System Dynamics Modelling, Analysis and Design of Assemble-to-Order Supply Chains

by

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Abstract

Background and purpose: The assemble-to-order supply chains (ATO) is commonly-adopted in personal computer (PC) and semiconductor industries. However, the system dynamics of PC and semiconductor ATO systems, one of the main sources of disruption, is not well-explored. Thereby this thesis aims to 1) develop a nonlinear system dynamics model to represent the real-world PC and semiconductor ATO systems, 2) explore the underlying mechanisms of ATO system dynamics in the nonlinear environment and 3) assess the delivery lead times dynamics, along with bullwhip and inventory variance.

Design/methods: Regarding the semiconductor industry, the Intel nonlinear ATO system dynamics model, is used as a base framework to study the underlying causes of system dynamics. The well-established Inventory and Order based Production Control System archetypes, or the IOBPCS family, are used as the benchmark models. Also, the IOBPCS family is used to develop the PC ATO system dynamics model. Control engineering theory, including linear (time and frequency response techniques) and nonlinear control (describing function, small perturbation theory) approaches, are exploited in the dynamic analysis. Furthermore, system dynamics simulation is undertaken for cross-checking results and experimentation.

Findings: The ATO system can be modelled as a pull (order driven) and a push (forecasting driven) systems connected by the customer order decoupling point (CODP). A framework for dynamic performance assessment termed as the 'performance triangle', including customer order delivery lead times, CODP inventory and bullwhip (capacity variance), is developed. The dynamic analysis shows that, depending on the availability of CODP inventory, the hybrid ATO system state can be switched to the pure push state, creating poor delivery lead times dynamics and stock-out issues.

Limitations: This study is limited to the analysis of a closely-coupled two-echelon ATO systems in PC and semiconductor industries. Also, the optimization of control policies is not considered.

Practical implications: Maintaining a truly ATO system state is important for both customer service level and low supply chain dynamics cost, although the trade-off control design between CODP inventory and capacity variance should be considered. Demand characteristics, including variance and mean, play an important role in triggering the nonlinearities present in the ATO system, leading to significant change in the average level of inventory and the overall transient performance.

Originality / value: This study developed system dynamics models of the ATO system and explored its dynamic performance within the context of PC and semiconductor industries. The main nonlinearities present in the ATO system, including capacity, non-negative order and CODP inventory constraints, are investigated. Furthermore, a methodological contribution has been provided, including the simplification of the high-order nonlinear model and the linearization of nonlinearities present in the ATO system, enhancing the understanding of the system dynamics and actual transient responses. The ‘performance triangle’ analysis is also a significant contribution as past analytical studies have neglected customer order lead time variance as an inclusive metric.

Publications

<u>Lin, Junyi</u>, Naim, Mohamed Mohamed. 2019. Why do nonlinearities matter? The repercussions of linear assumptions on the dynamic behaviour of assemble-to-order systems. *International Journal of Production Research.* In press: 10.1080/00207543.2019.1566669.

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Notation for Intel Assemble-to-Order system

A_G	Gross assembly completion rate	**MS**	Market share
A^*_G	Desired A_G	**pull A_G**	Governs A_G in pull mode
A_N	Net assembly completion rate	**push A_G**	Governs A_G in push mode
A^*_N	Desired A_N	**S**	Actual shipments
AWIP	Assembly work in process	**S***	Desired shipments
AWIP*	Desired AWIP	**S_{MAX}**	Feasible shipments
$AWIP_{ADJ}$	AWIP adjustment	**WOI^***	Desired weeks of Inventory $=T_{OP} + T_{SS}$
B	Backlog	**WS**	Wafer starts =WS*
ADI	Actual die inventory	**WS***	Desired wafer starts
B*	Target backlog	**WS_N^***	Desired net WS
B_{ADJ}	B adjustment	**Y_D**	Die yield
D	Actual order	**Y_L**	Line yield
D_i^*	Desired die inflow	**Y_U**	Unit yield
DD*	Desired delivery delay	**T_{DAdj}**	Forecasting smoothing constant
Di	Die completion rate	**T_A**	Assembly time
DPW	Die per wafer	**T_B**	Time to adjust backlog
ED	Long-term demand forecast	**T_{AWIP}**	Time to correct AWIP discrepancy
ES	Expected shipments	**T_F**	Fabrication time
F_G	Gross fabrication rate	**T_{FGI}**	Time to adjust FGI discrepancy
FGI	Finished goods inventory stock	**T_{FWIP}**	Time to adjust FWIP discrepancy
FGI*	Target FGI	**T_{OP}**	Information process time (Delay before shipments)
FGI_{ADJ}	FGI adjustment	**T_{SAdj}**	Shipping smoothing constant
FWIP	Fabrication work in process	**T_{SS}**	Safety stock coverage
FWIP*	Desired FWIP	**$FWIP_{ADJ}$**	FWIP adjustment

Notation for the generic Personal Computer Assemble-to-Order system

$AINV_{AS}$	CODP inventory at VMI hub site	**τ_A**	Time to average consumption
$AINV_{SA}$	CODP inventory at the supplier site	**τ_{AS}**	Transport delay for CODP inventory between the supplier site and VMI hub site
$AINV^*_{AS}$	Desired AINVAS level	**Pull $ORATE_{AS}$**	Desired $ORATE_{AS}$
$AINV^*_{SA}$	Desired AINVSA level	**Push $ORATE_{AS}$**	Maximum $ORATE_{AS}$
AVCON	Averaged consumption rate	**SH**	Actual shipment rate
BL	Backlog level	**SH***	Desired SH rate
BL*	Target backlog level	**SH_{MAX}**	Maximum shipment rate
BL_{ADJ}	Backlog adjustment	**τ_{AINV}**	Time to adjust $AINV_{SA}$ discrepancies
CODP	Customer order decoupling point	**τ_{BL}**	Time to adjust backlog discrepancies
CONS	Customer demand rate	**τ_I**	Time to adjust $AINV_{AS}$ discrepancies
$COMRATE_{AS}$	Final assembly completion rate	**τ_{WIP}**	Time to adjust WIP discrepancies
$COMRATE_{SA}$	Personal computer (PC) component completion rate	**τ_{DD}**	Order processing and transport delay in sub-assembly echelon
WIP	PC component manufacturing work in process level	**τ_{SA}**	PC component manufacturing delay
WIP*	Desired WIP level	**s**	s transform operator
WIP_{ADJ}	WIP adjustment	**a**	Exponential smoothing coefficient
VMI	Vendor-managed inventory	**b**	First order smoothing coefficient (final assembly)
$ORATE_{AS}$	Order rate for the replenishment of VMI inventory	**LT**	Delivery lead-time
$ORATE_{SA}$	Order rate for PC component manufacturing		

Other Notations

IOBPCS	Inventory and Order Based Production Control System
VIOBPCS	Variable Inventory and Order Based Production Control System
APIOBPCS	Automatic Pipeline, Inventory and Order Based Production Control System
APVIOBPCS	Automatic Pipeline, Variable Inventory and Order Based Production Control System

Chapter 1. Introduction

This chapter establishes the context of this thesis by outlining the main research motivations, which include theoretical justification and practical problems identified in two fields: *assemble-to-order (ATO) system* and *system dynamics*. More detail on both research areas and a full review of relevant research can be found in Chapter 2: Literature review. Based on the literature review and gaps identified, the research questions that emerged will be presented in Section 1.2. Section 1.3 reports the thesis roadmap, illustrating how chapters link with the research questions.

1.1. Research motivation

An increasing number of successful businesses have moved from mass production to mass customisation, and their supply chain strategies have become more customer-driven or even customer-centric (Wortmann et al., 1997; Potter et al., 2015; MacCarthy et.al. 2016; Wu et al. 2017) instead of product driven. Strategic advantages of mass customisation and delayed differentiation, that is, providing customised products and services that fulfil each customer's idiosyncratic needs without considerable trade-offs in cost, delivery and quality, are well-recognized (Liu et al., 2006; Squire et al., 2006; Sandrin et al., 2014). Manufacturing companies that benefit from these advantages manage to deal with the challenge of balancing their demand and supply. A useful way to consider the gradations of customisation possible, developed to facilitate control over the flow of goods, is offered by the customer order decoupling point (CODP) (Gosling et al., 2017). CODP refers to the point in the supply chain that provides a strategic buffer to absorb fluctuation customised orders and smoothing production rate (Naylor et al., 1999; de Kok and Fransoo, 2003). The upstream activities of CODP are characterised by speculative, aggregated and standardised production, while for the downstream of CODP, activities are typically predictable, attached to known orders, individualised and customised (Lampel and Mintzberg, 1996; Olhager, 2003; Rudberg and Wikner, 2004).

Depending on the CODP, different types of supply chains can be defined. These range from speculative "make-to-stock" (MTS) supply chains to highly customised "engineer-to-order" (ETO) structures (Hoekstra and Romme, 1992; Olhager, 2003; Gosling et al., 2007; Gosling et al., 2017). Among these supply chain strategies, the assemble-to-order (ATO) system has been well-recognised and implemented in many industries, including electronic consumer (Gupta and Weerawat, 2006), semiconductor (Lin et al., 2017) and the automobile industry (Choi et al., 2012), to name but a few. ATO supply chains refers to the strategy that combines Make-to-Order (MTO) delivery downstream and Make-to-Stock (MTS) production upstream of the CODP in the final assembly plant (Wikner et al., 2017). Given the attractiveness of the ATO strategy for companies, including increasing product variety, achieving quick response time and low cost, and benefiting from potential risk-pooling (Benjaafar and Elhafsi, 2006; Elhafsi, 2009; Elhafsi et al., 2015; ElHafsi et al., 2018), academics and practitioners have become increasingly interested in analysing ATO systems.

Despite the potential advantages, ATO supply chains suffer severely from system dynamics under the volatile conditions of the business environment, triggered by globalisation, the adoption of optimisation management practices (e.g. reducing inventory, decreasing the number of suppliers and outsourcing); and the increasing tendency of mass customisation for creating competitive advantage (Amaro et al., 1999). Dynamic characteristics, particularly the bullwhip effect (Lee et al., 1997), are considered the main sources of disruption in the business world (Christopher and Peck, 2004; Ivanov et al., 2016; Wang and Disney, 2016; Spiegler and Naim, 2017). The bullwhip effect refers to a phenomenon in which low variations in demand cause significant changes in upstream production for suppliers, with associated costs such as ramp down and ramp up machines, hiring and firing of staff and excessive inventory levels (Wang and Disney, 2016). As a result, ATO supply chains are considered within the context of system dynamics in this thesis.

1.1.1. General research scope: ATO system dynamics in Personal Computer and semiconductor industries

The Personal Computer (PC) and associated semiconductor industries have widely accepted the ATO order fulfilment strategy, due to the development of PC components modularity technology. As a result, companies can benefit from a competitive balance between agility (customer responsiveness) and leanness (cost efficiency). e.g. Dell (Zhou et al., 2014), Hewlett-Packard (HP) (Su and Ferguson, 2005), Intel (Lin et al., 2017) and IBM (Chen et al., 2012).

However, a serious issue that PC and semiconductor industries suffer is the poor control of supply chain dynamics (Karabuk and Wu, 2003; Gonçalves et al., 2005; Li and Disney, 2017; Vicente et al., 2017; Lin et al., 2017) due to great uncertainty driven by reduced product life cycles, unpredictable and customised demand, wide product variety due to overlapping product life cycles for different customers and long fabrication lead times and complex production processes (Geng and Jiang, 2009). In this thesis, control uncertainty (Mason-Jones and Towill, 1998; Towill and Gosling, 2014) is considered, which refers to the uncertainty resulting from the effort to cope with other uncertainties (e.g. supply, demand, process uncertainties). These control mechanisms are often employed in the *ordering system structure* including: forecasting; inventory and production; batching; information sharing policies; and so on. Control uncertainty is well recognised as the main source of supply chain dynamics (Burbidge, 1961; Sterman, 1989; Lee et al., 1997; Towill et al., 1997; Towill and Gosling, 2014; Naim et al., 2017). The corresponding dynamic issues, including the bullwhip effect, inventory variance and customer delivery time dynamics, may lead to a significant impact on operational costs and customer service levels (Ouyang and Daganzo, 2006; Wang and Disney, 2016).

For instance, in the PC sector, a serious issue customers may frequently experience is the long delivery delay in shopping for their customised PC products due to a shortage in the CODP inventory, i.e. insufficient required PC components for immediate final assembly and delivery; for example, as illustrated in Figure 1, customers need to wait for more than four weeks to receive PC products if they prefer to customise the Lenovo ThinkPad P51S by their official websites.

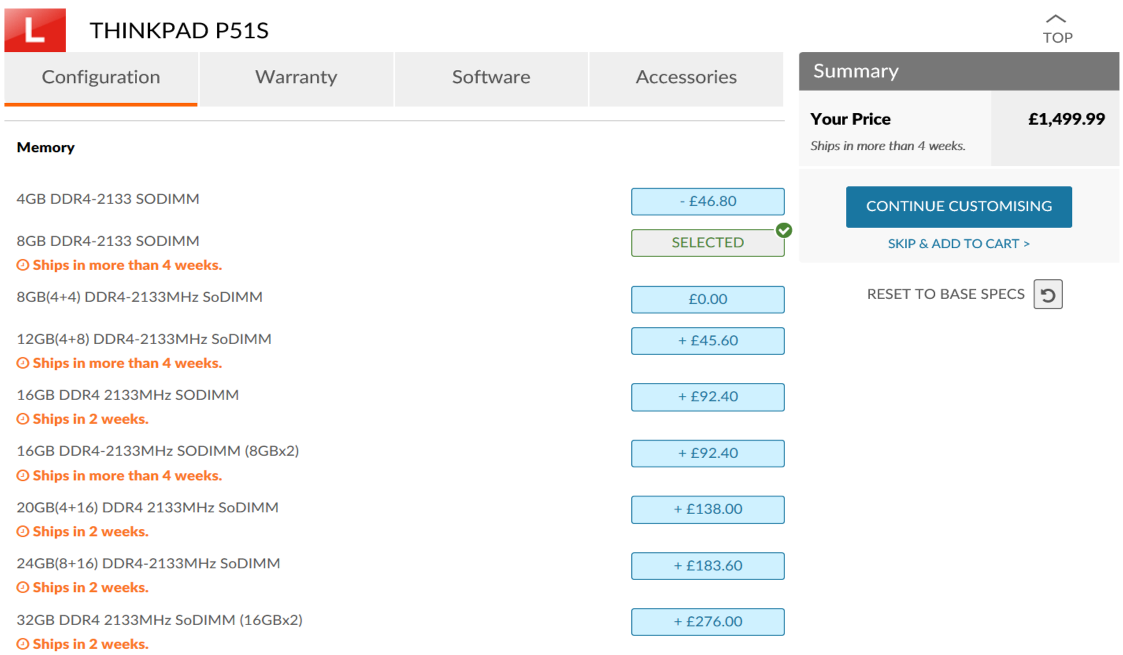


Figure1. 1. The screenshot for the online customisation of Lenovo ThinkPad P51S.

Source: https://www3.lenovo.com/gb/en/laptops/thinkpad/p-series/Thinkpad-P51s/p/20HBCTO1WWENGB0/customize.

Although the PC and semiconductor industries suffer severely from poor supply chain dynamics, few studies have explored the impact of ATO ordering structures on dynamic performance. Most present either linear-based analysis that is unable to represent the real-world nonlinear system (e.g. Wikner et al., 2007; Hedenstierna and Ng, 2011), or simulation-based analysis that lacks the analytical insights of ATO ordering system design and improvement (Gonçalves et al. 2005; Wikner et al., 2017). Consequently, ***the overall aim of this thesis is to systematically assess the impact of the ATO ordering structure on dynamic performance by offering a non-linear control engineering procedure for the design, modelling and analysis of ATO ordering systems.***

In this thesis, the author focuses on the system dynamics of the ATO system at an aggregate/single product level. The single-product ATO systems are studied by Glasserman and Wang (1998), Gallien and Wein (2001), Song and Yao (2002), Benjaafar and ElHafsi (2006) and Xu and Li (2007), to name but a few. Although in practice, PC and semiconductor companies offer a variety of customized products by a number of commodity components, the study of the ATO system dynamics based on a single product and a single component setting provide the insight of an aggregate system dynamics. This assists the long-term strategic planning (e.g. capacity planning, labour expansion, inventory holding) and offers the benchmark of system dynamics performance for subsequent dis-aggregate dynamic modelling and analysis.

The following sections of this chapter illustrate the detailed research gaps and corresponding research questions to be addressed by this thesis.

1.1.2. Research gap one: theoretical foundations in analysing the ATO system dynamics

When confronted with system dynamics, control theory techniques with feedback thinking and sufficient analytical tools can be utilised for analysing system dynamics (Dejonckheere et al., 2003; 2004). The application of classic control theory in a production system can be traced back to Simon (1952). By adopting classic control theory, Towill (1982) translated Coyle's (1977) system dynamics work to represent the Inventory and Order based Production Control System (IOBPCS) in a block diagram form. John et al. (1994) then extended the original model to the automatic pipeline, inventory and order-based production control system (APIOBPCS) by incorporating an automatic work-in-progress feedback loop. These two original models and their variants, i.e. the IOBPCS family, have been recognised as a base framework for analysing the dynamics of production planning and control, as well as supply chain systems (Lin et al., 2017).

Although the IOBPCS family has been widely adopted over the last three decades in the academic and industrial communities, very limited research developed a system dynamics model of the ATO systems based on the IOBPCS architypes. This is due to most studies adopted the IOBPCS family model to study make-to-stock/forecasting-driven supply chain systems by focusing on bullwhip and inventory variance as two main dynamic performance indicators. Wikner et al., (2007) developed a simple order-driven system dynamics model based on the IOBPCS family without considering the forecasting-driven part and the the CODP inventory. Wikner et al., (2017) overcome the limitations by developing a hybrid system dynamics model including the make-to-order and make-to-stock parts. However, their study is limited to the theoretical modelling and exploratory analysis.

So, the first research gap lies in the theoretical foundation of the ATO system dynamics. Based on Lin et al. (2017)'s systematic review of the IOBPCS family, the author aims to synthesize all IOBPCS based studies by reviewing how the IOBPCS archetypes have been adopted, exploited and adapted to study supply chain dynamics. This provides the state-of-the-art theories and methodologies for modelling and analysing the ATO system dynamics.

It should be noted that, while Axsater (1985), Edghill and Towill (1989) and Ortega and Lin (2004) provided an overview of control theory applications in studying supply chain dynamics, up-to-date reviews are needed. Furthermore, Sarimveis et al (2008) presented the review of the IOBPCS family but their study is limited to the narrow review method, comparing Lin et al. (2017)'s IOBPCS review.

1.1.3. Research gap two: the underlying causes of supply chain dynamics in ATO systems.

After developing the system dynamics model of the real-world supply chain system, one challenge that researchers and practitioners face is to explore the underlying mechanisms of supply chain dynamics for high-order, nonlinear dynamic systems. The high-order system refers to a system represented by more than second-order differential/difference equations. A nonlinear system, on the other hand, is a system that does not obey the principle of superposition. This means that the output of a nonlinear system is not directly proportional to the input and the variables to be solved cannot be expressed as a linear combination of the independent parts (Atherton, 1975). High-order nonlinear supply chain systems lead to difficulty in understanding the root causes of supply chain dynamics due to the complexities of dealing with seemingly intractable mathematics. As Forrester himself noted in an interview: "The trouble with systems thinking, is it allows you to misjudge a system. You have this high-order, nonlinear, dynamic system in front of you as a diagram on the page. You presume you can understand its behaviour by looking at it, and there's simply nobody who can do that" (Fisher, 2005).

The analytical understanding of root causes of high-order nonlinear dynamic supply chain systems is rare in the literature, apart from Wikner et al. (1992), Jeong et al. (2000) and Spiegler et al. (2016b). Wikner et al. (1992) explored a simplification approach to understanding the causes of the bullwhip effect, while Jeong et al. (2000) applied a linearisation approach but with analysis totally reliant on simulation. In addition, Spiegler et al (2016b) further investigated Forrester's system dynamics model (Forrester, 1961) by using advanced nonlinear control theory and proposing some system structure simplification and linearisation methods to give analytical insights into managing system dynamics in supply chain systems. However, all studies focus on MTS-based systems without considering the order-driven system dynamics, such as ATO systems widely adopted in many industries. Furthermore, several studies implemented simulation to analyse complex, high-order, nonlinear supply chain models (Forrester, 1961; Wikner et al., 1991; Naim and Towill, 1994; Gonçalves et al., 2005; Shukla et al., 2009; Spiegler et al., 2016a). However, simulating complex systems without having first performed some preliminary analysis can be exhaustive and unrewarding (Atherton, 1975). Hence, non-linear there is a need to develop methods to identify the underlying mechanisms of supply chain dynamics when confronted with high order and nonlinear ATO systems structure, so that the corresponding mitigation strategies can be proposed.

1.1.4. Research gap three: delivery lead-time dynamics and nonlinearities

The IOBPCS family traditionally represents a typical production system in which its service level capabilities are determined by net stock variance and capacity availability, the latter of which is often referred to as 'bullwhip' (Sarimveis et al., 2008; Lin et al., 2017). However, limited effort has been made to model and analyse the time-oriented production systems. This is the case in the ATO system in which end customer delivery lead times directly relate to the customer service level, since most customers need to wait some time before receiving their customised products.

The reason that lead time dynamic performance is ignored in the IOBPCS literature is because the underlying assumption in most analytical studies is that the system is linear (Lin et al., 2017) and final customer delivery lead times can be disregarded and set as zero. This has significantly limited the applicability of published results and has made it difficult to measure end customer delivery lead times dynamic performance. The customer delivery lead times measure is especially important in the MTO element of ATO systems due to capacity constraints, where products cannot always be delivered within the planned lead times (Wikner et al., 2007).

Nonlinearities can naturally occur through the existence of physical and/or controllable constraints in supply chain systems. For example, physical nonlinearities include fixed and variable capacity constraints in the manufacturing and shipping processes, and variable delays, while the controllable nonlinearities involve the safety stock settings and manufacturing strategy change depending on foreign exchange rate directions. Recent works have analytically studied some forms of nonlinearities in supply chain systems, such as capacity (Jeong et al., 2010; Spiegler et al., 2016a; Spiegler et al., 2016b), on-negative order constraints (Wang et al., 2012; Wang et al., 2014; Wang et al., 2015) and shipment constraints (Spiegler et al., 2017). The authors identified the impact of different nonlinearities on the system dynamics, such as the bullwhip effect, in responding to cyclical demand with different means and frequencies. Also, some system structure simplification and linearisation methods are proposed for giving further analytical insights in managing system dynamics in supply chain systems. However, most analysis is limited to the single echelon system and is restricted to analysis of the different nonlinearities individually. Furthermore, all studies solely explore the dynamic performance of an MTS-based production-inventory control system by utilizing bullwhip and inventory variance as performance indicators. As far as is known, no previous work has analytically explored the nonlinear ATO system by incorporating end customer delivery lead times dynamics.

1.2 Research questions

In summary, the three distinctive but interrelated literature gaps are identified, as shown in Figure 1.2. The first lies within the supply chain modelling theory that IOBPCS family models need to be systematically reviewed to offer the foundation and benchmark for modelling, designing and analysing the ATO system dynamics performance. Second, methodologically, there is a need for developing linearisation and simplification method to gain deep insight into the dynamic property of system structure in facing a high order nonlinear ATO system dynamics model. Finally, the end customer delivery lead times dynamics and main nonlinearities present in the ATO system need to be analytically assessed.

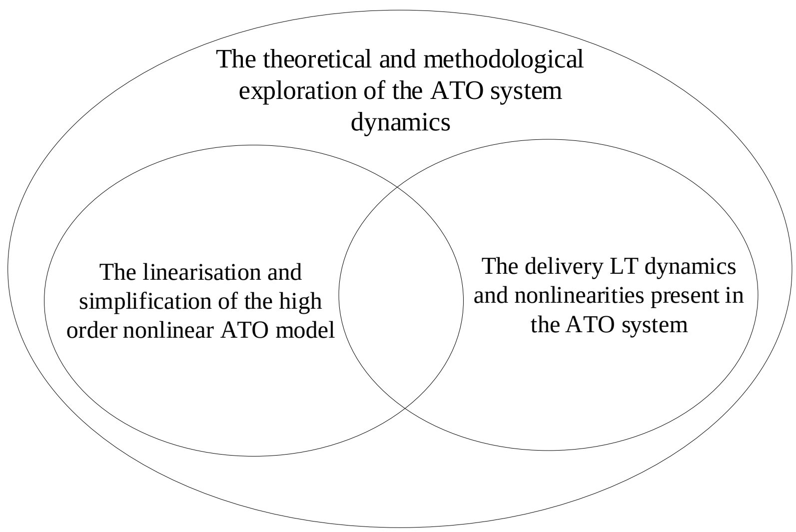


Figure1. 2. Research gaps identified in this thesis.

In order to provide a focus for this thesis, the following three research objectives and corresponding research questions have been formulated and are sought to be answered by this thesis:

Objective 1. Explore the theoretical foundation for studying the dynamics of ATO systems.

RQ1a. How may the IOBPCS family be utilised to study ATO system dynamics?

RQ1b. What kind of criteria can be utilised to assess the performance of the ATO system dynamics?

Objective 2. Dynamically design and assess the underlying causes of supply chain dynamics in ATO systems with the focus of physical nonlinearities and control policies, by utilising an existing semiconductor ATO system dynamics model.

RQ2a. How to design the nonlinear, high-order ATO supply chain to gain insight into its dynamic properties as personified by the Intel system dynamics model?

RQ2b. What are the underlying mechanisms of the dynamic behaviour in a semiconductor ATO supply chain and how can these dynamics be mitigated?

Objective 3. Explore delivery lead times dynamics and physical nonlinearities present in the Personal Computer ATO system by symmetrically modelling and analysing an ATO system

RQ3a. How to develop an ATO system dynamics model within the context of PC sector?

RQ3b. How to measure delivery lead times dynamics and how to analytically assess delivery lead times dynamics?

RQ3c. What are nonlinearities present in the PC ATO system and how do nonlinearities influence the dynamic performance of the ATO system?

1.3. Thesis roadmap

A brief overview of the structure of this thesis and how each chapter connects to each research question is provided in Figure 1.3. In summary, this thesis is organised in seven chapters and its contents can be summarised as:

Chapter 1: introduces the background of the fields of ATO system and system dynamics and presents the initial motivation for undertaking this research. Existing gaps in the literature are introduced and research questions are then formulated.

Chapter 2: conducts the literature review which provides an overview of previous research undertaken into the core themes of this thesis: ATO system and system dynamics. Moreover, this chapter defines the scope of this research and provides theoretical foundation for the thesis. The RQ1a, RQ1b, motivated by the fact that no IOBPCS based family model has been adopted for modelling the ATO system, will be answered and other gaps in the literature are identified, leading to the construction of RQ2a, RQ2b, RQ3a, RQ3b, RQ3c and RQ3d.

Chapter 3: outlines the methodology used to conduct this research, including the research ontological and epistemological positions, research design, methods and tools used. An objective, holistic and value-free view, and a deductive, logical reasoning and a conceptual research approach are chosen for undertaking this research. Control engineering and system dynamics simulation are the chosen techniques and the author reviews the linear and nonlinear control theory literature in order to identify suitable methods for the analysis of ATO system dynamics. Finally, the chapter introduces the two ATO models, including the existing Intel system dynamic model representing a typical ATO system in the semiconductor industry, as well as the general form of PC supply chains regarding their information and materials flow. Furthermore, the IOBPCS family of models is utilised as the benchmark models are introduced.

Chapter 4: analytically explores the underlying mechanisms of supply chain dynamics within the context of the semiconductor industry. The author uses the supply chain model of Intel, the leader in microprocessor manufacturing (Sampath et al., 2015), as reported empirically by Gonçalves et al. (2005), as a base framework to extract the simplified ATO supply chain by developing a linearisation and simplification method. Moreover, the simplified ATO model's dynamic behaviour is analysed and benchmarked with a well-established supply chain family of model archetype, the IOBPCS family.

Chapter 5: develop a generic two-echelon system dynamics model, consisting of a PC original equipment manufacturer (OEM) and a part supplier as an illustration of the typical hybrid ATO system, and explores the impact of ordering structure on dynamic performance. A linearisation method is developed for analytically assessing the end customer delivery lead times dynamics, and all main nonlinearities present in the ATO system are investigated regarding their impact on the ATO system dynamics performance.

Chapter 6: discusses insights gained from the literature review and research methods (Chapters 2 and 3), design and analysis of the semiconductor ATO system (Chapter 4), and modelling and analysis of a PC ATO system (Chapter 5). It also synthesises all findings in previous chapters to develop a framework for assessing the complex, nonlinear ATO systems from a system dynamics perspective.

Chapter 7: collates the findings from the analytical and simulation studies to provide summary answers to the research questions. In this chapter, the contributions of this research to the theory, methodology and practice is summarised. Finally, the limitations and potential lines for further investigation are discussed.

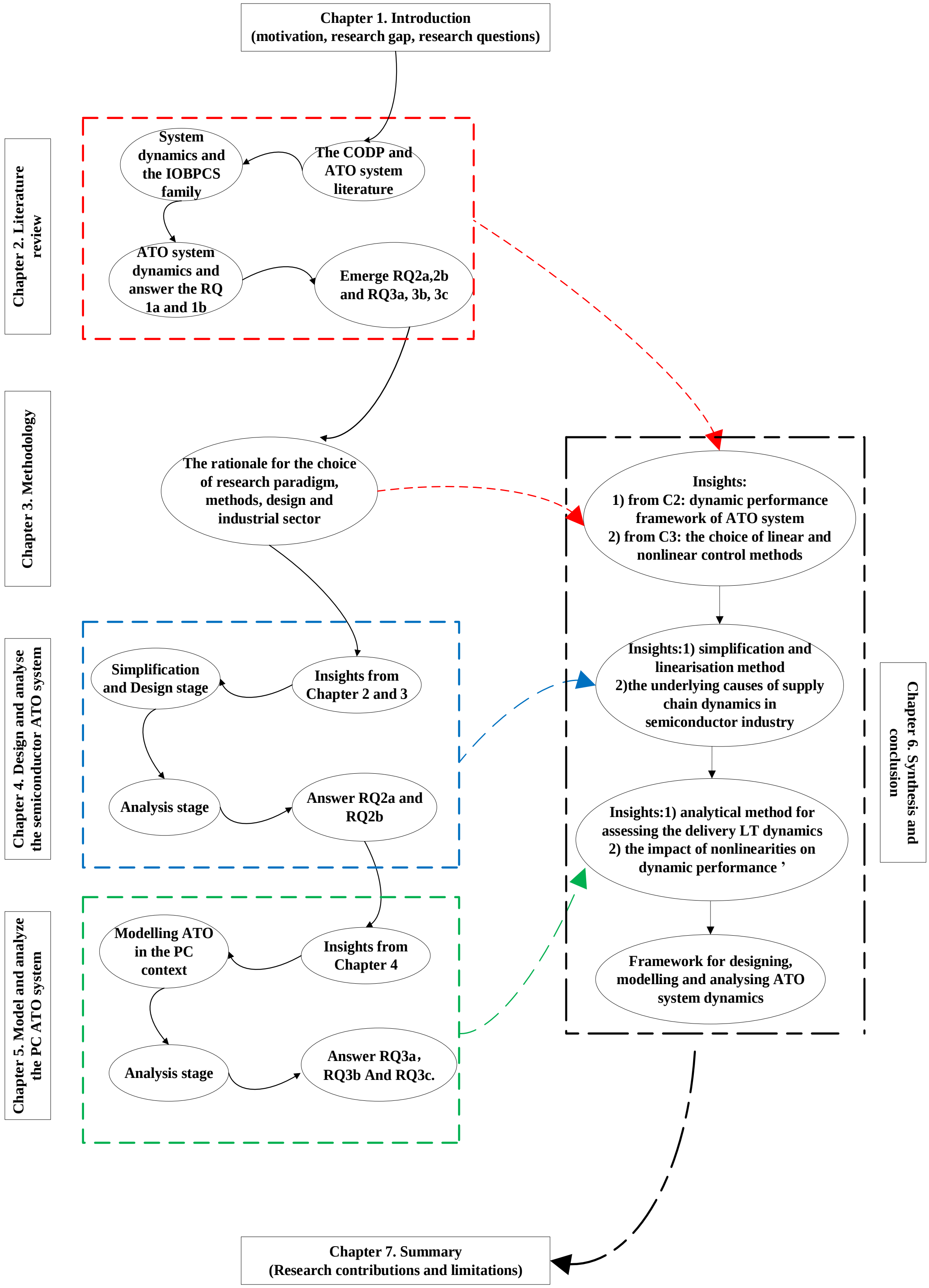


Figure1. 3. Thesis roadmap

1.4. Summary

This chapter has provided background information on the research theme, motivation and the research questions to be addressed in this thesis. The ATO system within the system dynamics context is focused. The structure of this thesis, including summative chapters and roadmap, is presented and explained. The next chapter will provide further context for the thesis through the literature review, as well as explain detailed literature gaps which this thesis seeks to address.

Chapter 2. Literature review

This chapter provides an overview of previous research undertaken into the core themes of this thesis: the ATO supply chain and the dynamics of supply chain systems. Due to the nature of this study, emphasis is given to the review of quantitative works that attempt to model, design, and measure the system dynamics of an ATO system.

The chapter consists of three major parts: 1) the CODP and ATO supply chains, 2) system dynamics and supply chain dynamics and 3) ATO supply chains within the context of system dynamics. To highlight the general location of the study, this chapter begins with a review of ATO systems within the broader supply chain management and CODP context. Then, Section 2.1.4 gives a detailed review of quantitative works for ATO systems, which summarise and establish the criteria of performance measurement in the general quantitative modelling context. Section 2.2 reviews the system dynamics and supply chain dynamics literature. Specifically, the history of system dynamics works within production planning and control is introduced in Section 2.2.1, followed by a detailed review of how the well-established production planning and control framework, the IOBPCS family, could be utilised to study supply chain dynamics.

The review provides theoretical foundations for modelling, designing and analysing the ATO system structure in this thesis. In particular, the most recent studies of nonlinearities by the IOBPCS family are reviewed in Section 2.2.3 to assist the choice of appropriate methods in analysing nonlinearities present in the ATO system. Finally, the review concentrates on system dynamics research in the context of ATO supply chains (Section 2.3) to highlight the previous studies and major gaps in addressing dynamic issues in the ATO system. As this thesis focuses on PC supply chains, the relevant ATO system dynamics works related to the upstream semiconductor industry and downstream OEM companies' supply chains are reviewed. Section 2.4 summarises the overall ATO system dynamics research gaps regarding theory and methodology.

2.1. ATO supply chains

2.1.1. Supply chains and cost-related performance

Ellram and Cooper's (2014) definition of a supply chain is commonly recognised as follows:

A supply chain is defined as a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer, (and return) (Mentzer et al., 2001, p. 4.).

The term "supply chain management", however, is relatively new in the literature, appearing first in 1982 (Oliver and Weber, 1982) to describe connecting logistics with other functions. The main aim of supply chain management is then to achieve balance between customer service, low inventory investment and low unit cost by synchronising customer requirement with the flow of materials from suppliers (Stevens, 1989); in other words, matching demand with supply in the most efficient and effective way.

The *total cost* is used to evaluate the financial performance of a supply chain. A general recognized strategy to reduce supply chain cost is to ensure the smooth flow of information and materials (Wikner et al., 1991). One of major challenge for supply chain management is the decision-making process, since the entire supply chain system cuts across different functional boundaries. For example, capacity investment impact on costs associated with inventory and order processing. Gunasekaran et al. (2001) developed a framework for measuring the supply chain performance at strategic, tactical and operational level. They presented a number of key performance metrics when dealing with suppliers, delivery, customer-service, and inventory and logistics operations in a supply chain, which is summarised in Table 2.1.

Type of supply chain cost	**Details**
Costs associated with the ordering process and supplier's relationship	1. For any company, the chain of business activities begins with the procurement of goods. The way the orders are generated and scheduled governs the performance of downstream activities and inventory levels. Supply chain response time can be reduced by decreasing the order cycle time (Gunasekaran et al., 2001). 2. On the other hand, order placement also generates cost. A number of transactions are needed every time for order placement, and this leads to the ordering costs for the company. The ordering cost includes order prepayment, supplier communication, delivery arrangement, payment, transaction record maintenance (Slack et al., 2010).
Costs associated with production	1. The next sequence is to produce the final products (e.g. manufacturing, final assembly) once orders are places and the goods are received. There are a lot of factors influencing the production cost, including labour and raw material cost, the variety and volume of products and service, throughput time, capacity utilization and maintenance, the effectiveness of the scheduling process etc. (Gunasekaran et al., 2001). 2. The production cost may also be increased driven by the high variation of production rate, such as ramps up and down machines (Towill, 1982).

Type of supply chain cost (continued)	Details
Costs associated with assets and return on investment	Supply chain assets include accounts receivable, plant, property and equipment, and inventories (Stewart, 1995). As the result, the cost related to each asset and their relations to the turnover should be measured to determine the productivity of a company (Gunasekaran et al., 2001). According to Stewart (1995), this can be measured as the average number of days required to transform the cash invested in assets into the cash collected from a customer.
Costs associated with delivery	1. Delivery performance can be measured by some key performance metrics, including the delivery channel, transport scheduling, and warehouse location play an important role in delivery performance (Gunasekaran et al., 2001). 2. The delivery performance also directly relates to customer satisfaction and the corresponding loyalty cost, especially in order-driven supply chain systems, such as MTO and ATO systems where every customer needs to wait before receiving their customised products

Table 2. 1. Description of different types of supply chain cost (Gunasekaran et al. 2001)

2.1.2. Mass customisation and CODP

It can be argued that customers (end consumers as well as industrial customers) put two major pressures on many companies (Rudberg and Wikner, 2004). First of all, many customers want products to fit their specific needs. Second, customers are not willing to pay high premiums for these customised products compared to competing standard products in the market. This new manufacturing environment has opened the doors for so-called mass customisation. Although mass customisation has been given many definitions in recent years, Kaplan and Haenlein's (2006) perspective is adopted here, in which mass customisation is a strategy that offer customized products at the mass-produced goods price through certain firm-customer interaction at the manufacturing/fabrication/assembly stage of the operations level.

One of the key issues in manufacturing mass customised products is to determine the position of the CODP. The CODP is one application of decoupling thinking, in which the latter has a long historical background in business operations. To better utilise the personal limited resources, i.e. labour, the concept of the division of labour is introduced (Adam Smith, 1776). By using the example of pins, he referred to it as the practice of decoupling the (pin-making) process into different steps and assigning each step to a specific worker, thus significantly increasing the overall productivity of the factory. This approach has been further developed into a foundation for mass production in scientific management (Taylor, 1911) and Skinner's (1974) notion of plant-within-a-plant (PWP).

Going beyond individual resources, PWP advocates segmentation of a manufacturing facility both organisationally and physically into homogeneous units. Each PWP concentrates on particular manufacturing tasks with, for example, its own objectives, operating procedures, human management approach, and organisation structure. Drawing on the PWP concept and including the role of customer contact in organisation design, Chase and Tansik (1983) define decoupling as separating activities of a service organisation, physically or organisationally, and placing them under separate supervision. This approach to decoupling, including front-office and back-office activities, does not only involve the resource perspective of Smith, Taylor, and Skinner, but also adds the perspective of the customer and the creation of customer value in the processes.

In manufacturing operations, the contact point with the customer is a key issue for decoupling, particularly in relation to process adaptation, i.e. *customisation*. The interest in processes for customisation dates back to at least the quality management movement, e.g. Deming (1982). This is when the actual transformation process was explicitly emphasised and consequently the resources mainly played a role as executors of the processes. In this context, the transformation process relates the resources to the needs of the customers, which is in line with the foundations of approaches such as lean thinking (Womack and Jones, 1996). From a process perspective, the driver that triggers the execution of a process is a key attribute. The process-based approach to early decoupling thinking highlighted the importance of placing inventory at key positions to decouple the flow related to the driver of the flow (see e.g. Hoekstra and Romme, 1992). This approach to decoupling thinking has been well established in the operations and supply chain literature, which has been reflected in manufacturing based concepts such as CODP, order penetration point (OPP), push-pull boundary, postponement and leagility (e.g. see Sharman, 1984; Giesberts and van der Tang, 1992; Hoekstra and Romme, 1992; Naylor et al., 1999; Chopra and Meindl, 2004; Kellar et al., 2016).

The CODP is an important consideration in structuring and configuring supply chains so that total value can be delivered to the end customers (Naylor et al., 1999). The exact position of the CODP is a balancing process between the market, inherent product properties and process related factors (Olhager, 2003). The key concept here is that the CODP is a point (Olhager and Östlund, 1990; Pagh and Cooper, 1998; Chopra and Meindl, 2004; Liu et al., 2015; Calle et al., 2016; Liu et al., 2016) where the organisation or the supply chain switches from producing to a forecast, i.e. forecasting driven (FD) and starts producing directly to a customer order, i.e. the service based customer driven (CD) (Wikner et al., 2017).

Specifically, two aspects of the CODP can be further highlighted based on the focus on the customer as the driver of the process (Wikner et al., 2017):

1) CODP as the buffer point: upstream of the buffer point, the production process, can benefit to the advantage of the bottleneck. In this way, the upstream production does not have to deal with fluctuating demand and a variety of different products. The corresponding inventory level and capacity can be determined by the aggregate demand (e.g. Hoekstra and Romme, 1992; Pagh and Cooper, 1998; Wikner et al., 2017). These strategies can reduce risk by pooling the variance of demand and is analogous with the concept of inventories centralisation (Eppen, 1979).
2) Differentiation or Customisation Point: here the CODP is described as the point where a good is produced for a specific customer order (Hoekstra and Romme, 1992; Pagh and Copper, 1998; Vanteddua and Chinnamb, 2014; Wikner et al., 2016). In this context, different production strategies can be classified based on different positions of CODP, e.g. assemble to order, make to stock, engineering to order, etc.).

