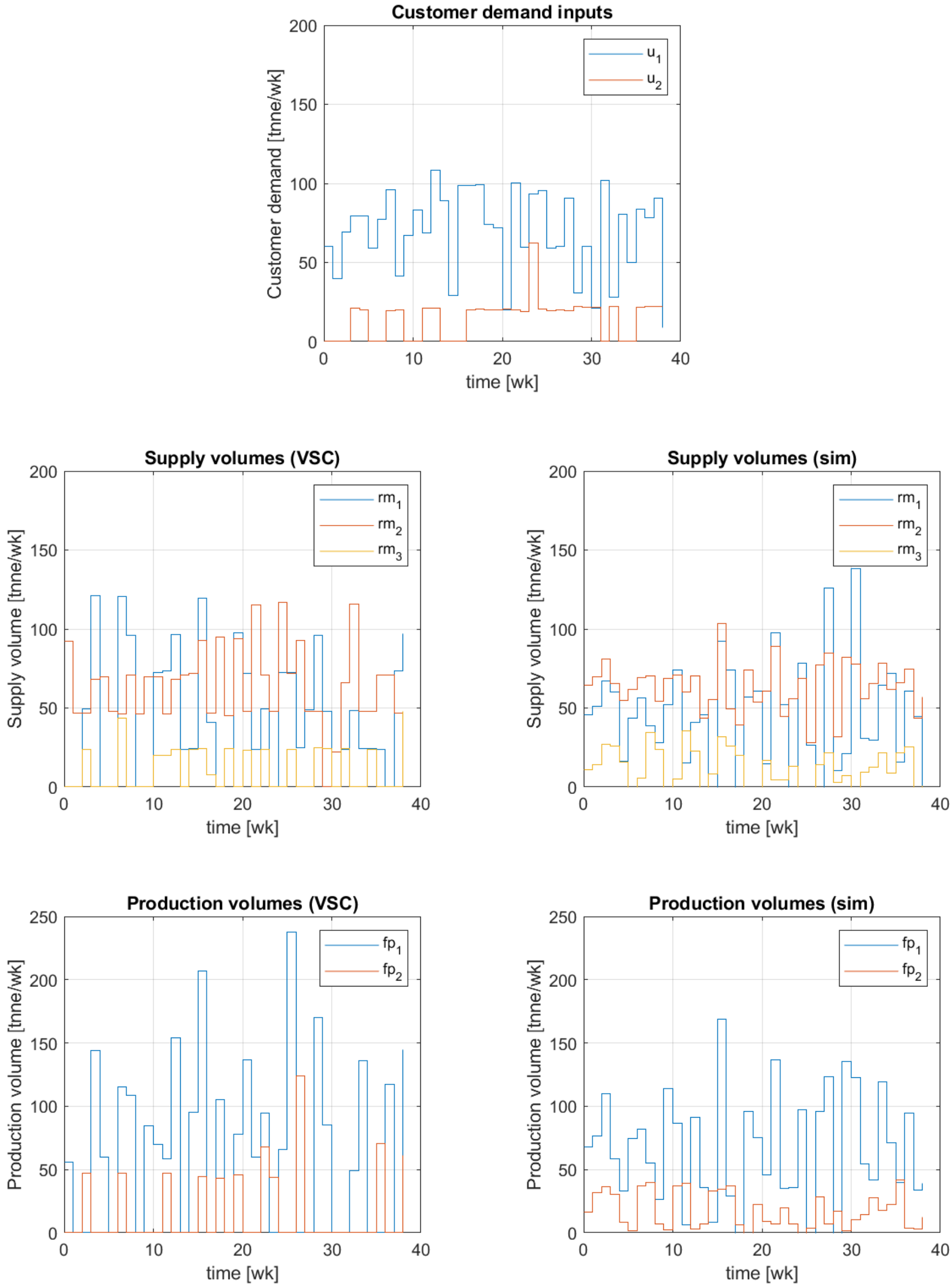


Figure 5-3: The model of the controlled section of the Valtris Specialty Chemicals supply chain is tuned so that its measured outputs from simulation (middle and bottom right) match the frequency behaviour observed in Valtris Specialty Chemicals data (middle and bottom left). Top to bottom: demand input, supply and production volumes. The indications 'u', 'rm' and 'fp' refer to the input, raw materials and finished products, respectively

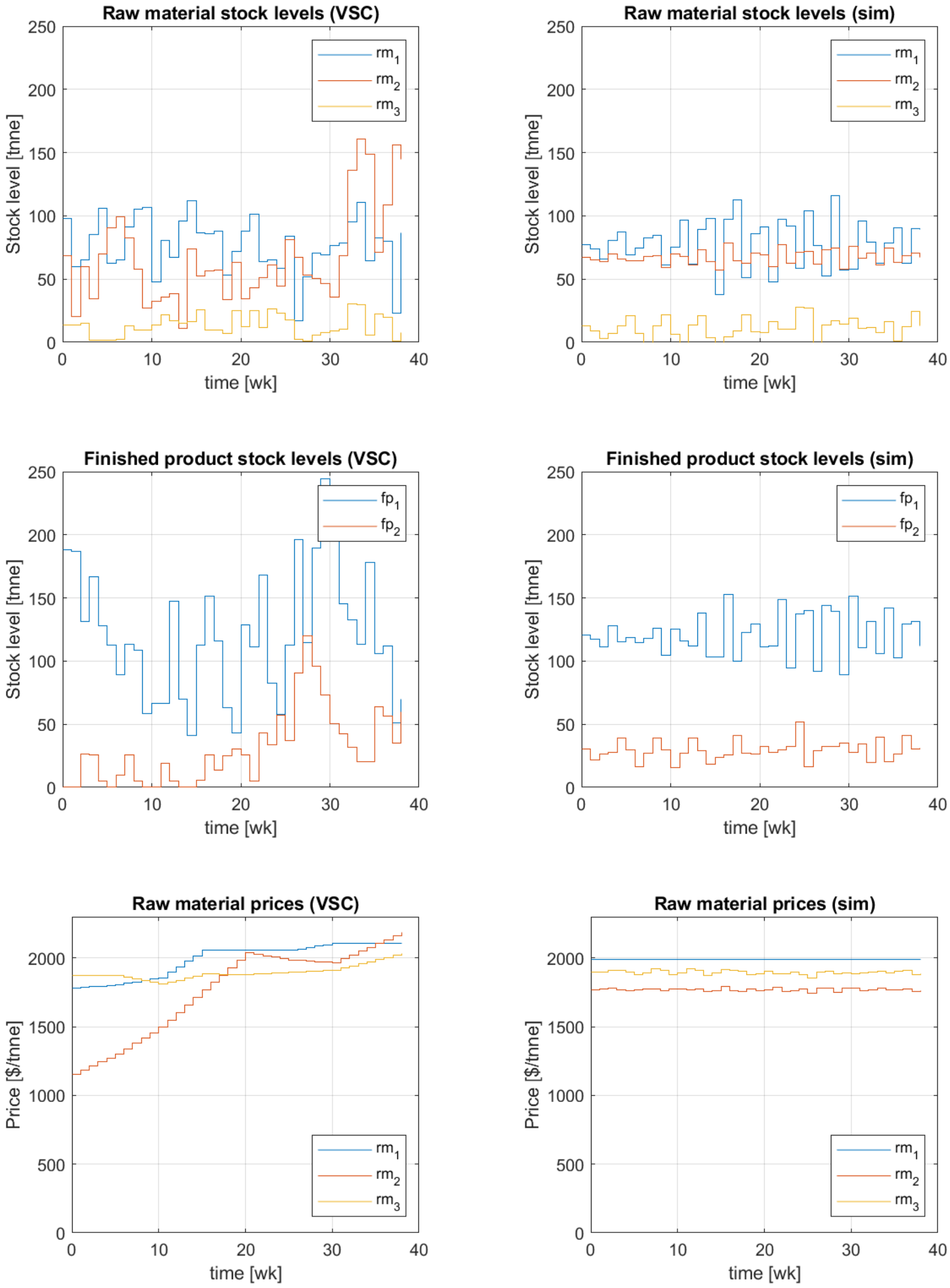


Figure 5-4: The model of the controlled section of the Valtris Specialty Chemicals supply chain is tuned so that measured outputs from simulation (middle and bottom right) match the frequency behaviour observed in Valtris Specialty Chemicals data (middle and bottom left). Top to bottom: raw materials stock levels, finished product stock levels, raw material prices. The indications 'rm' and 'fp' refer to raw materials and finished products, respectively

Material-Product Pair	Variance Ratio
Product 1 - Material 1	$\frac{Var(\mathrm{rm}_1)}{Var(\mathrm{fp}_1)} = \frac{1401.1}{687.5} = 2.04$
Product 1 - Material 2	$\frac{Var(\mathrm{rm}_2)}{Var(\mathrm{fp}_1)} = \frac{241.6}{687.5} = 0.35$
Product 2 - Material 2	$\frac{Var(\mathrm{rm}_2)}{Var(\mathrm{fp}_2)} = \frac{241.6}{157.5} = 1.53$
Product 2 - Material 3	$\frac{Var(\mathrm{rm}_3)}{Var(\mathrm{fp}_2)} = \frac{187.4}{157.5} = 1.19$

Table 5-2: The variance ratios calculated from the simulation outputs

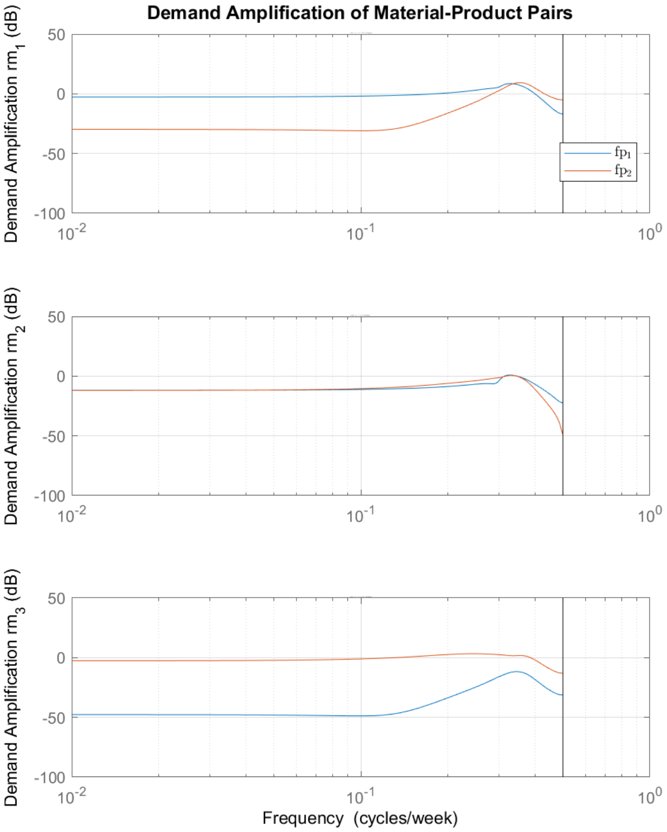


Figure 5-5: The magnitude plots of a Bode diagram for the section of the Valtris Specialty Chemicals supply chain quantify the Bullwhip Effect. The transfer functions are from customer demand to supply volumes. The frequency ranges with gain larger than 0 dB indicate the existence of the Bullwhip Effect

The amplification of customer demand fluctuations to supplier volumes oscillations for the relevant frequency range is observed in the magnitude plot of a Bode diagram. The transfer functions in this Bode diagram are from the customer demand volumes to the supply volumes for each material-product pair in question. Figure 5-5 shows peaks in the magnitude plot that reach values higher than 0 dB in the frequency range of $0.2 - 0.4$ cycles per week, or rather a cycle time of $2.5 - 5$ weeks. This implies that the section of the VSC supply chain displays the BWE in this range. The supply of material 1 shows the largest BWE. The BWE for the material 1 - product 2 pair is also relatively large, even though the material and product are not directly connected through production. The magnitude of the material 3 - product 1 frequency response on the other hand is much lower, as is expected due to the disconnection within the manufacturing plant. Material 2 displays little to no BWE for the entire relevant frequency range, although that increases when the supply is compensated for the weight ratio of materials required in the production of the finished product.

The controlled system is valid for the purpose of this thesis, as the supply volumes in simulation display behaviour that is very similar to that of the supply volumes in the VSC data. The fluctuations have similar amplitude and frequency in simulation and in the data. The variance ratios of the significant material-product pairs differ only slightly. Furthermore, the magnitude plots of a Bode diagram show the BWE for the material-product pairs that had variance ratios larger than 1 in the VSC data. This controlled system is therefore used in Section 5-4 to find a PID policy that mitigates the BWE.

5-4 Mitigating the Bullwhip Effect by Adjusting the PID Control Policies

This section explains how the parameter values of the PID controllers are adjusted so that the BWE is mitigated. The results of the newly obtained policies are then discussed.