Furthermore, Mason-Jones and Towill (1999) introduced the difference between the actual CODP driver and information driver regarding the Information Decoupling Point (IDP). Such a concept was later defined to as Demand Information Decoupling Point (DIDP) by Wikner (2014), which distinguish IDP from information decoupling related to availability of supply information, such as available capacity. The available capacity related information may directly assess to the load of resources at a supplier. Olhager et al. (2006) further investigate the relation between CODP and DIDP in relation to the Fisher model (Fisher, 1997). They recommend the position of the DIDP in relation to CODP and the concept of mediate demand (the undistorted demand information) was introduced, as illustrated in Figure 2.1. Since the CD flow is based on actual customer orders, so it is necessary to position the DIDP upstream of the CODP, or at least at the CODP. If the DIDP is positioned upstream of the CODP the forecast used for the FD flow can be improved due to the more transparent and up-to-date point-of-sales data.

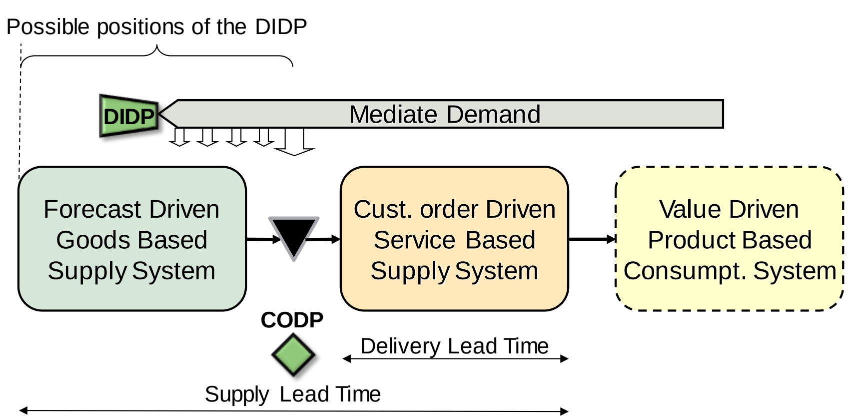


Figure 2. 1. Framework for structural modelling using decoupling points (Wikner et al., 2017).

2.1.3. An overview of the ATO supply chain system

As discussed in Section 2.1.2, depending on customisation or CODP point as defined in Section 2.1.2, different types of supply chains can be categorised. These range from very repetitive "make-to-stock" (MTS) supply chains to a very customised "engineer-to-order" (ETO) structure (Hoekstra and Romme, 1992; Olhager, 2003; Gosling et al., 2007; Gosling, 2017), as illustrated in Figure 2.2.

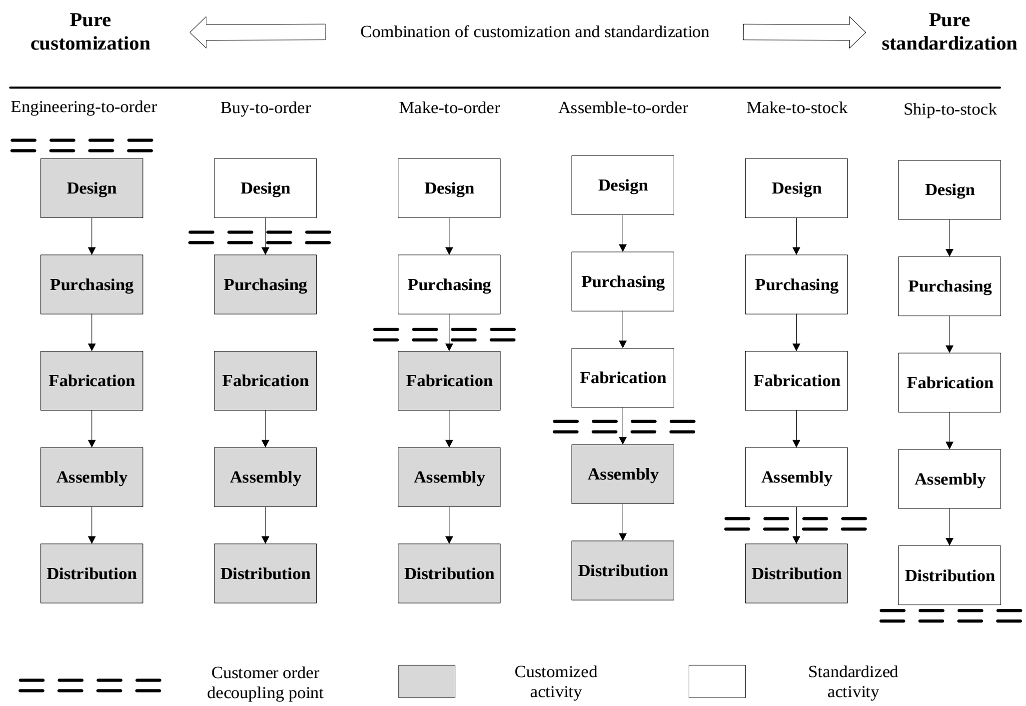


Figure 2. 2. The family of supply chain structure based on the position of CODP. Adapted from Gosling et al. (2017).

One of the most popular strategies, particularly in the high-tech, automotive and white goods manufacturing (ElHafsi et al., 2018), is the assemble-to-order (ATO) strategy, in which the CODP is located in the final assembly plant. Wemmerlöv's (1984, p. 348) definition of ATO manufacturing is adopted in this thesis:

ATO manufacturing is a strategy for which standard parts, components, and subassemblies are acquired or manufactured according to forecasts, while schedules for remaining components, subassemblies, and final assembly are not executed until detailed product specifications have been derived from booked customer orders

The ATO system, as illustrated in Figure 2.3, contains several components or subassemblies and multiple end products. The overall manufacturing process consists of two steps: component production (or procurement) and product assembly. Components are assembled into end products only after orders are placed by customers (ElHafsi et al., 2018). Such strategy is particularly attractive for those firms involving the supply chains with long component production (or supply) lead times and relatively short assembly time. The customer response time, as the result of ATO implementation, can be reduced through holding inventory of components ahead of demand and delaying final assembly of products until order is placed.

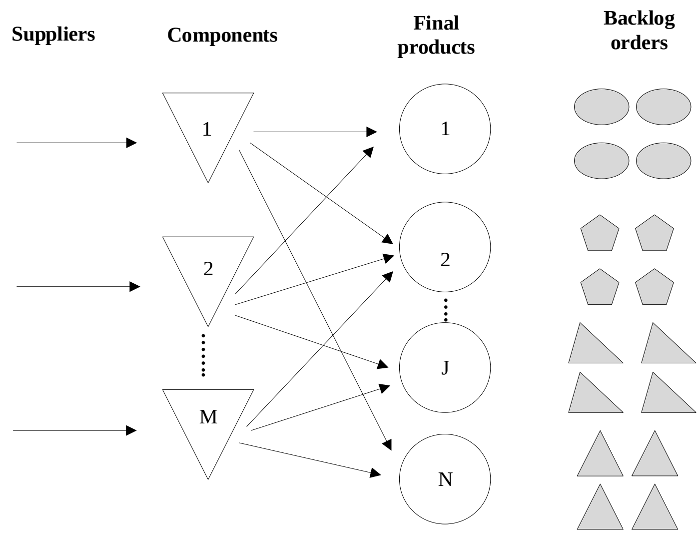


Figure 2. 3. The ATO systems.

It should be noted that a configure-to-order (CTO) (Song and Zipin, 2003) or build-to-order (BTO) system (Gunasekaran and Ngai, 2005) is a special case of the ATO strategy. The components are partitioned into subsets and the customer selects components from those subsets. A computer, for example, is configured by selecting a processor from several options, a monitor from several options, and so on. The difference between a CTO system and an ATO system is important at the demand-elicitation level. CTO is oriented from a one-of-a kind paradigm but is based on a pre-determined variety in which a low volume of products of a pre-determined high variety is manufactured using a cluster of components, whereas this is not the case in ATO, as the variety of product is not pre-determined (Gunasekaran and Ngai, 2005). At the operational level, however, the differences are minor. One well-known CTO system is Dell Computers. Dell lets the customer select among several processors, graphics monitors, disk drives, etc. – these are the components. Thus, Dell offers a huge combination of options (pre-determined variety of products) for end customers to customise their PC products. As a compromise, customers need to wait a certain amount of time before receiving their customised PC due to Dell only processing, finally assembling and delivering those customised products after receiving orders from customers. The performance assessment of the ATO system, based on supply chain cost metrics, demonstrated in Table 2.2, can be categorised as the following four elements: cost related suppliers/raw materials; cost related asset/component inventory; cost related production (component production and final assembly); and cost related delivery.

Cost-related ATO performance criteria	**Details and references (e.g.)**
Suppliers/raw materials	Supplier disruption, technology innovation (Rosling, 1989; Xu and Li, 2007; Shao and Dong, 2012)
Assets	CODP component inventory performance e.g. fill rate (Dayanik et al., 2003; Gao et al., 2010; Bušic et al., 2012); Inventory cost and product pricing (Feng et al., 2008; Keblis and Feng, 2012); Backlog cost/ Component inventory shortage cost (Benjaafar and Elhafsi, 2006; Elhafsi, 2009; Elhafsi et al., 2015)
Production	Limited final assembly capacity (Fu et al., 2006b, Inman and Schmeling, 2003) and Exogenous and endogenous production lead time (Benjaafar and Elhafsi, 2006; Cheng et al., 2011; Elhafsi, 2009; Elhafsi et al., 2015)
Time	Delivery lead time and order-based fill rate (Zhao, 2009; Lu et al., 2005; DeCroix et al., 2009); Delivery lead times related cost (Hsu et al., 2006; Hus et al., 2007; Fang et al., 2008).

Table 2. 2. General ATO performance criteria based on Gunasekaran et al.’s (2001) cost framework.

2.1.4. Stochastic studies of ATO supply chains

Due to the quantitative nature of this study, the author starts to review how the ATO systems can be quantitatively studied. Particularly the performance measures of the ATO system are reviewed to develop the assessment framework for exploring the dynamic performance of the ATO system. There are extensive literature focusing on the stochastic modelling, optimization and analysis of the ATO system and a briefly summary of recent works is presented in Table 2.2, although the full review can be found in Song and Zipkin (2003) and Atan et al. (2017).

Overall, in line with Gao et al. (2010) and Atan et al. (2017), the study of the ATO system from can be broadly categorized into two classes: one deals with periodic review models while the other deals with continuous review models. For each type of model, the study can be further classified as the single-end and multiple-end products depending on specific industries and products. The general purpose is to derive the optimal ordering decision making for the semi-finished components (i.e. CODP inventory), and possibly, the optimal component allocation decision making for multiple-end products based on specific objective functions (e.g. minimize inventory holding cost and backlog orders) and system constraints (e.g. limited final assembly capacity). The author summarizes those major performance metrics criteria utilized in the stochastic modelling and analysis literature in this section.

Specifically, the ATO system can be simplify described as a two-echelon production and assembly with one component inventory stock point system. For the supplier site, the possible impact of disruptions and technology innovation on the performance of ATO system usually are considered (Rosling 1989; Xu and Li 2007; Shao and Dong 2012). The production capacity availability, due to the constrained resources such as machines and raw materials, is also considered to influence the final optimal decision making. The researchers mainly consider the performance of CODP cost as the performance measure of ATO system, including inventory related cost such as the components inventory fill rate (Dayanik et al. 2003; Gao et al. 2010; Karaarslan et al. 2013; Bušic et al. 2012) and key components availability (Iravani et al. 2003), time related cost, e.g. components delivery lead time between suppliers and final assembler, and pricing (Feng, Ou, and Pang 2008; Feng et al. 2008 and Keblis and Feng 2012). The final delivery is another major metric for evaluating the ATO system performance, particular in the continuous review models, including delivery lead time and backlog fill rate performance (Zhao 2009; Lu et al. 2005; DeCroix et al. 2009). To conclude, there are four major metrics utilized for evaluating the ATO system performance, including delivery lead time, component (CODP) inventory, production/final assembly capacity and pricing from the stochastic modelling and analysis perspective.

To conclude, there are four major metrics utilized for evaluating the ATO system performance, including delivery lead time, component (CODP) inventory, production/final assembly capacity and pricing from the stochastic modelling and analysis perspective.

2.2. System dynamics and supply chain dynamics

2.2.1. A brief history of system dynamics and supply chain dynamics

Although the term SCM was first proposed by Oliver and Webber (1982) to designate a new form of strategic logistics management, the antecedents of *System Dynamics* are much older and appear to have originated with physical distribution and transport and are based on the discipline of Industrial Dynamics (1961), or what is now termed System Dynamics, the school of thought that relates system structures to dynamic behaviour in organisations. A fundamental principle of system dynamics is that … *feedback theory explains how decisions, delays, and predictions can produce either good control or dramatically unstable operation in nonlinear, complex systems* (Forrester, 1958).

Supply chain dynamics, however, refers to the design process of system dynamics in the supply chain context and expresses the need to integrate business processes and analyse supply chains from a holistic perspective. Researchers who advocate this view highlight the fact that improving a single echelon of the supply chain may not be able to improve the efficiency and effectiveness of the entire supply chain (Towill et al., 1992). An efficient supply chain system can only be designed and operated if the dynamic performance of the constituent parts is properly understood. Then the appropriate optimal control mechanism can be derived to balance the risk of stock-out and the cost of production fluctuation (Towill, 1982). Through the observation of real industry cases and the modelling and simulation of scenarios (Hennet, 2009), supply chain dynamics have been used within SCM research to provide insights into supply chain dynamical behaviour and the underlying causal relationships (Wolf, 2008).

System dynamics issues in supply chains are considered to be the main sources of disruptions in the business world (Christopher and Peck, 2004) and has huge impact on the key performance metrics utilised to assess supply chain financial performance (Naim et al., 2017). As a result, it is claimed that to improve supply chain performance, dynamics caused by the system itself should be reduced (Torres and Maltz, 2010).

Forrester's (1958; 1961) seminal works pioneered system dynamics issues in supply chains, i.e. a production-inventory system. The well-known 'Forrester Effect' refers to two specific supply chain problems frequently occurring in dynamic systems:

- Demand amplification. Thanks to Lee et al. (1997), this is also known today as the bullwhip effect.
- Rogue seasonality

Where the former refers to the high demand amplification ratio in relation to actual customer orders, i.e. in practice a ratio of 2:1 across each business interface is commonplace (Towill, 1997), while rogue seasonality is the phenomenon where significant 'rogue' alternating boom and bust type orders have been introduced by the system structure itself, instead of blaming external market demand fluctuation, which is more likely to be caused by a system's decision-making, itself driven by the system structure. After Forrester's works, many studies have explored different types of supply chain dynamic issues, identified the major causes and proposed corresponding solutions. Table 2.3 summarises these findings over the last 57 years.

Phenomenon	**Sources**	**Methods for mitigation**
Demand amplification (Burbidge 1961)	Batching/Ordering policy	Time compression Control system
	Multi-phased, multi-period ordering	Synchronisation
Demand amplification observed by Beer Game (Sterman, 1989)	Human misperception (Wrong assumptions in decision-making e.g. forecasting)	Improve communication between parties and education
Bullwhip Effect (Lee et al. 1997)	Demand signal process	Information transparency
	Order batching	Lead time reduction/supply chain collaboration
	Fluctuating prices	Discount on assorted truckload
	Shortage gaming	Special purchase contract Allocate based on past sales
'Backlash' effect (Shukla et al. 2009)	Orders profile reflection	Capacity management Control system design

Table 2. 3. Supply chain dynamics issues, their causes and mitigating solutions.

At the operational level, Burbidge (1961) indicated that another source of demand amplification is economic order quantity (EOQ) related to the decision-making process such as scheduling, ordering policy and batching policy. Furthermore, Lee et al (1997a) proposed that price fluctuation and shortage gaming are two additional reasons that lead to the bullwhip. Furthermore, the famous Beer Game simulation model developed by Sterman (1989) clearly demonstrates that demand and information distortion can be created because of human misperception. He suggests that better education and communication between parties are means to reduce such a problem.

Later, Lee et al. (1997) termed the phenomenon of demand amplification experience by Procter and Gamble as the ‘Bullwhip effect’. They also claimed that the demand amplification can be created even under the rational behaviour. Four main causes of bullwhip effect were pointed out: demand signalling as per Forrester, order batching as per Burbidge, fluctuating prices and shortage gaming. The corresponding solutions include physical lead time reduction, replenishment policy control, smart pricing strategies, information transparency.

More recently, studies have attempted to describe and understand the distortions that also occur in freight transport activities. Shukla et al. (2009) identified the so-called ‘Backlash’ effect, which is a reflection of the ‘Bullwhip effect’ and can be seen as ‘reverse amplification’ firstly discussed by Holweg and Bicheno (2000) during their observation of an ‘amplified and distorted supply model’ in the steel industry.

2.2.2. The IOBPCS family

Among a number of methods and tools that have been developed to design and control supply chain dynamics, Simon’s (1952) control theory with feedback thinking has long been widely recognised. In 1994, through the adoption of a classic control engineering approach, John et al. (1994) developed the APIOBPCS archetype, which extended the original IOBPCS archetype (Towill, 1982) by incorporating an automatic work-in-progress (WIP) feedback loop. Hence, IOBPCS is a subset, or special case, of APIOBPCS, and the IOBPCS family refers to the two original models and all their variants. These two original models and their variants have been recognised as a framework for a production planning and control system, as they consist of general laws that represent many supply chain contexts, including the famous beer game decision-making heuristic (Sterman, 1989), the order-up-to (OUT) policy (Zhou et al., 2010) as well as various industrial applications (e.g. Coyle, 1977; Disney and Towill, 2005; Cannella et al., 2011).

Based on Lin et al.'s (2017) systematic citations review of Towill (1982) and John et al. (1994) between 1982 and 2015, as well as an updated citations review to 2018, a summary of the review is presented in Figure 2.4. Specifically, the content of the reviewed papers was categorised into one of three types. The first type papers (116 citations) referred to passing citations that simply cite the two papers in order to increase the quality of the paper's main argument; thus, these will not be reviewed in this present study. A total of 113 papers (24 for second type papers and 89 for third type papers) that focus on the application of the IOBPCS family will be reviewed in detail in this paper. The second type category refers to papers that focus on one specific decision policy in the IOBPCS family: demand policy, inventory policy, lead time and pipeline policy. Three large clusters of papers emerge: Demand policy; Lead time/WIP; Inventory policy. The third type papers are those that used the complete APIOBPCS model to offer insights into dynamic behaviour or to represent specific supply chain scenarios (extension of the APIOBPCS model). These papers were then subcategorised based on four main elements of a control engineering system: sensing, assessing, selecting and acting (Fowler, 1999; Robson, 2004), due to the analogy between mechanical control systems and a supply chain system (Simon, 1952).

Regarding second type papers, a larger number of studies focus on lead time / WIP and their findings highlight that forecasting has a direct impact on bullwhip generation (e.g. Li et al., 2014; Dejonckheere et al., 2002, 2003b), while lead-time visibility is essential to designing a high-quality production/distribution control system (e.g. Mason-Jones et al.,1997; Towill et al., 1997; Riddalls and Bennett, 2002b; Wikner, 2003; Wilson, 2007; Disney and Towill, 2005; Aggelogiannaki and Sarimveis, 2008). Regarding the inventory control policy, the Proportional controller is most widely used and appears to reduce the bullwhip effect (e.g. White, 1999; Lin et al., 2003; Sourirajan et al., 2008; Chaudhari et al., 2011; Kumar et al., 2013), but the more complex proportional-integral (PI) and proportional-integral-derivative (PID) controllers received little attention in the literature.

Of papers focused on studies adopting the IOBPCS family as a whole system or extending it to study supply chain dynamics, during the sensing stage, various dynamic behaviours (the bullwhip effect, rogue seasonality, inventory resonance) were identified, e.g. Edghill et al. (1988); Ariffin (1992); Edghill and Towill (1990); Parsanejad et al. (2014); Hodgson and Warburton (2009); Shukla et al. (2012); Shukla and Naim (2015). Different criteria/sources of supply chain dynamics were then explored, including the stability property (Riddalls and Bennett, 2002a; Warburton et al., 2004; Venkateswaran and Son, 2007; Sipahi and Delice, 2010; Wang et al., 2012; Wei et al., 2013); batching (Potter and Disney, 2006; Hussain and Drake, 2011; Hussain et al., 2012) and price fluctuation effect (Naim, 2006; Naim et al., 2007; Campuzano Bolarin et al., 2011).

For the final action, the order-up-to (OUT) inventory replenishment (e.g. Disney et al., 2006a; Warburton, 2007; Csik et al., 2010; Cannella, 2014) rule was examined due to this policy's popularity in the industry. Moreover, the authors of the reviewed papers agreed that information sharing and supply chain collaboration are effective for bullwhip mitigation (e.g. Yang and Fan, 2014; White and Censlive, 2015a; Yang et al., 2011; Hosoda and Disney, 2012; Li et al., 2013), although many of the studies were theoretically-based and provided limited insights into the linear assumption for representation in a real system.

In summary, most studies utilize the IOBPCS family as a reference framework to model the MTS-based system where main elements, including forecasting, inventory feedback, delay (production and transport) and WIP inventory, are modelled and analysed. Bullwhip and inventory variance are used as main performance indicators for assessing the dynamic performance of the system, although backlog / orderbook metrics are assessed by several studies by extending the IOBPCS family (Wikner et al., 2007; Wikner et al., 2017). In general, time-oriented dynamic performance criteria from a customer perspective (e.g. delivery lead time) are not well-explored.

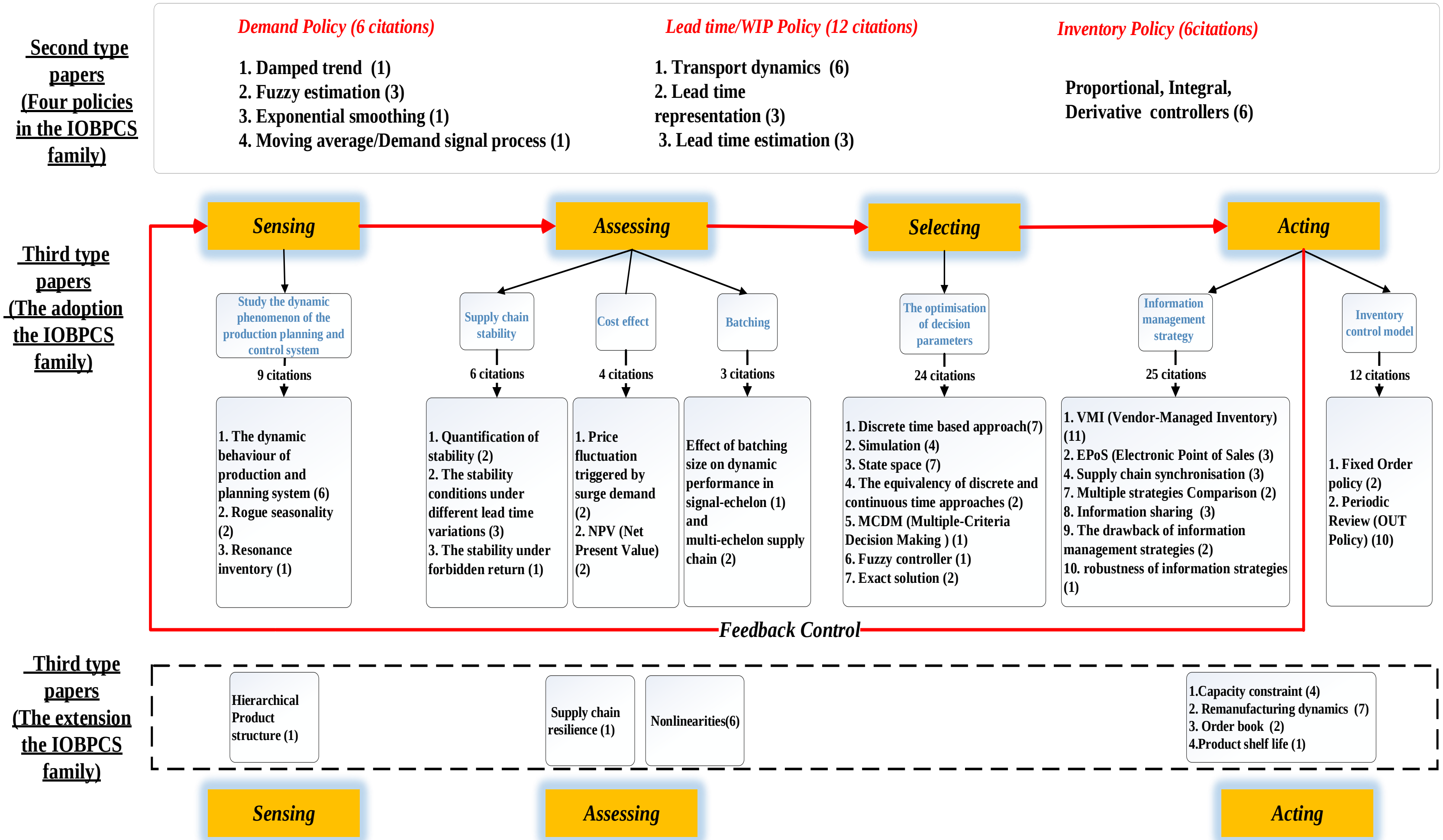


Figure 2. 4. Synthesis of the IOBPCS family in studying supply chain dynamics (extended from Lin et al., 2017)

2.2.3. The study of nonlinearities in the IOBPCS family

In addition to the impact of feedback loops and delays as the main sources of demand amplification as claimed by Forrester (1958), he also draws attention to the importance of considering nonlinear models to represent industrial and social processes. ‘Nonlinearity can introduce unexpected behaviour in a system’ (Forrester 1968), causing instability and uncertainty. In supply chain system structures, nonlinearities can naturally occur through the existence of physical and economic constraints; for example, fixed and variable capacity constraints in the manufacturing and shipping processes, variable delays and variable inventory constraints, to name but a few.

Capacity and non-negative order constraints are the two most common nonlinearities present in real-world supply chain systems and a number of simulation studies have analysed their impact. Regarding capacity constraints, Cannella et al. (2008) explored the relationship between constrained capacity and supply chain performance. Hussaina et al. (2015) analysed the influence of capacity constraint and safety stock on the bullwhip effect in a two-tier supply chain by using Taguchi experiment. Ponte et al. (2017) investigated the impact of capacity limit on bullwhip and fill rate in an OUT-replenishment policy environment. The general conclusion derived in the above studies are that the capacitated supply chains may benefit from an improved dynamic performance as compared to unconstrained ones, due to capacity limit acting as a production smoothing filter. However, Cannella et al. (2018) found that the capacity may negatively influence the supply chain performance under a load-dependent lead time environment, i.e. lead times modelled as a nonlinear function depending on the current work in progress (WIP) at the manufacturer and its capacity saturation limit and responsiveness (as the ability of the system in delivering the same product within a shorter lead time).

Several studies focus on the impact of demand smoothing and information sharing under non-negative order constraint supply chain systems (see Cannella et al., 2011; Cannella et al., 2014; Syntentos et al., 2011). They highlighted the benefit of demand smoothing and information sharing in reducing supply chain dynamics, but the non-negative order constraint is not studied in detail. Furthermore, Chatfield and Pritchard (2013) and Dominguez et al. (2015) conducted simulation studies regarding the impact of forbidden return policy on dynamic performance. The authors indicated that permitting returns significantly increases the bullwhip effect, and other factors, such as configuration of the supply chain network (serial vs. divergent) may play an important role in influencing the impact of non-negative order policy on supply chain dynamics (Dominguez et al., 2015).

Although many researchers offered a deep understanding of the impact of nonlinearities on supply chain dynamics, only simulation methods have been recommended to analyse nonlinear supply chain models. However, simulating complex systems without having first conducted some preliminary mathematical analysis can be exhausting and unrewarding, due to the trial-and-error nature of this approach that may hinder the system improvement process (Sarimveis et al., 2008, Lin et al., 2017). It is only recently that an emerging number of studies have adopted non-linear control engineering approaches to analytically explore the nature of different nonlinearities in ordering system structure. Table 2.4 gives a brief review of these works.

Although studies summarised in Table 2.4 contribute to an understanding of the effect of nonlinearities on the dynamic behaviour of the production-inventory system, there are several common limitations. Jeong et al. (2010) only use a simulation method to analyse the effect of different capacity constraints on the system dynamics behaviour, despite efforts to linearise a part of the model. Wang and Disney (2012), Wang et al. (2014) and Wang et al.'s (2015) studies are limited to analysis of the non-negative order constraint on the replenishment order. Although Spiegler et al. (2016a, 2016b) and Spiegler (2017) explore more complex nonlinearities, such as capacity and distribution shipment constraints, their analysis is limited to the single echelon supply chain system and to the analysis of different nonlinearities individually. Furthermore, all studies solely explore dynamic performance of MTS-based production control system by utilising bullwhip and inventory variance as main performance indicators. Despite the importance of time and order-based performance in the ATO system highlighted in Section 2.1.3, i.e. performance evaluation for the downstream part of the CODP such as backlog order and delivery lead times, no analytical work has explored the nonlinear ATO system from the system dynamics perspective by incorporating such performance metrics, although some papers have conducted simulation studies, e.g. Wikner et al. (2007) and Wikner et al. (2017). The following section provides a detailed review of system dynamics simulation works for the ATO/CODP-based systems.

Authors	The type of system	The assessment criteria	Control engineering methods	Key insights
Jeong et al. (2010)	MTS and Forrester Model	Stability, bullwhip and inventory variance	Matsubara time delay theorem; Small perturbation theory	Explore the effect of different capacity levels on the factory's production rate, unfilled orders.
Wang and Disney (2012) and Wang et al. (2014)	MTS (the order-up-to policy)	Bullwhip and Inventory variance	Eigenvalue methods	Explore the stability boundaries of a piecewise linear inventory control system (non-negative order constraint) and identify a set of behaviours in the unstable region.
Wang et al. (2015)	MTS (the order-up-to policy)	Bullwhip	Describing function	Identify the effect of non-negative order nonlinearity on the bullwhip effect in responding sinusoid demand, and propose strategies (forecasting, low ordering frequency) to mitigate bullwhip effect.
Wang and Gunasekaran (2017)	MTS and remanufacturing	Bullwhip and environmental dynamics	Taylor series expansion with small perturbation theory	Investigate the impact of production, environment, and demand variations on the dynamics and economic performance of sustainable supply chain systems. Their findings suggest that supply chain sustainability is essential to the continuous improvements of supply chain performance

Authors (Continued)	**The type of system**	**The assessment criteria**	**Control engineering methods**	**Key insights**
Spiegler et al. (2016a)	MTS (Empirical UK grocery model)	Bullwhip and inventory variance	Describing function	Identify the influence of demand characteristics (frequency and amplitude) caused by shipment and truckload constraints on system dynamics behaviour, such as backlog, inventory and system's resilience.
Spiegler et al. (2016b)	Forrester model (Forrester, 1961)	Bullwhip, inventory and shipment variance	Taylor series expansion with small perturbation theory; Matsubara low order modelling (Matsubara, 1965)	Propose a simplification technique to provide a better visualisation and understanding of the variable interactions in the Forrester's model. Also, the linearisation approaches offer further insights due to the possible derivation of system's transfer function and local stability boundaries.
Spiegler et al. (2017)	MTS (APIOBPCS)	Bullwhip, inventory variance and stability (Limit Cycle)	Describing function	Investigate the effect of non-negative order and shipment constraints on the dynamic performance of the APIOBPCS model. The phenomenon called limit cycle triggered by nonnegativity nonlinearity is also explored.

Table 2. 4. The review of non-simulation methods applied for analysing nonlinearities

2.3. ATO supply chains within the context of system dynamics

2.3.1. System dynamics studies in the context of the CODP, MTO and ATO systems

An important part of the ATO system is the position of CODP as well as the MTO phase, in which the latter is characterised by the order-driven, customized-centric operations environment. This is completely different from the MTS environment where tangible inventory plays the key role in influencing supply chain dynamics. Given that extensive MTS dynamic studies has been presented in literature (reviewed in Section 2.2), this section exclusively focuses on literature considering MTO, CODP and, the focus of this thesis,. the ATO system

Wikner et al. (2007) developed an MTO system dynamics model and explore its dynamic performance by using the order book feedback control concept. They suggested that managers may be able to control the level of capacity and lead time flexibility by selecting appropriate forecast smoothing and order book control parameters. The limitation of this work, however, is the ignoring of nonlinearities presented in the MTO system, and also, although the model could potentially be extended and used for the dynamic analysis of decoupled systems, it lacks a mechanism for integration between the MTS and MTO elements

Özbayrak, et al. (2007) developed four-echelon MTO based system dynamics model and analysed some key dynamic metrics such as inventory, WIP levels, backlogged orders and customer satisfaction. Although some insightful dynamic results were obtained and analysed, the pure simulation approach lacks the analytical power in giving guidance regarding the improvement and engineering of the supply chain system.

Anderson et al. (2005) assessed the dynamic performance of order-based service supply chains with different degrees of demand variability and information sharing. They developed a capacity management model for a serial chain by presenting related capacity, processing, backlog and service delays at each supply chain stage. By using the system dynamics simulation approach, they characterise the bullwhip phenomenon exist in such supply chain systems. The impact of different levels of information sharing and management strategies on capacity and service delay variability are also studied

By decoupling generic FD and CD models, Hedenstierna and Ng (2011) evaluated the dynamic consequences of shifting the position of the CODP and found that the ideal position depends on the frequency of demand. However, their model is simple and linear, lacking more realistic representations, such as capacity constraints and availability of material. Choi et al.'s (2012) developed a system dynamics simulation model from Lee and Tang's (1997) model and their experiences gained through a case study in a Korean automobile manufacturer. In contrast to Hedenstierna and Ng (2011), their model represents complex variable relationships, but their simulation results are limited to Korean global automobile companies.

Wikner et al. (2017) conceptually develop a hybrid MTS-MTO model that can represent a typical ATO system by decoupling the customer orders at the final assembly plant. By using system dynamics simulation, they highlight the significant impact of capacity constraint downstream of the CODP on backlog and CODP inventory dynamics, although the conceptual model does not explicitly consider the upstream capacity limit as well as the delivery LT measurement. Since this study focuses on the ATO system within the context of the semiconductor and PC industries, the corresponding relevant background and literature related to the system dynamics are now introduced.

In general, few studies have investigated the MTO, CODP and ATO system structure from the system dynamics perspective. The nature of most studies is conceptual without support of real-world context. Also, most studies adopted a pure system dynamics simulation approach and this leads to the difficulties in obtaining analytical insights regarding the control and design of appropriate policies in improving supply chain dynamics performance.

2.3.1. ATO system dynamics in the PC industry

Very limited effort has been found for modelling and analysing the system dynamics of the ATO system structure in the PC sector. Berry and Towill (1992) developed causal loop diagrams to explain the 'gaming' that yields bullwhip in the electronics supply chains, including semiconductor production, while Berry et al. (1994) undertook simulation modelling of a generic electronics industry supply chain to highlight the opportunities afforded by different supply chain reengineering strategies to mitigate bullwhip. However, their model did not explicitly represent the CODP and nonlinearities (e.g. shipment and inventory constraint, forbidden return) in the hybrid ATO system.

2.3.2. ATO system dynamics in the semiconductor industry

Overall, from a system dynamics perspective, very few studies focus on the ATO system in the semiconductor industry, apart from Gonçalves et al. (2005); Orcun, et al. (2006) and Orcun and Uzsoy (2011). Gonçalves et al. (2005) developed a system dynamics simulation model to explore how market sales and production decisions interact to create unwanted production and inventory variances in the Intel hybrid ATO supply chain. Using a system dynamics approach, Orcun et al. (2006) developed a capacitated semiconductor production model with load-dependent lead time, which overcomes the limitation of treating lead times as exogenous parameters independent of the decision variables that most linear dynamic models assume. The analysis suggested that nonlinear change at high capacity utilisation is consistent with insights from queuing models and industrial practices. Furthermore, Orçun and Uzsoy (2011) studied the dynamic behaviour of a simplified semiconductor supply chain system with two capacitated manufacturing echelons and one inventory echelon. They indicated that the dynamic properties of a supply chain system under optimisation-based planning models are qualitatively different from those operating under simple feedback policies system dynamics models.

Although these system dynamics simulations contribute to the representation of a real system by incorporating nonlinear components and complex structures, it is a trial-and-error approach that may hinder the system improvement process (Towill, 1982; Sarimveis et al., 2008). Despite the fact that semiconductor supply chains have suffered severely from the bullwhip effect (Chien et al., 2010; Terwiesch et al., 2005), limited research studies have explored the underlying system structures that cause the phenomenon. As a result, there is a need to consider analytical methods to understand the underlying mechanisms of bullwhip generation and propose corresponding mitigation approaches that are relevant for the semiconductor ATO supply chain.

2.4. Synthesis

This chapter explores literature regarding two key contexts, *the ATO supply chain systems* and *the System Dynamics*. The review starts by introducing mass customisation and CODP concept (Section 2.1.2) to identify the general academic location of the ATO system. Performance criteria for measuring the ATO system is then explored based on cost-related supply chain performance, as highlighted in Tables 2.1 and 2.2 in Section 2.1.3. It can be concluded that quantitative works on the ATO system mainly utilise the pricing of component and final products, and cost associated-metrics including CODP inventory (e.g. components fill rate, key component availability), capacity availability (final assembly and component production) and time/order (e.g. end customer delivery time, component delivery time, backlog order fill rate) as main indicators for assessing the ATO system performance. Although most works focus on stochastic modelling, this is not the focus of the current thesis; the review offers a deep understanding of how the ATO system is measured in the broader context.

When the supply chain system performance measurement is narrowed down to the context of system dynamics (Section 2.2), the history of system dynamics/supply chain dynamics is explored to understand the evolution of system dynamics research in production planning as well as the context of supply chain systems (Table 2.3). Note that, based on 57 years' system dynamics research works, Towill (1997) and Geary et al. (2006) summarised the Forrester and Burbidge (FORRIDGE) principles commonly recognised as the fundamental strategy for supply chain dynamics mitigation, which is supported by substantial experimental and mathematical evidence. Table 2.5 shows the details of FORRIDGE principles.

Principles	Details
Control system principle	Design and select a robust control system to achieve system objectives and avoid guesswork
Time compression principle	All supply chain activities should be kept at minimum reasonable time to achieve task goals

Information transparency principle	Up-to-date information, including 'noise' and personal bias, should share across all chain echelons
Echelon elimination principle	Unnecessary echelons should be eliminated
Synchronization principle	All events should be synchronized to keep visibility of orders and deliveries at discrete points in time

Table 2. 5. Five principles to reduce supply chain dynamics. Source: (Towill, 1997; Geary et al., 2006)

Drawing on the first ***Control System Principle*** and the classic control theory from the engineering field, the IOBPCS family, originally developed by Towill (1982) and John et al. (1994), is widely recognised for studying system dynamics within the context of supply chains. The systematic citation review of the two original papers is conducted to explore how the IOBPCS family is exploited and extended in studying supply chain dynamics. Based on Figure 2.4, it can be concluded that the IOBPCS family is mainly utilised for modelling and analysing the MTS based systems and that bullwhip (capacity utilisation) and inventory are the two main metrics, although few studies consider the utilisation of orderbook/backlog orders in the context of order-driven systems (e.g. Wikner et al. 2007; Wikner et al. 2017).

The RQ1a is thereby answered. The author found the IOBPCS can be well represented for the MTS based systems consisting of forecasting, inventory feedback and production/transport delay elements, and the corresponding dynamic performance can be assessed by bullwhip, inventory variance and stability. Clearly, the IOBPCS family literature lacks the study of dynamic behaviour of the order-driven or hybrid systems in which time performance becomes crucial. Also, there is a need for investigating both linear and nonlinear models based on the IOBPCS family to represent real-world supply chain system with resources/physical constraints, such as capacity, inventory and shipment constraints.

Based on the broader ATO supply chain performance criteria (Table 2.2) and the system dynamics (IOBPCS family) literature (Figure 2.4 and Table 2.4), Figure 2.6 synthesises performance evaluation for the ATO system. It can be concluded that delivery lead times and backlog order-based performance metrics need to be considered in assessing ATO system dynamics. Due to the fact that there is a direct link between order and time dimension (Zhao, 2009; Lu et al., 2005; DeCroix et al., 2009) in the ATO system, three important performance evaluation criteria for the ATO system from the system dynamics perspective emerge: ***Inventory variance, bullwhip, and lead-time variance,*** that is, the RQ 1b is answered. Furthermore, the general research objectives are formulated as a result of this: there is a need to dynamically model, design and analyse the ATO system within the context of system dynamics.

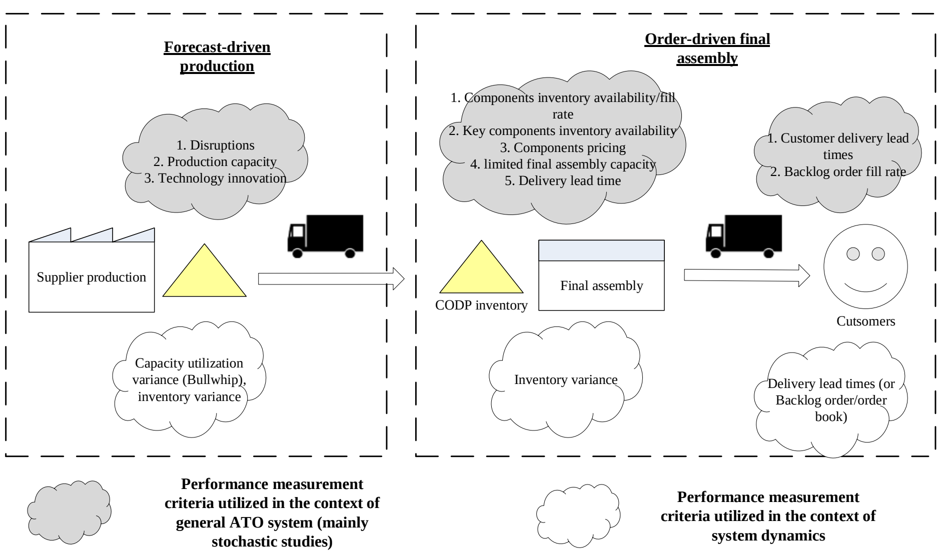


Figure 2. 5. Performance criteria utilised for assessing the ATO system based on literature review.

Source: the author.

Focusing on the PC and semiconductor industries, Table 2.6 further illustrates the detailed scope and main contributions of this thesis. It was evident that very limited study addressed the underlying mechanisms of ATO system dynamics based on the semiconductor industries, despite these industries suffering severely from supply chain dynamics (Hofmann, 2017; Li and Disney, 2017; Vicente et al., 2017), such as bullwhip. Furthermore, most studies, as shown in Table 2.6, utilise pure simulation approaches, although it is a trial-and-error approach that may hinder the system improvement process (Towill, 1982; Sarimveis et al., 2008). As a result, there is a need to propose analytical methods to understand the underlying mechanisms of bullwhip generation and propose corresponding mitigation approaches that are relevant for the ATO supply chains. This formulates the RQ 2a and 2b, i.e. gain insights by utilising the existing real-world ATO system as an example to understand the underlying mechanism of supply chain dynamics and propose mitigation solutions.

It is also clear that only two works have investigated the dynamic behaviour of PC supply chains, although the ATO supply chain strategies have been widely adopted in that industry. There is also a need for systematically modelling and analysing the PC ATO supply chains within the context of system dynamics. Furthermore, most modelling and analysis works do not consider analytical methods in assessing the ATO system structure, particularly the nonlinearities present in the system. Finally, the dynamic analysis of final customer delivery LT is largely ignored in the literature, although several works (e.g. Wikner et al., 2007; Wikner et al., 2017) may consider the related backlog orders for measuring the end customer order fulfilment performance. Based on these research gaps, the RQ 3a, 3b, 3c and 3d have emerged, which aim to develop system dynamics models of PC supply chains as an illustration of the typical hybrid ATO system and explore the dynamic performance of such models by incorporating delivery LT variance, beside commonly recognized indicators (capacity and CODP inventory), as the third measure. The author terms this as *'performance triangle'* (Klasse and Menor, 2007), i.e. the dynamic analysis of capacity variance at the supplier, the customer order decoupling point (CODP) inventory variance and the delivery LT variance (see Figure 2.6). Furthermore, nonlinearities present in the PC ATO system will be analytically explored utilising nonlinear control engineering approaches.

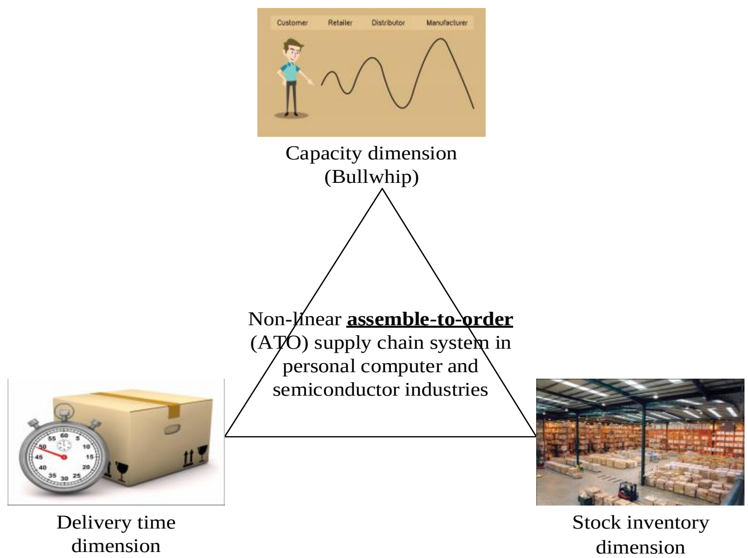


Figure 2. 6. Performance triangle within the context of ATO supply chain dynamics.

		Conceptual works				**Semiconductor sector**			**General PC sector**		***This thesis***
Author		Wikner et al. (2007)	Hedenstierna and Ng (2011)	Choi et al. (2012)	Wikner et al. (2017)	Gonçalves et al. (2005)	Orcun et al. (2006)	Orcun and Uzsoy (2011)	Berry and Towill (1992)	Berry et al. (1994)	
Scopus		MTO	MTS-MTO depending on CODP	MTS-MTO dependin g on CODP	MTS-MTO depending on CODP	ATO	ATO	ATO	ATO	ATO	***ATO***
CODP research scope	Material CODP position		√	√	√						
	DIDP position				√						
Sources of system dynamics	Feedback and delay	√	√	√	√	√	√	√	√	√	√
	Forecasting	√	√	√	√	√	√	√	√	√	√
	Pricing										
	Gaming										
	Order batching										
Performance metrics	Delivery lead-time variance										√
	Backlog /Order book variance				√	√					
	Capacity variation (bullwhip)	√	√	√	√	√	√	√	√	√	√
	Inventory variance	√	√	√	√	√	√	√	√	√	√
	Cost										
	Stability										√

Continued		**Conceptual works**				**Semiconductor sector**			**General PC sector**		***This thesis***
Nonlinearities	Single-valued				√	√	√	√			***√***
	Multi-valued				√	√					***√***
	Continuous										***√***
Methods	Simulation	√	√	√	√	√	√	√	√	√	***√***
	Analytical										***√***

Table 2. 6. Detailed scope of this thesis - SCM theory and methodology contributions. Source: the author.

2.5. Summary

This chapter has provided an overview of literature related to the ATO system and the system dynamics. The performance metrics for ATO system evaluation are explored in both general quantitative study and more specific system dynamics contexts. Regarding the system dynamics perspective, the IOBPCS family, widely recognised as the fundamental framework for modelling and analysing the system dynamics performance of the production-inventory, as well as supply chain systems, is systematically reviewed. A so-called ***'performance triangle'*** is developed to measure the dynamic performance of the ATO system, i.e. the dynamic analysis of capacity variance at the supplier, the CODP inventory variance and the delivery LT variance. The review of the IOBPCS family also highlights the need to analytically explore nonlinearities present in the supply chain systems, particularly in a time-oriented system such as the ATO system. When the literature is narrowed down to the system dynamics of the ATO system in the PC and semiconductor industries, very limited research has been found. Most works conceptually modelled the hybrid MTS-MTO system or the position of CODP to present implications of designing and analysing different combined systems. Also, simulation is the primary choice due to the complexity of the system dynamics model, i.e. the high-order nonlinear system dynamics model. Based on the literature review and general research gap highlighted in the Chapter 1, two further research objectives and corresponding RQs have emerged: 1) propose design methods including simplification and linearisation to overcome simulation limits that provide sparse analytical findings, and 2) develop a system dynamics model of the ATO within the context of the PC sector and analyse the dynamic performance of the nonlinear ATO system based on 'performance triangle'. Chapter 3 will present the details regarding appropriate epistemological positions and the corresponding methodology choice.

Chapter 3. Methodology

The previous chapters established the subject matter of this research and highlighted the relevant gaps that will be addressed through a consideration of the research questions. This chapter will explain how this research has been carried out, including the research ontological and epistemological positions, research design, methods and tools used.

This chapter will first outline the ontological and epistemological underpinnings of supply chain management research and the philosophical stance considered in this thesis. Next, further details on the research methods and tools used will be provided. This includes a review of the control engineering and system dynamic simulation. Finally, the research design used to answer the research questions will be explained.

3.1. Research philosophy and paradigm

A research paradigm refers to the involvement of an ontology, an epistemology and a methodology (Blanche et al., 2007). Ontological position represents the researchers' perception regarding the social reality. The fundamental debate is whether social reality is constructed as a series of interactions between people or naturally occurs. Epistemology emphasises how knowledge of social reality is constructed (Saunders et al., 2009). The methodological position is influenced via ontology and epistemology, which is the way in which knowledge of reality is interpreted. Methodological position further affects the selection of methods, theories and theoretical frameworks as it is the basis and rationale behind their selection.

The balance between generalisation / optimisation and meaning to explore the social phenomenon is crucial when conducting social science research. Researchers who prefer to use the quantitative research represents their purpose of generalization or external validity. However, qualitative methods are mainly utilized for internal validity or meanings (Golicic et al., 2005). Since this research is located in the discipline of supply chain management, the philosophy traditions in this area will be reviewed to identify the research paradigm.

3.1.1. Research philosophy and paradigms in supply chain management

Supply chain management research is fundamentally fragmented and multidisciplinary (Larson and Halldorsson, 2004) due to its involvement of various subjects including Management Science, Technology Management, Operations Research, industrial engineering (Kotzab et al., 2006). supply chain management is dominated by a value-free, objective and deductive research. The rationale behind this philosophical tradition is researchers recognized the supply chain as a kind of organisational form and its ontological identifiers are independent of social entities (Emmanuel et al., 2012). For example, researchers and practitioners design their supply chain based on desired criteria (e.g. cost). As a result of the ontological perspective of supply chain research, positivism epistemology dominates to this area through applying quantitative methods, e.g. mathematical modelling, statistical test (survey), experiment (Sachan and Datta, 2005; Burgess et al., 2006; Spens and Kovács, 2006; Aastrup and Halldórsson, 2008).

However, a branch of research supports the qualitative, anti-positivism methods in conducting supply chain management research (Näslund, 2002). Frankel et al. (2005) suggested a ‘white space’ in understanding logistics from an inductive and subjective view occurred due to the dominance of positivism, which highlights the need to conduct qualitative research (Näslund, 2002). Under this assumption, supply chain is socially constructed with interpretation flexibility, and specific interests and power structures are supported by each interpretation (New, 2004). As a result, interpretivism/constructionism and corresponding qualitative methods, such as action studies and interview, are preferred by researchers.

Standing on the middle place is the abductive approach (Kovács and Spens, 2005). The abduction combines the deductive and inductive approaches, rationalism and empiricism. The similarities and major difference between inductive, abductive and deductive research paths is highlighted in Figure 3.1. Specifically, the abductive process begins with a similar inductive approach but a link between theoretical framework and real-life observation is created. The remainder of the abductive process tracks deductive research. That is, applies/tests the hypothesis or proposition to make contributions to knowledge.

Although few papers refer to the term ‘abductive approach’ in their method strategy in supply chain management research, Spens and Kovács (2005) indicated the analogous abductive approach or research process has been adopted by some logistics authors. They also suggested that theory development by adopting abduction in a new research filed like logistics and supply chain management is important. As a result, mix-based methodology (e.g. case study) (Harrison and Easton, 2002; Kovacs et al., 2008) are preferred by thosesupply chain researchers advocated realism/critical realism as the research epistemology to challenge traditional positivist (Harrison and Easton, 2002; Kovacs et al., 2008).

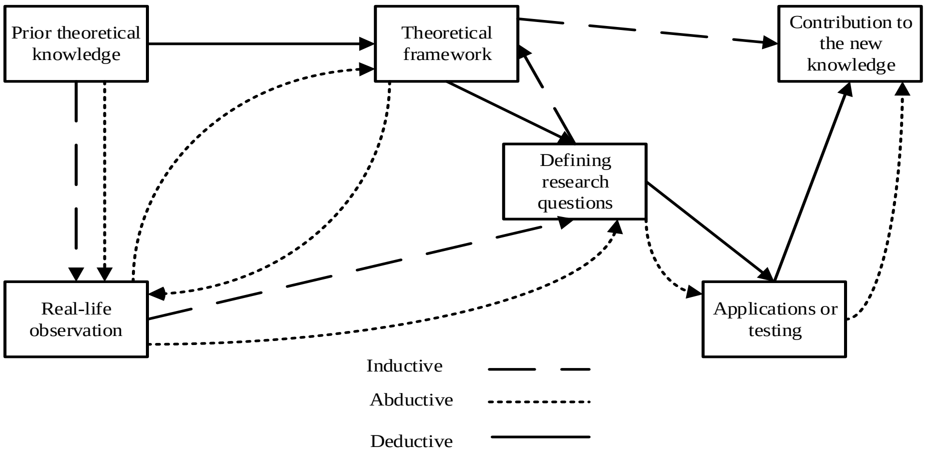


Figure 3. 1. The research process of deduction, induction and abduction. Source: Kovács and Spens (2005).

Based on the intermediate school of thought within logistics research, Gammelgaard (2004), who used a methodological framework from Arbnor and Bjerke (1997), categorised the existing supply chain management research as three groups: analytical, system and actors' approaches, representing the corresponding deductive, abductive and inductive research process, as illustrated in Figure 3.2.

	Analytical approach	System approach	Actor's approach
Theory type	1.Determine casual-effect relation 2.Explanation, Prediction, universal Laws	1.Models 2.recommendation 3.knowledge about concrete system	1.Interpretatin 2.Contextual knowledge understanding
Preferred methods	Quantitative (qualitative for validation)	Simulation and case study (mix methods)	Qualitative
Unit of anlysis	Concept and their relations	Concept and their relations	People and their interaction
Data analysis	Description and hypothesis testing	Mapping and modelling	Interpretation
Position of research	outside	Preferably outside	Inside, as the part of process

Figure 3. 2. Methodological framework for supply chain management research (Gammelgaard, 2004).

Specifically, researchers who adopt the analytical approach in studying supply chain management treat reality as objective that can be decomposed into smaller elements and then propose hypotheses to test them. On the other hand, advocates for the actors' approach emphasise the fact that reality is not objective but the result of social constructions, i.e. a high level of contextual-based study, which qualitative and inductive research approaches usually adopt. Standing in the middle is the system approach where researchers hold a holistic view of the supply chain as a system and study such system via understanding of entities, links, goals, and feedback mechanism in order to improve the system.

Based on research objectives and corresponding research questions, the author adopts the system approach in this thesis. This is because the nature of phenomenon, i.e. supply chain dynamics, is investigated through a holistic view of ATO supply chain as a system. Such bounded system includes questions of the causality between different system entities (stock, order and production rate, demand, capacity, policies etc.) and of mechanisms (the impact of one entity on others and/or on the supply chain dynamic performance). The systems approach is also theory-driven but this theory is contextual rather than universal. Reality is still considered objective and can be susceptible to influence, and thus it is preferable that the researcher stands outside the research object.

However, unlike the analytical and actor's approaches in which deductive positivism and inductive interpretivism are corresponding schools of thought, the systems approach is implicit for any of the social science schools of thought. Thus, the selection of epistemological positions of this study is considered in the next section.

3.1.2. Ontological position

There are two ontological positions recognised in studying social science research: objectivism and subjectivism. The social actors who support objective ontology consider social entities to exist as reality independent of his/her perceptions and interpretations. Subjectivism, on the other hand, means that the social actors create a social phenomenon via their perception and corresponding actions.

The author strongly believes that the phenomena; that is, supply chain dynamics to be investigated in this thesis exist independently of his own perspective and interpretations, which means the objectivity assumption is made for this research. In other word, the author treats the dynamic supply chain system as a tangible object that obeys rules, policies and standard process to achieve targeted objectives.

3.1.3. Epistemological position

Since the objective ontology is adopted in this study, there are three corresponding epistemological positions that need to be further considered: Positivism, Empiricism, and Critical Realism (May, 2001). Table 3.1 summarises the main characteristics of three epistemological positions.

Epistemological positions	Main characteristics
Positivism	(Objectivity: 'Fact' exists and is collectable, and is independent of people's perception of the social world (May, 2001); (Natural science perspective: produce causal relationship via predicting and explaining the behaviour (May, 2001) and scientific process is the only legitimate way to gather evidence (Hunter, 2002). • Deductive elements: theory is used for the purpose of developing testable hypotheses and explain laws (Bryman, 2012). • Law-like generalisation: knowledge is generated by gathering facts to create universal laws (Bryman, 2012). • Value-free principle: adopt an 'unbiased way' for data collection (Hunter, 2002).
Empiricism	• Shares the essence of positivism that there are 'facts' independent of people's perception and interpretation, which researchers can generalise to explain human behaviour by collecting and analysing data from the social world (May, 2001) • Unlike positivism, empiricism is implicit in the process of theory guiding data collection (May, 2001); thus, it is characterised by the catchphrase 'the facts speak for themselves'.
Critical realism	• Shares positivism's perspective (i.e. natural science perspective) regarding objectivity, causality, prediction and explanation (Bryman, 2012). • The matter of underlying mechanisms, including: 1. The presence of underlying mechanisms. However, it is not apparent and observable, as underlying mechanisms are allowable on the grounds in which their effects are observable (May, 2001). 2. The same outcome is the result of different roots. Single casual-effect relationship can not be explained by underlying mechanism; therefore, the cause must be regarded as 'tendencies' due to the different layers of reality. (Williams and May, 1996). 3. The priority of researchers is to reveal the fundamental structures of social relations (May, 2001). • The generation of social scientific knowledge is theory-driven (Carter, 2000).

Table 3. 1. Main characteristics of three epidemiological positions under objective ontology.

Based on the literature, both positivism and critical realism can be epistemological positions in studying supply chain dynamics. For example, both artificial paradigm dominated by an axiomatic and positivist approach, and direction observation of reality driven by the case studies and field experiments can underlie supply chain dynamics research (Dunn et al. 1994).

On the other hand, a system thinking approach related to critical realism is recognised in supply chain dynamics research (Gammelgaard, 2004), which holds the view that the various elements of the supply chain system are fundamentally interdependent. Specifically, the system thinking approach takes the perspective of theory as contextual rather than universal. Also, data collection and theory building seem to occur practically. However, reality is still regarded as objective and independent of actors' thoughts or beliefs.

Since the main objective is to explore the contextual based ATO system structure (i.e. PC and semiconductor sectors) by simulation, analytical experiment and modelling, and the author does not aim to propose hypotheses or test to make a universal claim, the system approach is more appropriate for this study. The systems approach allow the exploration of complex systems characterised by feedback loop control and interactions between different level and variables (Wolf, 2008). Feedback in this context means that one element might affect another and vice versa, which should be considered and investigated by a holistic system modelling approach (Forrester, 1961; Towill, 1991). As a result, the study of supply chain dynamics from the system approach perspective may fit into the critical realism principle. As Mingers (2000) suggested, some of the major premises of critical realism may be able to characterise the systems dynamics, since it is grounded in a holistic view and abductive approach. This approach tends to have been used by researchers who modelled supply chains via real-world observations.

However, positivism also fits into some areas of this study for two reasons. First, system dynamics research traditionally proposes and tests theories and then generates scientific laws, which is a fundamental principle of positivism. Second, for the deductive literature review process, an objective, holistic and value-free view will be taken. Knowledge (structured and narrow review) is created by collecting facts to generate universal laws (Bryman, 2012).

As a result, the author strongly believes the systems approach contains elements of both positivism and the critical-realism school of thought. The theoretical questions (RQ1a and 1b) can be explored by a positivist principle with deductive research process where there is no underlying mechanism of 'observable fact' (existing literature), knowledge (e.g. research gaps) can thereby be generalised by reviewing the papers. However, to explore the remaining theoretical and methodological questions, critical realism appears to be more appropriate. This is because underlying mechanisms exist and need to be explored. For example, the underlying mechanisms of bullwhip are not easily observable and greatly depend on system structure (e.g. MTS, MTO and ATO), policies (e.g. different ordering policy, inventory control policy) and contexts (e.g. industry). Also, different causes may have the same outcome (e.g. bullwhip) and need to be understood analytically. For example, as demonstrated in Table 2.3, there are multiple sources of bullwhip effect in production-inventory and supply chain systems including delay, feedback, forecasting, batching, nonlinearities, human beings' perception etc.

Although critical realism is more appropriate in answering *RQ2a, 2b and RQ3a,3b,3c,* it appears both deductive and abductive research processes would be valid. This means the research into ATO system dynamics can be conducted by either collecting real-world ATO supply chain information and material flow (e.g. observations, interview, business mapping with practitioners), or using existent ATO system dynamics models and/or developing system dynamics models based on existing materials. The former is more related to an empirical research process, while the latter study is conceptual in nature.

In this thesis, the utilisation of existent models and materials is selected by following the conceptual research process, since the use of well-established models is more appropriate in answering the methodological questions, and the secondary data has several advantages, including less time, money and fewer personnel for data collection (Rabinovich and Cheon, 2011; Ellram and Tate, 2016), high reliability and credibility due to the peer-reviewed process of paper publication. Hence, an abductive logic reasoning and a conceptual research approach were chosen in this thesis.

3.2. Research methods and tools

In order to illustrate the methodological position in this dissertation, Wolf's (2008) methodology hierarchy is followed (Figure 3.3).

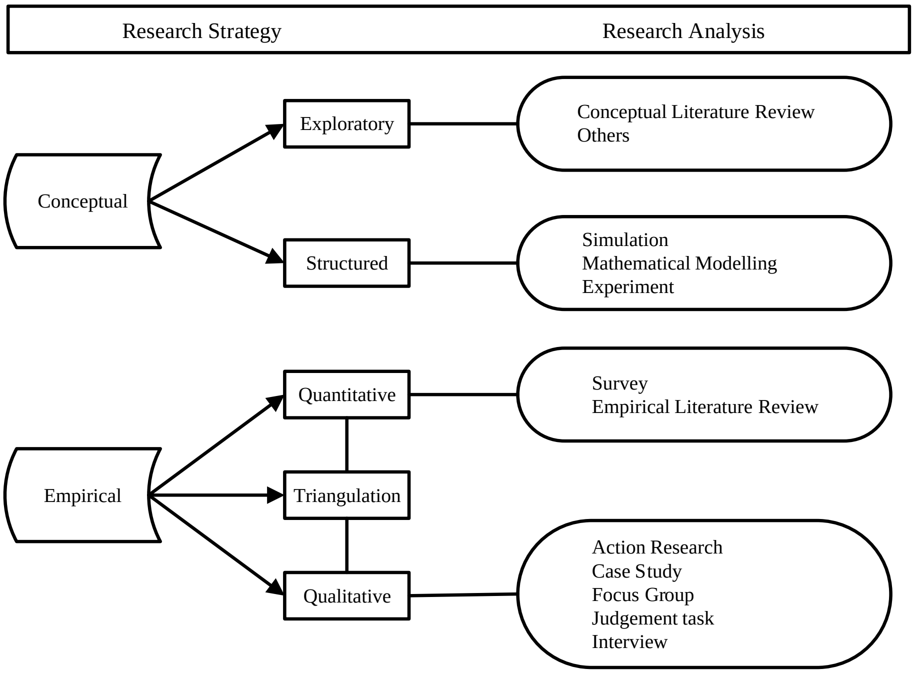


Figure 3. 3. Methodology hierarchy. Source: Wolf (2008)

To be more specific, a research strategy can be conceptual or empirical, depending on whether field data is gathered for the generation of theory or not. As discussed in

Section 3.1, since the conceptual research process is followed, mathematical modelling (control engineering), simulation and experiments can be utilised during the research analysis stage to generate artificial data and to give deep insights into existing models regarding system dynamics behaviour. The literature review process, on the other hand, can be conducted via a more exploratory way to generate new findings and pose questions.

3.2.1. Mathematical modelling: control engineering approach

Control theory is a branch of engineering and mathematics for the purpose of studying dynamical systems. A system refers to a set of elements connected by information and physical links (Leigh, 2004). Control theory is well-recognized in studying production-inventory as well as supply chain systems, due to it enables the systematic evaluation of feedback based systems and identification of causal relationship (Towill, 1982; Towill, 1992; John et al., 1994; Sarimveis et al., 2008; Lin et al., 2017; Naim et al., 2017).

3.2.1.1. Discrete and continuous time domain modelling choice

In order to analyse any dynamic system, it is possible to consider that variables change with time discretely or continuously. A production-inventory control system may operate in either continuous time, where the inventory and ordering status is reviewed continuously, or discrete time, such as in a periodic review process.

Several studies in both discrete and continuous time production control have been undertaken. Simon (1952) pioneered the continuous time domain approach in studying inventory control system. Also, the original studies of the IOBPCS family, Towill (1982) and John et al. (1994), adopted the continuous time domain approach. However, based on a systematic review of the IOBPCS family (Lin et al., 2017), the discrete approach has received more attention (Disney and Towill, 2003; Disney et al., 2004; Lalwani et al., 2006; White and Censlive, 2015), which is consistent with the fact that a real replenishment system is often monitored in a periodic way (Vassian, 1955). It should be noted that neither of these approaches is superior for application in different real scenarios (Disney et al., 2006b), e.g. examining the stability property through continuous time approaches while adopting a discrete time system for the stochastic response (Warburton and Disney, 2007).

A continuous time domain approach is adopted in this study for two reasons. First, vendor managed inventory (VMI) and continuous replenishment program (CRP) are commonly adopted in the PC industry (Kapuscinski et al., 2004; Huang and Li, 2010; Kumar and Craig, 2007; Katariya et al., 2014), i.e. the OEM PC parts replenishment for incoming customised orders is undertaken on a continuous time manner. Second, a continuous time approach has the advantage of handing nonlinearities present in the system in an easier way than a discrete time approach. Mathematically discrete control theory involves lengthy and tedious algebraic manipulation (Naim et al., 2004); also, when nonlinearities are included, the mathematics of discrete system become more complex and very limited sources of literature can be found and adopted (Spiegler, 2013). For these reasons, the author conducts the dynamic analysis of the ATO system in a continuous time manner. It should be noted that although the continuous time approach (e.g. Laplace transform, differential equations) are adopted in this thesis, the author uses difference equation to develop the dynamics model for simulation purpose in Chapter 4 and 5. Difference equations can give a better visualization of the relationship between different variables, e.g. avoid the integral sign, which has been well-recognized in the literature (e.g. Wikner et al. 2007; Spiegler et al. 2012)

3.2.1.2. Linear analysis techniques

A system can be defined as linear if the system follows principle of superposition, which means that the system's response given an input signal X+Y is the sum of the behaviour in following signals of magnitude X and Y applied separately (Towill, 1970). Also, only linear systems can be modelled in state space representation and be represented by a single transfer function. Block Diagram manipulation, Laplace Transforms, Transfer Functions, Characteristics equations (CEs) analysis are the main techniques used in investigating dynamical systems in this study. Table 3.2 presents an overview of these approaches.

From the observer perspective, the study of supply chain dynamics (bullwhip) can be categorised based on three different 'Len': the 'Variance', 'Shock' and 'Filter' lens (Towill et al., 2007). The 'Variance', or 'Noise' lens, is widely recognised by Operations Researchers (ORs), by which they assume time series demand is stochastic and unknown in nature but could be modelled by obeying different probability distribution and bullwhip is usually measured by variance ratio, standard deviation ratio, for example. The main purpose is to develop an objective function based on their desired criteria (e.g. cost function) and analytically maximise/minimise the objective functions.

Tools /Methods	***Description and advantages***	***References (e.g.)***
Block Diagram	Block diagrams are used to outline a system in which the principal parts or functions are represented by blocks connected by lines that show the relationships of the blocks.	Atherton (1975)
	The Block diagrams are useful to describe the overall concept of a complex system without concerning the details of implementation, which allow for both a visual and an analytical representation within a single entity. The adoption of block diagrams in studying supply chain dynamics has been well recognised in production planning and control literature.	Disney and Towill (2002); Dejonckheere et al. (2004); Spiegler et al. (2016)

Tools /Methods (Continued)	***Description and advantages***	***References (e.g.)***
Laplace Transformation	The Laplace transform is an integral transform which converts a function of a real variable *t* (time domain) to a function of a complex variable *s* (frequency domain): $$F(s) = \int_0^\infty e^{-st} f(t) d_t$$	Atherton (1975)
	The Laplace transform technique has great advantages of simplifying the algebraic manipulations required, analysing large systems and benchmarking good practice in studying supply chain dynamics.	Disney and Towill (2002); Disney et al. (2006)
Transfer Function	The transfer function of a system is a mathematical representation describing the dynamic behaviour in a linear, time-invariant (LTI) system algebraically. It can be defined as the ratio of s/z transform of the output variables to the s/z-transform of the input variables, depending on the consideration of variables change with time continuously or discretely.	Nise (2007)
	1. The transfer function approach can be used to model production/supply chain systems, since they can be seen as systems with complex interactions between different parts of the chain. 2. Transfer functions completely represent the dynamic behaviour of production/supply chain systems under a particular replenishment rule, i.e. the input to the system represents a specific demand pattern and the output refers to corresponding production orders.	Dejonckheere et al. (2003); Spiegler et al. (2012)
Characteristic Equation (CE)	CE is defined by equating the denominator of overall transfer function to zero.	Lin et al. (2017)
	CE can be used to find poles (roots), which give an initial understanding of the underlying dynamic mechanism including system stability and unforced system dynamic property (i.e. natural frequency and damping ratio).	

Table 3. 2. A brief review of linear control engineering tools/methods utilised in this study.

On the other hand, the control researchers who study supply chain dynamics based on ‘Shock’ and ‘Filter’ lens assume demand patterns are steeply or periodically changed. The cost-based function may not be a priority for researchers to develop, due to the fundamental logic behind these two perspectives that good cost control will follow ‘good’ dynamic behaviour control (Towill, 1994; Towill et al., 2003).

This thesis mainly uses step increase demand (‘Shock’ lens) and sinusoidal demand (‘Filter’ lens) in analysing the ATO system dynamics performance, while the stochastic demand signal is implemented for sensitivity analysis to verify the analytical results derived from the step and sinusoidal inputs.

Regarding the step increase demand, it is well documented (Towill, 1970) in general control theory for exploring the system’s capacity to respond to sudden but sustained change. Moreover, step change as the input is easily visualised and its response can be easily interpreted (John et al., 1994). Furthermore, the step increases provide rich information for the dynamic behaviour of the system (Coyle, 1977). From the supply chain point of view, the step demand can be regarded as the early stage of a new product or the opening of a new sales outlet (Zhou and Disney, 2006; Zhou et al., 2017), which fits the customer demand condition in the semiconductor and PC industries characterised by a short life cycle with a corresponding sudden change in demand during the release of new products (Lin et al., 2017).

The sinusoidal demand can be used to measure the steady state amplification ratio (i.e. bullwhip effect), which is the ratio between the amplitude of orders and amplitude of demand. For the PC industry, demand pattern can be approximated to an annual cycle i.e. with a winter holiday demand peak (e.g. Black Friday, Christmas shopping and Chinese New Year) followed by off-season demand (Zhou et al., 2017). Furthermore, there are two reasons why stochastics demand is no longer necessary to be used for the main system dynamics analysis. First, for sinusoidal inputs, the amplification ratio value is exactly the same as the ratio of the standard deviations of independent and identically distributed (i.i.d.) demand input over output (Jakšic and Rusjan, 2008; Udenio et al. 2017). Second, any real-life time series demand data, including stochastic data, can be decomposed to different constituent frequencies or periodicities by spectral analysis, which can be analysed by ‘the Filter’ lens using frequency domain analysis techniques; see Figure 3.4, while details can be found in Dejonckheere et al. (2003).

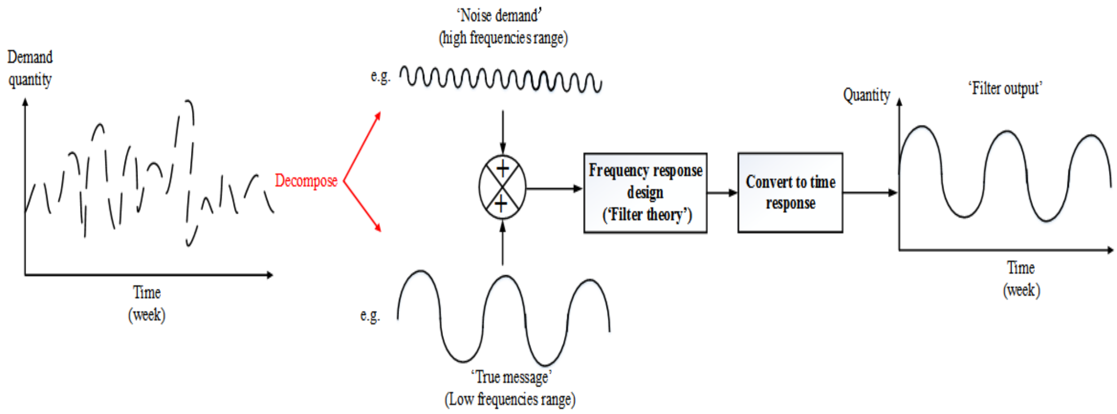


Figure 3. 4. Transmission by the frequency response design

3.2.1.2.1. Time domain analysis via the ‘Shock’ lens

The dynamic performance of replenishment system models will be assessed via the step demand input, also termed ‘Shock’ lens (Towill et al., 2007), in the time domain. The priority for analyzing the dynamic system via ‘Shock’ lens is to ensure the stability of the system. Stability is a fundamental property of a supply chain system. From the linear system perspective, the system is stable if the trajectory will eventually return to an equilibrium point irrelevant to the initial condition, while an infinity trajectory is presented if the system is unstable (Wang et al., 2012). Thus, the system response to any change in an input (demand) will result in uncontrollably increasing oscillations in the supply chain (Disney and Towill, 2002). A system also has critical stability when it is located at the edge of the stability boundary, and system oscillations are regular and infinite for such situations. Furthermore, as illustrated in Figure 3.5, several key indicators can be utilised for measuring the dynamic performance of the system in responding to a step demand input (Atherton, 1975; Nise, 2000). This includes:

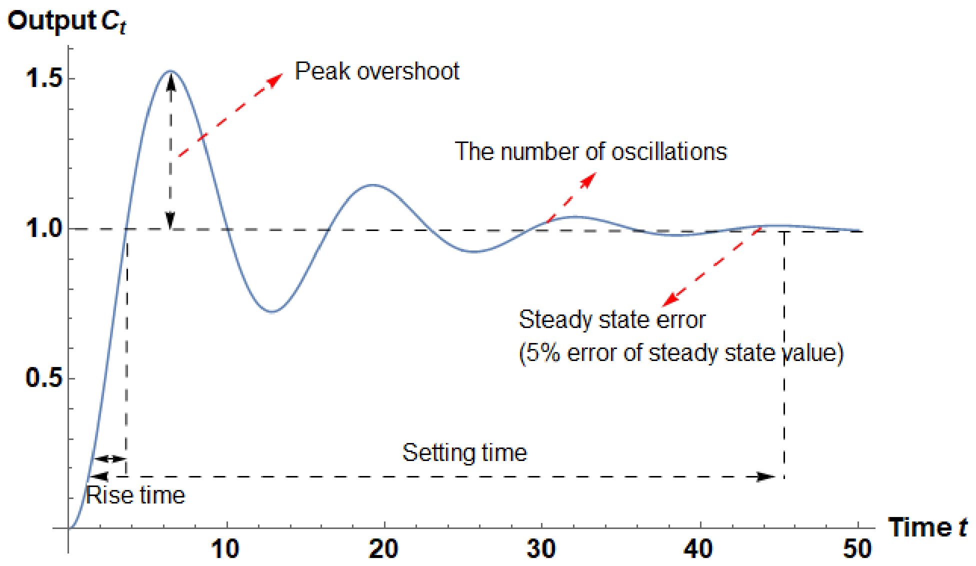


Figure 3. 5. Performance evaluation of time domain analysis via the 'shock' lens (i.e. a unit step demand increase).

Rise time: is the time taken by a signal to change from a 5% increase in initial value to reach a 95% of targeted value (i.e. the final demand). This indicator is utilised to illustrate the supply chain system response speed in meeting the target step customer demand.

Maximum overshoot (Peak level): is the output exceeding its final, steady-state value. In the supply chain dynamics context, this can be used for measuring the bullwhip level.

Number of oscillations: the number of oscillations before the system reaches the steady state condition. It is a useful metric in measuring dynamic behaviour. The fewer the number of oscillations, the better the cost control of supply chain dynamics system, due to the lower frequency of ramping up and ramping down machines, hiring and firing staff, inventory variance cost, etc.

Settling time: can be defined as the time required for the response curve to reach and stay within a range of a certain percentage (usually 5% or 2%) of the final value. This indicator is used for measuring the recovery speed (usually the inventory recovery speed) in responding sudden change in demand.

3.2.1.2.2. Frequency domain analysis via the 'Filter' lens

If periodic demand behaviour is observed, the frequency domain analysis can be utilised. Filter theory (Dejonckheere et al., 2002; Dejonckheere et al., 2003; Towill et al., 2003; Towill et al., 2007) can be utilised to design such systems based on frequency domain analysis. As shown in Figure 3.4 above and 3.6 as an example, system designers should discuss and think carefully about their definition of 'true message' (low frequencies range) and 'noise' (high frequencies range) within their specific context. Low frequencies demand pattern should be traced since they are genuine changes and corresponding resources and workforce should be properly allocated, while high frequencies demand patterns (e.g. rogue variations in demand) should be identified and filtered out so that excess costs due to unnecessary ramping up and down production or ordering levels are avoided.

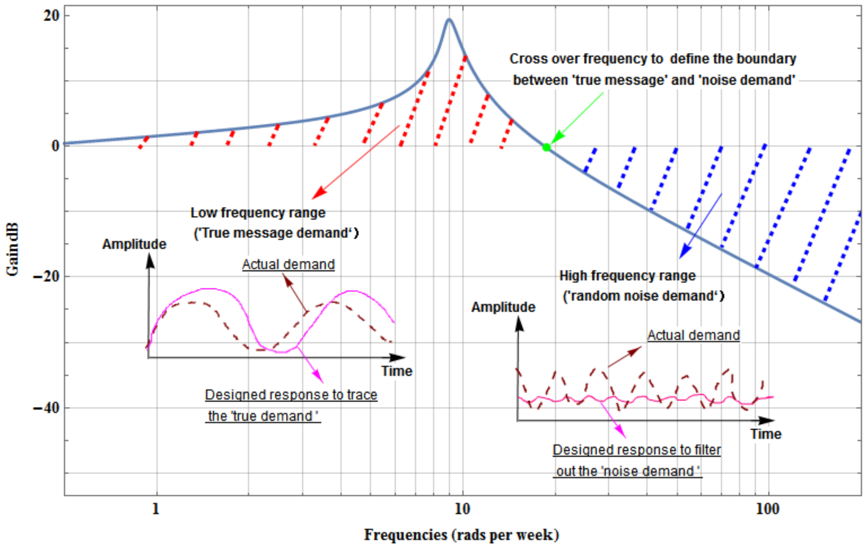


Figure 3. 6. Frequency response illustrated by Bode plot diagram. Adapted from Towill (1994) and Towill et al. (2003).

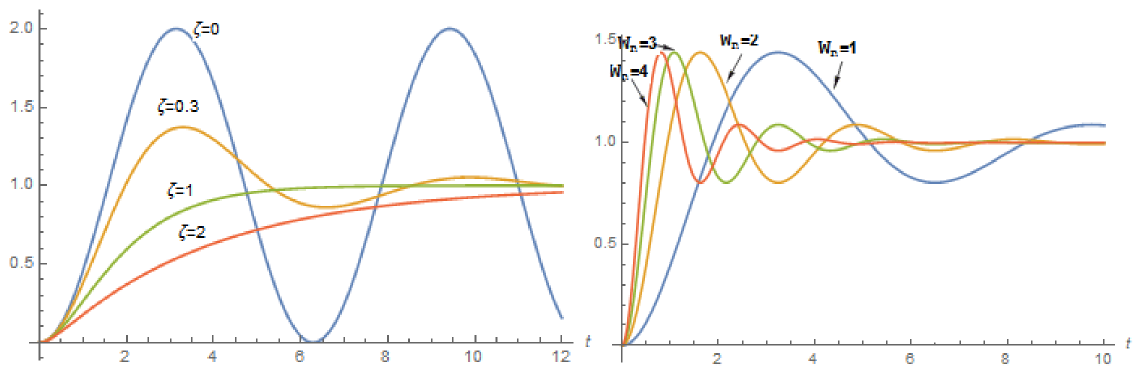


Figure 3. 7. Examples for the effect of ω_n and ζ in responding to a unit step input.

Furthermore, as illustrated in Figure 3.7, natural frequency (ω_n) and Damping ratio (ζ) can be utilized to assess the unforced dynamic property of the supply chain system when analysing system dynamics models via the 'Filter lens'. ω_n determines how fast the system oscillates during the transient response and can be used to indicate the system's speed to reach the steady state condition for responding to an external demand signal, e.g. the inventory recovery speed. ζ, on the other hand, describes how the system's oscillatory behaviour (i.e. variability) decays with time, and can be perceived as initial insight into the system's unforced dynamic performance; for example, the extent to which the order rate and inventory will oscillate with time. Figure 3.8 illustrates the effect of ω_n and ζ in responding to a unit step input.

3.2.1.3. Stability analysis techniques

Stability is a fundamental property of a supply chain system. From the linear system perspective, the system is stable if the trajectory will eventually return to an equilibrium point irrelevant to the initial condition, while an infinity trajectory is presented if the system is unstable (Wang et al.. 2012).Thus, the system response to any change in an input (demand) will result in uncontrollably increasing oscillations in the supply chain (Disney and Towill, 2002). A system also has critical stability when it is located at the edge of the stability boundary, and system will oscillate at a regular interval.

The generic form of the solution of linear dynamic system, S(t), i.e. the solution of linear ordinary differential equation with zero initial condition in time domain, can be written as follows:

$$S(t) = A \cdot e^{R_1 t} + B \cdot e^{R_2 t} + C \cdot e^{R_3 t} + \cdots \qquad (3.1)$$

Where A, B, C…. is the amplitude of system response R_1, R_2… are system roots (the denominator of the transfer function). That is, $R = \varphi + j\omega$, in which $j\omega$ is the imaginary part contributing to the system's oscillatory behaviour based on Euler's formula (i.e. $e^{j\omega} = \cos\omega + j\sin\omega$), while φ is the real part contributing to the exponential decay or increase of system response. Hence, the roots can be real, complex or purely imaginary and the real poles can also be positive, negative or repeated, influencing the transient response as well as the system's stability condition. The system can be stable if, and only if, the real part of all roots is negative, otherwise the $S(t)$ approaches infinity with the increase in *t*. Also, the system will produce an over-damped response if, and only if, there is no imaginary part of the roots, i.e. $j\omega = 0$.