5-4-1 Adjusting the Controllers' Parameter Values

The parameter values of the PID controllers are tuned to obtain policies for procurement and production that counteract the BWE. The PID controllers that were tuned to VSC data in Section 5-3 are adjusted, while keeping the parameters of the model the same. The changes made to the controllers' parameter values consist of increasing the proportional gain and decreasing the integral gain, while keeping the derivative gain negligibly low. The controller parameter values that were found to cause the lowest fluctuations were those that resulted effectively in PI controllers that each had an almost equal share of P and I action in terms of supply or production volume. The parameter values of the derivative elements were kept negligibly small, keeping the controllers as PI policies instead of PID policies. The parameter values of the new controllers are listed in Table 5-3 alongside the parameter values of the initial policy.

The adjusted controllers' parameter values imply changes in the policies of SCM for procurement and production. The increased proportional gain means that management should act more directly on imbalances in stock levels and on price changes in the raw materials market. More direct action would reduce lead times throughout the supply chain, reducing the BWE according to [6, 36, 73]. The decreased integral gain means that SCM should not overcompensate past imbalances in determining their procurement and production volumes. In practice, the procurement and production are often delayed because of batch-process manufacturing constraints or fixed-truckload procurement preferences [55]. This delay translates to more integral action in the PID policy. The supply chain benefits from more frequent and constant supply and production to decrease the BWE. [2] and [29] propose splitting up orders and

Parameter	Initial Parameter Value	Adjusted Parameter Value
$k_{P,proc1}$	1.7	8.3
$k_{I,proc1}$	$1.3 \cdot 10^{2}$	10
$k_{D,proc1}$	$1.0 \cdot 10^{-10}$	$1.0 \cdot 10^{-10}$
$k_{P,proc2}$	$1.7 \cdot 10^{-6}$	0.55
$k_{I,proc2}$	1.0	0.50
$k_{D,proc2}$	$1.0 \cdot 10^{-10}$	$1.0 \cdot 10^{-10}$
$k_{P,proc3}$	$1.7 \cdot 10^{-4}$	0.33
$k_{I,proc3}$	0.50	0.25
$k_{D,proc3}$	$1.0 \cdot 10^{-10}$	$1.0 \cdot 10^{-10}$
$k_{P,prod1}$	0.017	1.7
$k_{I,prod1}$	50	5.0
$k_{D,prod1}$	$1.0 \cdot 10^{-10}$	$1.0 \cdot 10^{-10}$
$k_{P,prod2}$	0.0083	0.083
$k_{I,prod2}$	0.45	0.25
$k_{D,prod2}$	$1.0 \cdot 10^{-10}$	$1.0 \cdot 10^{-10}$

Table 5-3: Parameter values of the initial and adjusted PID control policies

production batches instead of ordering and producing in large batches. Keeping the derivative action negligibly low implies not taking into account forecasted system states. This is an expected result as demand forecasting is seen as one of the main causes of the BWE [12, 29, 60]. Instead of forecasts, information from downstream or upstream supply chain members should be used, obtained by integrating information flow throughout the supply chain [34, 39, 42]. The interpretability of the controller elements enables direct implementation of the policy on a real supply chain by each member of SCM.

5-4-2 Results

The results of the adjusted controllers are shown in three steps and compared to the results with the initial PID policies from Section 5-3. First, the simulation with real customer demand data as inputs from Section 5-3 is carried out again to show the differences in system outputs. Second, the variance ratios are calculated from the outputs of the simulation and compared to the variance ratios of the outputs in the initial policy simulation. Finally, the Bode diagrams for the transfer functions from customer demand to supply volumes for all material-product pairs are used to display the comparison between the initial and the adjusted policies in terms of the BWE.

Real VSC sales data is used as inputs to the controlled system, like in Section 5-3. The simulation outputs with the new policy are compared to the outputs of the original simulation. Figures 5-6 and 5-7 show the outputs of both simulations alongside each other for comparison.

The largest difference in amplitude of oscillations is observed for the raw materials supply. The supply of raw material 1 is improved most and shows both smaller fluctuations and slower supply cycle frequencies compared to the supply volumes with the initial policy. The production volumes with the new policy display a slightly slower cycle for both products. This slower cycle results in lower frequency stock level changes for all materials and products.

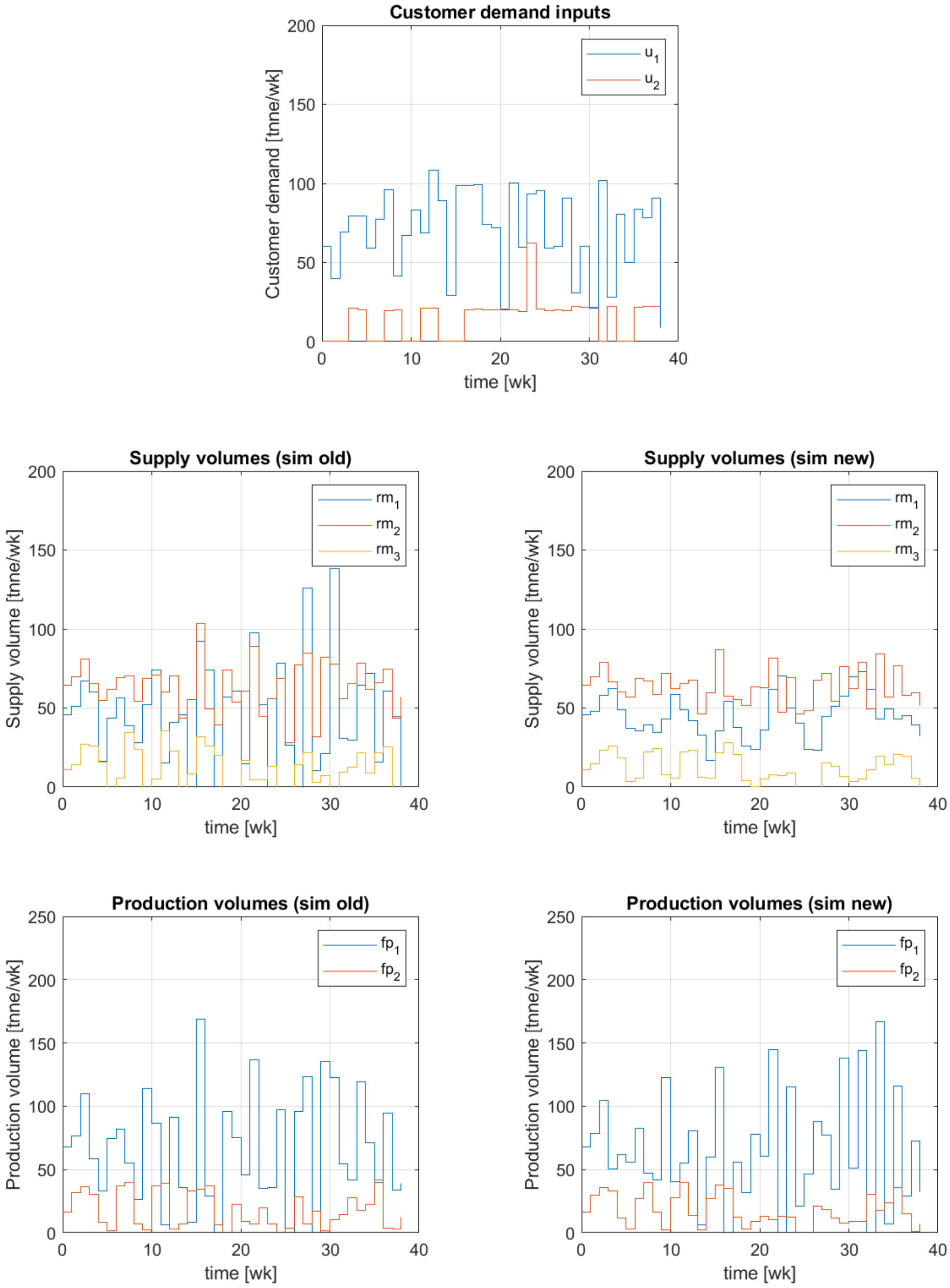


Figure 5-6: A comparison between simulation outputs of the model with the initial policies (middle and bottom left) and with the adjusted policies (middle and bottom right) illustrate the effect of adjusting the policies. The adjusted controller parameters result in lower fluctuations throughout the supply chain. Top to bottom: input demand, supply volumes and production volumes. The indications 'rm' and 'fp' refer to raw materials and finished products, respectively

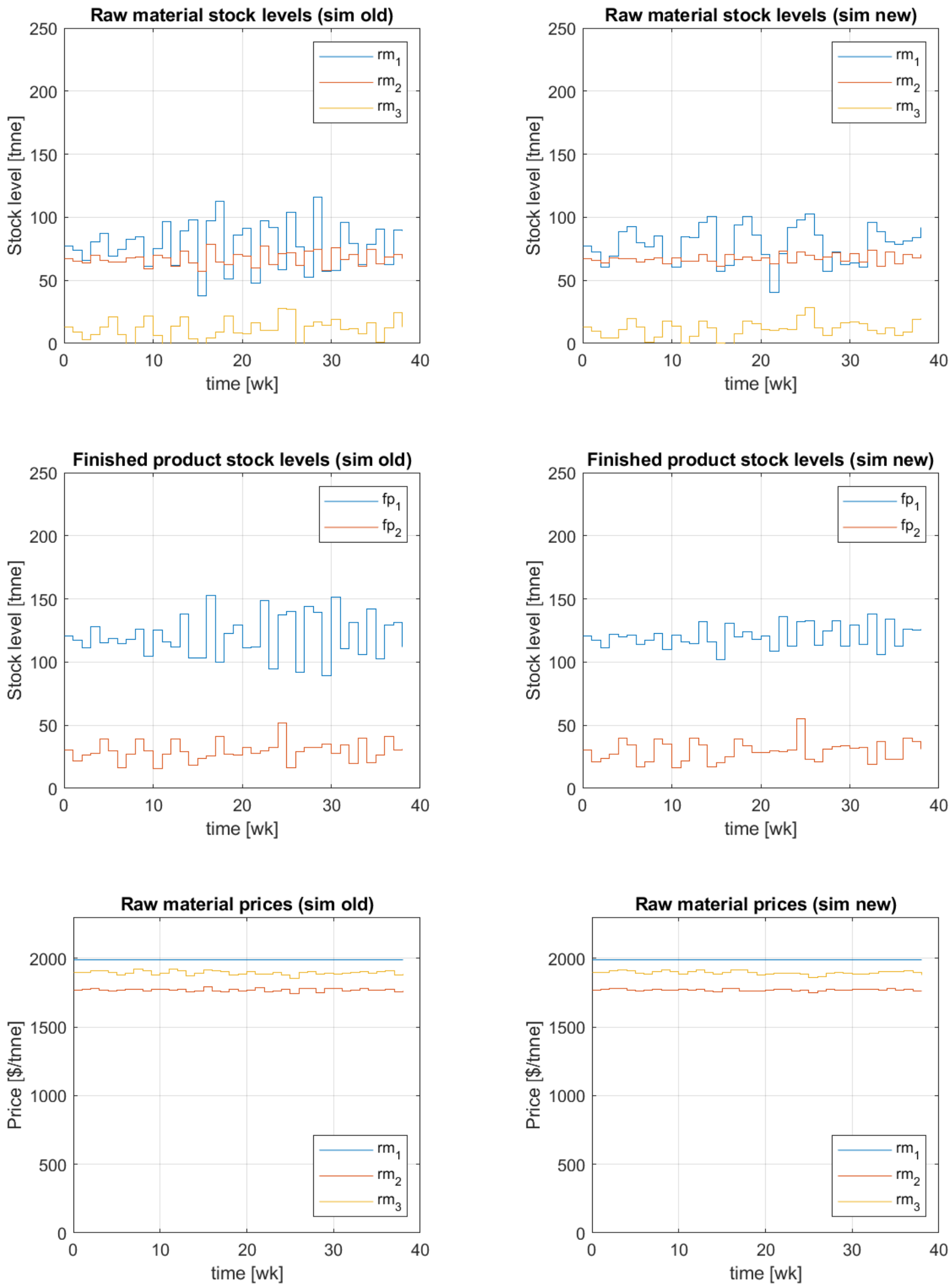


Figure 5-7: A comparison between simulation outputs of the model with the initial policies (middle and bottom left) and with the adjusted policies (middle and bottom right) illustrate the effect of adjusting the policies. The adjusted controller parameters result in lower fluctuations throughout the supply chain. Top to bottom: raw materials stock levels, finished product stock levels, raw material prices. The indications 'rm' and 'fp' refer to raw materials and finished products, respectively

The prices for raw materials display similar behaviour, although the difference is small when the prices are plotted on an absolute scale. The decrease in oscillations of supply volumes, without noticeable negative effects in the other outputs, is proof of the improvements of the adjusted policies in terms of mitigating the BWE.

The change in BWE is quantified by comparing the variance ratios of the outputs of the simulations with the initial policies and with the new policies. Table 5-4 lists the variance ratios of the material-product pairs for both simulations. The variance ratios for all material-product pairs are decreased to below the threshold of 1, meaning that the BWE is avoided in this section of the supply chain at the specific demand cycle that was simulated.