For assessing the system's stability condition, the Routh-Hurwitz stability criterion can be utilised. Such method has the advantage of easily and quickly determining system stability without solving the root of the differential/difference equations (Disney and Towill, 2002). Specifically, for a given system characterised by a high order polynomial:

$$a_0 s^n + a_1 s^{n-1} + a_2 s^{n-2} + a_{n-1} s + \cdots + a_n = 0 \qquad (3.1)$$

Where a_0, a_1 ... are coefficients of the high order polynomial. The system is only stable if none of the roots has positive real parts, which is subject to the necessary and sufficient condition that Hurwitz determinants of the polynomial must all be positive, where the determinants are given by Routh-Hurwitz array:

$$\begin{matrix} S^n \\ S^{n-1} \\ S^{n-2} \\ \vdots \\ S^0 \end{matrix} \begin{vmatrix} a_0 & a_2 & a_4 & a_6 & \dots \\ a_1 & a_3 & a_5 & a_7 & \dots \\ b_1 & b_2 & b_3 & \dots & \dots \\ c_1 & c_2 & c_3 & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \end{vmatrix} \quad (3.2)$$

And

$$b_1 = a_2 - \frac{a_0 a_3}{a_1}, \qquad b_2 = a_4 - \frac{a_0 a_5}{a_1} \quad (3.3)$$

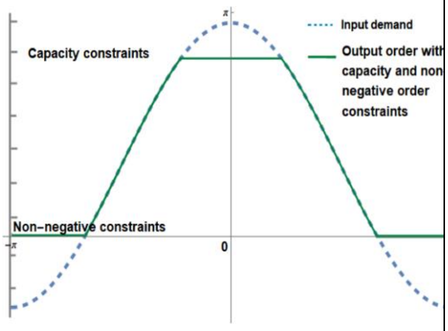
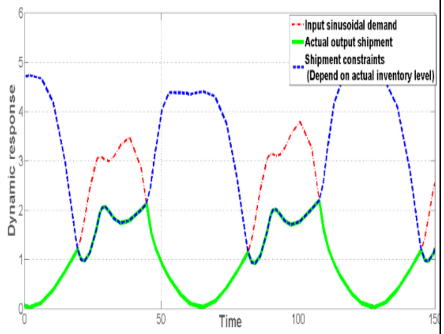
$$c_1 = a_3 - \frac{a_1 b_2}{b_1}, \quad c_2 = a_5 - \frac{a_1 b_3}{b_1} \text{... etc.}$$

The stability condition can be understood by inspecting the first column of the Equation (3.2), i.e. the system is guaranteed to be stable if there are no two sign changes in the first column.

3.2.1.4. Nonlinear analysis techniques

The principle of superposition is not valid in nonlinear system. This means that the output of a nonlinear system is not directly proportional to the input and the variables to be solved cannot be expressed as a linear combination of the independent parts

(Atherton, 1975). The nonlinearities in supply chains structure naturally exist due to the physical and economic constraints; for instance, fixed and variable capacity constraints in the production and shipment process, time-varying variables such as variable production delays and variable delivery time delays. Nonlinearities could also be intentionally introduced into the supply chains system to improve its performance. Nonlinearities presented in the supply chain systems can be categorised based on the rate of change in the output in relation to the input, i.e. the continuous or discontinuous nonlinearities (Towill, 1970; Vukic et al., 2003), as illustrated in Table 3.3.

Type of nonlinearity		**Main characteristics**	**Example and references (e.g.)**
Discontinuous nonlinearity	***Single-valued***	Sharp changes in output values or gradients in relation to input (e.g. piecewise linear function). Single-valued nonlinearities are characterised as memory-less nonlinearities, since the output of the system does not depend on the history of the input (Cook, 1986).	Fixed capacity constraints, non-negative order constraints (Spiegler et al., 2016) 
	Multi-valued	In contrast to the single-value nonlinearity, the output value of multi-valued discontinuous nonlinearity does depend on the history of the input. As the example shows, the output shipment does depend on history of input	Shipment constraints (Spiegler and Naim, 2017) 

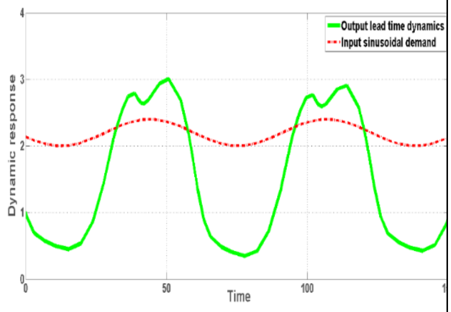
		demand, i.e. the variable shipment constraints (dynamic response) is driven by the history of demand	
Continuous nonlinearity		A feature of the outputs in continuous nonlinearity functions is that they are smooth enough to possess convergent expansions at all points and therefore can be linearised.	Delivery LT dynamics 

Table 3. 3. Brief introduction of different types of nonlinearities present in the supply chain system.

One of well-recognized approaches for dealing with nonlinear system is to linearize those nonlinear components. The rationale behind this approach is that a variety of linear techniques then can be applied to give further insights after linearization (Kolk and Lerman, 1992). This is generally considered a suitable approach when the solution can be obtained in this way. While the linear theory/approaches are well established, there is no agreement for nonlinear approaches for generality and applicability (Rugh, 2002). Since nonlinearities present in the supply chain system can be categorised as either discontinuous or continuous characteristics (Spiegler et al., 2012), the corresponding linearisation methods adopted in nonlinear control theory are summarised in Table 3.4.

Method	Applications for the type of nonlinearities	Assumptions/Possible drawback
Small perturbation theory with Taylor series expansion	Continuous Single-valued	Assumption that the amplitude of the excitation signal is small. Local stability analysis only
Describing function	Continuous, Discontinuous Single-valued, Multi-valued	Less accurate when nonlinearities contain higher harmonics. Analysis of systems with periodic or Gaussian random input only.
Small perturbation theory with Volterra/Wiener series expansion	Continuous Multi-valued	Assumption that the amplitude of the excitation signal is small. Difficulty in calculating the kernels and operators of the system, making it impractical for high order systems.
Averaging and best-fit line approximations	Continuous, Discontinuous Single-valued, Multi-valued	Gross approximation of real responses. Only when better estimates are not possible.

Table 3. 4. Linearisation methods for different types of nonlinearities in studying supply chain dynamics (Spiegler et al., 2012; Spiegler et al., 2016a; Spiegler et al., 2016b).

3.2.2. Simulation: System Dynamics approach

Simulation stands in the middle position between empirical research (observation, experiment, survey) and pure mathematical modelling (Wolf, 2008). One of major advantages of doing simulation research is it does not require specific mathematical background to obtain analytical solution or/and optimal solutions, as simulations proceed step-for-step using numerical approximation methods. A number of simulation techniques can be applied evaluate dynamical systems; e.g. system dynamics,d-event and agent-based simulations. In this thesis, the system dynamics simulation is utilized due to its great advantage of analysing dynamical systems characterised by feedback relations (Akkermans and Dellaert, 2005). Furthermore, system dynamics simulation can be utilised for verifying analytical results under many unrealistic assumptions in linear models (Lin et al., 2017).

Forrester (1961) developed system dynamics simulation in the 1960s. He mainly focused on the translation of dynamic behaviours between variables into a causal loop diagram/stock-flow diagram. Mathematically he converted these relations into differential equations, and then studied the output response in relation to specific external input disturbance to understand the cause and effect relations. There are four important elements to be considered when formulating system dynamics simulation models: levels, flow rates, decision functions and information channels (Forrester, 1961). A stock variable is measured at one specific time, and represents a quantity existing at that point in time which may have accumulated in the past, e.g. inventory. A flow variable is measured over an interval of time. Therefore, a flow would be measured per unit of time, e.g. the order rate per week. Decision functions are the differential or algebraic equations that state the policies used to control the rates between levels. Finally, information channels connect the information known about the levels with the decision functions. For instance, in a production-inventory system the levels of inventory and work in process can be used to determine the order rate. There are several techniques in modelling a dynamics system by utilising system dynamic language, including causal loop diagram and stock flow diagram, as described as follows:

The corresponding stock-flow diagram approach, shown by Figure 3.8, is adopted. The stock-flow diagram is a technique that visualises the major elements and their relationship in a dynamic system, including stock, flow, delay, feedback and nonlinearities elements. In addition to the four main elements in a dynamic system, there are two types of feedback loops in the production-inventory system, reinforcing (R) and balancing (B) loops, in which the former generates behaviour that takes the variable further away from its initial position, while the balancing feedback loop keeps the variable close to its original position (Fowler, 1999; Letmathe and Zielinski, 2016). Any movement away from the balancing position is pushed back.

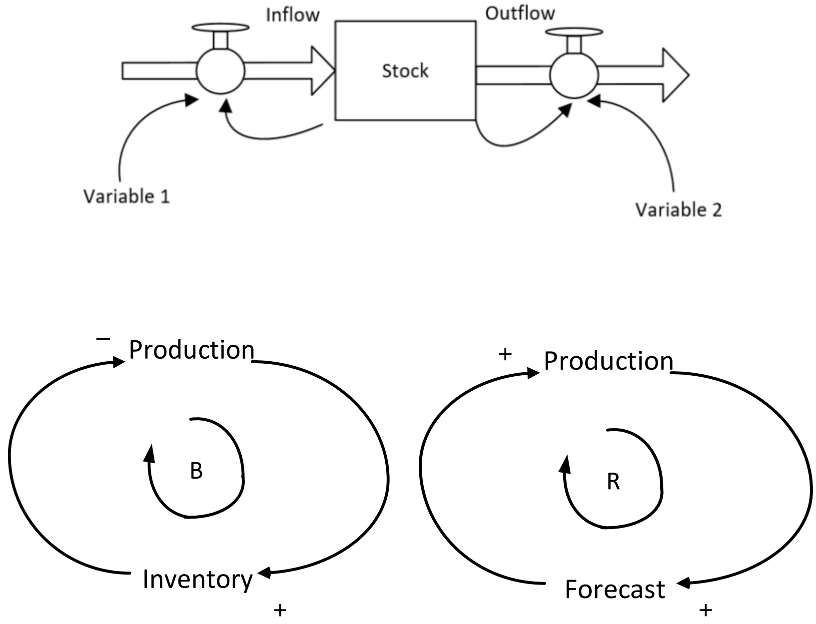


Figure 3. 8. The introduction of the stock-flow diagram and balancing and reinforcing casual loops

3.3. Research design

Figure 3.9 reports the research design for this thesis. As a deductive research methodology is adopted to answer RQ1a and RQ1b, this work started by reviewing the literature. Literature gaps related to supply chain theory (the ATO system dynamics and performance measurement) and methodology (nonlinear modelling and analysis of the ATO system) are identified, and the main research questions are established. Chapter 3 considers the selection of methods and ATO frameworks in studying system dynamics.

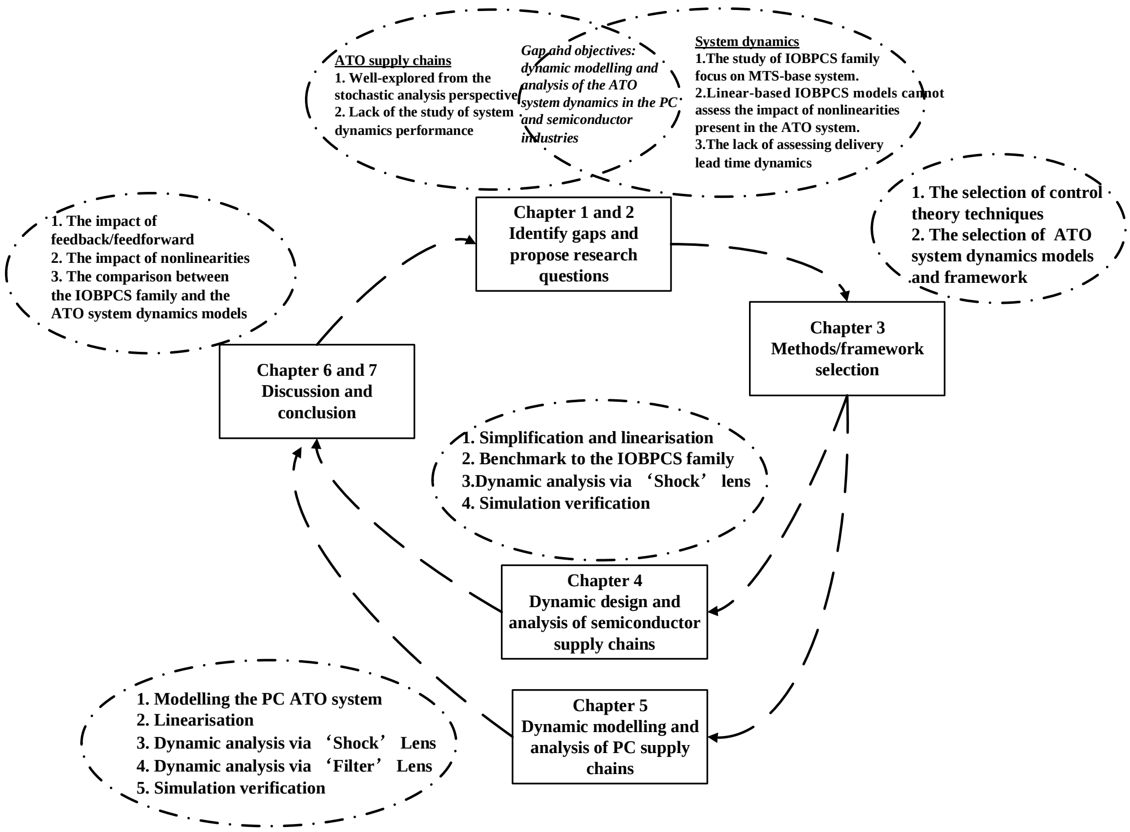


Figure 3. 9. Research design for this thesis.

The main analysis, Chapters 4 and 5, will present the detailed design, modelling and analysis of two ATO systems: Intel supply chain and a generic PC supply chain. Specifically, since the PC sector mainly includes upstream semiconductor and downstream subassemblies and OEM companies, the author decomposes the PC supply chain as two major parts: semiconductor and the PC OEM supply chain systems.

The secondary data from academic peer-reviewed papers will be used as the main source of this study. The use of secondary peer-reviewed publication data has several advantages in understanding the dynamics property of the ATO structure, including less time, money and fewer personnel for data collection (Rabinovich and Cheon, 2011; Ellram and Tate, 2016), high reliability and credibility due to the peer-reviewed process of paper publication. However, all secondary data and empirical data in general, whether voluntarily provided or mandated and standardised, is a snapshot at a point in time (Snow and Thomas, 1994). The Intel model published in 2005, for example, is only a snapshot of Intel supply chains in 2005 or before (Gonçalves et al., 2005), rather than at the current time. Nevertheless, the relatively old supply chain dynamics model still offers valuable information regarding the modern ATO supply chain structure and provides a good base model for further designing and analysing the dynamic property of a typical ATO system.

Specifically, in Chapter 4, a system dynamic model of Intel (Gonçalves et al., 2005), the leader in microprocessor manufacturing (Sampath et al., 2015) in representing the semiconductor industry, is selected. Due to no IOBPCS-based ATO model having been created and analysed, it is a good starting point to design and analyse the existing systems dynamic model and use the IOBPCS family as the benchmark to understand real-world dynamics ATO system structure. The author first models the Intel supply chain in a block diagram form based on the Intel model descriptions. Although the original model provided insights into lean inventory and responsive utilisation policies, the simulation approach could not reveal the explicit relationship between the system's outputs and the endogenous demand, thereby overlooking the real effects of some control parameters. After simplifying the block diagram and extracting the ATO scenario, we analyse the dynamic behaviour of the system by finding the system's transfer functions. The simplified model enables the drawing of an analogy with known archetypes of the IOBPCS family and the proposal of policies to overcome trade-offs in the system output responses. 'Shock' lens dynamic analysis will be conducted to provide rich dynamic property of the simplified system.

For Chapter 5, the author will develop the system dynamic model of a generic two-echelon PC supply chain based on multiple academic empirical publications (Kapuscinski et al., 2004; Kumar and Craig, 2007; Huang and Li, 2010; Katariya et al., 2014). Stock-flow diagram and block diagram of the generic model will be developed to illustrate the information and material flow and their connections. Both ‘Shock’ and ‘Filter’ lens analysis will be implemented to explore the generic ATO system structure as well as design system control policies to yield ‘good’ dynamic performance in facing different periodic demand patterns. Main nonlinearities presented in the ATO system will be analytically studied based on nonlinear control approach to determine the impact of nonlinearities on the dynamic performance. This offers analytical understanding about how the ATO system structure may characterise the dynamic oscillations and the possible strategy to avoid poor dynamic behaviour. Furthermore, lead times dynamics is explored as part of ‘performance triangle’, i.e. the CODP inventory, bullwhip and lead times, so that the trade-offs can be understood in designing ATO system dynamics.

The final two chapters discuss the insights gained from previous chapters to answer the research questions emerging in Chapters 1 and 2, which contribute to the theory (ATO dynamics modelling and analysis) and methodology (linear and nonlinear analysis via simplification and linearisation), hence closing the loop.

3.3.1 Literature review search process

The literatures review was initially based on an exploratory literature review process, which was initiated by conducting keyword searches in multiple databases, such as ABI/INFORM Global, EBSCOHost, Scopus, ScienceDirect and Emerald. Google Scholar was also found to be useful to locate conference papers and technical reports. For the first core topic review, i.e. the ATO supply chain systems, among the keywords searched, the author started with ‘customer order decoupling point’ and ‘supply chains’ in order to map out the research outlines of this field. In parallel, the keywords ‘decoupling point’, ‘postponement’ and ‘mass customization’ were searched alone so as to identify the various fields using these concepts. Later, the search was narrowed by combining ‘supply chain’ with ‘assemble-to-order’, ‘system’ and ‘ATO’. After this last search stage, the author collated all quantitative studies and qualitative studies that were relevant to developing the assemble-to-order supply chain performance assessment framework.

Regarding the second topic of literature, i.e. the system dynamics and the IOBPCS family, a similar narrow review is conducted in which a chronological search approach is adopted to review the history of system dynamics and supply chain dynamics work. Moreover, to review how the IOBPCS family is utilised to study supply chain dynamics and particularly the MTO and ATO systems, the author extracted Lin et al.'s (2017) systematic review work on the IOBPCS family by reviewing citations to original IOBPCS family studies (Towill, 1982 and John et al., 1994). Furthermore, due to Lin et al. (2017) reviewing citations only up to 2015, the author updated all citations of two seminal works to June 2018. Note that the detailed data collection process and review approach can be found in Lin et al. (2017).

3.3.2. The selection of ATO framework

3.3.1.1 Semiconductor supply chains: the Intel ATO system

Semiconductor industry is characterised as capital-intensive, short product life cycle, wide product variety due to overlapping product life cycles for different customers, long fabrication lead times and complex production processes (Geng and Jiang 2009). Although the complex material and equipment acquisition processes vary between different companies, a typical semiconductor manufacturing process consists of three main stages: wafer fabrication ('front-end' manufacturing), assembly and test, and product distribution ('back-end' operations), whose associated activities are usually involved in a globally-complex network to save labour costs and benefit from tax breaks (Rastogi et al., 2011). The ATO strategy is adopted in semiconductor production planning and control environment in which the CODP inventory is located in the final assembly part. The downstream assembly and distribution systems are essentially the MTO mode in which end customers' orders pull the available microprocessors from finished good inventory. The upstream wafer fabrication, however, is characterised by the MTS production style: long-term demand forecasting and the adjustment from downstream finished good as well as work-in-process inventory to determine the desired wafer production rate. Based on literature review chapter (Section 2.3), very limited work developed system dynamics model of the ATO system and analysed its dynamic performance. Also there is no existing IOBPCS-based framework for the ATO system. As the result, the author uses the existing system dynamics model of Intel, the leader in microprocessor manufacturing (Sampath et al. 2015), as reported empirically by Gonçalves et al. (2005), as a starting point to extract and analyse its ATO supply chain structure.

3.3.2.2. The PC ATO supply chain

Since the semiconductor ATO system is upstream of the entire PC supply chain system, the downstream of the PC ATO system should be considered. In general, PC supply chains have three main manufacturing echelons from upstream to downstream: component fabrication (i.e. semiconductor industry), sub-assembly and final assembly (Huang and Li, 2010).

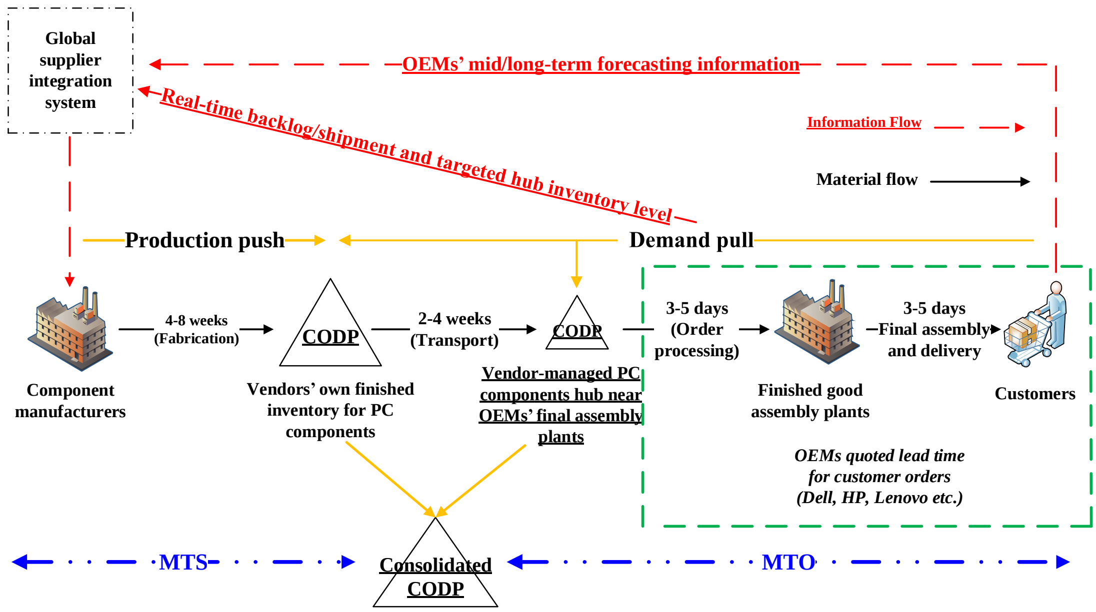


Figure 3. 10. Rich picture descriptions of PC supply chains. Based on Kapuscinski et al. (2004) Huang and Li (2010) and Katariya et al. (2014).

From the information flow perspective, as illustrated in Figure 3.10, the hybrid ATO production strategy is implemented in which the decoupling point is located in the OEMs' final assembly plants. The downstream production of the decoupling point (final assembly) essentially operates as an MTO in which end customers' orders pull the available CODP inventory based on their specific PC configurations. However, upstream production of the CODP, i.e. the PC components manufacturing, is characterised by MTS: long-term demand forecasting is shared by the OEM and the CODP inventory to determine production rates.

It should be noted that although the decoupling point is located in the OEM's final assembly plant, there are two CODP inventory stock points due to the adoption of the vendor-managed inventory (VMI) strategy in most PC supply chains (Huang and Li, 2010). Specifically, PC component suppliers are required to manage the finished PC components (CODP inventory) at both their manufacturing and OEMs sites, by renting or building inventory hubs near the OEMs' final assembly factories (i.e. the VMI inventory hub) to be pulled by customer orders at a high frequency. This is because of the long geographical distance between OEMs' final assembly and PC component suppliers' plants driven by the global supply chain strategy, i.e. longer delay between suppliers and OEMs compared with the short LT requirements pulled by end customer orders.

As a result, the VMI hub inventory is directly pulled by end customer order and the inventory at the supplier site is also pulled by the required replenishment of the VMI hub, while the suppliers' component manufacturing pushes the finished CODP inventory into its stock point. In return, the OEMs may share important information, e.g. long-term forecasting, real-time backlog and shipment, to help their suppliers make better CODP inventory replenishment decisions. In other words, the material CODP is incorporated into the final assembly site, while the information CODP (i.e. DIDIP) is moved to upstream supplier site to ensure information transparency.

3.3.2.3. The IOBPCS family as the benchmark framework

Towill (1982) developed the IOBPCS framework in a block diagram form to represent a feedback-based production/inventory system, extending the work conducted by Coyle (1977). The model focused on products at an aggregate level. Three system parameters were identified as the fundamental for ideal production/inventory control system design: lead time ($\mathrm{T_p}$) for production, a proportional controller ($\mathrm{T_i}$) to adjust the inventory discrepancy and a demand smoothing level ($\mathrm{T_a}$). John et al. (1994) then incorporated an automated WIP closed loop ($\mathrm{T_w}$) into the IOBPCS framework, which led to the APIOBPCS archetype, as shown in Figure 3.12.

There are two inputs - desired inventory (DINV) and consumption rate (CONS) - which represent the external disturbance, while the order rate placed on the pipeline (ORATE) is a decision variable determined by two feedback proportional controllers (T_i and T_w) as well as the averaged feedforward CONS (T_a). Thus, the APIOBPCS model can be described as follows: set the order rate as equal to the sum of demand averaged over T_a time units (demand policy), plus the T_i adjustment of inventory discrepancy (inventory policy) and the WIP adjustment of T_w (WIP policy), with due consideration of T_p (Pipeline policy). The APIOBPCS model is essentially equal to the IOBPCS model if $T_w = \infty$, i.e. in the case in which the WIP products are not included. Mathematical representations of four policies as well as systems' transfer functions can be found in Appendix 2.

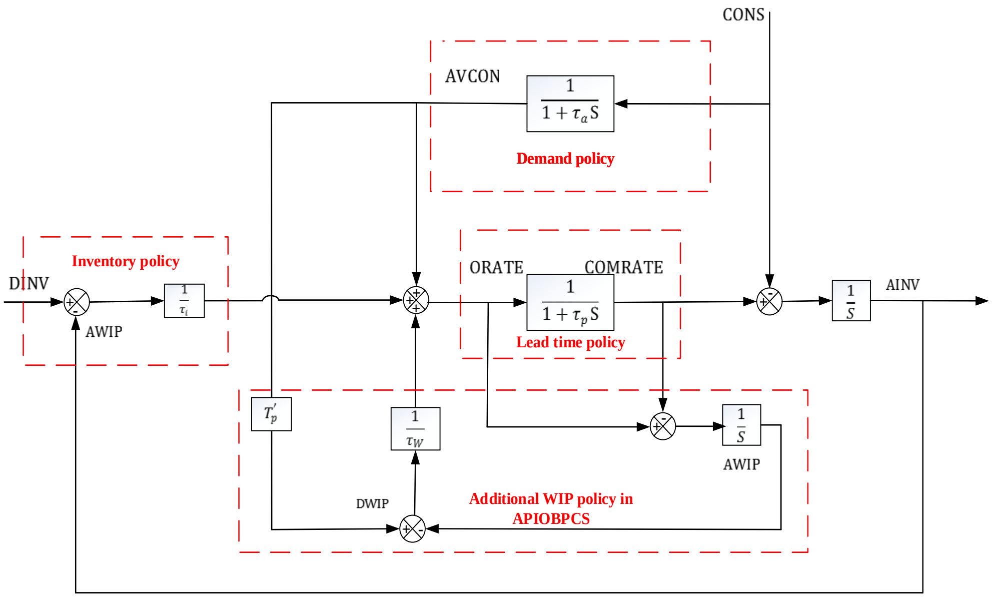


Figure 3. 11. Block diagram representation of APIOBPCS (including IOBPCS) archetype. Source: original diagram developed by John et al. (1994) and adapted by Sarimveis et al. (2008).

Therefore, given that T_p the decision makers need to select appropriate values for T_a, T_w and T_i, to achieve two conflicting objectives: 1) rapid inventory recovery and 2) attenuation of the unknown demand fluctuation. The second objective is also called the reduction of the bullwhip effect. The APIOBPCS archetype has been modified regarding its four inherent policies in the last three decades, which creates a 'family' of models shown in Table 3.6.

Specifically, the target inventory is either fixed or a multiple of smoothed market demand determined by the demand policy. The method of exponential smoothing is commonly applied in the demand policy in the main IOBPCS family. A proportional controller is utilised to correct WIP and inventory discrepancies, apart from the IOBPCS/VIOBPCS archetype that does not consider the WIP products. Finally, the four main IOBPCS archetypes usually adopt a first order lag to model lead time, representing production delay or production unit smoothing level in responding to ORATE change.

Model		**Target Inventory**	**Demand policy**	**WIP policy**	**Inventory policy**	**Lead time**
IOBPCS	Inventory and Order based Production Control System	Fixed	Exponential smoothing	$\frac{1}{\infty}$	$\frac{1}{T_i}$	First order lag
VIOBPCS	Various Inventory and Order based Production Control System	Multiple of Average market demand	Exponential smoothing	$\frac{1}{\infty}$	$\frac{1}{T_I}$	First order lag
APIOBPCS	Automatic Pipeline, Inventory and Order based Production Control System	Fixed	Exponential smoothing	$\frac{1}{T_w}$	$\frac{1}{T_I}$	First order lag
APVIOBPCS	Automatic Pipeline, Various Inventory and Order based Production Control System	Multiple of Average market demand	Exponential smoothing	$\frac{1}{T_w}$	$\frac{1}{T_I}$	First order lag

Table 3. 5. Main IOBPCS family members based on four policies and the target inventory.

Thus, the decision makers need to select appropriate value of T_a, T_w and T_i, to achieve two conflicting objectives: 1) The rapid inventory recovery and 2) Attenuation of unknown demand fluctuation. The second objective is also called the reduction of Bullwhip Effect (Lee et al., 1997). Standard control engineering approaches are used to quantify the performance of four policies that adhere to two objectives under linear, continuous, infinite system capacity assumptions in APIOBPCS. In terms of objective one, inventory response is evaluated by introducing a step input demand with respect to performance metrics, such as rise time, setting time and maximum overshoot. The initial and final value theorems, as well as Laplace inverse transform, are also applied to provide a mathematical crosscheck. Regarding objective two, noise bandwidth (W_N) measures the ability of the system decision parameters (T_i , T_a and T_w) to remove unwanted high-demand frequency. Using these measurement methods, John et al. (1994) developed a system that ensured a high level of customer service, while levelling the production rate by selecting $T_w = 2T_p$, $T_a = 2T_p$ and $T_i = T_p$. The authors also concluded that incorporating an automatic WIP controller damps the oscillations of COMRATE and reduces maximum overshoot, while eliminating the inventory drift by assuming that $T_p = T_{p'}$. These outcomes allowed for a high-quality control system, although a slight increase in setting time was identified.

3.4. Summary

This chapter has explained how the research was conducted, including the research ontological and epistemological positions, research design, methods and tools used in this thesis. The author holds an objective, value-free onotolgy for modelling and analysing the ATO system dynamics. Also, the author has chosen a deductive logic reasoning based on a systems and conceptual epistemological research (combined positivsim and critical realism).

A detailed methods selection was reviewed and justified. Specifically, the combined control engineering, including linear and nonlinear analysis techniqes and system dynamic simulation, were chosen to offer robust and analytical insights into ATO system dynamics analysis. The continuous time based modelling and analysis techinques were selected based on the nature of techniques and the PC industry.

Finally, the research design used to answer the research questions has been explained. This included the literature review process, the selection of two ATO frameworks, comprising an existing system dynamics model of the Intel (Gonçalves et al., 2005) and PC system dynamics background information that will be developed based on empirical evidence (Kapuscinski et al., 2004; Huang and Li, 2010; and Katariya et al., 2014).

Chapter 4. Dynamic design and analysis of a semiconductor ATO system

This chapter conducts the dynamic design and analysis of the Intel supply chain representing a typical ATO system in the semiconductor industry. By re-designing the original high-order nonlinear system dynamic model of the Intel supply chain, as well as using the IOBPCS family as benchmark models, the main aim is to explore analytically the underlying mechanisms of supply chain dynamics within the context of the semiconductor industry. There are two further objectives: 1) to explore the design procedures for gaining insight into the dynamic properties of nonlinear hybrid ATO model as personified by the Intel supply chain and 2) to investigate the underlying mechanisms of the dynamic behaviour in a semiconductor hybrid ATO supply chain and explore the possible mitigation strategy.

To achieve this, firstly, the Intel model description as well as the simplification method is given in Section 4.1. Then, by utilising a linear control engineering approach, including characteristics equation analysis and step input analysis, Sections 4.2 and 4.3 explore the fundamental dynamic property of the simplified ATO model and use the IOBPCS family to benchmark the model and compare the dynamic performance between simplified semiconductor ATO and the IOBPCS models. System dynamics simulation is utilised to verify the analytical insights gained from the linear analysis and for sensitive analysis of physical lead times and quality parameters in Section 4.

4.1 Intel ATO model description and manipulation

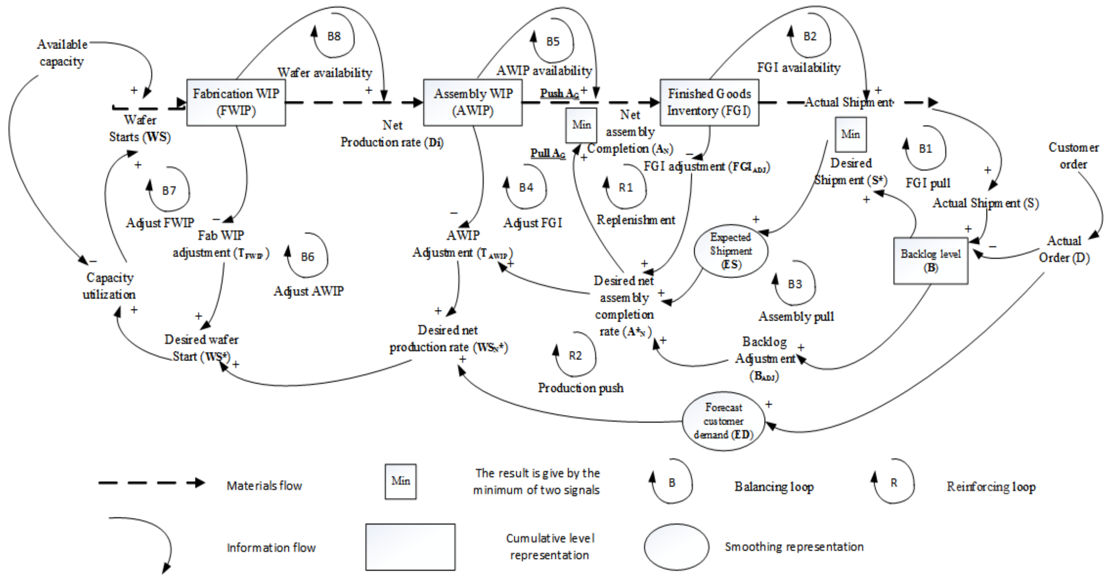


Figure 4.1. Basic structure of the production-inventory based semiconductor supply chain system. Based on Gonçalves et al. (2005).

Figure 4.1 shows the information and material flow of Intel ATO system based on the stock flow diagram technique. Specifically, there are two main manufacturing stages for microprocessor chip production from a material flow perspective: fabrication and final assembly. The polished disk-shaped silicon substrates (wafers) as inputs are taken into a wafer fabrication facility, and through several complicated sequences to produce fabricated wafers (composed of integrated circuits, i.e. dies). A vertical cross-section of an integrated circuit reveals several layers formed during the fabrication process. Lower layers include the critical electrical components (e.g. transistors, capacitors), which are produced at the "front-end" of the fabrication process. Upper layers, produced at the 'back-end' of the fabrication process, connect the electrical components to form circuits. In the second assembly phase, the fabricated wafers are cut into dies and stored in the ADI warehouse to wait for the assembly process. After passing assembly and test plants to ensure operability, the finished microprocessors are stored in the FGI for customer orders. A three-stage supply chain, including fabrication, assembly and distribution, is thereby created to represent the manufacturing process.

Regarding the information flow, the hybrid push-pull (ATO) information control strategy is implemented. The downstream assembly and distribution systems are essentially the MTO mode in which end customers' orders pull the available microprocessors from FGI if there are sufficient FGI and AWIP. The upstream wafer fabrication, however, is characterised by the MTS production style: long-term demand forecasting and the adjustment from downstream AWIP and FWIP to determine the desired wafer production rate.

The exogenous demand into the supply chain system begins when end customers' demand information is transmitted into the information system and tracked until it is shipped or cancelled. The actual shipment, S, is determined by the minimum value between S^* and S_{MAX}. By design, the distribution system operates as the pull state in which the S^* is given by the ratio of B and DD*. However, if insufficient FGI constrains S^*, the distribution system will automatically push all feasible FGI, which is estimated by FGI stock and T_{OP}, i.e. the system switches to the push state. Consequently, those backlogged orders directly pull product components from AWIP to increase the assembly order rate, under the condition that the assembly system still performs the pull-based production with enough AWIP. The delivery delay experienced by external customers is increased in such scenarios, since required orders cannot be fulfilled directly by FGI and it takes longer to assemble and distribute those backlogged orders.

While shipments deplete FGI, the A_N, defined by the A_G and Y_U, replenishes it. A_G is determined by the minimum of pull A_G and push A_G signal. By design, pull A_G is given by the desired pull signal under the MTO operation in the assembly system, i.e. A^*_N adjusted by Y_U. A_N^* is determined by the summation of the recent shipment, FGI adjustment and B adjustment. If all available AWIP still constrains the assembly activities, the assembly system can only complete what is feasible and thereby switch to the push production model, i.e. push A_G, which is estimated by the ratio between current AWIP and T_A.

The upstream fabrication plant follows the push-based production strategy in which the produced wafers are pushed into the ADI, the place where AWIP are stored until orders for specific product from downstream assembly and distribution pull/push them depending on its availability. While A_G depletes AWIP, D_I replenishes it. D_I, measured in die per month, depends on F_G (wafers per month), adjusted by DPW and Y_D, i.e. the fraction of good die per wafer and Y_L to indicate the fraction of the good fabricated wafers. For simplicity, a first order delay is utilised for the modelling process. While F_G depletes FWIP, WS* replenishes it. The fab managers determine WS* based on gross WS and $FWIP_{ADJ}$. The former is determined by D* required by assembly/test plants, which is based on a long-term demand forecast (ED) and an adjustment from AWIP, while $FWIP_{ADJ}$ depends on discrepancies between $FWIP^*$ and FWIP adjusted by T_{FWIP}.

The capacity utilisation (CU) is set based on the ratio between WS* and available capacity (K) operating at the normal capacity utilization level (CU_N= 90%). The remaining 10% spare capacity is utilised for engineering purpose and to deal with manufacturing instability. For a given D, K is determined by: $K = \frac{D \cdot MS}{CU_N \cdot DPW \cdot Y_D \cdot Y_L}$, where MS (market share) is not considered in this study. When WS* is larger than normal capacity utilisation, Fab managers try to increase CU_N and thus the spare capacity for engineering is reduced. On the other hand, when WS* falls below the normal CU_N, capacity utilisation will vary enough to exactly match WS*. However, field study (Gonçalves et al., 2005) showed that the managers prefer to build inventory by keeping Fab running even when WS* falls below the normal capacity utilisation. As a result, WS* can be fully met by adjusting capacity utilisation level and Fab managers prefer the "Lean-based" production to avoid machine shut down for the low capacity utilisation scenario.

Based on the stock-flow diagram description of the Intel supply chain, the Intel supply chain model in a block diagram form, using continuous Laplace s domain, can be developed (Figure 4.2). In a recent publication, Naim et al. (2017) accomplished the same resulting block diagram but in discrete time. Note the full mathematical modelling details (difference equations) in relation to block diagram can be found in Appendix 1.

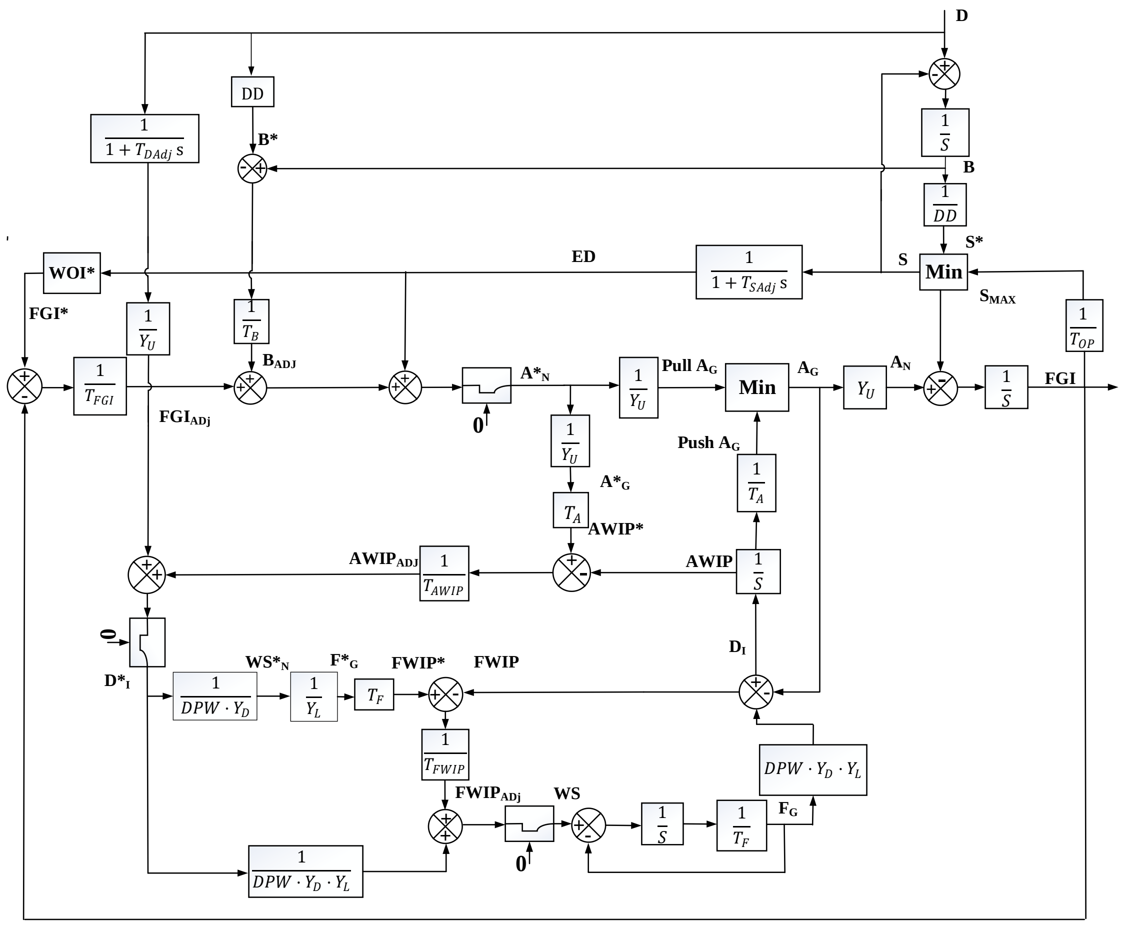


Figure 4. 2. Block diagram representation of the Intel supply chain.

It should be noted that the dynamic influence of customers' response, i.e. the customers' response to supply availability measured by the fraction of order fulfilment, is not considered, as we focus only on the effect of exogenous demand and internal dynamic production and inventory control in the Intel supply chain model. The impact of endogenous demand on the dynamic performance of the Intel supply chain, however, can be found in Gonçalves et al. (2005).

Based on Figure 4.1, two 'Min' functions, depending on the availability of two stock points: FGI and AWIP inventory, govern three different states of the Intel supply chain system, which can be categorised as follows:

The Intel supply chain can be categorised as three different operational states depending on availability of two stock points: FGI and AWIP inventory as follows:

1. ***Fabrication Push + Assembly Pull + Distribution Pull state**, **if $S^*<S_{MAX}$ and Pull A_G < Push A_G.*** Such a system is highly desirable, since the customers' orders can be fulfilled immediately by FGI (sufficient on-hand FGI and AWIP inventory). The only waiting time for customers is the *delivery delay*, which is assumed to be a first-order delay.

2. ***Fabrication Push + Assembly Pull + Distribution Pull state**, **if S^* > S_{MAX} and Pull A_G < Push A_G.*** Under such conditions, on hand FGI is insufficient for customers' orders; Intel, therefore, can only ship what is feasible (S_{MAX}) and transfer the backlog/inventory signal into the assembly process to raise the assembly rate. However, the assembly system still operates the MTO mode under the premise that there are sufficient AWIP. The lead time for backlogged orders is increased to the summation of the *delivery delay and assembly delay*.

3. ***Fabrication Push + Assembly Push + Distribution Push state, if S^* > S_{MAX} and Pull A_G > Push A_G.*** Specifically, if the assembly is also constrained by the feasible AWIP level, the whole supply chain system will switch to a pure push state. The customer orders cannot be fulfilled for a short time, due to the long delay in fabrication production, and the lead time for backlogged orders is increased to the summation of the *delivery delay, assembly delay and fabrication delay*.

To analytically explore the underlying dynamic behaviour of the Intel supply chain systems, the block diagram is simplified through the following procedure by following Wikner et al. (1992):

1. *Transfer non-negative components into linear approximations.*

   Eliminating three non-negative nonlinear constraints by assuming the relevant variables are never negative. Thus, non-negative constraints that restrict D^*_I, A^*_N, and WS are eliminated.

2. *Supply chain echelon elimination*

   Assume there is no distribution delay and that what is assembled into the FGI can be directly fulfilled by external customer demand, that is, the distribution echelon is eliminated. Thus, the backlog orders can be represented by negative FGI under the linear assumption of Step 1, and the switch between S^* and S_{MAX} is eliminated. The whole model now becomes **a two-stage** supply chain system.

3. *Redundancies elimination*

   a. Given the assumption that the shipment made is equal to the demand, that is, S=D, then B = DD·D and B* = DD*·D so that $B_{ADJ} = 0$

   b. ED=ES

   c. S_{MAX} is redundant, given Step 2.

4. *Collecting terms*

   Gross WS* is determined by the desired net wafer start rate adjusted by Y_L and in turn, the desired wafer production rate is determined by D* in assembly, adjusted by the DPW and the die yield Y_D, so we have the following relationship:

$$\text{Gross } WS^* = \frac{1}{DPW \cdot Y_D \cdot Y_L} D^*$$

To simplify the block diagram, the terms are collected as follows:

a. $K_1 = \frac{1}{DPW \cdot Y_D \cdot Y_L}$

b. $K_2 = K_1 \cdot T_F$

c. $K_3 = \frac{1}{K_1}$

Since the linear model shown in Figure 4.2 is now considerably simpler than the original complex supply chain, it can no longer be referred to as the Intel supply chain; instead, the model is, from now on, termed a semiconductor supply chain. One benefit of investigating the linear system is that it enables the analytical tracing of supply chain dynamics. Given that, in reality, semiconductor manufacturing suffers high capacity unevenness (Karabuk and Wu, 2003) due to reactive capacity adjustment driven by dynamic behaviour, there is a need for managers to proactively control the supply chain dynamics, and, especially, the bullwhip effect, by understanding the root causes of such dynamic capacity requirement responses. This can be attained by assuming linearity and using well-established linear control techniques to explore the impact of major control policies on dynamic behaviour. However, given that the simplification process and the linear assumptions necessary for the analytical investigation may impact on the accuracy of responses and on certain variable interactions, we will cross-check the analytical results (to be presented in Section 4.2) with numerical simulations of the nonlinear model (to be presented in Section 4.4) in order to enhance dynamic insights into the hybrid ATO supply chain model.

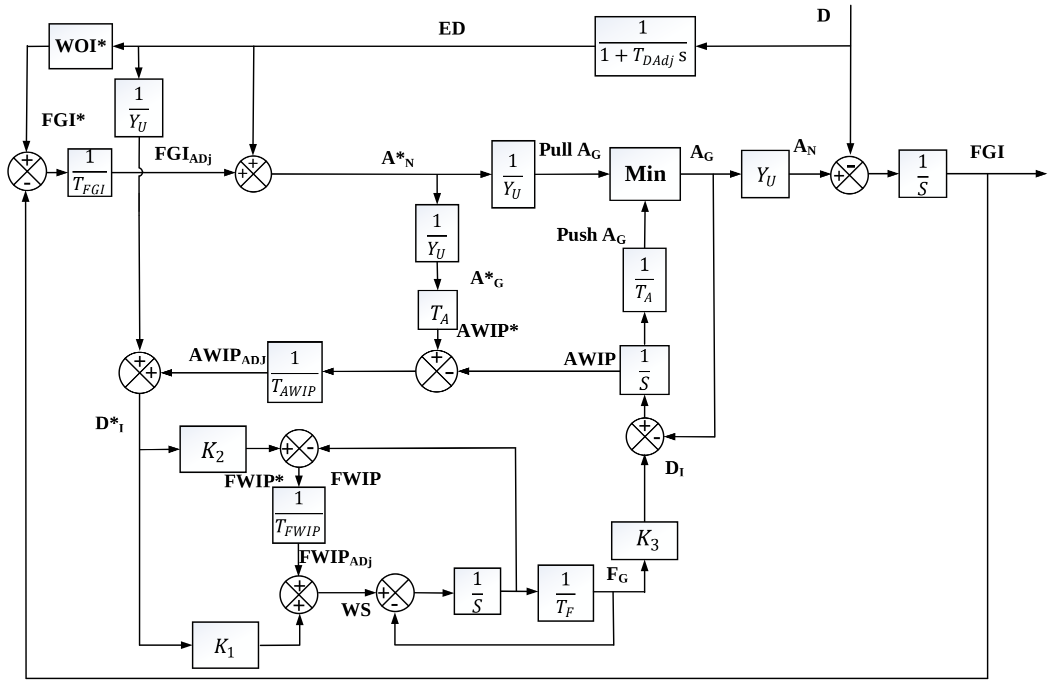


Figure 4. 3. Simplified block diagram for the hybrid ATO supply chain model.

As shown in Figure 4.3, the only nonlinearity left is the 'Min' function to govern the Push/Pull downstream assembly activity, which we have deliberately maintained at this stage as it governs the location of the decoupling point. The three interchangeable states, as described before based on Figure 4.1, now become two interchangeable states depending on the availability of AWIP. If there is sufficient AWIP, i.e. push A_G > pull A_G, for customer orders to pull chips from, then such a semiconductor system is fundamentally a hybrid ATO supply chain including a Push and a Pull parts, i.e. the forecasting-based wafer fabrication and order-driven assembly. Thus, AWIP is the CODP that separates the upstream wafer production and downstream assembly activities. By contrast, if the AWIP is insufficient to meet the pull signal, i.e. push A_G < pull A_G, all AWIP will be pushed into the assembly plant to meet customer orders as soon as possible, and the whole system will automatically switch to a pure Push-driven supply chain system. As the main objective of this paper is to understand the underlying dynamic properties of a hybrid ATO system, we focus exclusively on such a scenario.

4.2. Dynamic modelling and analysis of the semiconductor hybrid ATO supply chain

4.2.1 Modelling the hybrid ATO state

Consequently, the ‘Min’ function and push A_G in Figure 4.2 are removed and the whole system is now a typical hybrid ATO supply chain. The structure is rearranged to yield Figure 4.4 so as to draw an analogy with the IOBPCS family. It can be seen that the hybrid ATO system consists of a VIOBPCS (Edghill and Towill, 1990) ordering rule in the downstream assembly stage and a structure similar to the APVIOBPCS (Dejonckheere et al., 2003) ordering rule in the upstream fabrication.

The AWIP is the interface (CODP) connecting the fabrication and assembly production, i.e. the AWIP is the finished stock point for the push fabrication, while it supplies raw materials for the final assembly pulled by the customer ordering rate. For the downstream pull system, represented by the VIOBPCS, the only input is the customer demand signal. The block diagram also indicates that there is an instantaneous assembly process that has a zero-yield loss for what is required for assembly, due to the hybrid ATO condition that pull A_G is always larger than push A_G.

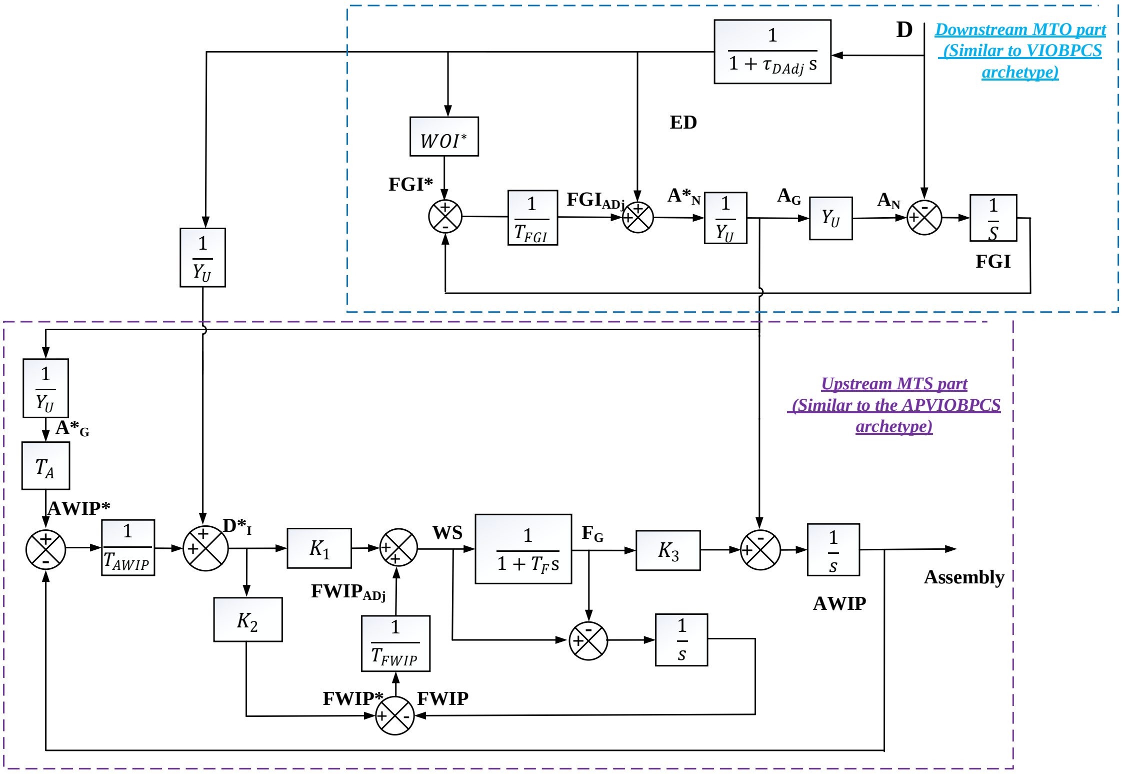


Figure 4. 4. Re-arranged block diagram for the hybrid ATO supply chain model.

As such, the desired rate (ordering rate), A_N^*, equals the net assembly complete rate (A_N) as follows:

$$A_N^*(t) = FGI_{ADJ}(t) + ED(t) \tag{4.1}$$

Where

$$FGI_{ADJ}(t) = \frac{1}{T_{FGI}} \cdot \left(ED(t) \cdot WOI^* - FGI(t)\right) \tag{4.2}$$

and

$$ED(t) = ED(t-1) + a \cdot \left(D(t) - ED(t-1)\right), \;\; a = \frac{1}{1 + \frac{T_{DAdj}}{\triangle T}} \;\text{(Towill, 1977)} \tag{4.3}$$

The upstream fabrication push system is similar to the APVIOBPCS replenishment rule that includes inventory feedback correction (AWIP), work-in-process feedback correction (FWIP) and feedforward forecasting compensation (ED). There are two inputs in such a system, including demand from the MTO system and the end customer, and feedforward forecasting, i.e. ED(t), is based on the end customer demand (D); in other words, DIDP is put on the upstream fabrication echelon. Therefore, the ordering rate for each replenishment cycle is given by:

$$WS(t) = \frac{K_1}{Y_U} \cdot ED(t) + K_1 \cdot AWIP_{ADJ}(t) + FWIP_{ADJ}(t) \qquad (4.4)$$

and $AWIP_{ADJ}(t)$ is determined by the fraction of difference between the desired assembly pull level and actual AWIP level, which equals:

$$AWIP_{ADJ}(t) = \frac{1}{T_{FWIP}} \cdot \left(A_N^*(t) \cdot \frac{T_A}{Y_U} - AWIP(t) \right) \qquad (4.5)$$

$FWIP_{ADJ}(t)$ is determined by a fraction of the difference between the desired inflow FWIP and the actual FWIP as follows:

$$FWIP_{ADJ}(t) = \frac{1}{T_{FWIP}} \cdot \left(T_F \cdot K1 \cdot \left(ED(t) \cdot \frac{1}{Y_U} + AWIP_{ADJ}(t) \right) - FWIP(t) \right) \quad (4.6)$$

It should be noted that the safety stock levels, AWIP and FGI*, and desired FWIP* are based on constant gains, WOI*, T_A and K_2/Y_U, that need to be set. Hence, there is an opportunity to further explore the impact of setting such levels, which gives more insight into the overall dynamic behaviour of the hybrid ATO system. e.g. see Manary and Willems's (2008) method to address the issue of systematically biased forecast experienced by the Intel supply chain. However, it is beyond the scope of this thesis to investigate the impact of parameter variation on the dynamics of the hybrid ATO semiconductor supply chain.

In summary, the final stylised hybrid ATO structure consists of two major ordering rules under the assumption that the CODP inventory is always available for end customers' orders. Downstream of the CODP is the VIOBPCS ordering rule with negligible lead time; while the upstream Push structure is similar to the APVIOBPCS, but there are some differences regarding the settings of the targeted WIP feedback loop, as well as the feedforward forecasting loop. Using a control engineering approach, the underlying dynamic behaviour of the semiconductor hybrid supply chain system is now explored.

4.2.2 Transfer function analysis

As we focus on the dynamic behaviour of the inventory and order rate in responding to the external demand signal under the hybrid ATO supply chains (Figure 5), the corresponding transfer functions, downstream FGI, A^*_N in relation to the demand (D), can be derived based on the following procedures:

- Substitute Equation (4.2) into (4.1);
- Substitute Laplace domain of ED in relation to D, i.e. $ED = D \cdot \frac{1}{1+T_{DAdj}s}$, into Equation (4.1);
- Substitute Laplace domain of FGI in relation to A^*_N, i.e. $= (A_N^* - D) \cdot \frac{1}{s}$, into Equation (4.2) and then Substitute Equation (4.2) into (4.1).

We now have the transfer function of A^*_N in relation to D:

$$\frac{A_N^*}{D} = \frac{1 + \left(T_{DAdj} + T_{FGI} + WOI^*\right)s}{1 + \left(T_{DAdj} + T_{FGI}\right)s + T_{DAdj}T_{FGI}s^2} \tag{4.7}$$

Substitute Equation (7) into $FGI = (A_N^* - D) \cdot \frac{1}{s}$, the transfer function of FGI can be derived thus:

$$\frac{FGI}{D} = \frac{WOI^* - T_{DAdj}T_{FGI}s}{1 + \left(T_{DAdj} + T_{FGI}\right)s + T_{DAdj}T_{FGI}s^2} \tag{4.8}$$

Similarly, the upstream WS and AWIP in relation to D can be derived by the following steps:

- Substitute Equations (4.5) and (4.6) into (4.4) in Laplace form to obtain:

$$WS = \frac{K_1}{Y_U} \cdot ED + K_1 \cdot \frac{1}{T_{AWIP}} \left(A_N^* \cdot \frac{T_A}{Y_U} - AWIP \right) + \frac{1}{T_{FWIP}} \cdot \left(T_F \cdot K1 \cdot \left(ED \cdot \frac{1}{Y_U} + \frac{1}{T_{AWIP}} \cdot \left(A_N^* \cdot \frac{T_A}{Y_U} - AWIP \right) \right) - FWIP \right) \qquad (4.9)$$

Where

$$FWIP = (WS - F_G) \cdot \frac{1}{s} = WS \cdot \frac{T_F}{1 + T_F s} \qquad (4.10)$$

$$AWIP \ = \ (F_G - A_N^*) \cdot \frac{1}{s} \ = \ \left(WS \cdot \frac{1}{1 + T_F s} - A_N^* \right) \cdot \frac{1}{s} \qquad (4.11)$$

$$ED = D \cdot \frac{1}{1 + T_{DAdj} s} \qquad (4.12)$$

- Substitute Equations (4.7), (4.10), (4.11) and (4.12) into (4.9)

Now we can obtain the transfer function of WS in relation to D as follows:

$$\frac{WS}{D} = \frac{K_1}{Y_U} \cdot \frac{\begin{gathered} (T_F + T_{\mathrm{FWIP}}) + \\ \begin{pmatrix} WOI^* T_F + T_{DAdj} T_F + T_{\mathrm{A}} T_F + T_{\mathrm{AWIP}} T_F + T_F^2 + T_F T_{\mathrm{FGI}} + WOI^* T_{\mathrm{FWIP}} + \\ T_{DAdj} T_{\mathrm{FWIP}} + T_{\mathrm{A}} T_{\mathrm{FWIP}} + T_{\mathrm{AWIP}} T_{\mathrm{FWIP}} + T_F T_{\mathrm{FWIP}} + T_{\mathrm{FGI}} T_{\mathrm{FWIP}} \end{pmatrix} s + \\ \begin{pmatrix} T_{\mathrm{AWIP}} T_F^2 + T_{\mathrm{A}} T_F T_{\mathrm{FGI}} + T_{\mathrm{AWIP}} T_F T_{\mathrm{FGI}} + T_F^2 T_{\mathrm{FGI}} + WOI^* T_{\mathrm{A}} T_{\mathrm{FWIP}} + \\ T_{DAdj} T_{\mathrm{A}} T_{\mathrm{FWIP}} + WOI^* T_F T_{\mathrm{FWIP}} + T_{DAdj} T_F T_{\mathrm{FWIP}} + \\ T_{\mathrm{A}} T_F T_{\mathrm{FWIP}} + T_{\mathrm{AWIP}} T_F T_{\mathrm{FWIP}} + \\ T_{\mathrm{A}} T_{\mathrm{FGI}} T_{\mathrm{FWIP}} + T_{\mathrm{AWIP}} T_{\mathrm{FGI}} T_{\mathrm{FWIP}} + T_F T_{\mathrm{FGI}} T_{\mathrm{FWIP}} \end{pmatrix} s^2 + \\ \begin{pmatrix} WOI^* T_{\mathrm{A}} T_F^2 + T_{DAdj} T_{\mathrm{A}} T_F^2 + T_{\mathrm{A}} T_F^2 T_{\mathrm{FGI}} + T_{\mathrm{AWIP}} T_F^2 T_{\mathrm{FGI}} + WOI^* T_{\mathrm{A}} T_F T_{\mathrm{FWIP}} + \\ T_{DAdj} T_{\mathrm{A}} T_F T_{\mathrm{FWIP}} + T_{\mathrm{A}} T_F T_{\mathrm{FGI}} T_{\mathrm{FWIP}} + T_{\mathrm{AWIP}} T_F T_{\mathrm{FGI}} T_{\mathrm{FWIP}} \end{pmatrix} s^3 \end{gathered}}{\begin{gathered} (T_F + T_{\mathrm{FWIP}}) + \begin{pmatrix} T_{DAdj} T_F + T_{\mathrm{AWIP}} T_F + T_F T_{\mathrm{FGI}} + \\ T_{DAdj} T_{\mathrm{FWIP}} + T_{\mathrm{AWIP}} T_{\mathrm{FWIP}} + T_{\mathrm{FGI}} T_{\mathrm{FWIP}} \end{pmatrix} s + \\ \begin{pmatrix} T_{DAdj} T_{\mathrm{AWIP}} T_F + T_{DAdj} T_F T_{\mathrm{FGI}} + T_{\mathrm{AWIP}} T_F T_{\mathrm{FGI}} + T_{DAdj} T_{\mathrm{AWIP}} T_{\mathrm{FWIP}} + \\ T_{\mathrm{AWIP}} T_F T_{\mathrm{FWIP}} + T_{DAdj} T_{\mathrm{FGI}} T_{\mathrm{FWIP}} + T_{\mathrm{AWIP}} T_{\mathrm{FGI}} T_{\mathrm{FWIP}} \end{pmatrix} s^2 + \\ \begin{pmatrix} T_{DAdj} T_{\mathrm{AWIP}} T_F T_{\mathrm{FGI}} + T_{DAdj} T_{\mathrm{AWIP}} T_F T_{\mathrm{FWIP}} + \\ T_{DAdj} T_{\mathrm{AWIP}} T_{\mathrm{FGI}} T_{\mathrm{FWIP}} + T_{\mathrm{AWIP}} T_F T_{\mathrm{FGI}} T_{\mathrm{FWIP}} \end{pmatrix} s^3 + \\ T_{DAdj} T_{\mathrm{AWIP}} T_F T_{\mathrm{FGI}} T_{\mathrm{FWIP}} s^4 \end{gathered}} \qquad (4.13)$$

Substituting Equations (7) and (13) into (11), we can obtain the transfer function of AWIP in relation to D:

$$\frac{AWIP}{D} = \frac{1}{Y_U} \cdot \frac{\begin{array}{c}(T_{\mathrm{A}} T_F + T_{\mathrm{A}} T_{\mathrm{FWIP}}) + \\ \left(\begin{array}{c} WOI^{*} T_{\mathrm{A}} T_F + T_{DAdj} T_{\mathrm{A}} T_F - WOI^{*} T_{\mathrm{AWIP}} T_F - T_{DAdj} T_{\mathrm{AWIP}} T_F + T_{\mathrm{A}} T_F T_{\mathrm{FGI}} + \\ WOI^{*} T_{\mathrm{A}} T_{\mathrm{FWIP}} + T_{DAdj} T_{\mathrm{A}} T_{\mathrm{FWIP}} - WOI^{*} T_{\mathrm{AWIP}} T_{\mathrm{FWIP}} - \\ T_{DAdj} T_{\mathrm{AWIP}} T_{\mathrm{FWIP}} - T_{\mathrm{AWIP}} T_F T_{\mathrm{FWIP}} + T_{\mathrm{A}} T_{\mathrm{FGI}} T_{\mathrm{FWIP}} \end{array}\right) s \\ + \left(-WOI^{*} T_{\mathrm{AWIP}} T_F T_{\mathrm{FWIP}} - T_{DAdj} T_{\mathrm{AWIP}} T_F T_{\mathrm{FWIP}} - T_{\mathrm{AWIP}} T_F T_{\mathrm{FGI}} T_{\mathrm{FWIP}}\right) s^2 \end{array}}{\begin{array}{c} (T_F + T_{\mathrm{FWIP}}) + \left(\begin{array}{c} T_{DAdj} T_F + T_{\mathrm{AWIP}} T_F + T_F T_{\mathrm{FGI}} + T_{DAdj} T_{\mathrm{FWIP}} + \\ T_{\mathrm{AWIP}} T_{\mathrm{FWIP}} + T_{\mathrm{FGI}} T_{\mathrm{FWIP}} \end{array}\right) s + \\ \left(\begin{array}{c} T_{DAdj} T_{\mathrm{AWIP}} T_F + T_{DAdj} T_F T_{\mathrm{FGI}} + T_{\mathrm{AWIP}} T_F T_{\mathrm{FGI}} + T_{DAdj} T_{\mathrm{AWIP}} T_{\mathrm{FWIP}} + \\ T_{\mathrm{AWIP}} T_F T_{\mathrm{FWIP}} + T_{DAdj} T_{\mathrm{FGI}} T_{\mathrm{FWIP}} + T_{\mathrm{AWIP}} T_{\mathrm{FGI}} T_{\mathrm{FWIP}} \end{array}\right) s^2 + \\ \left(\begin{array}{c} T_{DAdj} T_{\mathrm{AWIP}} T_F T_{\mathrm{FGI}} + T_{DAdj} T_{\mathrm{AWIP}} T_F T_{\mathrm{FWIP}} + \\ T_{DAdj} T_{\mathrm{AWIP}} T_{\mathrm{FGI}} T_{\mathrm{FWIP}} + T_{\mathrm{AWIP}} T_F T_{\mathrm{FGI}} T_{\mathrm{FWIP}} \end{array}\right) s^3 + \\ T_{DAdj} T_{\mathrm{AWIP}} T_F T_{\mathrm{FGI}} T_{\mathrm{FWIP}} s^4 \end{array}} \tag{4.14}$$

The transfer function represents the dynamic properties of the system. In particular, the characteristic equation, defined by equating the denominator of overall transfer function to zero, can be used to find poles (roots), which give an initial understanding of the underlying dynamic mechanism of the semiconductor hybrid ATO system including *system stability* and *unforced system dynamic property* (i.e. natural frequency and damping ratio).

By rewriting the denominator of Equations (4.7), (4.8), (4.13) and (4.14) as Equation (4.15), it can be seen that the Pull system is characterised by a second-order system, while a fourth-order polynomial describes the Push system:

$$\left(1 + T_{DAdj} s\right)(1 + T_{\mathrm{FGI}} s) = 0 \tag{4.15}$$

$$\left(1 + T_{DAdj} s\right)(1 + T_{\mathrm{FGI}} s)(T_F + T_{\mathrm{FWIP}} + (T_{\mathrm{AWIP}} T_F + T_{\mathrm{AWIP}} T_{\mathrm{FWIP}}) s + T_{\mathrm{AWIP}} T_F T_{\mathrm{FWIP}} s^2) = 0$$

Also, there is a second-order polynomial, $(1 + T_{DAdj} s)(1 + T_{\mathrm{FGI}} s)$, in the denominator of all transfer functions, which confirms that the dynamic property of the Pull system is not influenced by the Push system, while the dynamic performance of the MTS system can be partially manipulated by the Pull system under the hybrid ATO mode.

Initial Value Theorem (IVT) and Final Value Theorem (FVT) now is analysed. The IVT is a useful tool to cross-check mathematically the correctness of a transfer function and guide the appropriate initial condition required by a simulation. The FVT is useful to understand the steady state value of the dynamic response of a transfer function and can help verify the simulation. Equation 16 presents the initial and final values of FGI, A_N^*, WS and AWIP in responding to a unit step input for the semiconductor hybrid ATO system.

$$\lim_{s\to\infty} s\frac{A_N}{D} = 0 \qquad \lim_{s\to 0} s\frac{A_N}{D} = 1$$

$$\lim_{s\to\infty} s\frac{FGI}{D} = 0 \qquad \lim_{s\to 0} s\frac{FGI}{D} = WOI$$

$$\lim_{s\to\infty} s\frac{WS}{D} = 0 \qquad \lim_{s\to 0} s\frac{WS}{D} = \frac{K_1}{Y_U} \tag{4.16}$$

$$\lim_{s\to\infty} s\frac{AWIP}{D} = 0 \qquad \lim_{s\to 0} s\frac{AWIP}{D} = \frac{T_A}{Y_U}$$

As expected, the initial values of FGI, A_N^*, AWIP, FWIP and WS are zero; similar to the results obtained by John et al. (1994). Regarding the final value, the ordering rate (A^*_N) of the MTO system is unity and the steady state level of the FGI is WOI* as it is a function of the averaged demand. The final value of ordering rate (WS) for the upstream Push system is, as expected, a system constant value K_1/Y_U, and the final value of AWIP is determined by the coefficient T_A (the targeted inventory level in the APVIOBPCS). Since the downstream Pull system is not influenced by the upstream Push system, due to the assumption of infinite AWIP availability to maintain the Pull assembly while the dynamic behaviour of Push is influenced by the upstream Pull system, we analyse the dynamic properties of the Pull and Push systems separately.

4.2.3 Characteristic equation analysis of the Pull system

Since the transfer function of the Pull part is a second-order system, its associated dynamic properties are defined by ω_n and ζ, determined by the characteristic equation. Hence, ω_n and ζ are obtained as follows:

$$\omega_n = \sqrt{\frac{1}{T_{DAdj}T_{FGI}}} \qquad \zeta = \left(T_{DAdj}+T_{FGI}\right)\sqrt{\frac{1}{2\,T_{DAdj}T_{FGI}}} \qquad (4.17)$$

Based on Equation 4.17, both ω_n and ζ are determined by the control parameters T_{DAdj} and T_{FGI}. The natural frequency decreases as the values of T_{DAdj} and T_{FGI} increase, leading to a slower dynamic response and recovery to the steady state conditions for the Pull system. To illustrate the relationship between ζ and T_{DAdj} and T_{FGI}, Equation 4.17 as 4.18 is rewritten:

$$\zeta = \sqrt{\frac{1}{2}\left(\frac{T_{DAdj}}{T_{FGI}} + \frac{T_{FGI}}{T_{DAdj}}\right) + 1} \qquad (4.18)$$

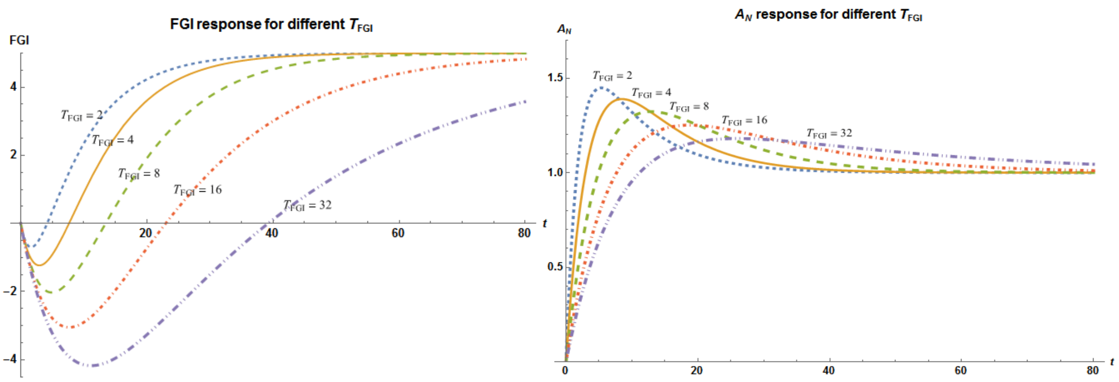
When $T_{DAdj} = T_{FGI}$, ζ always assumes the same value $\left(\sqrt{2}\right)$. When either T_{DAdj} or T_{FGI} increases, ζ increases further, decreasing the number of oscillations in response to external demand but making the system slow. The important message here is that $\zeta \geq 1$ for all positive values of T_{DAdj} and T_{FGI}, which means that the system always produces over-damped behaviour and is guaranteed to be stable. This is important because the system is permitted to be stable and robust for any choice of positive decision-making parameters. Furthermore, objectives of the rapid inventory recovery (natural frequency) and low level of bullwhip (i.e. maximum overshoot), determined by the damping ratio, cannot be achieved simultaneously. This trade-off has also been confirmed mathematically by Towill (1982).

4.2.4. Unit step response of the Pull system

The unit step input is utilised to assess the dynamic behaviour of the semiconductor hybrid ATO system. The step as an input source is well documented (Towill, 1970) in general control theory for exploring the system's capacity to respond to sudden but sustained change. Moreover, step change as the input is easily visualised and its response can be easily interpreted (John et al. 1994), especially for those important dynamic performance indicators such as bullwhip and inventory variance. Furthermore, the step increases give rich information for the dynamic behaviour of the system (Coyle, 1977). From the supply chain point of view, the step demand can be regarded as the early stage of a new product or the opening of a new sales outlet (Zhou and Disney, 2006), which fits the customer demand condition in the semiconductor industry characterised by a short life cycle with a corresponding sudden change in demand during the release of new products.

Due to the analogy between the VIOBPCS and the Pull part of the semiconductor hybrid supply chain system, the set of parameters utilised is as suggested by Edghill and Towill (1990) with 4 units of assembly lead time (T_A=4). Based on the transfer functions of the Pull system, i.e. Equations (4.11) and (4.12), the value of required system parameters for simulation are thereby (weeks):

$$T_{DAdj}=8,\ T_{FGI}=4 \text{ and } WOI^*=5$$



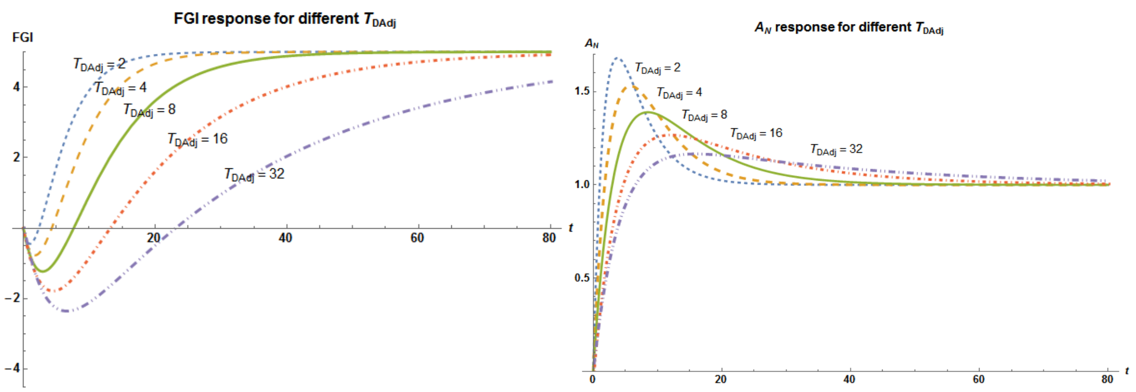


Figure 4. 5. The impact of T_{DAdj} and T_{FGI} for FGI and A_N unit response.

Figure 4.5 demonstrates the impact of T_{DAdj} and T_{FGI} for the unit step response of the FGI and A_N. The solid line represents the recommended settings utilized in the VIOBPCS archetype. There is always an initial drop for the FGI response due to the transient response of a unit step increase in demand, and the absolute FGI drop value can thereby be utilised for setting initial stock levels to maintain supply to the Pull system. When T_{FGI} increases, the FGI response experiences a larger initial drop with a longer setting time, while the A^*_N has a shorter setting time at the expense of higher peak level. Similarly, a larger undershot and longer recovery time of the FGI response are observed when the value of T_{DAdj} increases, while the A^*_N experiences less bullwhip at the expense of a longer settling time.

To summarise, the downstream Pull assembly system always produces over-damped dynamic behaviour and such a system is guaranteed to be stable and robust, although there is an overshoot for A_N transient response due to the effect of the numerator of transfer functions. Bullwhip results from T_{DAdj} and T_{FGI}, which confirms the fact that forecasting (Dejonckheere et al., 2002) and feedback loops (Lee et al., 1997) are the major sources of bullwhip generation, even when the lead time is negligible. In particular, T_{DAdj} places a major emphasis on the bullwhip level, while T_{FGI} has a major impact on the FGI variance. This result also provides evidence that bullwhip is mainly caused by the feedforward compensation, instead of the feedback loop/production delay usually suggested. Although this phase advance/predictive component (Truxal and Weinberg, 1955) in the hardware control engineering field has the advantage of ordering in advance to ensure stock availability, some solutions such as more sophisticated forecasting algorithms (Dejonckheere et al., 2002) must be implemented to reduce the bullwhip level.

4.2.5. Characteristic equations analysis of the Push system

Based on Equation (4.15), the Push system is characterised as a fourth-order polynomial that can be rewritten as the product of two second-order polynomials. As the second-order polynomial, i.e. $\left(1+T_{DAdj}s\right)(1+T_{\mathrm{FGI}}s)$, was already analysed in the MTO system, we derive the natural frequency and damping ratio for the other second-order polynomial as follows:

$$\omega_n = \sqrt{\frac{1}{T_{\mathrm{AWIP}}T_{\mathrm{FWIP}}} + \frac{1}{T_{\mathrm{AWIP}}T_F}} \qquad \zeta = \frac{1}{2}\sqrt{\frac{T_{\mathrm{AWIP}}}{T_F} + \frac{T_{\mathrm{AWIP}}}{T_{FWIP}}} \qquad (4.19)$$

For a fixed T_F (physical fabrication lead time), ω_n and ζ are determined by T_{AWIP} and T_{FWIP}. The system response will become slower (smaller value of ω_n) as T_{AWIP} and T_{FWIP} increase. However, T_{AWIP} and T_{FWIP} have a reverse impact on ζ. The system will be more oscillatory as T_{FWIP} increases or T_{AWIP} decreases. It should be noted that T_{AWIP} has a major influence on the damping ratio compared to T_{FWIP}, which means the CODP inventory policy plays a major role in the system's dynamic behaviour.

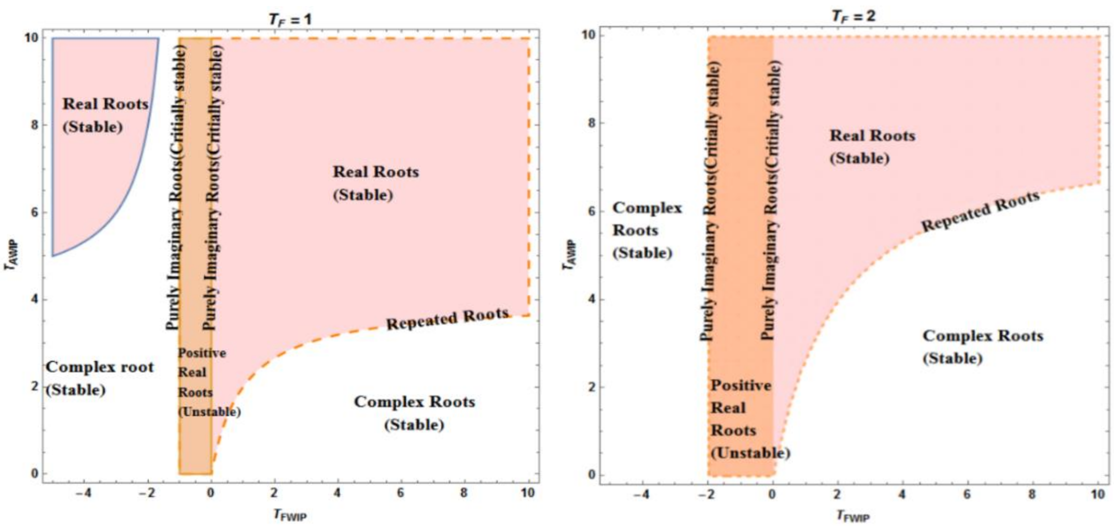
To further understand the dynamic properties of the Push system, including transient response and stability, we derive the four poles based on Equation (4.15) as follows:

$$R_1 = -\frac{1}{T_{FGI}}\,, \qquad R_2 = -\frac{1}{T_{DAdj}}$$

$$R_3 = R_4 = \frac{-T_{\text{AWIP}}T_F - T_{\text{AWIP}}T_{\text{FWIP}} \pm \sqrt{T_{\text{AWIP}}}\sqrt{T_F + T_{\text{FWIP}}}\sqrt{T_{\text{AWIP}}T_F + T_{\text{AWIP}}T_{\text{FWIP}} - 4T_F T_{\text{FWIP}}}}{2T_{\text{AWIP}}T_F T_{\text{FWIP}}} \quad (4.20)$$

There is no imaginary part for the roots of the first and second polynomials (R_1 and R_2), and therefore oscillatory behaviour cannot be generated. For R_3 and R_4, the roots can be real, complex or purely imaginary and the real poles can also be positive, negative or repeated, influencing the transient response as well as the stability condition. We plot the different results of roots based on different fixed T_F values ranging from 1 unit to 4 units as shown in Figure 4.6.

Specifically, the roots are positive for the region between the line of purely imaginary roots and $T_{FWIP} = 0$; thus, the pair choice of T_{AWIP} and T_{FWIP} in this area will lead to an unstable system. Also, we consider the impact of negative FWIP feedback controller (T_{FWIP}) on the results of the roots, although, conventionally, it is assumed to be a positive value range. The negative T_{FWIP} has been investigated in the case of a uniformed and irrational replenishment rule design (Wang et al., 2012; 2014). Based on Figure 4.6, the roots will become purely imaginary if the real part of the roots is zero (i.e. T_{FWIP}= -T_F). Furthermore, the purely imaginary roots are the critically stable point; as such, the system response will be sustainably oscillatory.