Material-Product Pair	Variance Ratio (initial policies)	Variance Ratio (new policies)
Product 1 - Material 1	$\frac{Var(\mathrm{rm}_1)}{Var(\mathrm{fp}_1)} = \frac{1401.1}{687.5} = 2.04$	$\frac{Var(\mathrm{rm}_1)}{Var(\mathrm{fp}_1)} = \frac{185.1}{687.5} = 0.27$
Product 1 - Material 2	$\frac{Var(\mathrm{rm}_2)}{Var(\mathrm{fp}_1)} = \frac{241.6}{687.5} = 0.35$	$\frac{Var(\mathrm{rm}_2)}{Var(\mathrm{fp}_1)} = \frac{113.4}{687.5} = 0.16$
Product 2 - Material 2	$\frac{Var(\mathrm{rm}_2)}{Var(\mathrm{fp}_2)} = \frac{241.6}{157.5} = 1.53$	$\frac{Var(\mathrm{rm}_2)}{Var(\mathrm{fp}_2)} = \frac{113.4}{157.5} = 0.72$
Product 2 - Material 3	$\frac{Var(\mathrm{rm}_3)}{Var(\mathrm{fp}_2)} = \frac{187.4}{157.5} = 1.19$	$\frac{Var(\mathrm{rm}_3)}{Var(\mathrm{fp}_2)} = \frac{95.9}{157.5} = 0.61$

Table 5-4: The variance ratios for the simulation with adjusted policies compared to the ratios for the simulation with the initial policies

A comparison is made in terms of the magnitude of the BWE with the use of Bode diagrams. Figure 5-8 shows the magnitude plots of the transfer function from customer demand to supply volumes. The magnitude plots for the system with new policies (dashed lines) show lower peaks, moved to lower frequencies than for the system with the initial policies (solid lines). The peaks are not below the 0 dB line for all frequencies, meaning that the BWE is not completely eradicated from the supply chain. However, the effect of the BWE is only noticeable for customer demand with a cycle time of about 10 weeks and is significantly lower than the BWE with the initial policies. The new policies are effective at mitigating the BWE for the largest part of the relevant frequency range.

5-5 Conclusions

The application of the systems and control framework to the VSC supply chain results in SCM policies that are effective at mitigating the BWE. The economic engineering model of the section of the supply chain together with the PID controllers produce outputs that match the behaviour observed in VSC data, after initial tuning of the parameter values. The PID control policies for raw materials procurement and production of finished products mitigate the BWE in a section of the VSC supply chain after adjusting the parameter values of the controllers, specifically. Increasing the proportional gain and decreasing the integral gain of the controllers, keeping the derivative gain negligibly small, is most effective for counteracting the BWE. The managerial implications of the controller parameter adjustments match solutions that have been proposed in literature. SCM should reduce order batching and manufacture in smaller batches, while reducing time delays throughout the supply chain and refraining from basing procurement and production on forecasted data. The new policies can be implemented directly in the real supply chain by members of SCM to mitigate the BWE in real life.

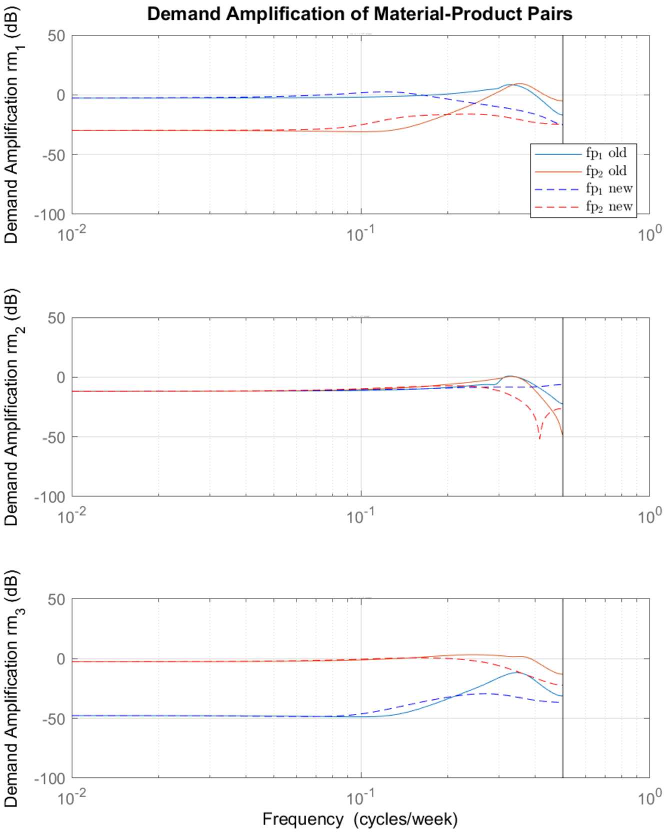


Figure 5-8: A comparison is made between the frequency responses of the supply chain with the initial policies (solid lines) and with the adjusted policies (dashed lines) using the magnitude plots of Bode diagrams. The supply chain with the new policies has lower peaks at resonance frequencies than the supply chain with the initial policy, indicating a decreased Bullwhip Effect. The transfer functions are from customer demand to supply volumes. The indications 'rm' and 'fp' refer to raw material and finished product, respectively

Chapter 6

Conclusions

The framework developed in this thesis provides Supply Chain Management (SCM) with a method to analyze the effects of dynamic supply chain disruptions on the flow of goods and to design policies that counteract these disruptions. The PID control policies developed in this thesis mitigate the Bullwhip Effect (BWE) in a supply chain through control of raw materials procurement, production planning and finished product pricing. The modular economic engineering modeling method enables SCM to easily construct a model of their supply chain. The inclusion of price dynamics makes it possible to analyze the reciprocal effect of fluctuating prices on the BWE. Bode diagrams quantify the BWE and the Reversed Bullwhip Effect in Pricing (RBP) and provide direct insight into the existence of resonance frequencies in the supply chain. The RBP and BWE amplify each others' effect at these resonance frequencies and are mitigated jointly by the PID control policies to a level where they are of negligible influence on the supply chain. The interpretability of the policies and the close match with a manager's behaviour allow SCM to directly apply the policies to their own supply chain.

Further development of the systems and control framework is required to provide a closer match with real supply chains. Currently, only simple supply chain structures have been used to demonstrate the method proposed in this thesis, while real supply chains are more complex. Real SCM policies are also more complex, often focusing on costs and profits besides optimizing the flow through a supply chain, while ensuring that constraints are met. However, the framework already provides managerial insight for mitigating the BWE that confirms solutions proposed in literature:

- Increase of proportional action implies more immediate action on current imbalances in stocks, demand and supply. This reduces time delays throughout the supply chain, decreasing imbalances in stock levels. Ordering and manufacturing in large batches is counterproductive, resulting in incorrect representations of actual supply and demand and thus leading to incorrect forecasts.
- Decrease of integral action for procurement and production implies less overcompensation of past imbalances in stock levels. Inflation of orders in the case of shortage gaming leads to incorrect representation of demand.

- Negligibly low derivative action implies no anticipation by SCM to changes in supply, demand and stock levels in the determination of procurement and production volumes.
- The pricing policy output implies prices to be kept as constant as possible to avoid excessive changes in customer demand. Every-Day-Low-Pricing (EDLP) is recommended as a method of keeping both prices and demand from fluctuating.

The development of the interpretable PID control method as management policy for procurement, production and pricing contributes to the solutions currently available to SCM for mitigating the BWE. The PID policies can be tuned offline with the use of the economic engineering supply chain model and applied directly to the appropriate management processes in the supply chain. The quantitative and dynamic nature of the proposed solution gives it a distinctive advantage over current qualitative or static solutions listed in literature.

This thesis also contributes to the frequency-domain methods available to SCM for analyzing their supply chain's characteristics. While the magnitude plot of a Bode diagram has been leveraged before to illustrate the amplification of demand fluctuations, the interpretation of the phase plot as measure of relative lead time provides additional managerial insight. The application of the Bode diagram to supply chains is further extended to the quantification of the RBP, enabled by the inclusion of price dynamics in the economic engineering supply chain model.

Chapter 7

Recommendations

This chapter presents opportunities for future work following from the research into Supply Chain Management (SCM) and the Bullwhip Effect (BWE) that this thesis started. The recommendations are threefold. Section 7-1 discusses the possibilities for extending the supply chain model. The recommendations in Section 7-2 concern alternative control methods as representations of SCM policies that either serve other purposes or aim to reach the same goal of mitigating the BWE through different means. All recommendations provided in the following sections aid in the development of a more complete economic engineering toolkit for SCM to achieve their goals.

7-1 Supply Chain Model Extensions

The supply chain model designed in Chapter 3 is based on the core functionality of a supply chain and can be extended in order to better fit a real supply chain. Many extensions are possible, of which this section names a few.

Multiple Suppliers and Customers

The interaction between suppliers and customers resulting from a supply chain network with parallel supply chain members can not be simulated with a serial supply chain [43]. A supply chain member commonly receives a material from multiple suppliers to spread risk and sells a product to multiple customers. The total demand for a product then consists of the combined demand from the customers, that may each order at different rates and frequencies. Extending the model to a network supply chain brings this research one step closer to modeling the dynamics of a real supply chain.

Ouyang and Li [43] provide analytical BWE measures for a network supply chain structure, but without the inclusion of prices. The economic engineering modeling method would extend their research by enabling the analysis of the reciprocal effect of fluctuating prices on the BWE.

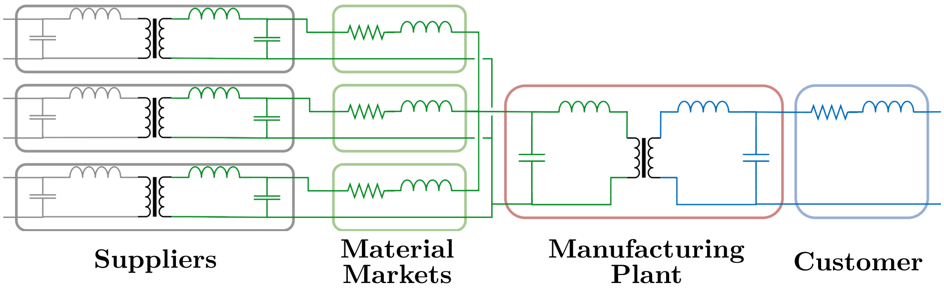


Figure 7-1: Multiple suppliers for a single material can be modeled by extending the raw material markets

A concept for modeling multiple suppliers for a single raw material as an extension of the serial supply chain model designed in Chapter 3 is illustrated in Figure 7-1. Each supplier is connected to the manufacturing plant in question via a market. The suppliers in parallel are now competition as they are supplying the same product to the same plant. The structure of this market is the same as that presented in Chapter 3. Control as representation of procurement can therefore be applied to each market separately to determine the raw materials volume to be ordered. The same concept can be applied to the case of multiple customers, on the other side of the manufacturing plant.

Distribution Centers as Supply Chain Members

The supply chain model presented in this thesis currently consists of only manufacturing plants, but a real supply chain may contain one or more distribution centers as well. A distribution center is defined as a location used to store inventory, typically designed for rapid distribution to customers [49]. The distribution center structure consists of storage, with procurement and pricing as major SCM influences. Meegdes [37] models a distribution center in his thesis work as a storage element alone. However, the inclusion of management influences can not be left out in modeling supply chains. The distribution center is connected to markets on either side similar to the manufacturing plant in Chapter 3. The center can therefore easily be included in a supply chain model by connecting it to one of the markets in the supply chain. A concept of the model of a distribution center with markets on the receiving and outgoing sides is illustrated in Figure 7-2.

It would be valuable for BWE research to quantify the influence of distribution centers on the BWE when price dynamics are taken into account.

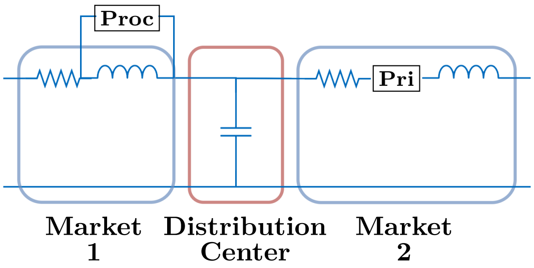


Figure 7-2: The electrical circuit concept of a distribution center with procurement and pricing

Nonlinearities in the Supply Chain

The current supply chain model assumes linearity for all elements the model is constructed of, even though real supply chain behaviour is nonlinear. The following nonlinearities can be considered for inclusion in supply chain models in future research.