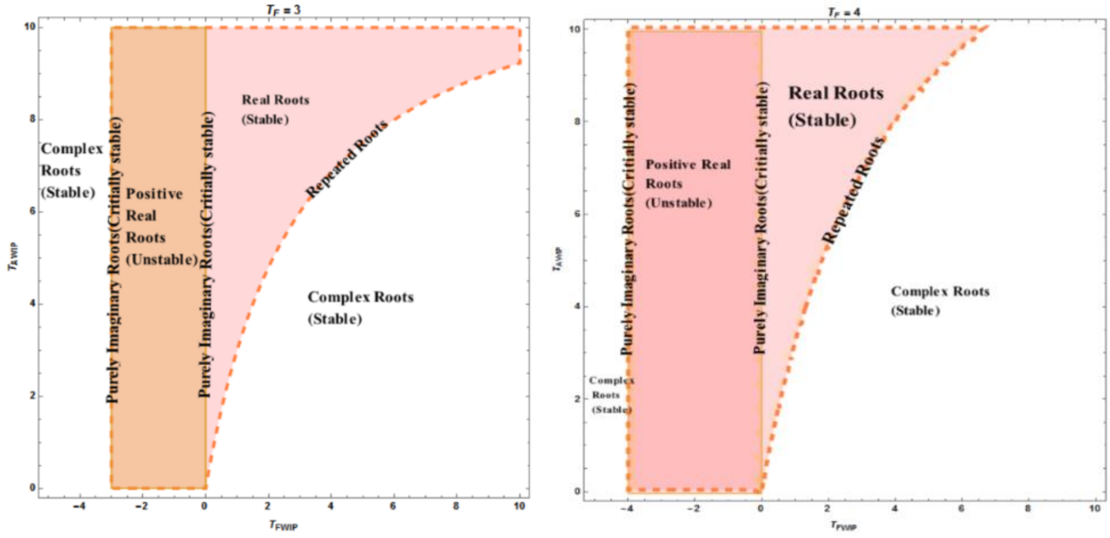


Figure 4. 6. Real, complex and imaginary region of R_3 and R_4 based on different T_F.

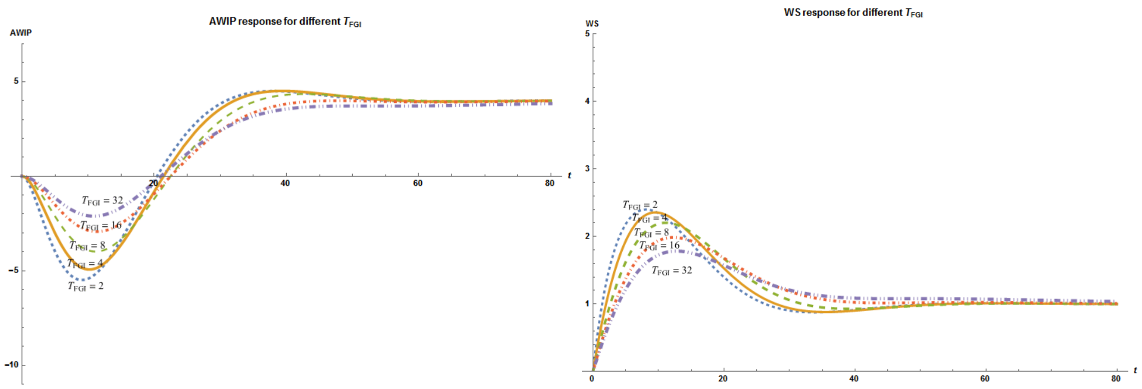
Although the transient response of the fourth-order system is multifaceted, determined by the dominant pole(s) that is/are closest to the origin of the s plane, i.e. the combination of different control policies, the result in Figure 4.6 gives a qualitative understanding of the system's dynamic properties, i.e. whether stable or unstable, for different parameter choices. For instance, we can specify the range of T_{FWIP} and T_{AWIP} to generate real poles, i.e. a 'good' system dynamic design without generating oscillations. As a result, semiconductor companies may benefit from associated cost reduction by improved supply chain dynamics performance. In addition, the real poles region becomes smaller as fabrication lead time, T_F, increases, which means that the system is more likely to generate oscillatory behaviour based on different choices of decision parameter settings. Managers thus need to be aware that their upstream Push systems are more likely to be oscillatory under their control policies if fabrication lead times become longer. Finally, it can be concluded that such a semiconductor hybrid ATO system is stable for all positive decision parameter choices (T_{FWIP}, T_{AWIP}, T_{FGI}, T_{DAdj}).

4.2.6 Unit step response of the Push system

To understand the impact of four system policies (T_{FWIP}, T_{AWIP}, T_{FGI}, T_{DAdj}) in influencing the transient response of the hybrid ATO system, a step response analysis is conducted, through the initial settings suggested by John et al. (1994), i.e. $T_{AWIP} = T_{DAdj} = T_F, T_{FWIP} = 2T_F$ for the dynamic performance of the Push system. The recommended settings of both VIOBPCS and APVIOBPCS will be utilised as the initial design to determine whether such parameter settings can still produce 'good' dynamic performance in the hybrid environment. The system's constant parameters, including K_1, K_2, K_3 and Y_u , will be discarded, as they do not influence the system's dynamic behaviour.

Assume that the lead times ratio between assembly and fabrication is 1:2 (i.e. 4 and 8 for assembly and fabrication) to represent the long-term upstream fabrication and relatively short time for the customised assembly. Thus, the initial setting is as follows (weeks):

$$T_F = 8, \qquad T_{AWIP} = 8, \qquad T_{FWIP} = 16$$



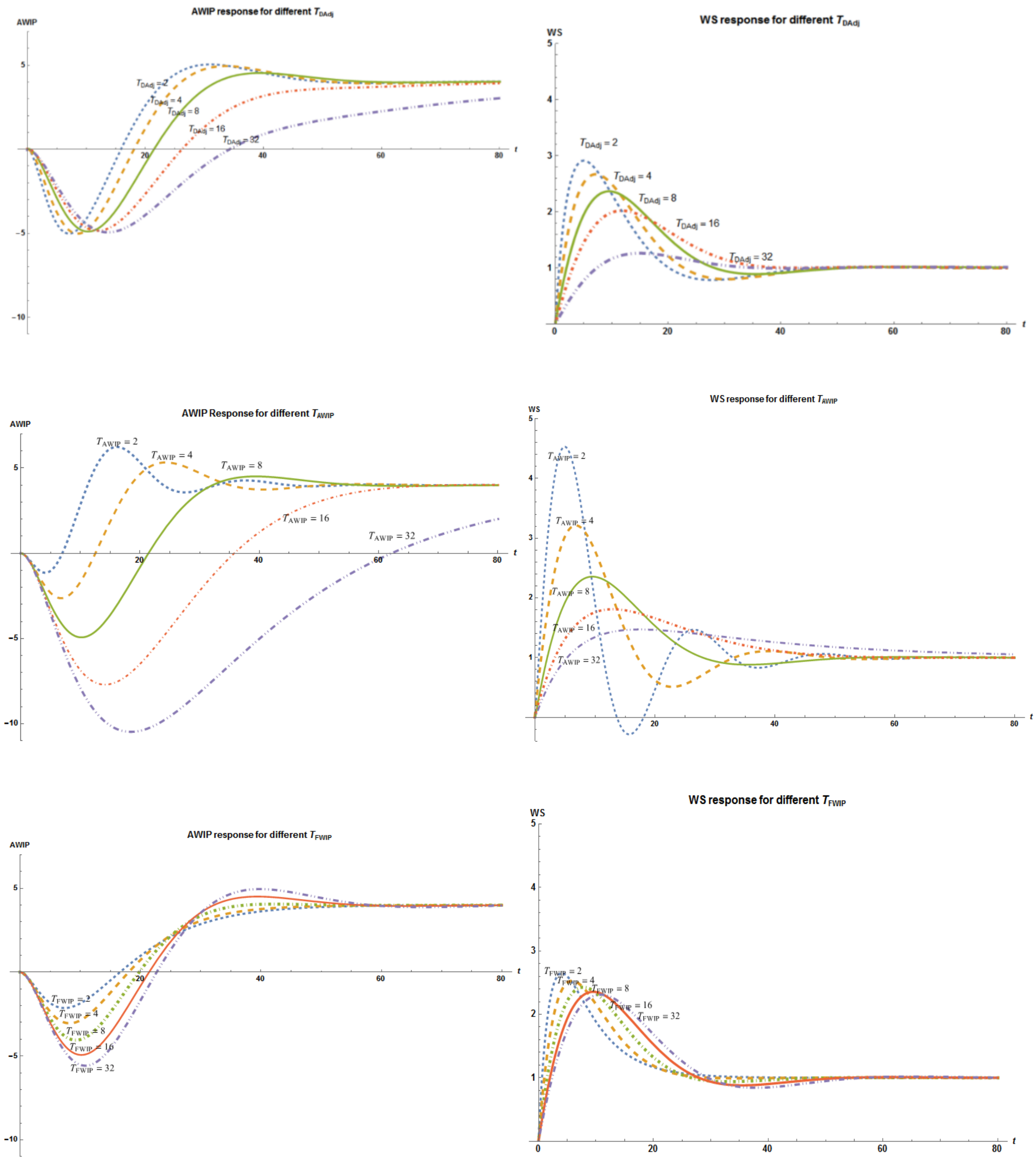


Figure 4. 7. The effect of decision policies for the AWIP and WS in response to unit step increases.

Figure 4.7 shows the impact of T_{FWIP}, T_{AWIP}, T_{FGI} and T_{DAdj} on the dynamic behaviour of the WS and AWIP in the Push system. The solid line represents the recommended settings used in the VIOBPCS and APIOBPCS archetypes. Compared to the downstream Pull system, the bullwhip and inventory variance are more significant in the upstream Push system, due to the dynamic behaviour being amplified from the end customer to the far position of the entire supply chain (e.g. manufacturer). The AWIP always experiences an initial drop in response to unit step input, as the AWIP must meet the downstream customer Pull signal during the transient period to maintain the hybrid ATO state. The AWIP recovers to the desired level with a gradual increase in the fabrication production complete rate to match the unit step demand increase. The absolute decline level is helpful to indicate the safety inventory required to maintain the hybrid mode during the transient period.

Based on Figure 4.7 and Table 4.2, an increase in T_{DAdj} leads to a longer peak time and setting time, but less oscillation of the AWIP. Moreover, an increase in T_{DAdj} slightly reduces the peak level of the AWIP. It should be noted that the AWIP exhibits oscillatory behaviour for small values of T_{DAdj} in response to unit step increase, due to the long-term fabrication delay (T_F) and the amplified pull signal downstream (A_N) as the input of the Push part. Similarly, the WS also experiences less bullwhip and fewer oscillations as T_{DAdj} increases at the expense of a longer setting time. Similarly, an increasing T_{FGI} reduces the overshot and undershot of the AWIP compromised by a slightly longer setting time. However, for a sufficiently long FGI correction time (large T_{FGI}), there is no system overshot for the AWIP with a much shorter setting time. The WS experienced a high bullwhip level and more oscillation under small values of T_{FGI}.

Regarding the decision parameters in the upstream system, T_{AWIP} significantly influences the dynamic response of the AWIP and WS. An increase in T_{AWIP} dramatically increases the undershot (also peak time) and setting time of the AWIP, while the WS has less bullwhip, fewer oscillations and a shorter setting time. In particular, a small T_{AWIP} introduces extra oscillatory behaviour in response to the AWIP and WS, due to the feedback loop control and long production delay. An increase in T_{FWIP} damages the dynamic performance of the FWIP by producing more undershot and oscillations with a longer setting time. Similarly, the WS response has more oscillations and a longer setting time at the expense of less bullwhip as T_{FWIP} increases. Since the target FWIP is the summation of ED and $AWIP_{ADJ}$ (AWIP feedback loop has been included for $AWIP_{ADJ}$), the long correction time for the feedback FWIP loop will further amplify the effect of the AWIP feedback loop by introducing extra dynamic behaviour for the AWIP and WS, which damages their dynamic performance by introducing more oscillations. Furthermore, based on Figure 4.6, the recommended settings in the APIOBPCS and VIOBPCS can still be utilised in the hybrid ATO supply chain to yield a 'good' dynamic response when considering the trade-off between bullwhip and inventory recovery. Table 4.1 summarises four decision parameters' impact on the hybrid ATO step response by increasing their value:

Decision	AWIP			WS			FGI			A_N		
parameters	p	t_p	t_s	p	t_p	t_s	p	t_p	t_s	p	t_p	t_s
T_{sAdj}	0	↓	↓	↑	↓	↑	↓	↓	↓	↑	↓	↓
T_{FGI}	↑	↓	↑	↑	↓	↑	↓	↓	↓	↑	↓	↓
T_{AWIP}	↓	↓	↓	↑	↓	↑	0	0	0	0	0	0
T_{FWIP}	↓	↓	↑↓	↑	↓	↓	0	0	0	0	0	0

Table 4. 1.. Summary of the system response by increasing the value of decision parameters (p: peak level, t_p: time for peak level, t_s: setting time, ↑: better performance. ↓: worse performance, 0: no influence, ↑↓: from worse to better performance due to extra oscillations).

It can be concluded that maintaining the hybrid ATO system in the semiconductor industry is highly desirable since customer orders can be fulfilled immediately. Feedforward forecasting compensation and three feedback correction loops (FGI, AWIP, FWIP) have an impact on the bullwhip level. In particular, the CODP inventory policy (T_{AWIP}) and the forecasting policy (T_{DAdj}) significantly influence the bullwhip level; T_{AWIP} also plays a major rule in the system's oscillatory behaviour. Thus, managers should carefully tune T_{AWIP} to balance the benefit between the cost of holding CODP inventory and the cost of supply chain dynamics. Moreover, practitioners should consider the choice of T_{FGI} to balance the levels of two safety stock points (AWIP and FGI), as such a policy has a reverse influence on the AWIP and FGI. Finally, the recommended settings in the APVIOBPCS and VIOBPCS are still 'good' in the semiconductor hybrid system, although there are some differences between the APVIOBPCS-based reorder system and the MRP-based replenishment rule. Furthermore, the dynamic response of A_N and WS, e.g. rising time, peak level and setting time, gives useful guidance for benchmarking the results derived from the nonlinear dynamic system to set an optimal capacity in the nonlinear system, which may balance the cost of bullwhip and inventory variance in response to a sudden but sustained change in demand.

4.3. Comparing semiconductor ATO system with the IOBPCS family models

As analysed in Section 4.2.1, the stylised semiconductor hybrid ATO system consists of a VIOBPCS without lead times and similar APVIOBPCS archetypes. To benchmark the dynamic behaviour of the upstream Push representation with an exact APVIOBPCS, the block diagram in Figure 4.4 is re-drawn to represent the exact APVIOBPCS system, as shown in Figure 4.8.

From Figures 4.3 and 4.7, unlike the traditional APVIOBPCS ordering rule that has only one input, i.e. demand from the MTO system, two inputs are utilised for the wafer production rate in the semiconductor MTS system: 1) demand from the next-level supply chain echelon; and 2) demand from the end customer order. Such a structure is, fundamentally, a material requirement planning (MRP) system, while the APVIOBPCS has been defined as a 're-order system' (Popplewell and Bonney, 1987). Table 4.2 summarises the difference between the two ordering rules for the MTS system.

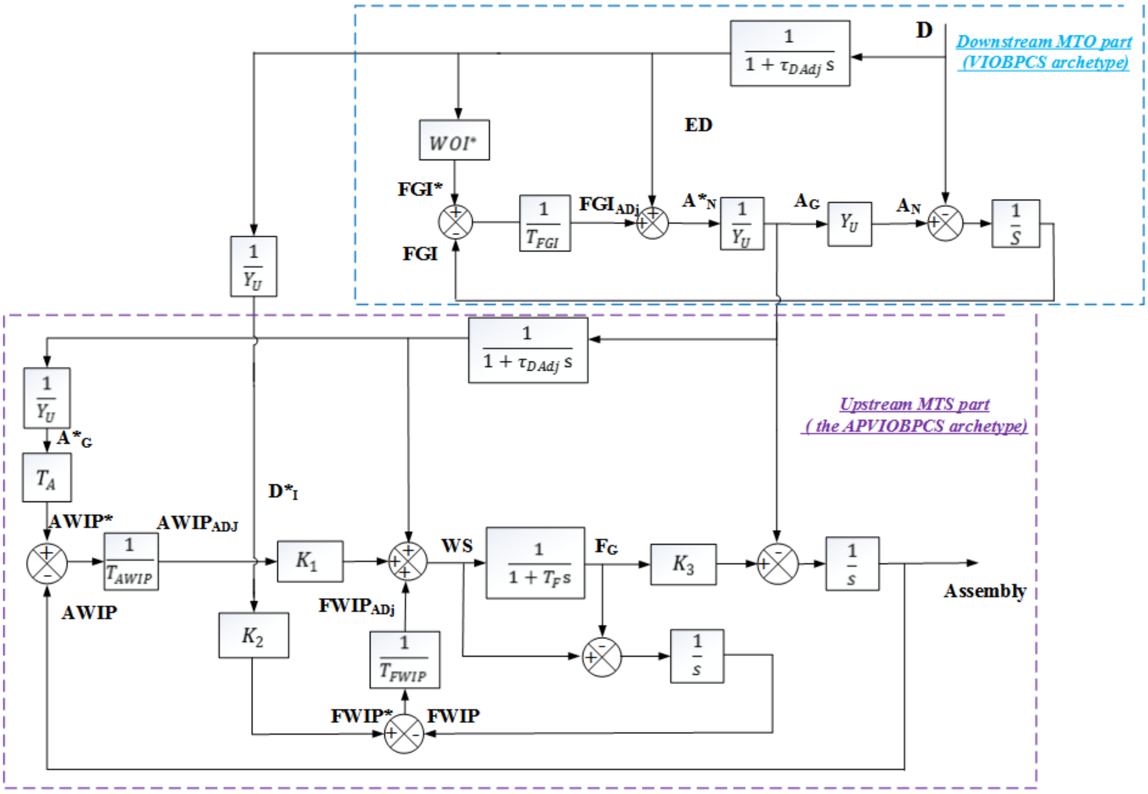


Figure 4. 8. The APVIOBPCS-based hybrid ATO in block diagram form

Type of system (the Push)	*Targeted Inventory (feedback loop)*	*Targeted WIP (feedback loop)*	*Feedforward forecasting loop*
Semiconductor MRP system (Figure 4.3)	As a function of demand from the ordering rate at assembly production (A_N*)	As a function of the summation of inventory correction (AWIP) and demand from end customer (D)	Based on final customer demand (D)
Reorder system (APVIOBPCS) (Figure 4.7)	As a function of demand from the ordering rate at assembly production (A_N*)	As a function of demand from the ordering rate at assembly production (A_N*)	Based on demand from the ordering rate at assembly production (A_N*)

Table 4. 2. The comparison of system structure between the semiconductor MRP and APVIOBPCS systems.

To analytically explore the dynamic behaviour difference between these two archetypes, their nature frequency (ω_n) and damping ratio (ζ) can be derived as follows:

Semiconductor MRP system:

$$(1+ST_A)(1+ST_{\mathrm{FGI}})(T_F+T_{\mathrm{FWIP}}+S(T_{\mathrm{AWIP}}T_F+T_{\mathrm{AWIP}}T_{\mathrm{FWIP}})+S^2T_{\mathrm{AWIP}}T_FT_{\mathrm{FWIP}}) \quad (4.21)$$

Re-order system:

$$(1+ST_A)(1+ST_{\mathrm{FGI}})(T_F+S(T_{\mathrm{AWIP}}T_F+T_{\mathrm{AWIP}}T_{\mathrm{FWIP}})+S^2T_{\mathrm{AWIP}}T_FT_{\mathrm{FWIP}}) \quad (4.22)$$

It can be seen that all polynomials, including $(1+ST_A)(1+ST_{\mathrm{FGI}})$, refer to the property of downstream MTO final assembly system, and as highlighted before, such second order polynomials always produce over-damped dynamic behaviour due to the value of damping ratio always being greater than one under the positive value of T_A and T_{FGI}. Also, such a system cannot generate oscillatory behaviour because the discriminant is always greater than or equal to zero (real roots).

Hence, for simplicity we can remove such second order differential equations and compare another second order polynomials involving more complex dynamic behaviour. Table 4.3 reports the comparison of system properties based on ω_n and ζ. It can be seen the natural frequency in a semiconductor MRP system is always larger than the corresponding re-order APVIOBPCS archetype for the same decision policy choice. Such a result indicates that the dynamic recovery speed of semiconductor MRP system is faster than the APVIOBPCS system, which may benefit the higher customer service level by increasing the inventory recovery speed in response to customer demand. However, re-order APVIOBPCS always has larger ζ than an MRP-based system for all positive values of T_{FWIP} and T_{AWIP}, which means an MRP system will produce more oscillations under the same policies settings and its associated production activities and cost, such as ramp up and ramp down machines, hiring and firing staff, has to be considered in designing such production control systems.

System type	**Structure of CEs**	**Natural frequency (ω_n)**	**Damping ratio (ζ)**
Semiconductor MRP system (Figure 4.3)	Second order polynomials	$\sqrt{\frac{1}{T_{\text{AWIP}}T_{\text{FWIP}}}+\frac{1}{T_{\text{AWIP}}T_F}}$	$\frac{1}{2}\sqrt{\frac{T_{\text{AWIP}}}{T_F}+\frac{T_{\text{AWIP}}}{T_{FWIP}}}$
Re-order APVIOBPCS (Figure 4.7)	Second order polynomials	$\sqrt{\frac{1}{T_{\text{AWIP}}T_{\text{FWIP}}}}$	$\frac{1}{2T_{\text{F}}}\sqrt{T_{\text{AWIP}}T_{FWIP}}+\frac{1}{2}\sqrt{\frac{T_{\text{AWIP}}}{T_{FWIP}}}$

Table 4. 3. System properties comparison based on nature frequency and damping ratio.

Although a system's transient response will depend on all poles and zeros, it can be concluded that for the same policy settings, an MRP-based production control system always has rapid system recovery ability, at the expense of more oscillations occurring during transient response compared to a reorder-based APVIOBPCS system. Unlike the APVIOBPOCS system in which WIP loop cancels out inventory signal and provides feedforward forecasting loop more contributions for reaching steady state (longer settings time with less overshoot), the MRP-based system utilises both averaged demand (forecasting) as well as inventory correction information as the desired WIP and thereby provides less contribution to feedforward forecasting loop to reach steady state (more peak with short setting time). Also, utilisation of inventory feedback loop in the WIP feedback loop introduces extra oscillations to the system due to the effect of multiple feedback loops.

It can be concluded that production managers who design their production-inventory system as a typical MRP-based ordering rule seek more responsiveness than leanness. The purpose, based on the analytical findings, is to ensure customer service level in response to customer demand while maintaining low inventory. This is a typical target in the semiconductor industry under long-term fabrication lead times but short-term technology redundancy. The Intel supply chain (Gonçalves et al., 2005), as the example in this study, adopted the MRP-based ordering rule by frequently adjusting their capacity utilisation to avoid high backlog orders (high responsiveness) and high inventory level.

4.4. Numerical study

4.4.1. Simulation enhancement

Although the analytical results derived from the linear system above offer deep insights into the system dynamic behaviour of a semiconductor ATO supply chain, linear assumptions are often criticised for being incapable of capturing nonlinear characteristics of the real supply chain system with resources constraints (e.g. capacity, non-negative order constraints) (Lin et al., 2017). To enhance the qualitative insights obtained from the linear analysis, we incorporate the nonlinearities to represent the capacity, as a CLIP function (

) and non-negativities in the hybrid ATO model of Figure 4.4. It should be noted that a number of other capacity forms can be used to represent the capacitated semiconductor fabrication environment. e.g. see Orcun et al.'s (2006) exploration of the dynamic behaviour of Clearing Function (CF) based capacity models in a simple capacitated production system.

The hybrid mode is still assumed to be in operation but in a resources-constrained environment, reflected in the block diagram representation shown in Figure 4.9. Note that the CLIP function is an addition that is not in the representation of Gonçalves et al. (2005).

Like the linear system analysis, a step input is utilised and all system and control policy settings remain the same. Capacity limit in the MTS part is set at 50% larger than the step demand (i.e. 1.5), since, on average, manufacturing capacity must be greater than required demand to keep the system stable. Figure 4.10 presents the impact of four system control policies (T_{DAdj}, T_{FGI}, T_{AWIP} and T_{FWIP}) on the dynamic behaviour of the Push part in the hybrid mode. The solid line represents the recommended settings in the original APVIOBPCS and VIOBPCS archetypes, although it does not need to be 'optimal' in the nonlinear environment, depending on the specific trade-offs design between inventory and capacity. It should be noted that the corresponding control policies assessment for the Pull part independent of the Push part is not reported here, due to the small dynamic impact of non-negative nonlinearity in response to a step increase in demand, i.e. the same dynamic behaviour is observed in the nonlinear Pull system

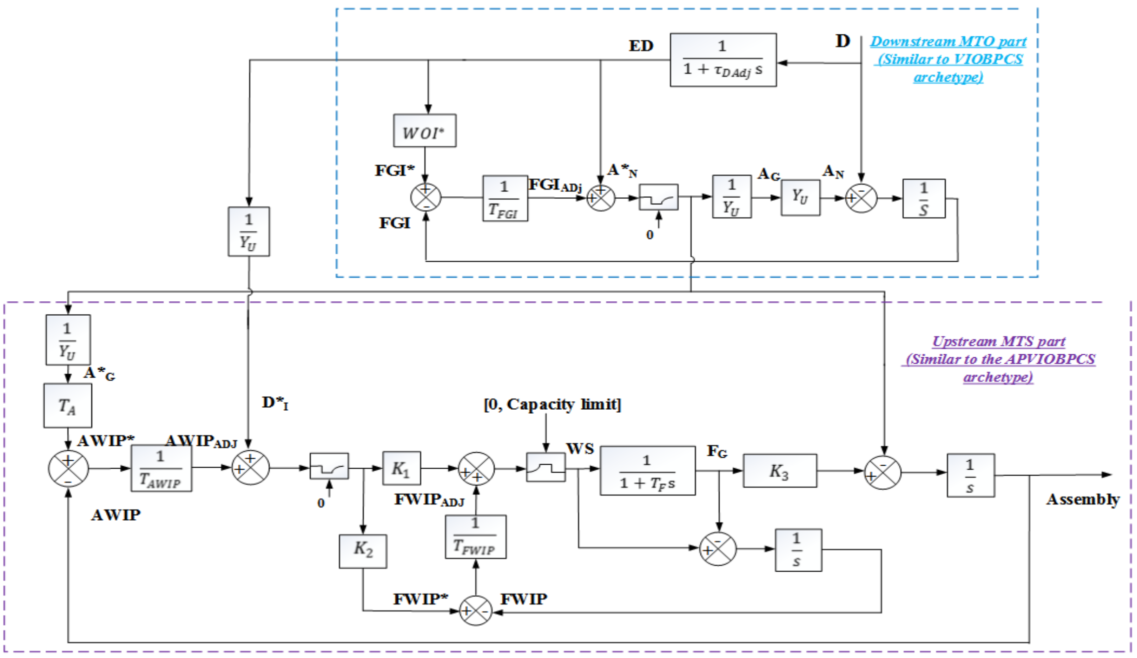
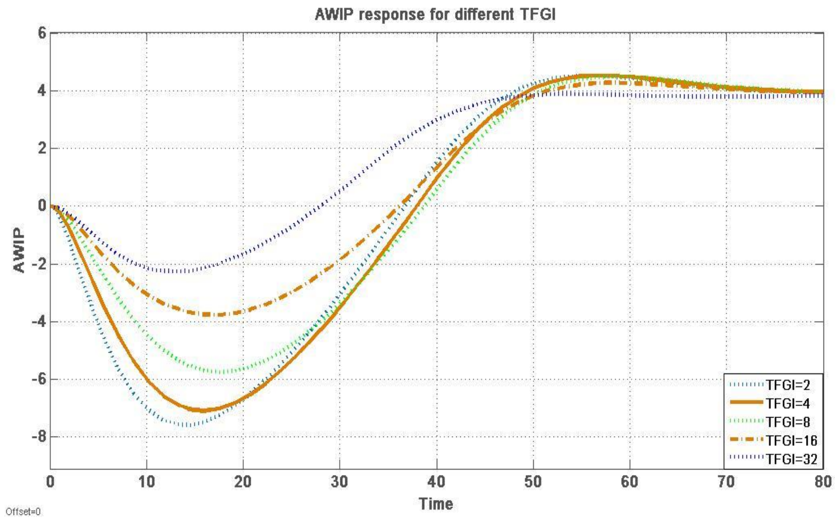
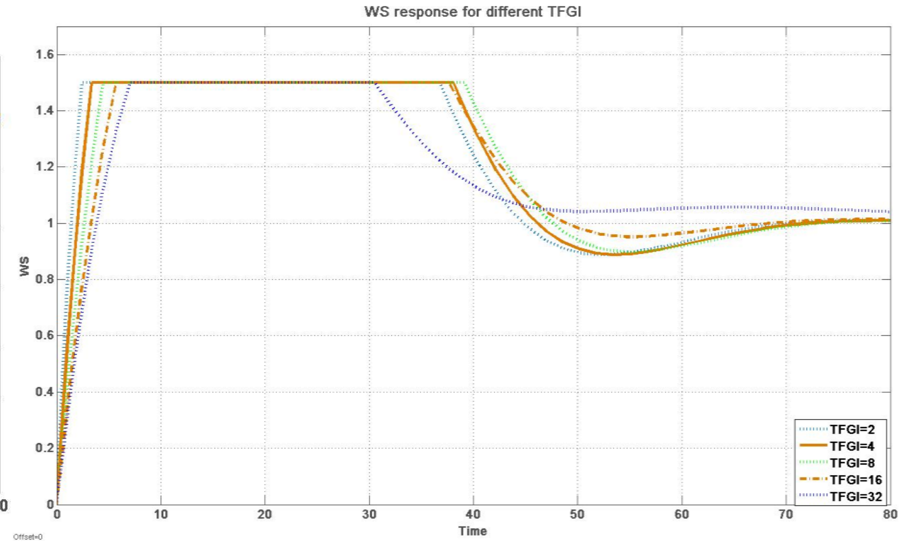
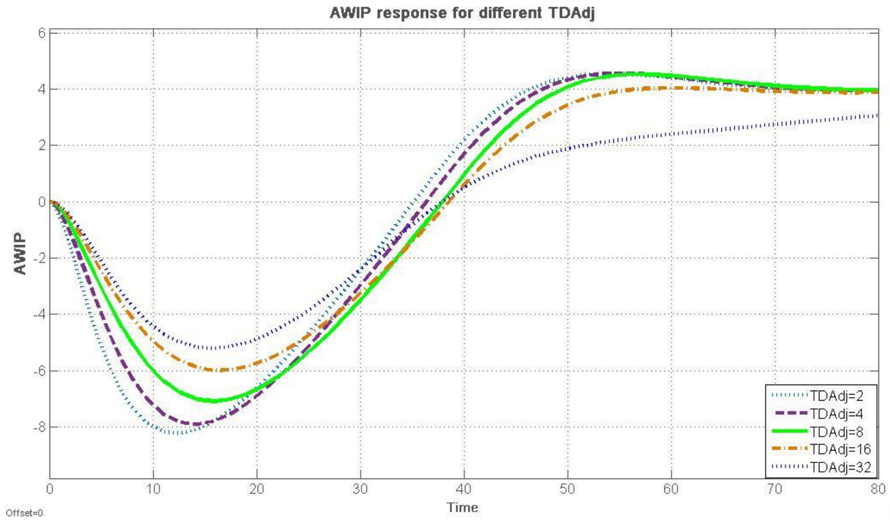
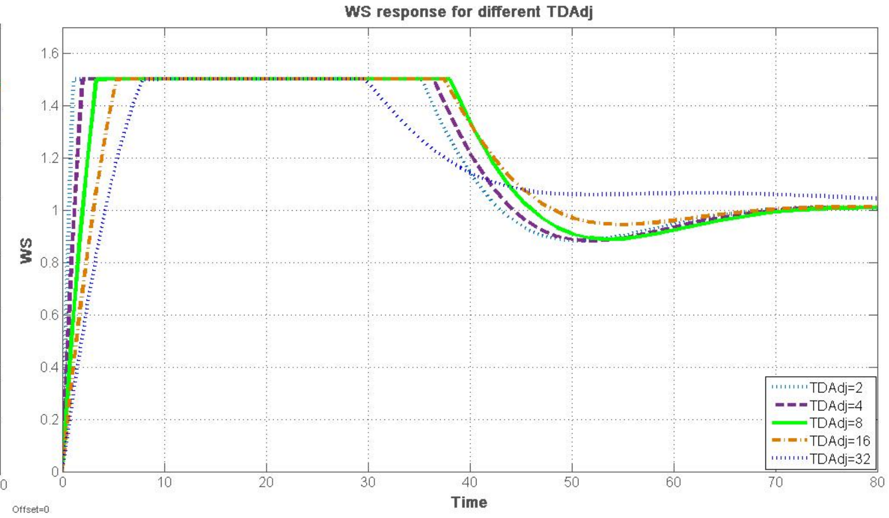


Figure 4. 9. The semiconductor hybrid ATO supply chain in the nonlinear block diagram form.


AWIP response for different TFGI
AWIP
Time
TFGI=2
TFGI=4
TFGI=8
TFGI=16
TFGI=32
Offset=0


WS response for different TFGI
WS
Time
TFGI=2
TFGI=4
TFGI=8
TFGI=16
TFGI=32


AWIP response for different TDAdj
AWIP
Time
TDAdj=2
TDAdj=4
TDAdj=8
TDAdj=16
TDAdj=32
Offset=0


WS response for different TDAdj
WS
Time
TDAdj=2
TDAdj=4
TDAdj=8
TDAdj=16
TDAdj=32
Offset=0

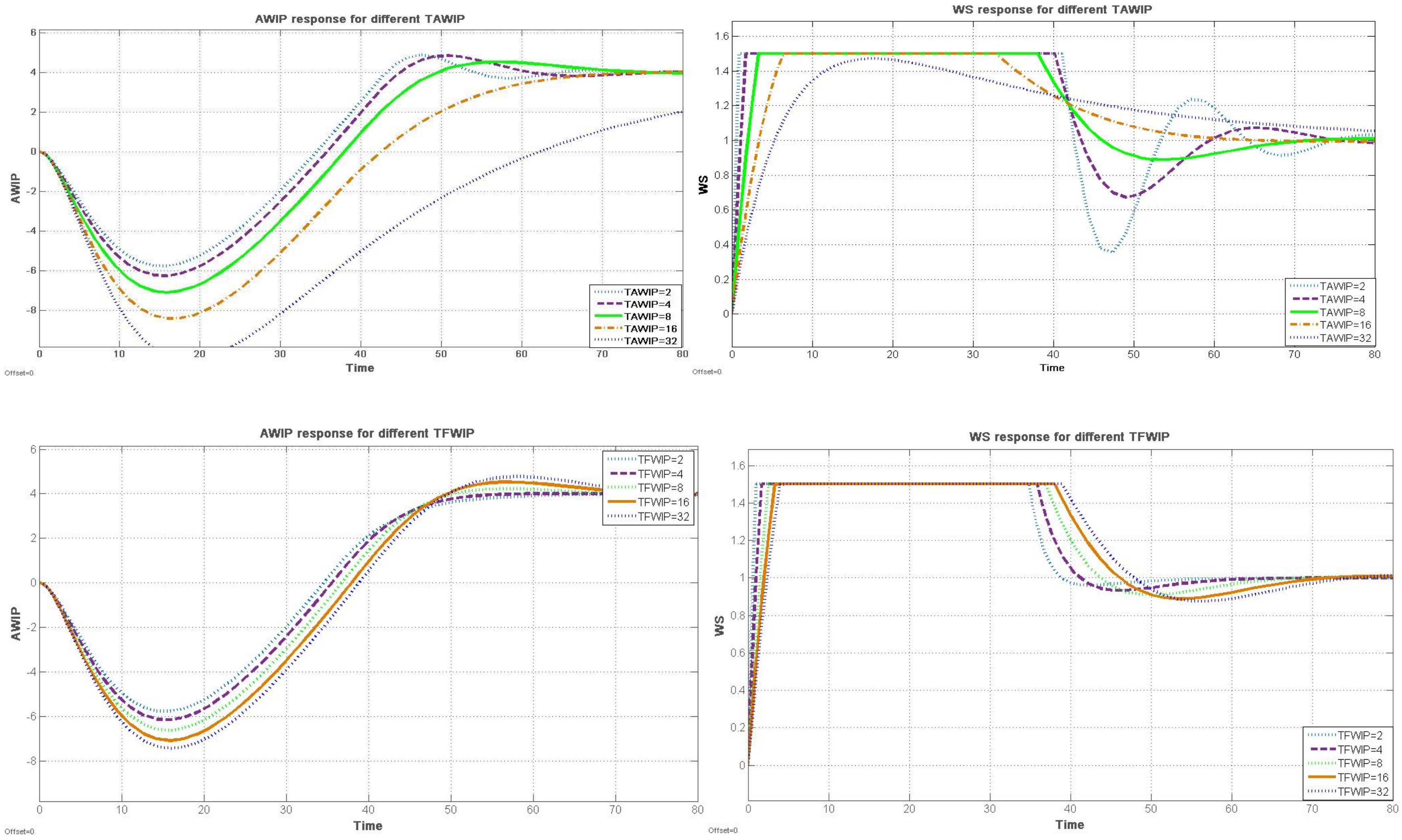


Figure 4. 10. WS and AWIP responses for a step demand increase in the nonlinear settings

In general, the simulation of a nonlinear hybrid ATO system shows that the insights obtained from the linearised analytical results are correct. The increase of policies in the Pull part, i.e. T_{FGI} and T_{DAdj}, negatively influences the dynamic performance of the CODP inventory (AWIP) by introducing more undershoot and longer setting time, while the better dynamic responses of WS are found with fewer oscillations and fast recovery speed. However, as expected, comparing the linear results (Figure 4.7) under the same control policy settings, the step increase in demand gives a higher initial drop of AWIP and slower recovery speed of AWIP and WS in the nonlinear environment. This is because more CODP inventory (AWIP) is needed and longer recovery time is influenced by the period when the manufacturing rate hits the capacity limit. Furthermore, T_{AWIP} significantly influences the dynamic performance of the Push part in the nonlinear hybrid system in terms of oscillations and recovery speed. The WIP correction policy in the Push part, that is T_{FWIP}, as expected, reported the same qualitative insights obtained from the linear system in which an increase in T_{FWIP} led to worse dynamic behaviour of AWIP and WS by introducing more undershoot and oscillations. The whole hybrid ATO system experiences a significant reduction of bullwhip level (WS) at the expense of more AWIP variability in a capacitated based nonlinear system, in comparison with results obtained from the linear system.

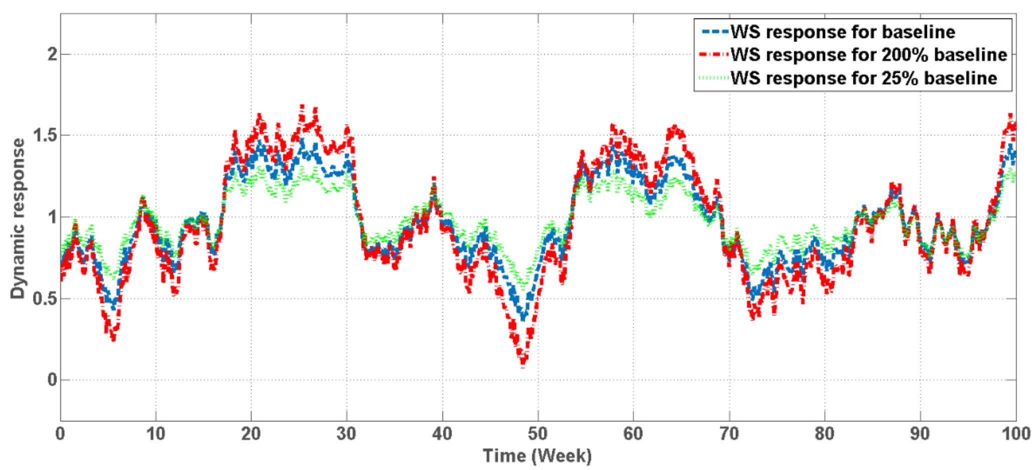
4.4.2. Sensitivity analysis

In system dynamics study, one of the fundamental assumptions is that the supply chain design involving the selection of control parameters is based on a known and given lead-time. Furthermore, the semiconductor production and assembly quality or yield rate are important parameters that need to be considered regarding their impact on the dynamic performance of the semiconductor supply chains (Gonçalves et al., 2005; Orcun et al., 2006;

Orcun and Uzsoy, 2011; Mönch et al., 2013). By undertaking a sensitivity analysis, it is possible to check on the dynamic performance due to possible changes in lead-time and production yield rate; that is, the physical parameters that designers cannot control or change.

Lead-time sensitivity analysis

Returning to the simplified hybrid ATO semiconductor system, there are only upstream fabrication lead times (T_F) due to the assumption that the hybrid state is always operating, and final assembly delay is not considered. Also, such assumption leads to the fact that T_F does not have an impact on the downstream final assembly echelon. Given the nominal system parameter settings of the simplified nonlinear semiconductor ATO models, as illustrated by Figure 4.9, the impact of changes in T_F (T_F =8 in baseline setting) on the system performance, including WS and FWIP, is evaluated via using stochastic demand (i.i.d. demand with mean=1 and variance =0.5). All results are shown in Figure 4.11.



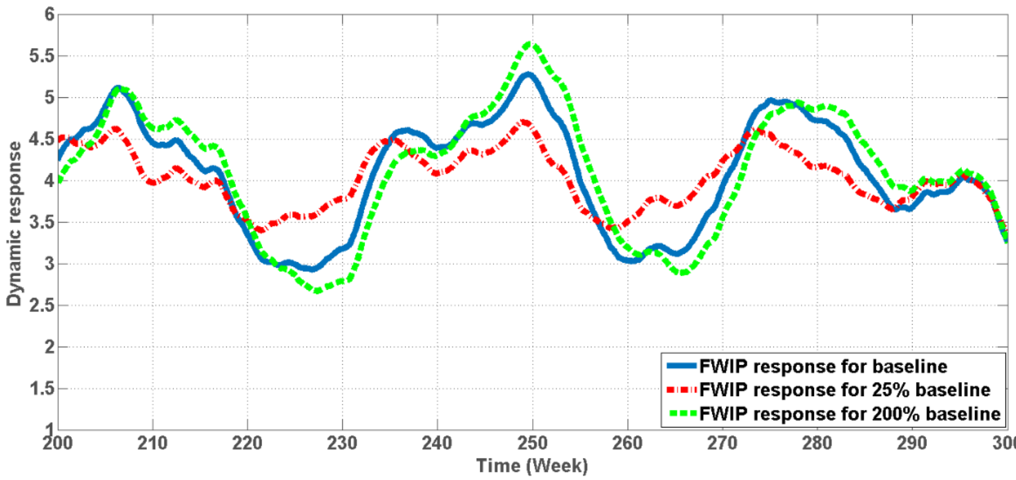


Figure 4. 1. Sensitivity analysis for semiconductor fabrication lead times.