- Excess supply or demand functions (or price-response functions) come in various (nonlinear) forms and are chosen for modeling based on the market they ought to represent. Simon and Fassnacht [56] name various price-response functions that are commonly used in economic modeling practices. The linear function is most widely used, but is limited in its match with observed real world economic behaviour.
- Storage and convenience are nonlinear in real supply chains due to the inherent capacity constraints. Risks of stock-outs and overfull inventories cause convenience of holding inventory to change nonlinearly near the limits of storage. Near stock-outs result in disproportionally high inconvenience, for instance. The supply chain model with nonlinear storage elements will behave as though soft constraints are imposed on the inventories.
- Specific delays are present throughout the entire supply chain, that might be a major cause of the BWE [29]. Transport lead times for supply and production lead times in the manufacturing process cause inventory discrepancies when supply is purely reactive to customer demand. Such discrepancies may lead to overcompensation from SCM and in turn cause amplification of demand fluctuations. The delays vary from a few hours to multiple weeks and become more significant to the system's behaviour as the sampling time of the model is decreased. If the sampling time is decreased in future research, the addition of fixed time delays should be considered for production and procurement.
- The supply chain is modeled in a deterministic manner in this research, while the stochastic evolution of a supply chain is an important modeling aspect [48]. Previous BWE modeling efforts have included stochasticity in lead times [26, 40] and demand [8, 75]. The addition of parameter and input uncertainty would bring the modeling and control method closer to reality.

7-2 Controller Types for Supply Chain Management

The PID control method is effective at mitigating the BWE and provides interpretable management policies. However, alternative control methods with different characteristics can be developed using the dynamic supply chain model. Some control methods are also suitable for mitigating the BWE, while others are better suited for another economic purpose.

7-2-1 Model Predictive Control

Model Predictive Control (MPC) is a versatile control method that has been applied in economic engineering research and BWE research to achieve various goals. As the objective function of the MPC can be specified as desired, the approach lends itself well for fulfilling any objective that can be expressed mathematically. Within the economic engineering research, MPC has been used in various fields. Slits [58] develops a MPC that maximizes the profits of a trader in the energy market. Meegdes [37] also presents a profit-maximizing MPC that controls scheduling of incoming and outgoing goods of a warehouse in the Shell supply chain. Orie [41] proposes the use of MPC for price adjustment in the global crude oil market. In BWE research, the MPC control method is not used often yet. Fu et al. [15] develop MPC to decrease the BWE in a 4-echelon serial supply chain. The research into SCM presented in this thesis provides another opportunity for the application of MPC.

The MPC may represent SCM that aims to maximize the profits of a manufacturing plant through procurement, production and pricing. The objective function of the MPC is specified as the maximization of the sum of profits (Π) until a time horizon (N). The maximization is subject to constraints such as the dynamics of the supply chain, the capacities of storage and production. The formulation of the MPC problem would be as follows.

$$
\begin{aligned}
\Pi = \underset{\mathbf{u}_{\text{proc}},\mathbf{u}_{\text{prod}},\mathbf{u}_{\text{pri}}}{max} \sum_{k=1}^{N} & \underbrace{(\lambda_{\text{fp}}(k) + \overline{\lambda}_{\text{fp}})(\mathbf{I}_{\text{fp}}(k) + \overline{I}_{\text{fp}})}_{\text{revenue}} - \\
& \underbrace{(\lambda_{\text{rm}}(k) + \overline{\lambda}_{\text{rm}})(\mathbf{I}_{\text{rm}}(k) + \overline{I}_{\text{rm}}) + C_{\text{prod}}(\mathbf{u}_{\text{prod}}(k))}_{\text{costs}} \\
\text{s.t.} \quad \mathbf{x}(k+1) &= A\mathbf{x}(k) + B\mathbf{u}(k) \\
\mathbf{y}(k) &= C\mathbf{x}(k) + D\mathbf{u}(k) \\
0 \leq \mathbf{q}(k) + \overline{q} &\leq q_{\max} \\
0 \leq \mathbf{u}_{\text{prod}}(k) + \overline{u}_{\text{prod}} &\leq u_{\text{prod,max}}
\end{aligned}
\tag{7-1}
$$

$\mathbf{x}$ is the state vector of the system, consisting of the relative price levels (λ) and the relative stock levels ($\mathbf{q}$), $\mathbf{y}$ contains the outputs consisting of the relative price levels and the incoming and outgoing flows of goods ($\mathbf{I}_{\text{rm}}$, $\mathbf{I}_{\text{fp}}$).

The parameters with an overline are the equilibrium values that the LTI model is linearized around. These equilibrium values are used to obtain the absolute values that are required in the calculation of profit.

The MPC as formulated in Eq. (7-1) is a non-convex problem that has no certainty of global optimality. The MPC could be extended to a hybrid optimization problem by also including the constraints on manufacturing line occupancy or the constraints inherent to batch-process manufacturing. The use of the YALMIP toolkit in Matlab is recommended in both cases, as is also used by [58] in his optimization of a profit-maximizing MPC.

The possible benefits of using MPC to represent SCM are numerous:

- Constraints can be included easily with MPC. Not only are constraints an important influence on SCM decision making, but through simulation one can also find the most limiting constraint on the maximization of profits and make adjustments in the real supply chain.

- The MPC optimization takes into account future states of the system instead of solely the current state, which matches the behaviour of SCM in reality

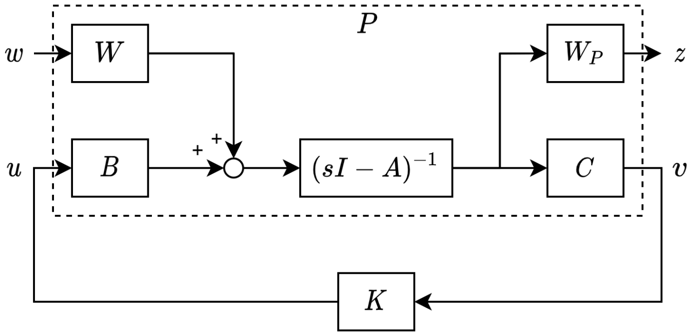


Figure 7-3: The general control configuration for $\mathcal{H}_\infty$ controller design

- The MPC approach allows for the inclusion of other information sources than just those of the manufacturing plant itself. This way, the effect of information sharing can be analyzed, which is a commonly proposed solution to the BWE [39]

7-2-2 Robust Control

$\mathcal{H}_\infty$ control can be developed for minimizing the BWE in a more formal manner compared to the PID control method designed in this thesis. The $\mathcal{H}_\infty$ controller is not as easily interpreted as the PID controllers, but might result in better robust performance. The $\mathcal{H}_\infty$ controller minimizes the largest singular value in the sensitivity function and therefore minimizes the BWE.

The general control configuration for $\mathcal{H}_\infty$ controller design is illustrated in Figure 7-3. The matrices A, B and C are inherited from the supply chain model developed in this thesis, the matrix W transforms the input disturbance signal so that it applies to the correct state, W_P calculates the upstream supply volumes from the states of the system and K is the controller.

The cost function of the optimization problem that is solved to obtain the BWE minimizing $\mathcal{H}_\infty$ controller is

$$\left\| \begin{bmatrix} w_1 S \\ w_2 K S \end{bmatrix} \right\|_\infty , \tag{7-2}$$

with w_1 a low pass filter to decrease the singular values in the sensitivity function S in the low frequency range and w_2 a high pass filter to limit the controller gain in the high frequency range.

The inclusion of the KS term is important for limiting the size and bandwidth of the controller [57]. In the context of supply chains this means that the controller does not output excessively large procurement or production volumes or unrealistic price changes.

$\mathcal{H}_\infty$ controller synthesis may not result in a desired controller for SCM. The attenuation of the largest singular values of the sensitivity function can result in a low gain for a large part of the frequency range. This low gain can cause SCM to only barely react to changes in demand. The BWE will be negligibly low, but changes in finished product inventory may become too large and lead to stock-outs or overfull storage. Inclusion of relative stock levels in the error signal output z may solve this issue. Additionally, the $\mathcal{H}_\infty$ control method does not maximize profits or minimize costs. Similar to the PID control method, the goal of the $\mathcal{H}_\infty$ controller is only to decrease the BWE. The overall goal of SCM may therefore not be attained through the implementation of $\mathcal{H}_\infty$ control policies.

7-2-3 Genetic Algorithm

Genetic algorithms have been applied by O'Donnell et al. [40] to decrease the BWE in a multi-echelon serial supply chain. The algorithm controls the procurement volumes of each echelon based purely on the orders of the next downstream supply chain member. The results of their research are significant mitigation of the BWE throughout the supply chain.

The application of genetic algorithms to the economic engineering model designed in this thesis would be relevant because of the inclusion of price dynamics. The genetic algorithm can make decisions based on more than just the orders from the downstream supply chain member and may control production and pricing besides procurement. These extensions may prove to be even more effective at mitigating the BWE than the current research already has been able to achieve.

7-2-4 Supply Chain Specific Control Rules

Instead of attempting to fit a control method on a supply chain, previous research has also taken existing decision rules or policies and modeled them as they are to quantify their influence on the BWE. The order-up-to policy for procurement has been investigated many times in previous research [9, 30, 34]. Other policies that have been analyzed include nonlinear policies [72] and inventory-on-hand policy [21]. Previous research however has not include prices in their modeling effort, limiting the conclusiveness of their results. Experimenting with existing policies on the economic engineering model of a supply chain would lead to quantifiable results about the influence of each policy on the BWE and may provide new conclusions for SCM.

Appendix A

The 3-Echelon Serial Supply Chain Model - Parameter Values and State-Space Representations

This appendix lists the parameter values of the 3-echelon serial supply chain model and shows the state-space representations of both model configurations presented in Chapter 3 in Figure 3-5. The model with the parameters indicated alongside the elements they belong to is shown in Figure A-1. The parameter values for these parameters are listed in Table A-1. The state space representations of the models are shown in Eq. (A-1) and Eq. (A-2). The C matrices are designed in such a way that the outputs illustrated in Chapter 3 Section 3-6 are obtained. However, the system is theoretically fully observable so any state (q, λ), flow of goods (I) or price change ($V = \frac{d\lambda}{dt}$) can be selected as output. Eq. (A-1) concerns the case with an upstream excess supply disturbance, where Market 0 is replaced with an input for the flow of goods to Plant 1. Eq. (A-2) concerns the case with a downstream excess supply disturbance, where Market 3 is replaced with an input for the flow of goods from Plant 3.

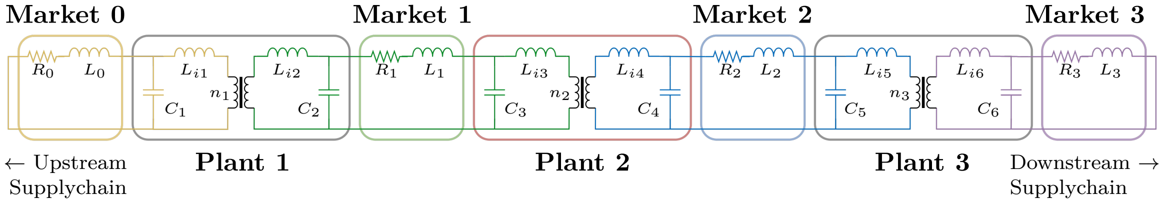


Figure A-1: The 3-echelon serial supply chain model with parameters indicated for each element

Supply chain part	Parameter	Parameter value	Parameter unit
Market 0	R_0	0.18	$\frac{\$}{tnne^2}$
	L_0	1.8	$\frac{\$\cdot wk}{tnne^2}$
Plant 1	C_1	2.7	$\frac{tnne^2\cdot wk}{\$}$
	C_2	2.7	$\frac{tnne^2\cdot wk}{\$}$
	L_{i1}	0.33	$\frac{\$\cdot wk}{tnne^2}$
	L_{i2}	0.33	$\frac{\$\cdot wk}{tnne^2}$
	n_1	1	-
Market 1	R_1	0.12	$\frac{\$}{tnne^2}$
	L_1	2.0	$\frac{\$\cdot wk}{tnne^2}$
Plant 2	C_3	2.2	$\frac{tnne^2\cdot wk}{\$}$
	C_4	2.2	$\frac{tnne^2\cdot wk}{\$}$
	L_{i3}	0.51	$\frac{\$\cdot wk}{tnne^2}$
	L_{i4}	0.51	$\frac{\$\cdot wk}{tnne^2}$
	n_2	1	-
Market 2	R_2	0.061	$\frac{\$}{tnne^2}$
	L_2	2.2	$\frac{\$\cdot wk}{tnne^2}$
Plant 3	C_5	1.4	$\frac{tnne^2\cdot wk}{\$}$
	C_6	1.4	$\frac{tnne^2\cdot wk}{\$}$
	L_{i5}	0.68	$\frac{\$\cdot wk}{tnne^2}$
	L_{i6}	0.68	$\frac{\$\cdot wk}{tnne^2}$
	n_3	1	-
Market 3	R_3	0.042	$\frac{\$}{tnne^2}$
	L_3	2.4	$\frac{\$\cdot wk}{tnne^2}$

Table A-1: Parameter values for the 3-echelon serial supply chain model

$$
\frac{d}{dt}\begin{bmatrix} q_1 \\ q_2 \\ \lambda_1 \\ \lambda_{i1} \\ \lambda_{i2} \\ q_3 \\ q_4 \\ \lambda_2 \\ \lambda_{i3} \\ \lambda_{i4} \\ q_5 \\ q_6 \\ \lambda_3 \\ \lambda_{i5} \\ \lambda_{i6} \end{bmatrix} = \begin{bmatrix}
0 & 0 & 0 & -\frac{1}{L_{i1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -\frac{1}{L_1} & 0 & \frac{1}{L_{i2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{C_2} & -\frac{R_1}{L_1} & 0 & 0 & -\frac{1}{C_3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{n_1^2 L_{i1}}{C_1 L_{i2}}\alpha & -\frac{n_1 L_{i1}}{C_2 L_{i2}}\alpha & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{n_1}{C_1}\alpha & -\frac{1}{C_2}\alpha & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{1}{L_1} & 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_{i3}} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_2} & 0 & \frac{1}{L_{i4}} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{C_4} & -\frac{R_2}{L_2} & 0 & 0 & -\frac{1}{C_5} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{n_2^2 L_{i3}}{C_3 L_{i4}}\alpha_2 & -\frac{n_2 L_{i3}}{C_4 L_{i4}}\alpha_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{n_2}{C_3}\alpha_2 & -\frac{1}{C_4}\alpha_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_2} & 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_{i5}} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_3} & 0 & \frac{1}{L_{i6}} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{C_6} & -\frac{R_3}{L_3} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{n_3^2 L_{i5}}{C_5 L_{i6}}\alpha_3 & -\frac{n_3 L_{i5}}{C_6 L_{i6}}\alpha_3 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{n_3}{C_5}\alpha_3 & -\frac{1}{C_6}\alpha_3 & 0 & 0 & 0
\end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ \lambda_1 \\ \lambda_{i1} \\ \lambda_{i2} \\ q_3 \\ q_4 \\ \lambda_2 \\ \lambda_{i3} \\ \lambda_{i4} \\ q_5 \\ q_6 \\ \lambda_3 \\ \lambda_{i5} \\ \lambda_{i6} \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} w
$$

$$
y = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \\ q_5 \\ q_6 \\ I_{prod1} \\ I_{prod2} \\ I_{prod3} \\ I_{proc2} \\ I_{proc3} \\ \lambda_1 \\ \lambda_2 \end{bmatrix} = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{L_{i2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_{i4}} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_{i6}} \\
0 & 0 & \frac{1}{L_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ \lambda_1 \\ \lambda_{i1} \\ \lambda_{i2} \\ q_3 \\ q_4 \\ \lambda_2 \\ \lambda_{i3} \\ \lambda_{i4} \\ q_5 \\ q_6 \\ \lambda_3 \\ \lambda_{i5} \\ \lambda_{i6} \end{bmatrix} \tag{A-1}
$$

With $\alpha_1 = \frac{1}{1+n^2\frac{L_{i1}}{L_{i2}}}$, $\alpha_2 = \frac{1}{1+n^2\frac{L_{i3}}{L_{i4}}}$, $\alpha_3 = \frac{1}{1+n^2\frac{L_{i5}}{L_{i6}}}$.

$$
\frac{d}{dt}\begin{bmatrix}\lambda_0\\ q_1\\ q_2\\ \lambda_1\\ \lambda_{i1}\\ \lambda_{i2}\\ q_3\\ q_4\\ \lambda_2\\ \lambda_{i3}\\ \lambda_{i4}\\ q_5\\ q_6\\ \lambda_{i5}\\ \lambda_{i6}\end{bmatrix}
=
\begin{bmatrix}
-\frac{R_0}{L_0} & -\frac{1}{C_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
\frac{1}{L_0} & 0 & 0 & 0 & -\frac{1}{L_{i1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & -\frac{1}{L_1} & 0 & \frac{1}{L_{i2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & \frac{1}{C_2} & -\frac{R_1}{L_1} & 0 & 0 & -\frac{1}{C_3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & \frac{n_1^2 L_{i1}}{C_1 L_{i2}}\alpha & -\frac{n_1 L_{i1}}{C_2 L_{i2}}\alpha & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & \frac{n_1}{C_1}\alpha & -\frac{1}{C_2}\alpha & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & \frac{1}{L_1} & 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_{i3}} & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_2} & 0 & \frac{1}{L_{i4}} & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{C_4} & -\frac{R_2}{L_2} & 0 & 0 & -\frac{1}{C_5} & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & \frac{n_2^2 L_{i3}}{C_3 L_{i4}}\alpha & -\frac{n_2 L_{i3}}{C_4 L_{i4}}\alpha & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & \frac{n_2}{C_3}\alpha & -\frac{1}{C_4}\alpha & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_2} & 0 & 0 & 0 & 0 & -\frac{1}{L_{i5}} & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_{i6}}\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{n_3^2 L_{i5}}{C_5 L_{i6}}\alpha & -\frac{n_3 L_{i5}}{C_6 L_{i6}}\alpha & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{n_3}{C_5}\alpha & -\frac{1}{C_6}\alpha & 0 & 0
\end{bmatrix}
\begin{bmatrix}\lambda_0\\ q_1\\ q_2\\ \lambda_1\\ \lambda_{i1}\\ \lambda_{i2}\\ q_3\\ q_4\\ \lambda_2\\ \lambda_{i3}\\ \lambda_{i4}\\ q_5\\ q_6\\ \lambda_{i5}\\ \lambda_{i6}\end{bmatrix}
+
\begin{bmatrix}0\\ 0\\ 0\\ 0\\ 0\\ 0\\ 0\\ 0\\ 0\\ 0\\ 0\\ 0\\ -1\\ 0\\ 0\end{bmatrix} w
$$

$$
y = \begin{bmatrix} q_1\\ q_2\\ q_3\\ q_4\\ q_5\\ q_6\\ I_{prod1}\\ I_{prod2}\\ I_{prod3}\\ I_{proc1}\\ I_{proc2}\\ I_{proc3}\\ \lambda_1\\ \lambda_2\end{bmatrix}
=
\begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & \frac{1}{L_{i2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_{i4}} & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_{i6}}\\
\frac{1}{L_0} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & \frac{1}{L_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_2} & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}\lambda_0\\ q_1\\ q_2\\ \lambda_1\\ \lambda_{i1}\\ \lambda_{i2}\\ q_3\\ q_4\\ \lambda_2\\ \lambda_{i3}\\ \lambda_{i4}\\ q_5\\ q_6\\ \lambda_{i5}\\ \lambda_{i6}\end{bmatrix}
\tag{A-2}
$$

Appendix B

Valtris Data for Model Validation

This appendix shows Valtris Specialty Chemicals (VSC) data used for validation of the supply chain model presented in Chapter 3. Graphs of the data are shown in Figure B-1 and Figure B-2. The data concerns the flows of goods and the stock levels for a period of 40 weeks for one of the products of VSC and the two materials it is manufactured from. Due to confidentiality, the names of specific materials and products are not shown and neither are their prices or the period in time the data was taken from. The data is used as practical reference for supply chain behaviour and provides an example of the dynamics of a manufacturing plant and the surrounding markets.

Figure B-1 shows the demand, production output and stock levels for a VSC product. The demand does not display cyclical behaviour and fluctuates around a constant average weekly demand volume. The production is planned so that demand can be met and no stock-outs occur, within the limitations of batch-process manufacturing. This means that production follows the movement of demand. In periods of higher demand the production is increased in order to maintain a steady stock level. Some weeks, production volumes are equal to 0 and no product is manufactured, while other weeks display a relatively constant production output. This has to do with the limitations of batch-process manufacturing, where a production line can be occupied by other products and manufacturing setup costs are taken into account in production planning. The production output graph shows slight cyclical behaviour, inherent to the batch-process manufacturing methods and production planning policies like the product wheel [27]. Stock levels change in accordance with the difference between demand and production output.

Figure B-2 shows the supply and stock levels for the two materials required in the production of the product in Figure B-1. The supply of material 4 fluctuates more strongly than the demand for the product does and this is also displayed in the graph of the stock levels for this material. When stock levels of material 4 are high, supply decreases gradually and a still steady production level results in a decrease of the material's stock level. When stock levels return back to the desired value, the supply is increased again and the cycle repeats. The cyclical behaviour is stronger for the materials than for the products.

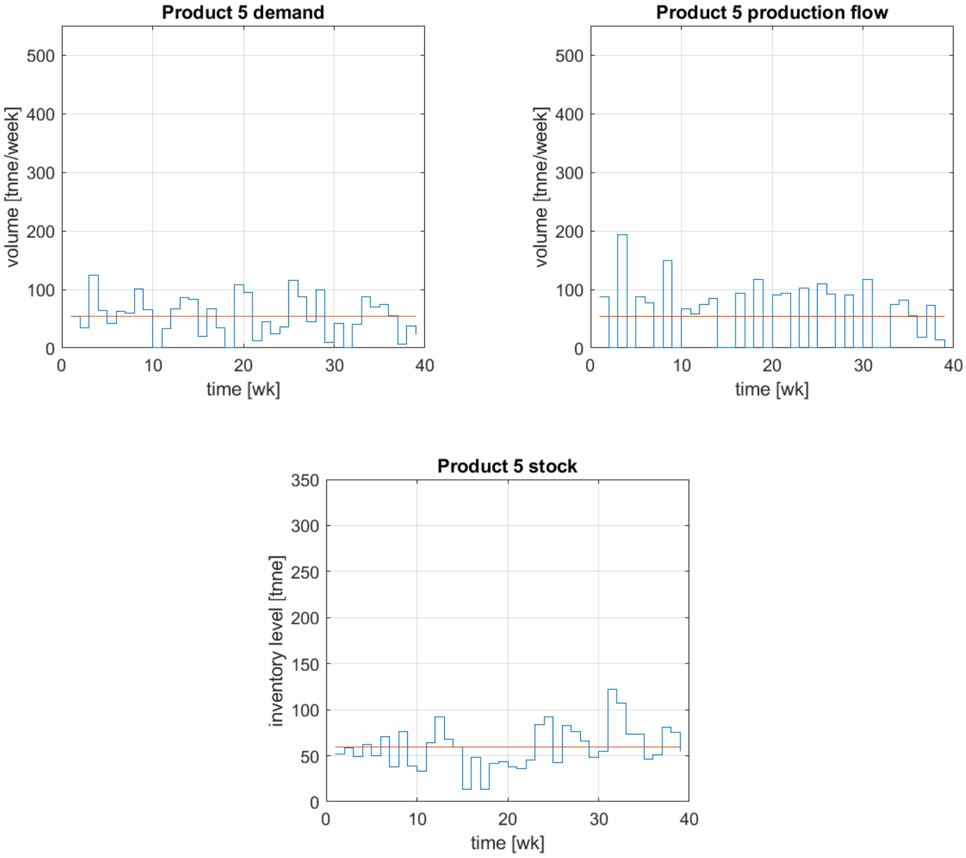


Figure B-1: Valtris Specialty Chemicals finished product data provides a real world example of the behaviour of demand, production and stock levels. Demand and production show bounded oscillations, while the difference in these volumes is equal to the change in product stock level. Increased demand is matched with increased production to minimize inventory imbalance. The orange line indicates the average value of the data

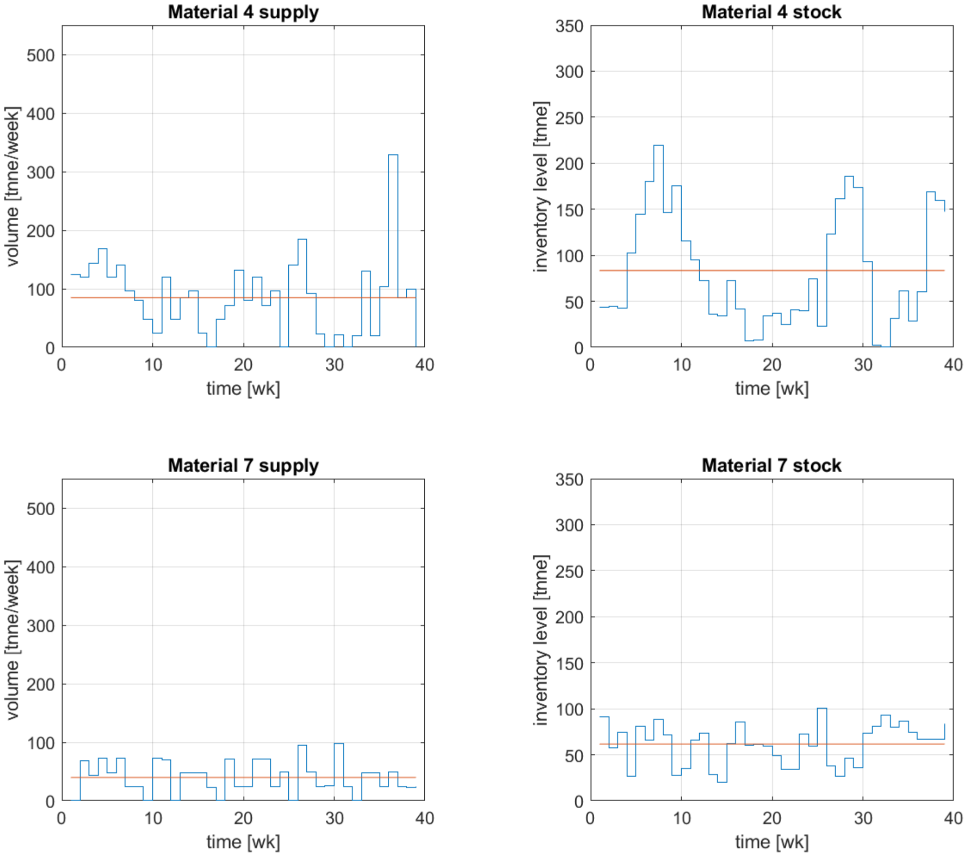


Figure B-2: Valtris Specialty Chemicals raw material data provides a real world example of the behaviour of supply and stock levels. High stock levels decrease supply and low stock levels increase supply. High supply in turn increases stock levels, resulting in cyclical behaviour. The orange line indicates the average value of the data

Appendix C

PID Policies for All Members of a Supply Chain

This appendix shows the results of using PID control for the procurement, production and pricing of all members in the serial supply chain from Chapter 3. The exact same controllers for procurement, production and pricing that were used for Plant 2 in Chapter 4 are now applied to all the other possible control locations in the supply chain.