The results show that dynamic performance, including bullwhip and inventory variance, is sensitive to the change of fabrication lead times. As the T_F increases, the bullwhip and inventory variance increase as well, leading to an increase of production on cost as well as a decrease of customer service level due to possible stock-out issues. The negative impact of long lead times on supply chain dynamics is well-recognised in literature (Towill, 1997; Geary et al., 2006; Towill and Gosling, 2010; Ponte et al., 2018).

Production yield rate sensitivity analysis

There are three production quality related parameters in the semiconductor ATO supply chain system: the unit yield (Y_U, the percentage of good chips for each assembly die); assembly line yield rate (Y_L, the percentage of good wafers per total); and the line yield (Y_D, the percentage of good die per fabricated wafers). Since Y_D and Y_L are always connected, i.e. the yield rate in upstream wafer fabrication, it can be considered as a single quality parameter in the sensitivity analysis. Table 4.5 demonstrates the baseline settings by following Gonçalves et al. (2005), while ±10% yield rate variation assumption is adopted to explore the impact of quality on the dynamic performance of the ATO system.

Parameters	Baseline setting	±10% variation	
Y_U	90%	100%	80%
$Y_D \cdot Y_L$	90%	100%	80%

Table 4. 4. The baseline and variation settings of yield rate in semiconductor ATO system.

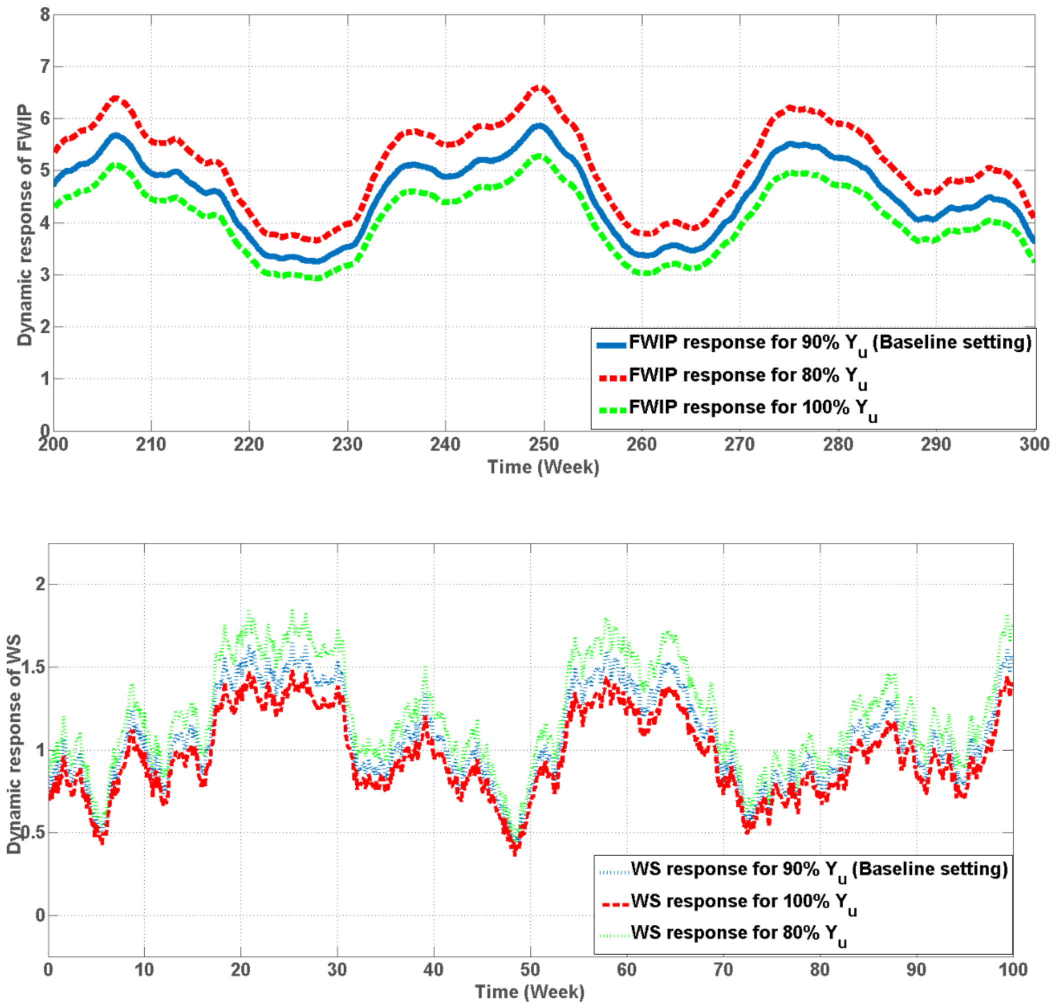


Figure 4. 2. Sensitivity analysis for different Y_U.

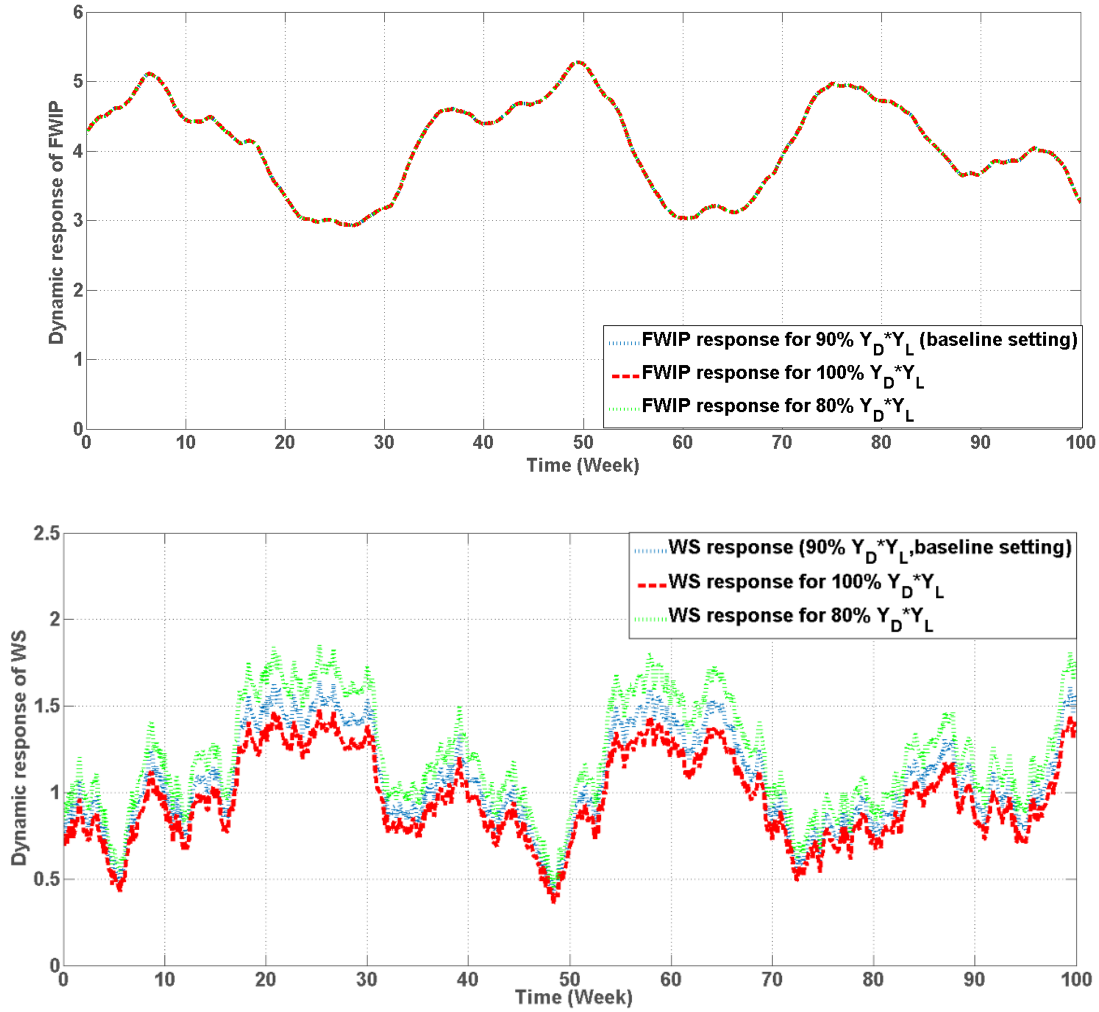


Figure 4. 3. Sensitivity analysis for different $Y_L \cdot Y_D$.

Figure 4.12 and 4.13 illustrates the sensitivity analysis results. It is apparent that the percentage of good chips for each assembly die (Y_U) is less sensitive for the dynamic performance, although the decrease of Y_U leads to higher mean level of inventory and order rate. This is because the decrease of downstream assembly line yield increases the requirement for the system's safety stock level, including AWIP* and FWIP*, to ensure the same production complete rate (customer service level).

Furthermore, the upstream fabrication yield, including die and line yield rate, influences the steady state of WS. The higher the Y_L and Y_U, the less the WS to be prepared, indicating less mean level of WS, although such parameters is less sensitive for the dynamic performance of the fabrication system. Note that the upstream fabrication yield does not have an impact on the FWIP due to the setting of safety FWIP as the function of Y_U and final assembly time.

4.5. Summary

In this chapter, the dynamic properties of a hybrid ATO supply chain system within the context of the semiconductor industry have been analytically explored. The author used the supply chain model, empirically reported by Gonçalves et al. (2005), as a benchmark model, to extract the hybrid ATO (MTS-MTO) model and explore the underlying properties of such hybrid systems in the semiconductor production environment. By utilising control engineering techniques and the well-known IOBPCS family of archetypes, the author addressed the limitations of Gonçalves et al.'s (2005) simulation work, which lacks analytical results and guidance for practitioners regarding the underlying root causes of supply chain dynamics in an ATO supply chain environment.

For the first objective, insight into the dynamic properties of the hybrid ATO supply chain system can be gained by designing the original complex system dynamic model; that is, simplifying and linearising the original complex dynamic model, including developing the block diagram form, removing nonlinearities and redundancies and eliminating one echelon of the supply chain system. Thus, it is possible to extract the scenario of the linear hybrid ATO and implement a linear control engineering approach to analyse its fundamental dynamic properties. Although the simplification method is based on the semiconductor supply chain system, this design approach can be applied to a broad production-inventory based manufacturing system.

Also, through control engineering approaches, including Laplace transform, characteristic equations and the unit step response analysis, it was revealed that feedforward forecasting compensation and the CODP inventory correction policy play a major role in the bullwhip effect in the semiconductor hybrid ATO system, instead of the production delay/feedback loop usually claimed in practice. Also, semiconductor managers may need to cautiously consider the balance between the cost of keeping an adequate CODP inventory to maintain the mode of ATO and the cost of supply chain dynamics, due to the policies' settings in the CODP point being significantly sensitive to inventory variance and the bullwhip level. This finding is helpful for practitioners to carefully consider relevant trade-offs when designing their hybrid ATO system in the semiconductor industry.

Furthermore, comparing the traditional APVIOBPCS archetype, dynamic recovery speed of semiconductor MRP system (i.e. the upstream of the CODP point) is faster comparing the traditional APVIOBPCS archetype, due to its natural frequency is always larger than the APVIOBPCS system for all positive control policy. However, semiconductor MRP system will produce more oscillations under the same policies settings and its associated production activities and cost, such as ramp up and ramp down machines, hiring and firing staff, have to be considered in designing such production control systems. This is driven by the fact that APVIOBPCS always has larger damping ratio than MRP-based system for all positive value.

Finally, sensitivity analysis of physical fabrication lead times, as well as quality yield, was conducted. The long fabrication time and low quality yield rate negatively impact on the dynamic performance of the semiconductor ATO system by increasing operational cost driven by the increase of bullwhip and inventory variance.

Chapter 5. Dynamic modelling and analysis of a personal computer ATO system

This chapter provides detailed modelling and analysis of the ATO system ordering structure from a system dynamics perspective. Based on supply chain material and information flow empirically evidenced by several PC companies, including Dell, HP and Lenovo (Kapuscinski et al., 2004; Huang and Li, 2010; Darwish and Odah, 2010; Katariya and Tekin, 2014), a stylised two-echelon system dynamics model, consisting of an original equipment manufacturer (OEM) and a part supplier as an illustration of the typical hybrid ATO system, is investigated in Section 5.1. Section 5.2 exclusively focuses on the truly hybrid ATO state in which all incoming orders can be satisfied in a desired time period. Particularly, capacity and non-negative order constraint nonlinearities are explored under the desired hybrid ATO state. Section 5.3, on the other hand, analyses the other two operational states when the CODP inventory is insufficient to cover the required incoming end customer orders and/or VMI replenishment orders. A linearisation method for delivery LT dynamics is proposed, so that analytical tools such as transfer functions can be implemented to gain deep insights into delivery LT dynamics. The dynamic performance of the nonlinear ATO system is explored based on the "performance triangle", i.e. capacity and the CODP inventory at the supplier and the delivery LT at the final assembly OEM echelon.

5.1. Dynamic modelling of the PC ATO supply chains

In general, PC supply chains have three main manufacturing echelons from upstream to downstream: component fabrication (i.e. semiconductor industry), sub-assembly and final assembly (Huang and Li, 2010). Specifically, as visualized in Figure 5.1a, the component and sub-assembly manufacturers, called the suppliers, offer the 'commodities' required by downstream Original Equipment Manufacturers (OEMs), e.g. Lenovo, Apple, HP, Dell, for final assembly and delivery, and the corresponding delay is measured by 4-8 weeks (Gunasekaran and Ngai, 2005). For each component, suppliers offer a variety of products, e.g. Intel core processors with i3, i5, i7 processors and Disk suppliers give a number of capacity and write/read speed options. Thereby, OEMs are able to provide end customers a wide range of production configurations, and the final assembly and delivery are only triggered after customers place their customised orders.

As material flows downstream, production moves from automated fabrication to highly manual assembly. Final assembly of a PC at the finished good assembly echelon is a largely manual process to allow quick changeover and high level of flexibility. The corresponding delay can be as short as hours, although final customers have to wait one to two weeks to receive their product due to the major delay of order processing (3-5 days) and third-party logistics shipment (3-5 days) (Kumar and Craig, 2007).

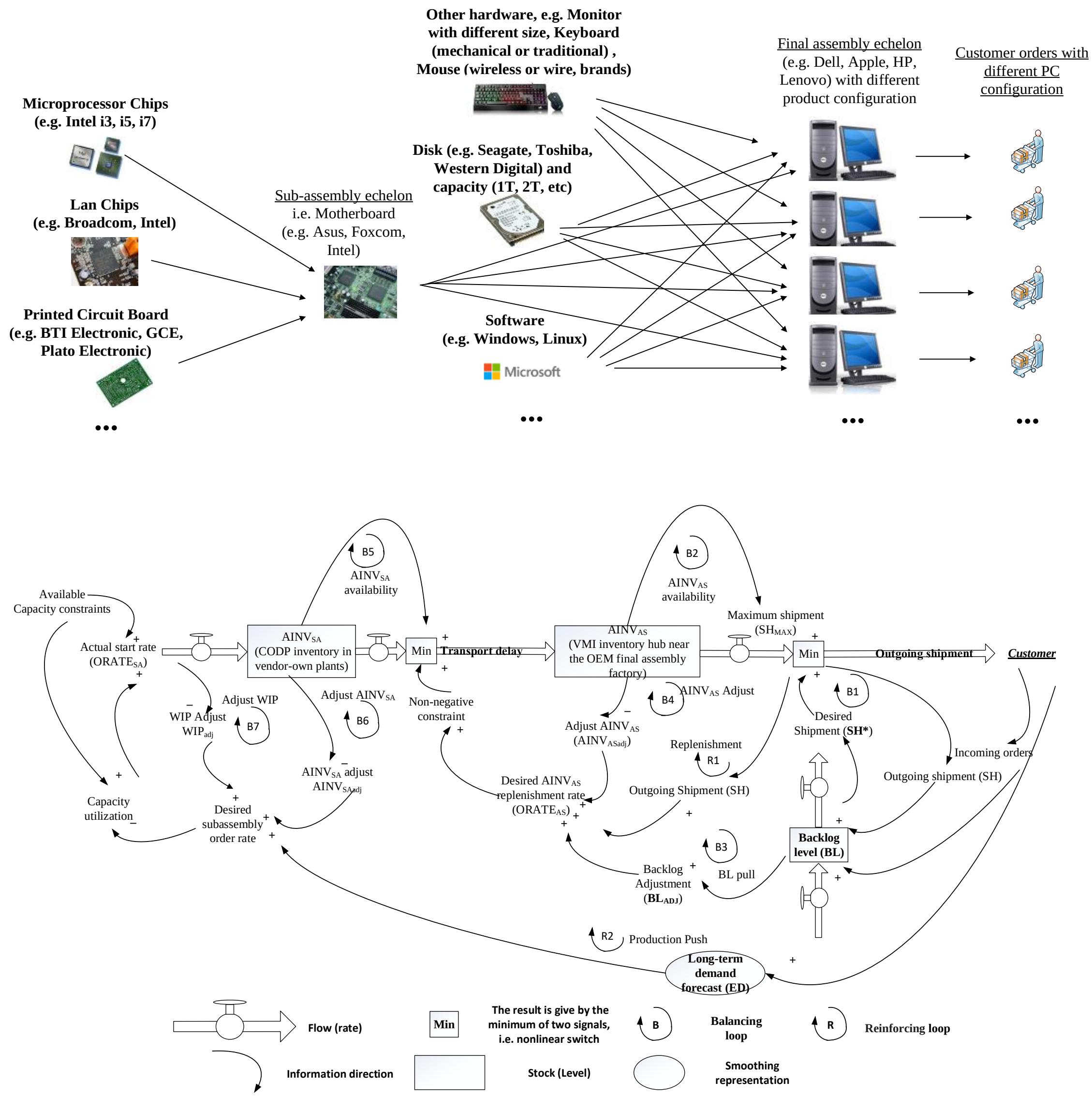


Figure 5.1a and 5.1b. Rich picture description and stock flow diagram of the PC ATO system.

The materials/information flow of the PC ATO supply chain is modelled at an aggregate level, the model is restricted to one player per echelon and this corresponds to the minimum number of echelons required to analyse its dynamic behaviour. The entire supply chain is modelled as a two-echelon system, i.e. *a PC component manufacturer (supplier) and a final assembler (OEM)*.

Based on Figure 5.1a, the detailed mathematical modelling process is now presented. The exogenous demand into the supply chain system begins when end customers' demand information is received. The OEM checks the availability of $AINV_{AS}$ at the VMI hub and starts assembly and delivery. From the aggregate perspective, SH for each period is determined by the minimum value between SH^* and SH_{MAX}. The first order lag approach (Sarimveis et al., 2008) can be utilised to model MTO based final assembly process. Depending on the availability of $AINV_{AS}$, the output of first order delay, i.e. SH, is determined by

$$SH(t) = Min\left(SH^*(t), SH_{MAX}(t)\right) \qquad (5.1)$$

If required $AINV_{AS}$ are available for immediate final assembly, $SH=SH^*$, the difference between inflow CONS and outflow SH^* is calculated as measure of BL. i.e. a kind of work-in-progress orders, WIP (Wikner, 2003):

$$BL(t) = BL(t-1) + CONS(t) - SH(t) \quad (5.2)$$

The output SH* is the result of the fraction of WIP ($1/\tau_{DD}$). In other words, τ_{DD} is the average delay of the production unit. As suggested by Atan et al. (2017), a fixed τ_{DD} is a realistic assumption due to high flexibility and reliable delivery time for the final assembly process.

$$SH(t) = SH^*(t) = \frac{BL(t)}{\tau_{DD}} \quad (5.3)$$

Under such conditions, all incoming customised orders can be fulfilled by quoted τ_{DD}, that is, customers need to await physical final assembly and transport time only. However, if insufficient $AINV_{AS}$ constrains SH*, the OEM can only ship SH_{MAX} estimated by current $AINV_{AS}$ and τ_{DD}.

$$SH(t) = SH_{MAX} = \frac{AINV_{AS}(t)}{\tau_{DD}} \quad (5.4)$$

As a result, the average delivery LT may be increased due to insufficient, and the further replenishment process of, $AINV_{AS}$. Here $AINV_{AS}$ depends on accumulation between the replenishment from $COMRATE_{AS}$ and the depletion of SH:

$$AINV_{AS}(t) = AINV_{AS}(t-1) + COMRATE_{AS}(t) - SH(t) \quad (5.5)$$

While SH depletes $AINV_{AS}$, $COMRATE_{AS}$ replenishes it. $COMRATE_{AS}$ depends on delayed $ORATE_{AS}$ (transport delay between the supplier manufacturing and the OEM's final assembly plant). A first order lag is used to model such a delay, in line with Sipahi and Delice (2010),

$$COMRATE_{AS}(t) = COMRATE_{AS}(t-1) + b\left(ORATE_{AS}(t) - COMRATE_{AS}(t-1)\right) \quad (5.6)$$

Where $b = \frac{1}{(1+\frac{\tau_{AS}}{\Delta T})}$ (Towill, 1977)

$ORATE_{AS}$ is determined by the minimum between desired Pull $ORATE_{AS}$ from the final assembly echelon and feasible Push $ORATE_{SA}$ from the supplier echelon:

$$ORATE_{AS}(t) = Min\left(Pull\ ORATE_{AS}(t), Push\ \ ORATE_{SA}(t)\right) \quad (5.7)$$

If there are enough finished PC parts in the supplier manufacturing echelon, the customer's orders still pull the replenishment of $AINV_{AS}$, otherwise the supplier plant pushes all feasible $AINV_{SA}$ to meet VMI inventory requirement as soon as possible. By design, Pull $ORATE_{AS}$ aims to eliminate gaps for $AINV_{AS}$ and BL (adjusted by $\boldsymbol{\tau}_I$ and $\boldsymbol{\tau}_{BL}$ respectively). SH, as a more reliable proxy, is also utilised for deciding Pull $ORATE_{AS}$ and a non-negativity constraint is given to avoid negative orders placed on the supplier:

$$Pull\ ORATE_{AS}(t) = Max\left(0,\ AINV_{ASadj}(t) + SH(t) + BL_{ADJ}(t)\right) \quad (5.8)$$

$AINV_{ASadj}$ is the $AINV_{AS}$ feedback adjustment loop based on the discrepancies between $AINV_{AS}$* and $AINV_{AS}$ adjusted by $\boldsymbol{\tau}_I$:

$$AINV_{ASadj}(t) = \frac{1}{\tau_I}\left(AINV_{AS}^*(t) - AINV_{AS}(t)\right), \qquad AINV_{AS}^*(t) = \tau_{AS}SH(t) \quad (5.9)$$

and BL_{ADJ} is the backlog control loop adjusted by $\boldsymbol{\tau}_{BL}$:

$$BL_{ADJ}(t) = \frac{1}{\tau_{BL}}\left(BL(t) - BL_{(t)}^*\right),\ BL_{(t)}^* = \tau_{DD}CONS(t) \quad (5.10)$$

The depletion of $AINV_{SA}$ will be replenished by $COMRATE_{SA}$. Due to the long production delay (usually 4-8 weeks, $\boldsymbol{\tau}_{SA}$), the supplier echelon is characterised by push production. The APVIOBPCS archetype (Wang et al., 2014), well recognised as the representation of the push-based system, can be utilised to model such a system. For each replenishment cycle, $ORATE_{SA}$ is determined:

$$ORATE_{SA}(t) = Min\left(Capacity\ Limit, AVCON\ (t) + AINV_{ASadj}(t) + FWIP_{ADJ}(t)\right) \quad (5.11)$$

Where a capacity limit (Min) is utilised to represent the manufacturing plant production resources constraints, AVCON(t) is a feedforward forecasting policy by directly utilising end customer demand shared by the OEM to forecast future demand, i.e. the DIDP is upstream of the CODP to ensure information transparency**.** The well recognised exponential smoothing is adopted (Dejonckheere et al., 2002; 2003):

$$AVCON\ (t) = AVCON\ (t-1) + a\big(CON(t) - AVCON\ (t-1)\big), \qquad a = \frac{1}{(1+\frac{\tau_A}{\triangle T})} \quad (5.12)$$

$AINV_{SAadj}$ is the CODP inventory feedback loop adjusted by τ_{AINV} and safety stock ($AINV_{SA}$*). It should be noted that safety stock for upstream suppliers is based on actual pull $ORATE_{AS}$ and $\boldsymbol{\tau}_{SA}$, although different setting methods may be adopted based on different companies' policy:

$$AINV_{SAadj}(t) = \frac{1}{\tau_{AINV}}\left(AINV_{SA}^{*}(t) - AINV_{SA}(t)\right), \qquad AINV_{SA}^{*}(t) = \tau_{SA} Pull\ ORATE_{AS}(t) \quad (5.13)$$

where $AINV_{SA}$ depends on the accumulation between $COMRATE_{SA}$ and $ORATE_{AS}$:

$$AINV_{SA}(t) = AINV_{SA}(t-1) + COMRATE_{SA}(t) - ORATE_{AS}(t) \quad (5.14)$$

Furthermore, the dynamic role of WIP inventory in the sub-assembly system is considered in an MRP ordering system, which can be interpreted as products queuing at a disaggregate level. In line with John et al.'s (1994) standard modelling approach, a fraction of WIP error (WIP_{ADJ}) is corrected based on the difference between WIP* and WIP:

$$WIP_{ADJ} = \frac{1}{\tau_{\mathrm{WIP}}}\left(WIP^{*}(t) - WIP(t)\right) \quad (5.15)$$

Where WIP* depends on AVCON and estimated $\boldsymbol{\tau}_{SA}$ (assume equal to actual $\boldsymbol{\tau}_{SA}$, consistent with John et al., 1994), and WIP is an accumulative level between $COMRATE_{SA}$ and $ORATE_{SA}$:

$$WIP^{*}(t) = \tau_{SA}AVCON(t), \qquad WIP(t) = WIP(t-1) + ORATE_{SA}(t) - COMRATE_{SA}(t) \quad (5.16)$$

A first order delay is used to model the supplier manufacturing time, which can be interpreted as a production smoothing element representing how slowly the production units adapt to changes in $ORATE_{AS}$ (Wikner, 2003):

$$COMRATE_{SA}(t) = COMRATE_{SA}(t-1) + c\left(ORATE_{SA}(t) - COMRATE_{SA}(t-1)\right),$$
$$where\ c = \frac{1}{(1+\frac{\tau_{SA}}{\triangle T})} \quad (5.17)$$

Furthermore, as delivery LT is implicit in the ATO model, we incorporate the nonlinear division loop ($\textcircled{\Pi}$) to represent the delivery LT dynamics based on Little's Law (Simchi-Levi and Trick, 2011):

$$LT(t) = \frac{BL(t)}{SH(t)} \qquad (5.18)$$

Based on Equations (5.1) - (5.18), we developed the generic PC ATO supply chain model in block diagram form, using the continuous time domain, Laplace s, representation as shown in Figure 5.2. The entire system consists of a form of VIOBPCS (Edghill and Towill, 1990) (VIOBPCS plus final distribution and BL adjustment loops) and an exact APVIOBPCS archetype. Also, as in the Intel supply chain, there are two Min functions governing different operational states based on availability of $AINV_{SA}$ and $AINV_{AS}$. The difference between the two systems, however, is the geographical location of supply chain systems. The Intel supply chain is an internal production-inventory system including fabrication, final assembly and distribution within their plant, while the PC ATO supply chain includes multiple parties (supplier, VMI and third-party Logistics) globally located in different areas; thus, the modelling of both production and logistics transport delay needs to be considered. Nevertheless, the logic of two Min functions remains the same; that is, compare the desired replenishment rate and maximum allowable rate as the input of the system. As a result, the similar interchangeable operational states based on two Min functions in the ATO system can be categorised as follows:

1. Supplier manufacturing Push + final assembly (Pull+ Pull) state, known as the *Push-Pull-Pull state*. The system performs as the desired ATO production if there are enough $AINV_{AS}$ and $AINV_{SA}$, all incoming orders thereby can be fulfilled by $\boldsymbol{\tau}_{DD}$.
2. Supplier manufacturing Push + final assembly (Pull+ Push) state, named as the *Push-Pull-Push* state. If $AINV_{AS}$ is insufficient for incoming orders' pull, the final assembly plant can only assemble what they have ($AINV_{AS}$) and ship the

corresponding SH_{MAX}. The increased backlog and inventory correction signals increase the replenishment rate of $AINV_{AS}$, given the condition that customer orders can still pull the $AINV_{SA}$ at the supplier manufacturing site. The averaged delivery LT is larger than $\boldsymbol{\tau}_{DD}$, due to the extra PC part transport acquisition time ($\boldsymbol{\tau}_{AS}$) needed.

3. Supplier manufacturing Push + final assembly (Push+ Push) state, termed the *Pure Push* state. If $AINV_{SA}$ still constrains the pull $ORATE_{AS}$, the whole supply chain system will switch to the pure push production, i.e. all $AINV_{SA}$ and $AINV_{AS}$ are 'pushed' out as long as they are produced at the supplier site or arrive at the VMI hub. The increase of customer orders cannot be fulfilled for a short time period due to the long supplier manufacturing delay.

Having developed the model, it is important to verify the logic and correctness of the model (Spiegler et al., 2016). This verification process is done by simulation on Matlab™. Although we do not show the full verification results, part of the simulation analysis is reported in Table 5.1. The verification result shows the hybrid ATO model is logical and correct. Furthermore, Table 5.2. reports main nonlinearities present in the ATO system dynamic model and corresponding linearisation/simplification methods utilised in this chapter.

There are several nonlinearities in the hybrid ATO system and, depending on the rate of change in the output in relation to input, they can be categorised as continuous and discontinuous nonlinearities. To analytically explore the dynamic 'performance triangle' of the ATO supply chains, a brief explanation of the main characteristics of different types of nonlinearities and corresponding simplification / linearisation approaches are reported in Table 5.2.

Verification test	**Details**	**Verification process**	**Verification results**
Family member and parameters	Behaviour reproduction for cognate system and consistent with system data and description	1.Regarding the final assembly system, we use a similar Intel supply chain model (Lin et al., 2017) to reproduce its dynamic behaviour by utilising the same system parameter settings, i.e. $\tau_{AS} = \tau_I = \tau_{BL} = 2\tau_{DD} = 4$ with a unit step increase. 2. For the supplier manufacturing system, since it is an exact APVIOBPCS archetype, order-up-to policy settings (i.e. $\tau_{SA}=\tau_A/2=8$, $\tau_{AINV}= \tau_{WIP}=1$) are utilised to check whether the dynamic behaviour is consistent with Dejonckheere et al., (2003)	1. Dynamic behaviour of the final assembly is consistent with the Intel hybrid supply chain model e.g. maximum overshoot/undershoot, rising time and setting time. 2. The dynamic performance of the order-up-to policy can be reproduced.
Boundaries and Structure	Include all important factors and are consistent with system description	Related empirical works including Kapuscinski et al. (2004), Katariya et al. (2014) and Huang and Li (2010) are utilised to check the consistency regarding the system framework and important factors of the PC ATO supply chain.	1. The ATO system dynamic model is consistent with empirical descriptions characterised by combined order- and forecasting-driven production, VMI strategy, and material and information CODP. 2. All important factors are included for the system dynamic model. Also, the model is cross-checked by corresponding Intel supply chain (Lin et al., 2017), APVIOBPCS and VIOBPCS archetypes (Edghill and Towill, 1990; John et al., 1994; Dejonckheere et al., 2003).

Verification test (Continued)	**Details**	**Verification process**	**Verification results**
Extremities	Model is logical for extreme values	1. We check whether the dynamic performance of the final assembly system is consistent with the VIOBPCS archetype (Edghill and Towill, 1990) if $\tau_{BL} = \tau_{DD} = \infty$ 2. For the supplier manufacturing part, we increased the value of τ_{WIP}, τ_{AINV} and τ_{A} to extreme conditions to see whether the system can generate the expected dynamic outcome.	1. The dynamic behaviour of the final assembly system is consistent with corresponding performance in the original VIOBPCS if the backlog and shipment loops are removed. 2. The extreme values of τ_{A}, τ_{AINV}, and τ_{WIP} will lead to the expected dynamic performance in responding to a step demand increase. For example, the infinite τ_{AINV} will remove the inventory feedback loop, which results in the permanent inventory drift in response to a step increase, as expected.

Table 5. 1. The verification of the hybrid PC supply chain model

Type of nonlinearity in this study	**Simplification/linearisation methods in this study**
Single-valued discontinuous nonlinearity: 1) Non-negative order constraint in final assembly plant, i.e. Equation (5.8). 2) Capacity constraint in the supplier manufacturing plant, i.e. Equation (5.11).	Describing function, to be presented in Section 5.2.
Multi-valued discontinuous nonlinearity: 1) Shipment constraint, i.e. Equation (5.1) 2) CODP inventory constraint, i.e. Equation (5.7).	Two multi-valued nonlinearities govern three operational states of the hybrid ATO system, depending on the feasible $AINV_{AS}$ and $AINV_{SA}$; the author analysed them separately by assuming all discontinuous nonlinearities are not active and temporarily operate as a certain state. i.e. analysis of *Push-Pull-Pull* (Section 5.2), *Push-Pull-Push* and *Pure Push* (Section 5.3) separately.
Continuous nonlinearity: Delivery LT, as shown by Equation (5.18).	Taylor series expansion with small perturbation theory will be utilised to linearise the delivery LT measurement (Section 5.3).

Table 5. 2. Main nonlinearities present the ATO system dynamic model and corresponding simplification and linearisation methods.

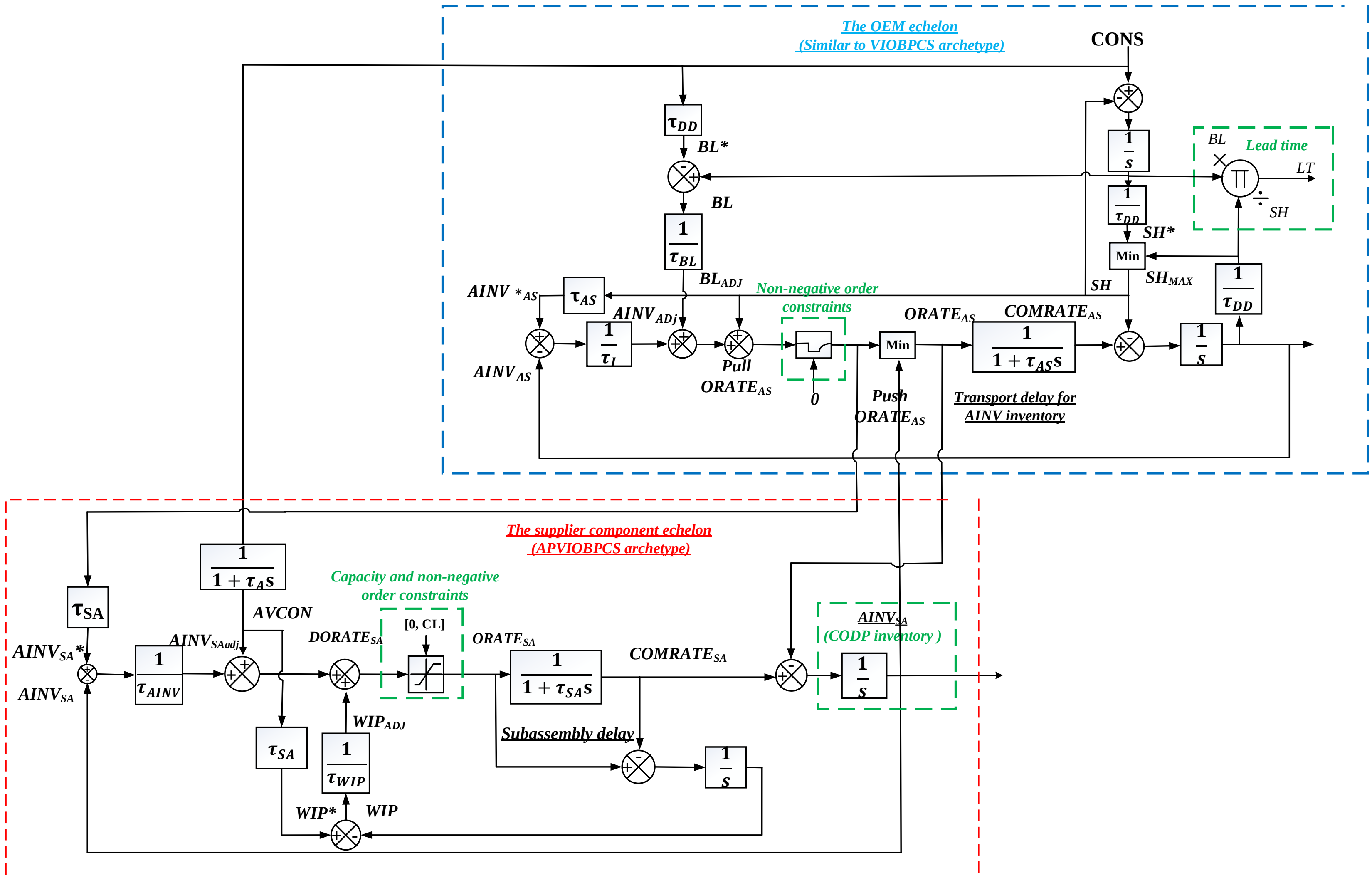


Figure 5. 2. System dynamics model for the PC hybrid ATO supply chain.

5.2. Dynamic analysis of the hybrid Push-Pull-Pull state

As illustrated in Section 5.1, two multi-valued nonlinearities (i.e. Min functions) govern three operational states of hybrid ATO system depending on the feasible $AINV_{AS}$ and $AINV_{SA}$. In this section, the *Push-Pull-Pull* state (i.e. the true ATO state) is analysed separately, although the switch between different states driven by two multi-valued nonlinearities will be analysed in Section 5.3. Based on the empirical evidence (Kapuscinski et al., 2004; Huang and Li, 2010; Katariya et al., 2014), the hybrid *Push-Pull-Pull* state should be maintained for most of the time in responding to customised demand orders to balance cost efficiency and customer agility. Thus, it is important to explore the impact of such a structure on dynamic performance, including *the feedback, feedforward* and *nonlinearities* present in the structure, to provide supply chain dynamics related cost implication for companies.

Specifically, by assuming the hybrid *Push-Pull-Pull* state is always operated, the two Min functions can be removed, i.e. $SH(t) = SH^{*}(t) < SH_{MAX}(t)$ and $ORATE_{AS}(t) = Pull\ ORATE_{AS}(t) < Push\ ORATE_{SA}(t)$. Also, under this assumption, the delivery LT becomes a constant level; that is, $\boldsymbol{\tau}_{DD}$. Therefore, it is not necessary to assess its dynamic performance. Consequently, the important system variables are two CODP stock points ($AINV_{AS}$ and $AINV_{SA}$) and capacity adjustment at the supplier ($ORATE_{SA}$). The block diagram of hybrid Push-Pull-Pull state is demonstrated in Figure 5.3.

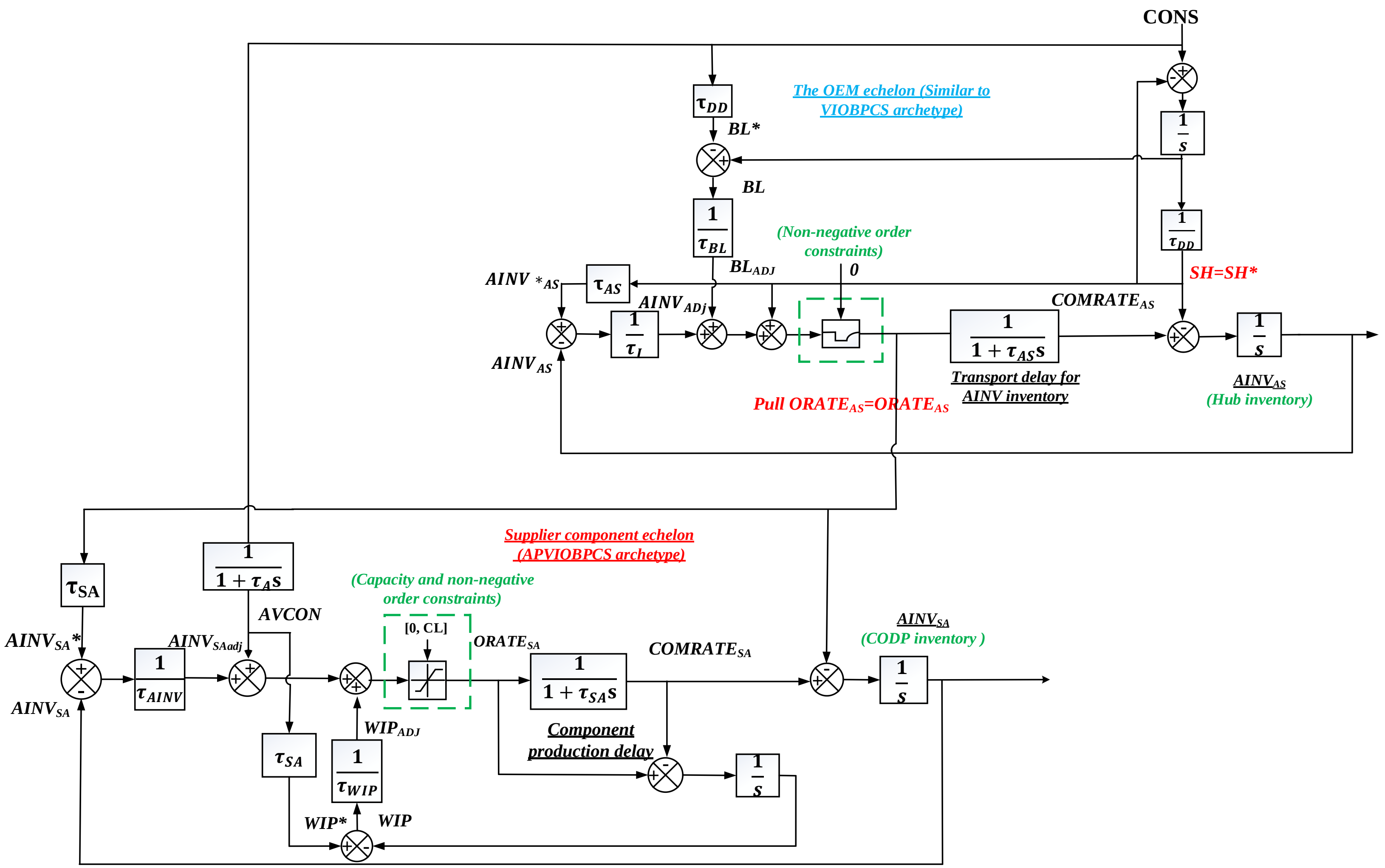


Figure 5. 3. System dynamics model for push-pull-pull state (true hybrid ATO state).