The effect of the extra controllers on the Bullwhip Effect (BWE) is observed in the magnitude plots of Bode diagrams for transfer functions from downstream excess customer demand to upstream excess supply. Figure C-1 shows both the original frequency response of the controlled system from Chapter 4 and the response of the system with PID control applied at all procurement, production and pricing locations in the supply chain.

The amplification of customer demand oscillations is decreased at all locations in the supply chain for the entire relevant frequency range. The supply to Plant 1, which is furthest away from the downstream demand, shows the largest difference as that signal is attenuated the most amount of times, having been passed through 3 plants that each decrease the BWE. The phase lag remains similar for the case with control of all plants in the relevant frequency range. As the amplification is now below the 0 dB threshold for all frequencies, the incoming customer demand signal is only attenuated, never amplified. The application of PID control policies for all plants in the supply chain results in complete attenuation of the BWE.

The effect of the extra controllers on the outputs of the system is observed in scenario analysis of cyclical demand, similar to the simulations carried out in Chapter 3 and Chapter 4. Figure C-2 shows the outputs of the system with control of all plants in the supply chain for a cyclical downstream excess customer demand input.

The fluctuations of all outputs throughout the supply chain are attenuated when the serial supply chain is subjected to the cyclical excess demand. The stock levels of and supply to Plant 3 are the only outputs that still display any significant oscillations. The attenuation after Plant 3 is large enough that the rest of the outputs along the supply chain remain nearly constant.

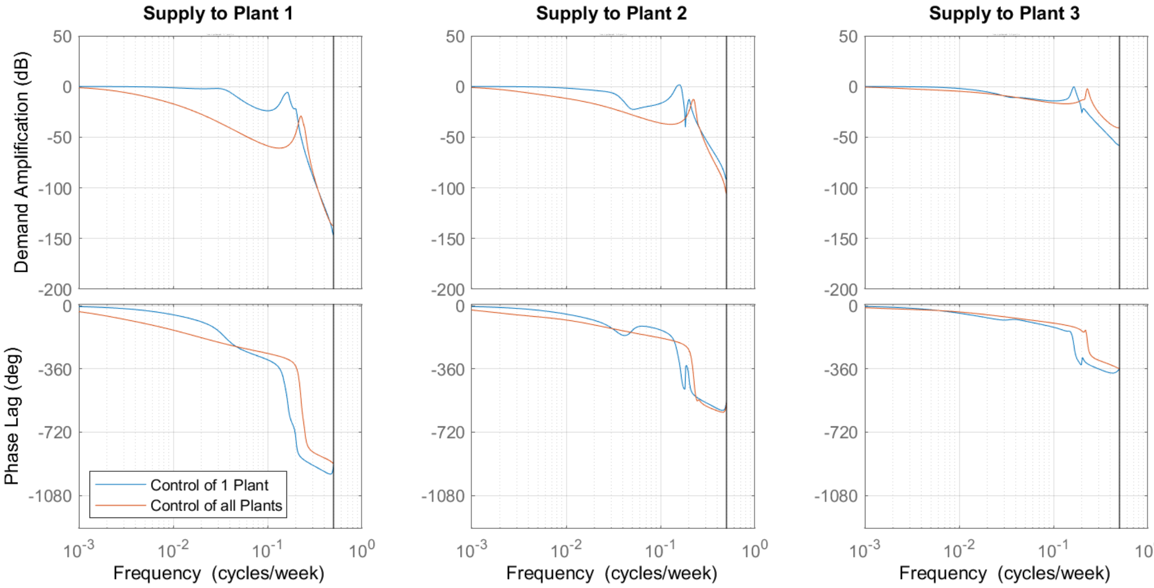


Figure C-1: Bode diagrams show the comparison in terms of the Bullwhip Effect between the supply chain with control for only Plant 2 and with control for all plants in the supply chain. The gain in the magnitude plots is lower with control for all plants in the largest part of the relevant frequency range. The gain is below the 0 dB level for all frequencies, meaning the BWE is avoided entirely. The phase plots indicate lower relative lead times for high frequency demand cycles and higher relative lead times for lower frequencies with control for all plants. The transfer functions are from downstream excess customer demand to upstream excess supply to all plants

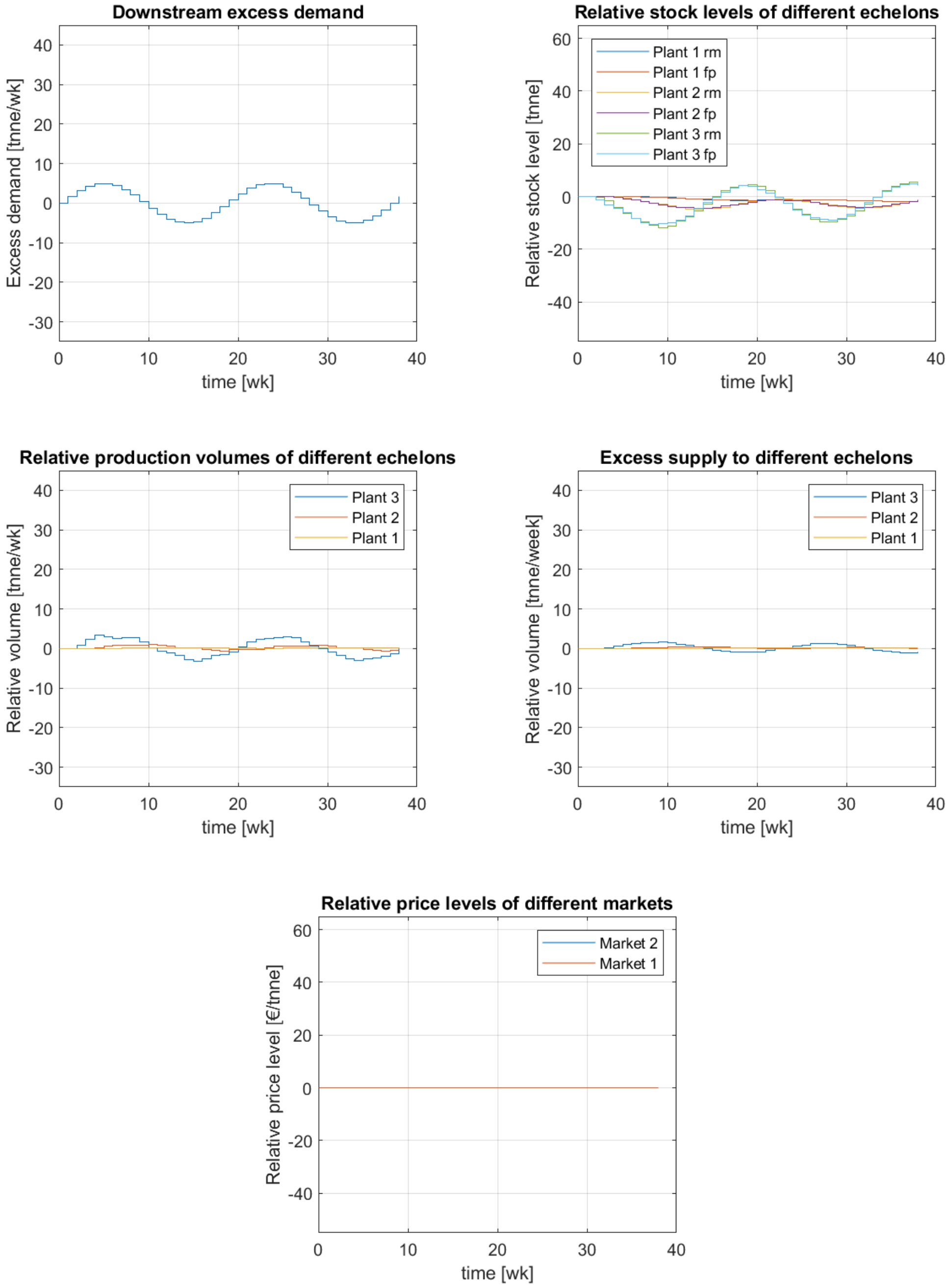


Figure C-2: Simulation of cyclical downstream customer demand for the supply chain with control of all plants shows attenuation of oscillations for all outputs. The indications 'rm' and 'fp' refer to raw materials and finished products

Appendix D

Frequency Response for Stock Levels of a Controlled Supply Chain

This appendix demonstrates the issue of high amplitude stock level fluctuations for Plant 3 in the controlled supply chain model from Chapter 4. Figure D-1 shows the amplification of excess customer demand fluctuations to stock level oscillations. Note that the Bode diagrams display amplification of signals that do not have matching units. The Bode diagrams should therefore only be used for demonstrative purposes and not to draw quantitative conclusions.

The magnitude plots of the Bode diagrams both show higher amplification of excess demand oscillations to stock level fluctuations in the lower frequency range for the controlled model. This means that the stock levels of Plant 3 for both raw materials and finished products grow to unmanageable levels in case the customer demand changes slowly. The result is either stock-outs or inadequate storage capacity for dealing with high stock levels. Where the uncontrolled model was capable of adapting to long-term changes in demand, the new model fails to do so.

The response of the controlled model to fast changing demand remains similar to that of the uncontrolled model.

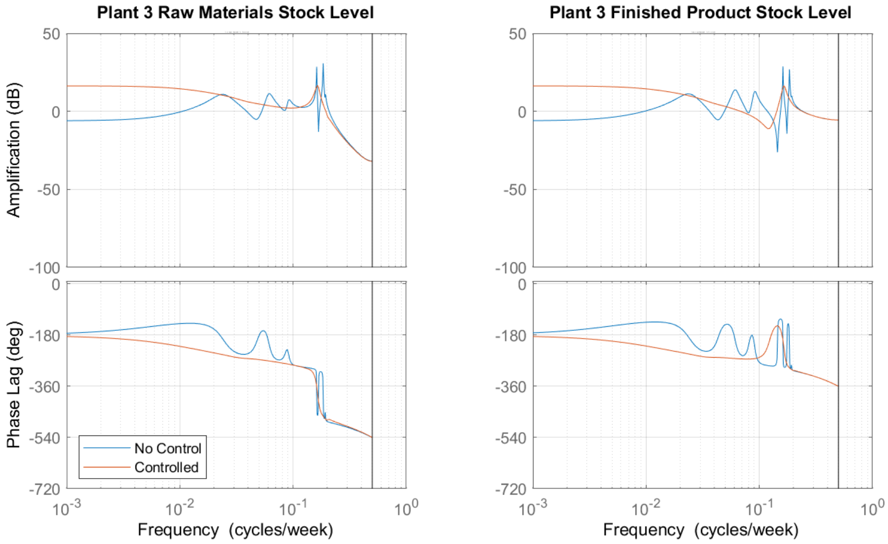


Figure D-1: The Bode diagrams for the transfer functions from excess downstream customer demand to the relative stock levels of Plant 3 illustrate the effect on stock levels of low supply response to demand changes. The stock levels oscillate at lower frequencies with highly amplified amplitudes, growing to unmanageable levels in case customer demand changes slowly

Appendix E

The Valtris Specialty Chemicals Model - Parameter Values and State-Space Representation

This appendix lists the parameter values for both the model of part of the Valtris Specialty Chemicals (VSC) supply chain and for the controllers and shows the state-space representation of the model presented in Chapter 5 in Figure 5-2. The model with the parameters indicated alongside the elements they belong to is shown in Figure E-1. The parameter values for these parameters are listed in Table E-1. The state space representations of the model is shown in Eq. (E-1).

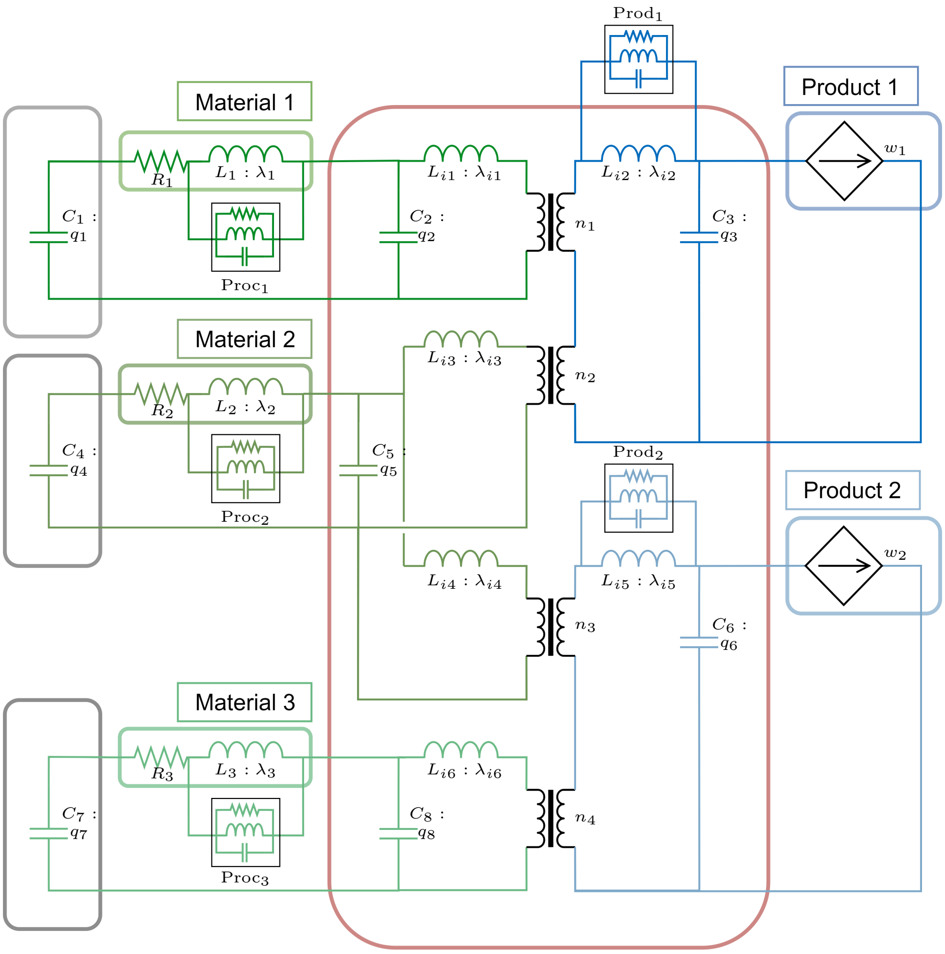


Figure E-1: The model of part of the Valtris Specialty Chemicals supply chain and PID control as Supply Chain Management (indicated with the black boxes), with labeled parameters, variables and disturbance inputs. The state-space representation of this model is given in Eq. (E-1)

Model Parameter	Parameter Value
C_1	$5.5 \cdot 10^2$
C_2	19
C_3	1.3
C_4	2.2
C_5	0.16
C_6	0.16
C_7	5.5
C_8	0.25
R_1	0.015
R_2	0.36
R_3	1.9
L_1	0.20
L_2	2.0
L_3	2.3
L_{i1}	0.010
L_{i2}	0.010
L_{i3}	1.0
L_{i4}	1.0
L_{i5}	8.0
L_{i6}	0.30
n_1	0.79
n_2	0.29
n_3	0.29
n_4	0.79

Controller Parameter	Parameter Value
$k_{P,proc1}$	1.7
$k_{I,proc1}$	$1.3 \cdot 10^2$
$k_{D,proc1}$	$1.0 \cdot 10^{-10}$
$k_{P,proc2}$	$1.7 \cdot 10^{-6}$
$k_{I,proc2}$	1.0
$k_{D,proc2}$	$1.0 \cdot 10^{-10}$
$k_{P,proc3}$	$1.7 \cdot 10^{-4}$
$k_{I,proc3}$	0.50
$k_{D,proc3}$	$1.0 \cdot 10^{-10}$
$k_{P,prod1}$	0.017
$k_{I,prod1}$	50
$k_{D,prod1}$	$1.0 \cdot 10^{-10}$
$k_{P,prod2}$	0.0083
$k_{I,prod2}$	0.45
$k_{D,prod2}$	$1.0 \cdot 10^{-10}$

Table E-1: Parameter values of the model (left table) and controllers (right table) for part of the Valtris Specialty Chemicals supply chain

$$
\frac{d}{dt}\begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \\ q_5 \\ q_6 \\ q_7 \\ q_8 \\ \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_{i1} \\ \lambda_{i2} \\ \lambda_{i3} \\ \lambda_{i4} \\ \lambda_{i5} \\ \lambda_{i6} \end{bmatrix} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_1} & 0 & 0 & -\frac{1}{L_{i1}} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_{i2}} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_2} & 0 & 0 & 0 & -\frac{1}{L_{i3}} & -\frac{1}{L_{i4}} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_{i5}} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_3} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_3} & 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_{i6}} \\
\frac{1}{C_1} & -\frac{1}{C_2} & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{R_1}{L_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{C_4} & -\frac{1}{C_5} & 0 & 0 & 0 & 0 & -\frac{R_2}{L_2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{C_7} & -\frac{1}{C_8} & 0 & 0 & -\frac{R_3}{L_3} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{n_1^2 L_{i1}}{C_2 L_{i2}}\alpha_1 & -\frac{n_1 L_{i1}}{C_3 L_{i2}}\alpha_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{n_1}{C_2}\alpha_1 & -\frac{1}{C_3}(\alpha_1+\alpha_2) & 0 & \frac{n_2}{C_5}\alpha_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -\frac{n_2 L_{i3}}{C_3 L_{i2}}\alpha_2 & 0 & \frac{n_2^2 L_{i3}}{C_5 L_{i2}}\alpha_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{n_3^2 L_{i4}}{C_5 L_{i5}}\alpha_3 & -\frac{n_3 L_{i4}}{C_6 L_{i5}}\alpha_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{n_3}{C_5}\alpha_3 & -\frac{1}{C_6}(\alpha_3+\alpha_4) & 0 & \frac{n_4}{C_8}\alpha_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -\frac{n_4 L_{i6}}{C_6 L_{i5}}\alpha_4 & 0 & \frac{n_4^2 L_{i6}}{C_8 L_{i5}}\alpha_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}\begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \\ q_5 \\ q_6 \\ q_7 \\ q_8 \\ \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_{i1} \\ \lambda_{i2} \\ \lambda_{i3} \\ \lambda_{i4} \\ \lambda_{i5} \\ \lambda_{i6} \end{bmatrix} + \begin{bmatrix}
-1 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & -n_1 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & -1 & 0 & 0 & 0 \\
0 & 1 & 0 & -n_2 & -n_3 \\
0 & 0 & 0 & 0 & 1 \\
0 & 0 & -1 & 0 & 0 \\
0 & 0 & 1 & 0 & -n_4 \\
-R_1 & 0 & 0 & 0 & 0 \\
0 & -R_2 & 0 & 0 & 0 \\
0 & 0 & -R_3 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}\begin{bmatrix} u_{proc1} \\ u_{proc2} \\ u_{proc3} \\ u_{prod1} \\ u_{prod2} \end{bmatrix} + \begin{bmatrix}
0 & 0 \\
0 & 0 \\
-1 & 0 \\
0 & 0 \\
0 & 0 \\
0 & -1 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0
\end{bmatrix}\begin{bmatrix} w_1 \\ w_2 \end{bmatrix}
$$

$$
y = \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_{i2} \\ V_{i5} \end{bmatrix} = \begin{bmatrix}
\frac{1}{C_1} & -\frac{1}{C_2} & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{R_1}{L_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{C_4} & -\frac{1}{C_5} & 0 & 0 & 0 & 0 & -\frac{R_2}{L_2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{C_7} & -\frac{1}{C_8} & 0 & 0 & -\frac{R_3}{L_3} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{n_1}{C_2}\alpha_1 & -\frac{1}{C_3}(\alpha_1+\alpha_2) & 0 & \frac{n_2}{C_5}\alpha_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{n_3}{C_5}\alpha_3 & -\frac{1}{C_6}(\alpha_3+\alpha_4) & 0 & \frac{n_4}{C_8}\alpha_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}\begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \\ q_5 \\ q_6 \\ q_7 \\ q_8 \\ \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_{i1} \\ \lambda_{i2} \\ \lambda_{i3} \\ \lambda_{i4} \\ \lambda_{i5} \\ \lambda_{i6} \end{bmatrix} + \begin{bmatrix}
-R_1 & 0 & 0 & 0 & 0 \\
0 & -R_2 & 0 & 0 & 0 \\
0 & 0 & -R_3 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}\begin{bmatrix} u_{proc1} \\ u_{proc2} \\ u_{proc3} \\ u_{prod1} \\ u_{prod2} \end{bmatrix} \tag{E-1}
$$

With $\alpha_1 = \frac{1}{1+n_1^2 \frac{L_{i1}}{L_{i2}}}$, $\alpha_2 = \frac{1}{1+n_2^2 \frac{L_{i3}}{L_{i2}}}$, $\alpha_3 = \frac{1}{1+n_3^2 \frac{L_{i4}}{L_{i5}}}$, $\alpha_4 = \frac{1}{1+n_4^2 \frac{L_{i6}}{L_{i5}}}$.

The controllers take the local price changes (V) from the outputs (y) of the discretized system and give as the output a relative flow of goods (I). The C and D matrices consist of specific rows from the A and B matrices, respectively, to obtain these price changes. The controller outputs are fed back as inputs (u) to the system. The discrete time PID controller equation that governs the control process is

$$I = k_P V + k_I \sum VT + k_D \frac{\Delta V}{T}, \tag{E-2}$$

as presented in Chapter 4, with $V = \frac{\Delta\lambda}{T}$ and T the sampling time of 1 week.

Bibliography

[1] Ziaul Haq Adnan and Ertunga Özelkan. Bullwhip effect in pricing under different supply chain game structures. *Journal of Revenue and Pricing Management*, 18(5):393–404, 2019.

[2] Ranjan Bhattacharya and Susmita Bandyopadhyay. A review of the causes of bullwhip effect in a supply chain. *International Journal of Advanced Manufacturing Technology*, 54(9-12):1245–1261, 2011.

[3] Robert L. Bray, Yuliang Yao, Yongrui Duan, and Jiazhen Huo. Ration gaming and the bullwhip effect. *Operations Research*, 67(2):453–467, 2019.

[4] Gérard P. Cachon, Taylor Randall, and Glen M. Schmidt. In search of the bullwhip effect. *Manufacturing and Service Operations Management*, 9(4):457–479, 2007.

[5] Francisco Campuzano and Josefa Mula. *Supply Chain Simulation.* Springer London, London, 2011.

[6] Bin Bin Cao, Zhong Dong Xiao, and Jia Nan Sun. A study of the bullwhip effect in supply- and demand-driven supply chain. *Journal of Industrial and Production Engineering*, 34(2):124–134, 2017.

[7] Leonardo Chwif, Marcos Ribeiro Pereira Barretto, and Eduardo Saliby. Supply chain analysis: spreadsheet or simulation? In *Proceedings of the Winter Simulation Conference*, volume 1, pages 59–66. IEEE, 2002.

[8] Rachel Croson and Karen Donohue. Behavioral causes of the bullwhip effect and the observed value of inventory information. *Management Science*, 52(3):323–336, 2006.

[9] Jeroen Dejonckheere, Stephen M. Disney, Marc R. Lambrecht, and Denis R. Towill. Measuring and avoiding the bullwhip effect: A control theoretic approach. *European Journal of Operational Research*, 147(3):567–590, 2003.

[10] Roemer Dolman. Optimal Production Scheduling and Pricing: A Review and Research Proposal, 2021.

[11] Jay Forrester. Industrial Dynamics: a major breakthrough for decision makers. *Harvard Business Review*, pages 67–96, 1958.

[12] Jay Forrester. *Industrial Dynamics.* MIT Press, 1961.

[13] Gene F. Franklin, J. David Powell, and Emami-Naeini Abbas. *Feedback Control of Dynamical Systems.* Pearson Education, 7 edition, 2017.

[14] Jan C. Fransoo and Marc J.F. Wouters. Measuring the bullwhip effect in the supply chain. *Supply Chain Management*, 5(2):78–89, 2000.

[15] Dongfei Fu, Clara Ionescu, El Houssaine Aghezzaf, and Robin De Keyser. Quantifying and mitigating the bullwhip effect in a benchmark supply chain system by an extended prediction self-adaptive control ordering policy. *Computers and Industrial Engineering*, 81:46–57, 2015.

[16] Reyhaneh Gamasaee and Mohammad Hossein Fazel Zarandi. Incorporating demand, orders, lead time, and pricing decisions for reducing bullwhip effect in supply chains. *Scientia Iranica*, 25(3E):1724–1749, 2018.

[17] Steve Geary, Stephen M. Disney, and Denis R. Towill. On bullwhip in supply chains - Historical review, present practice and expected future impact. *International Journal of Production Economics*, 101(1 SPEC. ISS.):2–18, 2006.

[18] Vincent Giard and Mustapha Sali. The bullwhip effect in supply chains: A study of contingent and incomplete literature. *International Journal of Production Research*, 51(13):3880–3893, 2013.

[19] Ward Hanson. The dynamics of cost-plus pricing. *Managerial and Decision Economics*, 13(2):149–161, 3 1992.

[20] Ford W. Harris. How many parts to make at once. *Factory, The Magazine of Management*, 10(2):135–136, 1913.

[21] Kai Hoberg, James R. Bradley, and Ulrich W. Thonemann. Analyzing the effect of the inventory policy on order and inventory variability with linear control theory. *European Journal of Operational Research*, 176(3):1620–1642, 2007.

[22] Wayne Holland and Manmohan S. Sodhi. Quantifying the effect of batch size and order errors on the bullwhip effect using simulation. *International Journal of Logistics Research and Applications*, 7(3):251–261, 2004.

[23] Dmitry Ivanov. Supply Chain Risks, Disruptions, and Ripple Effect. In *Introduction to Supply Chain Resilience*, pages 1–28. Springer, 1 edition, 2021.

[24] Dmitry Ivanov, Alexander Tsipoulanidis, and Jörn Schönberger. Inventory Management. In *Global Supply Chain and Operations Management*, pages 361–406. Springer International Publishing Switzerland, 2019.

[25] Uday S Karmarkar and Milind M Lele. The Marketing/Manufacturing Interface: Strategic Issues. In Amiya K. Chakravarty and Jehoshua Eliashberg, editors, *Managing Business Interfaces*, volume 16 of *International Series in Quantitative Marketing*, pages 311–328. Springer-Verlag, 1 edition, 2005.

[26] Jeon G. Kim, Dean Chatfield, Terry P. Harrison, and Jack C. Hayya. Quantifying the bullwhip effect in a supply chain with stochastic lead time. *European Journal of Operational Research*, 173(2):617–636, 2006.

[27] Peter King. *Lean for the Process Industries: Dealing with Complexity.* Productivity Press, first edit edition, 2009.

[28] Hau L. Lee, V. Padmanabhan, and Seungjin Whang. Information distortion in a supply chain: The bullwhip effect. *Management Science*, 43(4):546–558, 1997.

[29] Hau L. Lee, V. Padmanabhan, and Seungjin Whang. The bullwhip effect in supply chains. *Sloan Management Review*, 15(2):89–100, 1997.

[30] Qinyun Li, Stephen M. Disney, and Gerard Gaalman. Avoiding the bullwhip effect using Damped Trend forecasting and the Order-Up-To replenishment policy. *International Journal of Production Economics*, 149:3–16, 2014.

[31] Huynh Trung Luong. Measure of bullwhip effect in supply chains with autoregressive demand process. *European Journal of Operational Research*, 180(3):1086–1097, 2007.

[32] Junhai Ma, Wandong Lou, and Yi Tian. Bullwhip effect and complexity analysis in a multi-channel supply chain considering price game with discount sensitivity. *International Journal of Production Research*, 57(17):5432–5452, 2019.

[33] Yungao Ma, Nengmin Wang, Ada Che, Yufei Huang, and Jinpeng Xu. The bullwhip effect on product orders and inventory: A perspective of demand forecasting techniques. *International Journal of Production Research*, 51(1):281–302, 2013.

[34] Yungao Ma, Nengmin Wang, Ada Che, Yufei Huang, and Jinpeng Xu. The bullwhip effect under different information-sharing settings: A perspective on price-sensitive demand that incorporates price dynamics. *International Journal of Production Research*, 51(10):3085–3116, 2013.

[35] Alfred Marshall. *Principles of Economics.* Palgrave Macmillan, eight edition, 1920.

[36] Peter McCullen and Denis Towill. Diagnosis and reduction of bullwhip in supply chains. *Supply Chain Management*, 7(3):164–179, 2002.

[37] Jordan Meegdes. Model-Driven Objective Functions in MPC using Economic Engineering Systems Theory: With an Application to Supply-Chain Scheduling at Shell, 2021.

[38] Max B. Mendel. Principles of Economic Engineering - Lecture Notes, 2019.

[39] Thierry Moyaux, Brahim Chaib-Draa, and Sophie D'Amours. Information sharing as a coordination mechanism for reducing the bullwhip effect in a supply chain. *IEEE Transactions on Systems, Man and Cybernetics Part C: Applications and Reviews*, 37(3):396–409, 2007.

[40] Tina O'Donnell, Liam P. Maguire, Ronan McIvor, and Paul Humphreys. Minimizing the bullwhip effect in a supply chain using genetic algorithms. *International Journal of Production Research*, 44(8):1523–1543, 2006.

[41] Nicolaas G. Orie. Dynamic Modelling and Control of the Oil Market: An Economic Engineering Approach, 2020.

[42] Yanfeng Ouyang. The effect of information sharing on supply chain stability and the bullwhip effect. *European Journal of Operational Research*, 182(3):1107–1121, 2007.

[43] Yanfeng Ouyang and Xiaopeng Li. The bullwhip effect in supply chain networks. *European Journal of Operational Research*, 201(3):799–810, 2010.

[44] Ertunga C. Özelkan and Metin Çakanyildirim. Reverse bullwhip effect in pricing. *European Journal of Operational Research*, 192(1):302–312, 2007.

[45] Ertunga C. Özelkan and Churlzu Lim. Conditions of reverse bullwhip effect in pricing for price-sensitive demand functions. *Annals of Operations Research*, 164(1):211–227, 2008.

[46] Ertunga C. Özelkan, Churlzu Lim, and Ziaul Haq Adnan. Conditions of reverse bullwhip effect in pricing under joint decision of replenishment and pricing. *International Journal of Production Economics*, 200:207–223, 2018.

[47] Seung Kuk Paik and Prabir K. Bagchi. Understanding the causes of the bullwhip effect in a supply chain. *International Journal of Retail and Distribution Management*, 35(4):308–324, 2007.

[48] Fredrik Persson and Mirko Araldi. The development of a dynamic supply chain analysis tool-Integration of SCOR and discrete event simulation. *International Journal of Production Economics*, 121(2):574–583, 2009.

[49] Paul H. Pittman and J. Brian Atwater. *APICS Dictionary.* ASCM, Chicago, 16 edition, 2019.

[50] Carol A. Ptak and Chad J. Smith. *Orlicky's Material Requirements Planning.* McGraw-Hill Education, LLC, New York, 3rd edition, 2011.

[51] Jafar Rezaei and Mansoor Davoodi. A joint pricing, lot-sizing, and supplier selection model. *International Journal of Production Research*, 50(16):4524–4542, 2012.

[52] Juliana Keiko Sagawa and Marcelo Seido Nagano. Dynamic models for production control and scheduling: A brief review. *Proceedings - 2013 12th Mexican International Conference on Artificial Intelligence, MICAI 2013*, pages 38–44, 2013.

[53] Juliana Keiko Sagawa and Marcelo Seido Nagano. A Review on the Dynamic Decision Models for Manufacturing and Supply Chain. In *Decision Models in Engineering and Management*, pages 77–108. Springer International Publishing Switzerland, 2015.

[54] Haralambos Sarimveis, Panagiotis Patrinos, Chris D. Tarantilis, and Chris T. Kiranoudis. Dynamic modeling and control of supply chain systems: A review. *Computers and Operations Research*, 35(11):3530–3561, 2008.

[55] David Simchi-Levi, Philip Kaminsky, and Edith Simchi-Levi. *Designing and Managing Supply Chain.* McGraw-Hill Education, LLC, 1 edition, 2003.

[56] Hermann Simon and Martin Fassnacht. *Price Management.* Springer International Publishing, Cham, 2019.

[57] Sigurd Skogestad and Ian Postlethwaite. *Multivariable Feedback Control.* John Wiley & Sons, 2 edition, 2001.

[58] Wouter S. Slits. A Price-Dynamic Model of Flexibility in the Electricity Market of the Future, 2022.

[59] Adam Smith. An Inquiry into the Nature and Causes of the Wealth of Nations. *London Business School Review*, pages 46–49, 1776.

[60] John D. Sterman. Modeling Managerial Behavior: Misperceptions of Feedback in a Dynamic Decision Making Experiment. *Management Science*, 35(3):321–339, 1989.

[61] John D. Sterman. Booms, Busts, and Beer: Understanding the Dynamics of Supply Chains. *The Handbook of Behavioral Operations Management: Social and Psychological Dynamics in Production and Service Settings*, pages 203–237, 2015.

[62] Jayashankar M. Swaminathan and Sridhar R. Tayur. Models for supply chains in e-business. *Management Science*, 49(10):1387–1406, 2003.

[63] Pham Duc Tai, Truong Ton Hien Duc, and Jirachai Buddhakulsomsiri. Measure of bullwhip effect in supply chain with price-sensitive and correlated demand. *Computers and Industrial Engineering*, 127:408–419, 2019.

[64] Denis R. Towill and Antonio Del Vecchio. The application of filter theory to the study of supply chain dynamics. *Production Planning and Control*, 5(1):82–96, 1994.

[65] Denis R. Towill, Li Zhou, and Stephen M. Disney. Reducing the bullwhip effect: Looking through the appropriate lens. *International Journal of Production Economics*, 108(1-2):444–453, 2007.

[66] Hal R. Varian. *Intermediate Microeconomics.* W. W. Norton & Company, New York, 8th edition, 2010.

[67] Michel Verhaegen and Vincent Verdult. *Filtering and System Identification: A Least Squares Approach.* Cambridge University Press, 1st edition, 2007.

[68] Harvey M. Wagner and Thomson M. Whitin. Dynamic Version of the Economic Lot Size Model. *Management Science*, 5(1):89–96, 10 1958.

[69] Nengmin Wang, Jizhou Lu, Gengzhong Feng, Yungao Ma, and Huigang Liang. The bullwhip effect on inventory under different information sharing settings based on price-sensitive demand. *International Journal of Production Research*, 54(13):4043–4064, 2016.

[70] Nengmin Wang, Yungao Ma, Zhengwen He, Ada Che, Yufei Huang, and Jinpeng Xu. The impact of consumer price forecasting behaviour on the bullwhip effect. *International Journal of Production Research*, 52(22):6642–6663, 2014.

[71] Xun Wang and Stephen M. Disney. The bullwhip effect: Progress, trends and directions. *European Journal of Operational Research*, 250(3):691–701, 2016.

[72] Zhaodong Wang, Xin Wang, and Yanfeng Ouyang. Bounded growth of the bullwhip effect under a class of nonlinear ordering policies. *European Journal of Operational Research*, 247(1):72–82, 2015.

[73] Joakim Wikner, Denis R. Towill, and Mohamed M. Naim. Smoothing supply chain dynamics. *International Journal of Production Economics*, 22(3):231–248, 1991.

[74] Brent D. Williams and Travis Tokar. A review of inventory management research in major logistics journals: Themes and future directions. *The International Journal of Logistics Management*, 19(2):212–232, 2008.

[75] Xiaolong Zhang and Gerard J. Burke. Analysis of compound bullwhip effect causes. *European Journal of Operational Research*, 210(3):514–526, 2011.

[76] Saad Zighan. Managing the great bullwhip effects caused by COVID-19. *Journal of Global Operations and Strategic Sourcing*, 2021.

[77] Giulio Zotteri. An empirical investigation on causes and effects of the Bullwhip-effect: Evidence from the personal care sector. *International Journal of Production Economics*, 143(2):489–498, 2013.

Glossary

List of Acronyms

MPC	Model Predictive Control
VSC	Valtris Specialty Chemicals
BWE	Bullwhip Effect
RBP	Reversed Bullwhip Effect in Pricing
SCM	Supply Chain Management
P&G	Procter & Gamble
GA	Genetic Algorithm
MS	Master Schedule
MPS	Master Production Schedule
MRP	Material Requirements Planning
BOM	Bill of Materials
EDLP	Every-Day-Low-Pricing

List of Symbols

Abbreviations

λ	Relative price level
ω	Natural frequency
Π	Accounting profit
C	Inverse of convenience yield
I_{dem}	Excess demand volume
I_{fp}	Relative finished products volume from production
I_{net}	Net relative flow of goods into inventory
I_{proc}	Procurement controller relative procurement volume
I_{prod}	Production controller relative production output volume
I_{rm}	Relative raw materials volume to production
I_{sup}	Excess supply volume
k	Discrete time
k_D	Derivative controller gain
k_I	Integral controller gain
k_P	Proportional controller gain
L	Inverse of price elasticity of supply
N	Length of prediction horizon
n	Weight ratio of raw materials to finished products in production
q	Relative stock level
R	Appreciation rate
T	Sampling time
t	Time
u	Control input
V_{conv}	Convenience of holding inventory
V_{fp}	Internal finished products price change
V_{pri}	Pricing controller price adjustment
V_{prop}	Proportional price adjustment
V_{rm}	Internal raw materials price change
V_{sup}	Total raw materials price change
w	Disturbance input
y	System output