5.2.1. The impact of feedback and feedforward on the hybrid Push-Pull-Pull system dynamics

By assuming all nonlinearities are inactive (i.e. negative orders are permitted and no CL), it is possible to formulate the transfer functions of $AINV_{AS}$, $AINV_{SA}$ and $ORATE_{SA}$. That is, based on Equations (5.1) to (5.17) and following the approach derived from Section 4.2.2 (Transfer function analysis), two inventories and the supplier's capacity adjustment, in relation to CONS can be derived as follows:

$$\frac{AINV_{AS}}{CONS}=\frac{\left(-\tau_i\tau_{\mathrm{DD}}^2s^2+\tau_{\mathrm{BL}}s(\tau_i+\tau_{\mathrm{AS}})+\tau_{\mathrm{BL}}\right)(1+\tau_{\mathrm{AS}}s)}{(1+\tau_i s+\tau_i\tau_{\mathrm{AS}}s^2)(\tau_{\mathrm{BL}}+\tau_{\mathrm{BL}}\tau_{\mathrm{DD}}s)} \qquad (5.19)$$

$$\frac{ORATE_{SA}}{CONS}=\frac{(1+\tau_{\mathrm{SA}})\begin{pmatrix}(1+\tau_A s)(1+\tau_{\mathrm{AS}}s)(\tau_{\mathrm{BL}}+\tau_i\tau_{\mathrm{BL}}s+\tau_{\mathrm{AS}}\tau_{\mathrm{BL}}s-\tau_i\tau_{\mathrm{DD}}^2s^2)(1+\tau_{\mathrm{SA}}s)\tau_{\mathrm{WIP}}\\+s\tau_{\mathrm{AINV}}\left(1+\tau_i s(1+\tau_{\mathrm{AS}}s)\right)\tau_{\mathrm{BL}}(1+\tau_{\mathrm{DD}}s)(\tau_{\mathrm{SA}}+\tau_{\mathrm{WIP}})\end{pmatrix}}{\begin{matrix}(1+\tau_i s+\tau_i\tau_{\mathrm{AS}}s^2)(\tau_{\mathrm{BL}}+\tau_{\mathrm{BL}}\tau_{\mathrm{DD}}s)(1+\tau_A s)\\(\tau_{\mathrm{WIP}}+(\tau_{\mathrm{AINV}}\tau_{\mathrm{SA}}+\tau_{\mathrm{AINV}}\tau_{\mathrm{WIP}})s+\tau_{\mathrm{AINV}}\tau_{\mathrm{SA}}\tau_{\mathrm{WIP}}s^2)\end{matrix}} \qquad (5.20)$$

$$\frac{AINV_{SA}}{CONS}=\frac{\begin{pmatrix}\tau_{\mathrm{AINV}}s\left(-\tau_{\mathrm{AS}}(2+\tau_{\mathrm{AS}}s)\tau_{\mathrm{BL}}+\left(1+\tau_i s(1+\tau_{\mathrm{AS}}s)\right)\tau_{\mathrm{BL}}\tau_{\mathrm{DD}}+\tau_i s(1+\tau_{\mathrm{AS}}s)\tau_{\mathrm{DD}}^2\right)\tau_{\mathrm{SA}}\\+\begin{pmatrix}\tau_{\mathrm{AINV}}s\begin{pmatrix}-\tau_{\mathrm{AS}}(2+\tau_{\mathrm{AS}}s)\tau_{\mathrm{BL}}+\left(1+\tau_i s(1+\tau_{\mathrm{AS}}s)\right)\tau_{\mathrm{BL}}\tau_{\mathrm{DD}}\\+\tau_i s(1+\tau_{\mathrm{AS}}s)\tau_{\mathrm{DD}}^2\end{pmatrix}\\-(\tau_{\mathrm{AINV}}s-1)(1+\tau_{\mathrm{AS}}s)\left((1+(\tau_i+\tau_{\mathrm{AS}})s)\tau_{\mathrm{BL}}-\tau_i\tau_{\mathrm{DD}}^2s^2\right)\tau_{\mathrm{SA}}\end{pmatrix}\tau_{\mathrm{WIP}}\\-\tau_A s(1+\tau_{\mathrm{AS}}s)\left((1+(\tau_i+\tau_{\mathrm{AS}})s)\tau_{\mathrm{BL}}-\tau_i\tau_{\mathrm{DD}}^2s^2\right)\\(\tau_{\mathrm{AINV}}\tau_{\mathrm{SA}}+(\tau_{\mathrm{AINV}}+(\tau_{\mathrm{AINV}}s-1)\tau_{\mathrm{SA}})\tau_{\mathrm{WIP}})\end{pmatrix}}{\begin{matrix}(1+\tau_i s+\tau_i\tau_{\mathrm{AS}}s^2)(\tau_{\mathrm{BL}}+\tau_{\mathrm{BL}}\tau_{\mathrm{DD}}s)(1+\tau_A s)\\(\tau_{\mathrm{WIP}}+(\tau_{\mathrm{AINV}}\tau_{\mathrm{SA}}+\tau_{\mathrm{AINV}}\tau_{\mathrm{WIP}})s+\tau_{\mathrm{AINV}}\tau_{\mathrm{SA}}\tau_{\mathrm{WIP}}s^2)\end{matrix}} \qquad (5.21)$$

The starting point is the analysis of IVT and FVT to mathematically crosscheck the correctness of the transfer function, guide the appropriate initial condition required by a simulation and to understand the final steady state value of the dynamic response to help verify any simulation. The initial and final values of $AINV_{AS}$, $AINV_{SA}$, and $ORATE_{SA}$ in responding to a unit step input are obtained.

$$\lim_{s\to\infty} s\frac{AINV_{AS}}{CONS} = 0 \qquad \lim_{s\to 0} s\frac{AINV_{AS}}{D} = \tau_{\mathrm{AS}}$$

$$\lim_{s\to\infty} s\frac{AINV_{SA}}{CONS} = 0 \qquad \lim_{s\to 0} s\frac{AINV_{SA}}{D} = \tau_{\mathrm{SA}}$$

$$\lim_{s\to\infty} s\frac{ORATE_{SA}}{CONS} = 0 \qquad \lim_{s\to 0} s\frac{ORATE_{SA}}{CONS} = 1 \qquad (5.22)$$

As expected, the initial values of $\mathrm{AINV_{AS}}$, $\mathrm{AINV_{SA}}$ and $\mathrm{ORATE_{SA}}$ are zero, like the results obtained by John et al. (1994). The final value of the $\mathrm{ORATE_{SA}}$ for the upstream sub-assembly system is, as expected, equal to demand, i.e. 1. The final value of the $\mathrm{AINV_{SA}}$ and $\mathrm{AINV_{AS}}$ is determined by the coefficient τ_{SA} and τ_{AS}, i.e. the steady state of two inventories in response to a step demand equal to the desired inventory level. Based on Equations (5.19) to (5.21), the dynamic property of the final assembly system is characterised as a third-order polynomial, while a sixth-order polynomial describes the dynamic property of the supplier's manufacturing system.

Also, there is a third-order polynomial, $(1 + \tau_i s + \tau_i \tau_{\mathrm{AS}} s^2)(\tau_{\mathrm{BL}} + \tau_{\mathrm{BL}}\tau_{\mathrm{DD}} s)$, in both CEs, i.e. the denominator of Equations (5.19) and (5.21), suggesting that the dynamic property of the final assembly system is not influenced by the sub-assembler manufacturing system, while the dynamic performance of the supplier manufacturing system can be partially manipulated by the final assembly control policies under the ATO system. The roots can be obtained based on equations (5.19) - (5.21) as follows:

$$R_{1\&2} = -\frac{1}{2\tau_{AS}} \pm \frac{\sqrt{\tau_i^2 - 4\tau_i\tau_{\mathrm{AS}}}}{2\tau_i\tau_{\mathrm{AS}}}, \qquad R_3 = -\frac{1}{\tau_A}, R_4 = -\frac{1}{\tau_{DD}}$$

$$R_{5\&6} = -\frac{1}{2}\left(\frac{1}{\tau_{SA}} + \frac{1}{\tau_{WIP}}\right) \pm \frac{\sqrt{-4\tau_{\mathrm{AINV}}\tau_{\mathrm{SA}}\tau_{\mathrm{WIP}}^2 + (\tau_{\mathrm{AINV}}\tau_{\mathrm{SA}} + \tau_{\mathrm{AINV}}\tau_{\mathrm{WIP}})^2}}{2\tau_{\mathrm{AINV}}\tau_{\mathrm{SA}}\tau_{\mathrm{WIP}}} \quad (5.23)$$

Inspecting Equation (5.23):

1. Given that the physical delays, τ_{SA} and τ_{AS}, are positive, the *Push-Pull-Pull* state is permitted to be stable for any positive control policies, i.e. possible value of $\tau_{\mathrm{A}}, \tau_{\mathrm{AINV}}, \tau_{\mathrm{WIP}}$ and τ_{I}. However, the system's response will be continuously oscillatory if $\tau_{SA} = -\tau_{WIP}$, that is, the $R_{5\&6}$, become purely imaginary with no real part.

2. Three feedback inventory loops, $\mathrm{AINV_{AS}}$, $\mathrm{AINV_{SA}}$ and WIP adjustment, may characterise oscillations of the Push-Pull-Pull state if the square root part of $R_{1\&2}$ and $R_{5\&6}$ becomes negative, i.e. ${\tau_I}^2 - 4\tau_I\tau_{AS} < 0$ and $-4\tau_{\mathrm{AINV}}\tau_{\mathrm{WIP}}^2\tau_{\mathrm{SA}} + (\tau_{\mathrm{AINV}}\tau_{\mathrm{WIP}} + \tau_{\mathrm{AINV}}\tau_{\mathrm{SA}})^2 < 0$. The corresponding CODP inventory-based control policies, τ_I, τ_{AINV} and τ_{WIP}, should be carefully adjusted to avoid a possible oscillatory system response.

3. There are two independent negative feedback loops at final assembly ($\mathrm{AINV_{AS}}$ adjustment) and supplier manufacturing site ($\mathrm{AINV_{SA}}$ and WIP adjustment), suggesting a two degree-of-freedom system with possibly two underdamped natural frequencies subject to the control policy design, which may lead to a complex dynamic response including superposition or separation of dynamic oscillation, e.g. separated two-resonant peak frequencies (that is, the dynamic system can generate peak oscillations with greater amplitude, e.g. high bullwhip, at two different demand frequencies), as illustrated as an example in Figure 5.4. As a result, if the hybrid *Push-Pull-Pull* structure should be maintained, it is beneficial for different companies to collaboratively design the

replenishment policy to reduce the influence of two-resonance peak frequencies. This result also supports the benefit of those adopted operational strategies in practice, e.g. collaborative planning, forecasting and replenishment (CPFR).

4. Given the supplier manufacturing delay, τ_{SA}, and associated inventory adjustment time (τ_{WIP}) are longer than downstream transport acquisition delay τ_{AS}, the real part of $R_{5\&6}$, $-\frac{1}{2}\left(\frac{1}{\tau_{SA}}+\frac{1}{\tau_{WIP}}\right)$, is smaller than the real part of $R_{1\&2}$, i.e. $-\frac{1}{2\tau_{AS}}$. In other words, $R_{5\&6}$ are located in a closer position to the origin s plane compared to the location of $R_{1\&2}$. Consequently, the upstream inventory feedback loops and forecasting loop may dominate the dynamic behaviour of the entire Push-Pull-Pull state. Particularly, inventory loop-based control policies, τ_{AINV} and τ_{WIP}, play a key role in influencing the whole state's oscillatory behaviour.

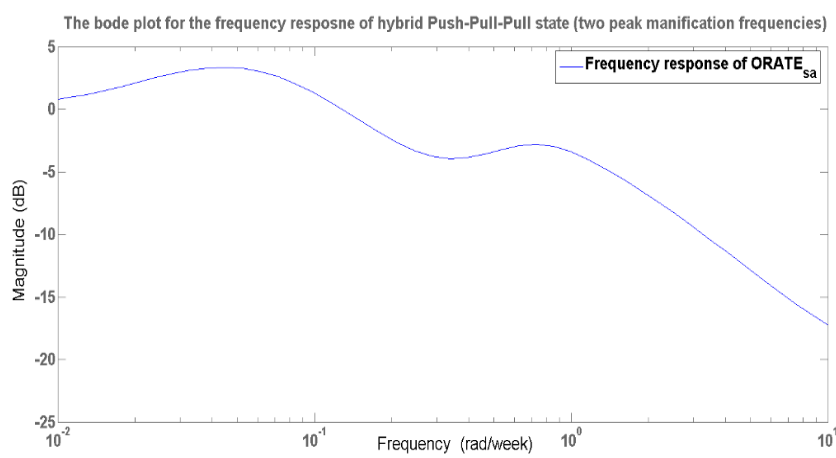


Figure 5. 4. An example of the frequency response of ORATE$_{SA}$ for the *Push-Pull-Pull* state with two peak magnification frequencies ($\tau_{\mathrm{A}}=16, \tau_{\mathrm{AINV}}=\tau_{\mathrm{WIP}}=24, \tau_{\mathrm{SA}}=8, \tau_{\mathrm{DD}}=0.5, \tau_{\mathrm{I}}=2,\ \tau_{\mathrm{AS}}=1$)

To further understand the oscillation and system recovery properties, we derive the ω_n and ζ of two second order polynomials, $(1+\tau_i s+\tau_i\tau_{\mathrm{AS}}s^2)$ and $(\tau_{\mathrm{WIP}}+(\tau_{\mathrm{AINV}}\tau_{\mathrm{SA}}+\tau_{\mathrm{AINV}}\tau_{\mathrm{WIP}})s+\tau_{\mathrm{AINV}}\tau_{\mathrm{SA}}\tau_{\mathrm{WIP}}s^2)$:

$$\omega_{n1}=\sqrt{\frac{1}{\tau_{AS}\tau_I}} \qquad \zeta_1=\frac{1}{2}\sqrt{\frac{\tau_I}{\tau_{AS}}} \qquad (5.24)$$

$$\omega_{n2}=\sqrt{\frac{1}{\tau_{\mathrm{AINV}}\tau_{\mathrm{SA}}}}, \quad \zeta_2=\frac{(\tau_{\mathrm{SA}}+\tau_{\mathrm{WIP}})}{2\tau_{\mathrm{WIP}}}\sqrt{\frac{\tau_{\mathrm{AINV}}}{\tau_{\mathrm{SA}}}}$$

For VMI inventory ($\mathrm{AINV_{AS}}$) at the OEM site, both ω_{n1} and ζ_1 are determined by τ_I under physically fixed τ_{AS}, and τ_I has the reverse impact on nature frequency and damping ratio. The OEM system's response and inventory recovery speed will be slower than the increase of τ_I, due to the decrease of ω_{n1}. However, the increase of τ_I will give the larger value of damping ratio and lead to the corresponding more 'damped' system with fewer oscillations. ω_{n1} and ζ_1 could also lead to such impact on the dynamic behaviour of $\mathrm{AINV_{SA}}$ and $\mathrm{ORATE_{SA}}$ at the supplier site. Furthermore, τ_{AINV} and τ_{SA} negatively determine the value of natural frequency for upstream supplier $\mathrm{AINV_{SA}}$ feedback loop, whereby increasing their value will lead to slow system recovery speed to reach the steady state condition due to the decrease of value of ω_{n2}. Moreover, τ_{AINV} and τ_{WIP} have the reverse impact for damping ratio. For a fixed system lead time, the increase of τ_{AINV} lead to less oscillatory while the increase of τ_{WIP} will produce more oscillations.

5.2.2. The impact of nonlinearities on the hybrid *Push-Pull-Pull* system dynamics

When capacity and non-negative order constraints are active in the OEM and upstream supplier sites, the dynamic behaviour becomes more complex due to the influence of such nonlinearities. The describing function method can be utilised to explore the impact of two nonlinearities separately in responding to sinusoidal demand.

5.2.2.1. Linearisation of capacity and non-negative order constraints at the supplier site

In the linear system, upstream supplier production capacity is assumed to be unlimited and the order is permitted to be negative. This means that the supplier can freely return the raw materials to their suppliers and any order rate received can be allocated for immediate production. These are unrealistic assumptions due to the expensive production line system, e.g. see Lin et al. (2017), and the forbidden return policy usually agreed between material suppliers and the sub-assembler manufacturers. Thus, both constraints should be considered when analysing the dynamic property of the ATO system. We now linearise such nonlinearity before analysing its impact on the dynamic property of the ATO system. Specifically, in an open-loop form of such nonlinearity, an input $DORATE_{SA}(t)$

$$DORATE_{SA}(t) = A\cos(\omega t) + B \qquad (5.25)$$

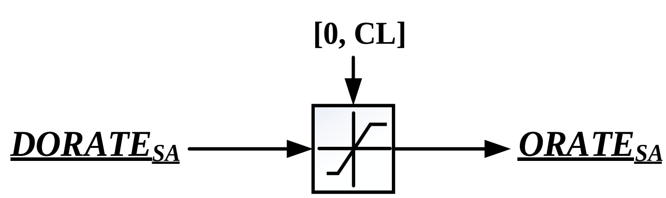
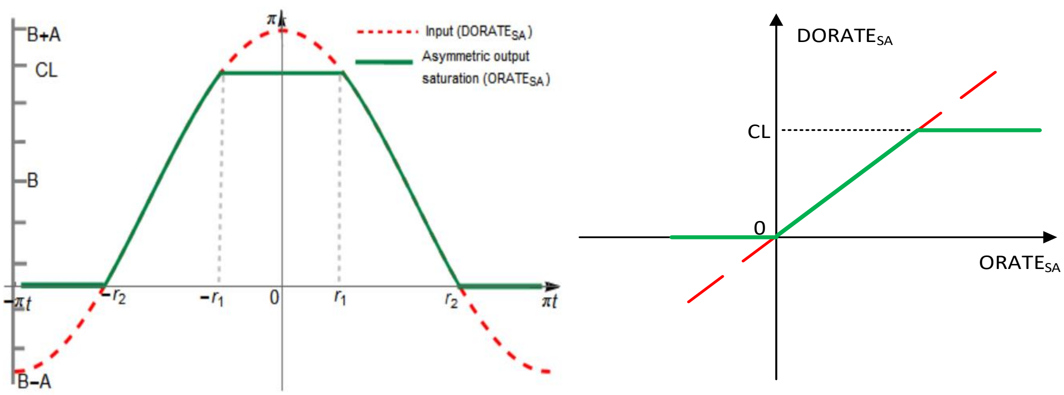


Figure 5. 5. The open loop form of saturation nonlinearity function in the supplier system extracted from Figure 5.3.

where A is the amplitude, B is the mean and ω is the angular frequency ($\omega = \frac{2\pi}{t}$), will produce an output $ORATE_{SA}(t)$ with the same frequency but different mean and amplitude. Figure 5.6 reports the main characteristics of this nonlinearity. The output $ORATE_{SA}$ does not rely on the past value of the input $DORATE_{SA}$, but it varies, depending on the actual status of input based on upper and lower limit.



(a) Time series for $DORATE_{SA}$ and $ORATE_{SA}$ (b) The property of single-valued nonlinearity

Figure 5. 6. Asymmetric output saturation in relation to sinusoidal input $DORATE_{SA}$

It should be noted that a fundamental requirement for the system is that CL must be at least larger than average demand due to the accumulative errors driven by the feedback integrator (1/s). In other words, the $DORATE_{SA}$ will increase exponentially if manufacturing capacity is less than averaged demand rate and the system will become unstable. Under such a fundamental assumption, the output function, $ORATE_{SA}$, can be represented by three linear piecewise equations, as follows:

$$ORATE_{SA}(t) = \begin{cases} 0 & if \quad DORATE_{SA} < 0 \\ DORATE_{SA} & if \quad 0 < DORATE_{SA} < CL \\ CL & if \quad DORATE_{SA} > CL \end{cases} \quad (5.26)$$

To analyse the discontinuous nonlinearities in the ATO system, the describing function method can be applied (Spiegler et al., 2016; Spiegler and Naim, 2017). This method is a quasi-linear representation for a nonlinear element subjected to specific input signal forms such as Bias, Sinusoid and Gaussian process and the system's low-pass filter property (Vander and Wallace, 1968). The principle advantage of utilising the describing function method is it enables the aid of analytically designing nonlinear systems. The basic idea is to replace the nonlinear component by a type of transfer function, or a gain derived from the effect of input (e.g. sinusoidal input). For an asymmetric saturation, as illustrated in Figure 5.7, since $DORATE_{SA}$ is smaller than zero or greater than CL, at least two terms need to be identified: one term describes the change in amplitude ($N_{A(CA)}$) in relation to the input amplitude and the other defines the change in mean ($N_{B(CA)}$) in relation to the input mean. Furthermore, output phase angle (φ) in relation to the input angle may also be changed.

Therefore, given the input, i.e. Equation (5.25), the output $ORATE_{SA}$ can be approximated to:

$$ORATE_{SA}(t) = N_{A(CA)} A\text{Cos}(\omega t + \phi) + N_{B(CA)} B \quad (5.27)$$

The Fourier series expansion can be applied to obtain the terms of describing functions (N_A, N_B and φ):

$$ORATE_{SA}(t) \approx b_0 + a_1 \cos(\omega t) + b_1 \sin(\omega t) + a_2 \cos(2\omega t) + b_2 \sin(2\omega t) + \cdots$$

$$\approx b_0 + \sum_{n=1}^{\infty} (a_n \cos(n\omega t) + b_n \sin(n\omega t)) \qquad (5.28)$$

Where the Fourier coefficient can be determined by:

$$a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} ORATE_{SA}(t) \cos(n\omega t)\, d_{\omega t} \qquad (5.29)$$

$$b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} ORATE_{SA}(t) \sin(n\omega t)\, d_{\omega t} \qquad (5.30)$$

$$b_0 = \frac{1}{2\pi} \int_{-\pi}^{\pi} ORATE_{SA}(t) d_{\omega t} \qquad (5.31)$$

and $ORATE_{SA}$ is the piecewise linear function (Figure 6a):

$$ORATE_{SA}(t) = \begin{cases} 0 & -\pi < \omega t < -r_2 \\ A\cos(\omega t) + B & -r_2 < \omega t < -r_1 \\ CL & -r_1 < \omega t < r_1 \\ A\cos(\omega t) + B & r_1 < \omega t < r_2 \\ 0 & r_2 < \omega t < \pi \end{cases} \quad (\, 0 < r_1 < r_2 \le \pi) \quad (5.32)$$

To approximate periodic series, only the first, or fundamental, harmonic is needed and thereby we need to find the first order coefficient of Fourier series expansion demonstrated in Equation (29)-(31). Note that such approximation is often useful for the symmetric system, including only odd functions and thus high order harmonic can be effectively attenuated by the linear dynamic of the system, i.e. the property of low-pass filter. For the asymmetric system, the aid of simulation is recommended (Atherton, 1975) to verify the analytical results derived from the fundamental harmonic approximation. The first harmonic of the piecewise linear Equation (5.32) can be obtained as follows:

$$ORATE_{SA}(t) = b_0 + a_1 \cdot \cos(\omega t) + b_1 \cdot \sin(wt) = b_0 + \sqrt{a_1^2 + b_1^2}\cos(wt + \phi) \quad (5.33)$$

Where $\phi = \arctan(\frac{b_1}{a_1})$

By comparing Equations (5.27) and (5.33), we have the gain of describing function as follows:

$$N_{A(CA)} = \frac{\sqrt{a_1^2 + b_1^2}}{A} \text{ and } N_{B(CA)} = \frac{b_0}{B} \quad (5.34)$$

Due to the property of such single-valued nonlinearity, there is no output phase shift in relation to input; that is, $b_1 = 0$ and $\phi = 0$. By calculating the Fourier coefficient a_1 and b_0 (Mathematica[TM]), the describing function gains are obtained as follows:

$$N_{A(CA)} = \frac{A\text{Cos}(r_1)\text{Sin}(r_1) + \left(2B + A\text{Cos}(r_2)\right)\text{Sin}(r_2) - Ar_1 + Ar_2}{A\pi} \quad (5.35)$$

$$N_{B(CA)} = \frac{A\left(\text{Sin}(r_2) - \text{Sin}(r_1)\right) + Ar_1\text{Cos}(r_1) + Br_2}{B\pi} \quad (5.36)$$

Where $r_1 = \text{Cos}^{-1}(\frac{CL-B}{A})$ *and* $r_2 = \text{Cos}^{-1}(\frac{-B}{A})$ and Equations (5.35) and (5.36) can be further simplified as:

$$N_{A(CA)} = \frac{(\text{CL} - B)\sqrt{1 - \frac{(\text{CL} - B)^2}{A^2}} + B\sqrt{1 - \frac{B^2}{A^2}} - A\cos^{-1}\left(\frac{\text{CL} - B}{A}\right) + A\cos^{-1}\left(-\frac{B}{A}\right)}{A\pi} \quad (5.37)$$

$$N_{B(CA)} = \frac{A\left(\sqrt{1-\frac{B^2}{A^2}} - \sqrt{1-\frac{(\mathrm{CL}-B)^2}{A^2}}\right) + A(\mathrm{CL}-B)\cos^{-1}\left(\frac{\mathrm{CL}-B}{A}\right) + B\cos^{-1}\left(-\frac{B}{A}\right)}{B\pi} \quad (5.38)$$

Figure 5.6 gives the density plot for the value of N_A as the increase of A from CL to 8CL, and the increase of B from 0.1 CL to CL. Overall the amplitude of $DORATE_{SA}$ plays a major role in influencing the value of $N_{A(CA)}$. This means the higher the bullwhip, the lower the proportion of $DORATE_{SA}$ that will be manufactured. Depending on different values of A and B, $N_{A(CA)}$ ranges between 0 and 1. Specifically, for a fixed B, $N_{A(CA)}$ monotonically decreases in A and this implies that only a fraction of $DORATE_{SA}$ will be manufactured due to the capacity and non-negative order constraints. However, the influence of B on amplitude gain depends on the relationship between A and CL. If A is larger than CL, B has little influence on amplitude gain due to the dominant influence of A on the $N_{A(CA)}$. if A is located within 0 and CL, $N_{A(CA)}$ depends on both A and B. $N_{A(CA)}$ may equal to 1 (the system will behave as linear) if $DORATE_{SA}$ do not exceed the constraint range, i.e. [0, CL], while only a fraction of $DORATE_{SA}$ will be manufactured if $N_{A(CA)} <1$.

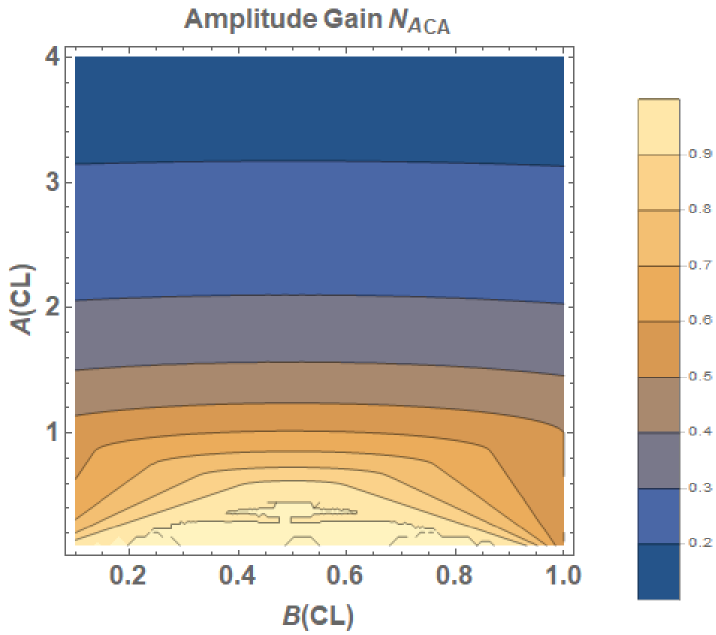


Figure 5. 7. The density plot of N_A based on A and B in relation to CL

To explore how the relationship of A, B and CL influences the output mean gain, N_B, we differentiate Equation (5.38) with respect to A and yield the following expression:

$$\frac{d_{N_{B(CA)}}}{d_A} = \frac{\sqrt{1-\frac{B^2}{A^2}} - \sqrt{1-\frac{(\mathrm{CL}-B)^2}{A^2}}}{B\pi} \quad (5.39)$$

Equation (5.39) shows that the zero gradient can be achieved if $\mathrm{B} = \frac{1}{2}\mathrm{CL}$ and we obtain the corresponding value of N_B:

$$N_{B(CA)}\big|_{B=\frac{1}{2}CL} = \frac{\mathrm{Cos}^{-1}(-\frac{\mathrm{CL}}{2A}) + \mathrm{Cos}^{-1}(\frac{\mathrm{CL}}{2A})}{\pi} = 1 \quad (5.40)$$

Thus, output mean gain, $N_{B(CA)}$, equals 1 irrelevant of input amplitude A if averaged input mean is half of CL, due to the fact that the system has a symmetric saturation in this case, i.e. equal influence of upper capacity and nonnegative order constraints. Also, the increase of A leads to the increase of $N_{B(CA)}$ if $B < \frac{1}{2}CL$, while $N_{B(CA)}$ is monotonically decreasing in A if $B > \frac{1}{2}CL$. This means that if averaged input demand is less than half of CL, the non-negative order constraint has more impact on $N_{B(CA)}$ than the corresponding capacity constraint and thereby $N_{B(CA)}$ decreases by the increase of A due to order rate reaching zero more often than hitting CL. However, if averaged input demand is greater than the half of CL, $N_{B(CA)}$ is monotonically decreasing in A because the impact of capacity constraint dominates the output mean gain compared to the corresponding non-negative order constraint. Such findings are consistent with Spiegler et al.'s (2016a; 2016b) separate investigation of the effect of capacity constraint and non-negative order constraints on output mean gain. Figure 5.8 demonstrates two examples how $N_{B(CA)}$ varies as the increase of A related to AL when B=0.2CL and B=0.8CL.

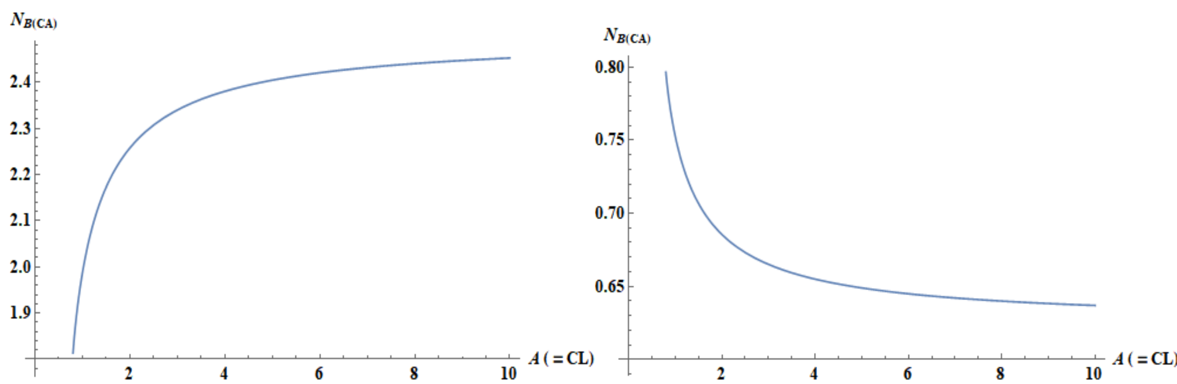


Figure 5. 8. The change of $N_{B(CA)}$ as the increase of A in relation to AL when B=0.2CL (Left) and B=0.8CL (Right).

5.2.2.2. Linearisation of non-negative order constraints at the OEM site

In linear ATO system, $ORATE_{AS}$ at the VMI site is permitted to take negative values. It means that excess PC components at the VMI inventory hub can be freely returned to the supplier site. This is an unrealistic assumption due to long geographical distance and export/import policies between the final assembly and their PC parts subassemblies. As a result, the non-negative order constraint should be put into the model to prevent the free inventory return from final assembly site to the supplier site. The main characteristics of non-negative nonlinearity is reported in Figure 5.9 and Equation (5.41) shows the piece linear function of $ORATE_{AS}$:

$$ORATE_{AS}(t) = \begin{cases} 0 & if \quad Pull\ ORATE_{AS} < 0 \\ Pull\ ORATE_{SA} & if \quad Pull\ ORATE_{SA} > 0 \end{cases} \qquad (5.41)$$

Where $Pull\ ORATE_{SA}(t) = A_1 \cdot \cos(\omega t) + B_1$ and $ORATE_{AS}(t)$ can be approximated by

$$ORATE_{AS}(t) \approx N_{A_{(NO)}} A_1 \cos(\omega t + \phi) + N_{B_{(NO)}} B_1 \qquad (5.42)$$

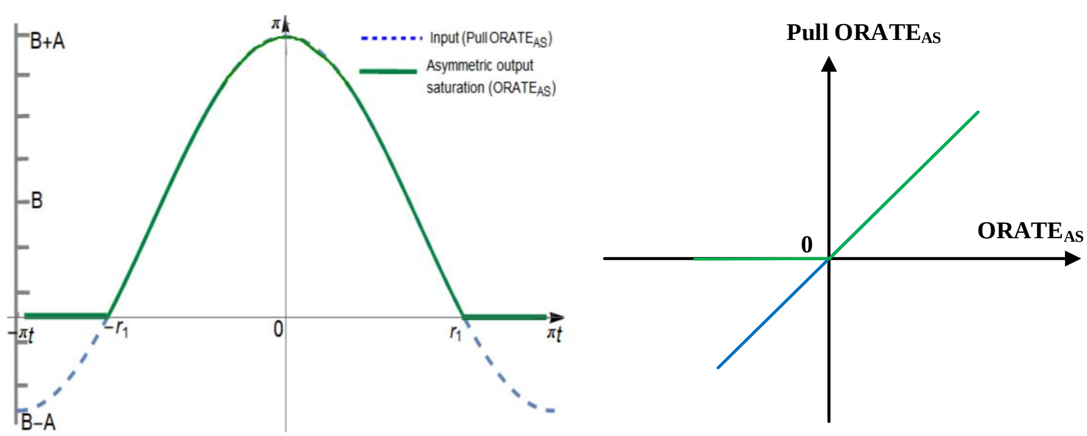


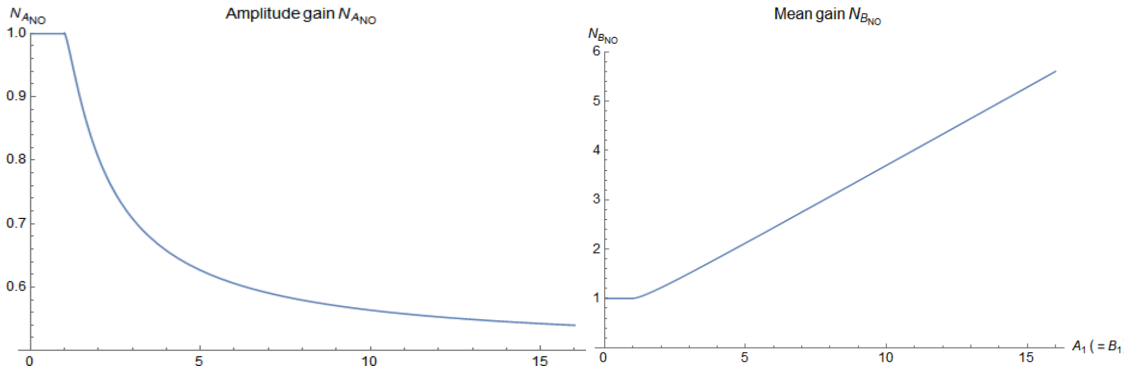
Figure 5. 9. Main characteristics of non-negative order constraint at the VMI site.

Where $N_{A(NO)}$ is the change in amplitude in relation to the input amplitude and $N_{B(NO)}$ is the change in mean in relation to the input mean under non-negative order constraint policy. Like the linearisation of capacity and non-negative constraints for the supplier production, the describing function method can be applied for linearising such nonlinearity. The corresponding describing function gain can be derived as follows:

$$N_{A_{(NO)}} = \frac{\frac{B\sqrt{1-\frac{B^2}{A^2}}}{A} + \mathrm{Cos}^{-1}(-\frac{B}{A})}{\pi} \quad (5.43)$$

$$N_{B_{(NO)}} = \frac{A\sqrt{1-\frac{B^2}{A^2}} + B\mathrm{Cos}^{-1}(-\frac{B}{A})}{B\pi} \quad (5.44)$$

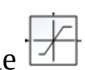
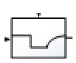
Figure 5.10 illustrates how the coefficients of the describing function vary as A_1 increases for any $B_1 > 0$. For values of A_1 lower than B_1, the system behaves as linear and output o(t) will be equal to the input do(t) corresponding to $N_{A(NO)} = 1$ (Figure 5.10a). However, when A_1 increases, then only a fraction of this rate will actually be ordered corresponding to $N_{A(NO)} < 1$. By inspecting Equation (5.43), we find that as A do approaches infinity, N_{A1} approaches 0.5. Thus, the amplitude gain of the describing function can only vary from 0.5 to 1. On the other hand, the value of N_{B1} rises as A_1 increases because the limit value of the order rate is at its minimum (Figure 5.10b).



a) Amplitude gain b) Mean gain

Figure 5. 10. Terms of describing function for the non-negativity constraint.

5.2.2.3. Predict system dynamics behaviour

Although two nonlinearities in the ATO system have different features, they both decrease their corresponding output amplitude gains ($N_{A(CA)}$ and $N_{A(NO)}$) as the increase of input amplitude. Root locus techniques (Spiegler et al., 2016; Spiegler and Naim, 2017) can be used to predict how these nonlinearities affect the system responses. By replacing the  and  with the corresponding amplitude gains, $N_{A(CA)}$ and $N_{A(NO)}$ respectively, and using block diagram algebra, we find the new system CEs and compare with CEs in linear ATO state based on Equation (5.19) - (5.21).

$$CE_{OEM}: (\tau_{\mathrm{BL}} + \tau_{\mathrm{DD}}\tau_{\mathrm{BL}}s)\left(N_{A(NO)} + \tau_i s + \tau_i \tau_{\mathrm{AS}} s^2\right) \quad (5.45)$$

$$CE_{supplier}: \frac{(1 + \tau_A s)(\tau_{\mathrm{BL}} + \tau_{\mathrm{DD}}\tau_{\mathrm{BL}}s)\left(N_{A(NO)} + \tau_i s + \tau_i \tau_{\mathrm{AS}} s^2\right)}{\left(N_{A(CA)}\tau_{\mathrm{WIP}} + (\tau_{\mathrm{AINV}}\tau_{\mathrm{WIP}} + \tau_{\mathrm{AINV}}\tau_{\mathrm{SA}}N_{A(CA)})s + \tau_{\mathrm{AINV}}\tau_{\mathrm{WIP}}\tau_{\mathrm{SA}}s^2\right)} \quad (5.46)$$

The ω and ζ can be derived as follows:

$$\omega_{n1} = \sqrt{\frac{N_{A(NO)}}{\tau_{AS}\tau_I}} \qquad \zeta_1 = \frac{1}{2}\sqrt{\frac{\tau_I}{\tau_{AS}N_{A(NO)}}} \qquad (5.47)$$

$$\omega_{n2} = \sqrt{\frac{N_{A(CA)}}{\tau_{\text{AINV}}\tau_{\text{SA}}}}, \quad \zeta_2 = \frac{(N_{A(CA)}\tau_{\text{SA}} + \tau_{\text{WIP}})}{2\tau_{\text{WIP}}}\sqrt{\frac{\tau_{\text{AINV}}}{\tau_{\text{SA}}N_{A(CA)}}}$$

Regarding the downstream final assembly system, the incorporation of $N_{A(NO)}$ (ranging between 0.5 - 1) will result in a reverse impact on ω_{n1} and ζ_1; that is, the decrease of ω_{n1} but increase ζ_1 as the decrease of $N_{A(NO)}$. This means the incorporation of non-negative order constraint at the final assembly site leads to a 'more damped' system with fewer oscillations at the expense of slow system recovery speed. Also, as indicated by the Section 4.2.2, the $N_{B(NO)}$ will increase as the increase of input demand amplitude. The dynamic response of upstream sub-assembler variables, however, are influenced by both nonlinearities. The decrease of output amplitude gain, $N_{A(CA)}$, resulting from the capacity and non-negative order constraints, leads to the decrease of ω_{n2} and ζ_2. This gives both a slower and more oscillatory dynamic response of the ATO system. Note that, depending on the relationship between mean of input demand and the half of capacity constraint (i.e. the dominant zone), the increase of demand amplitude may lead to the increase or decrease of $N_{B(NO)}$.

5.2.2.4. Numerical studies

In this section, numerical simulation is conducted to test whether the analytical results derived from the linearized model (Sections 5.2.2.1-5.2.2.3) hold under the non-linear case. Specifically, the true non-linear hybrid ATO model (Figure 5.3), including capacity and non-negative order constraints, is used as the base simulation model and the numerical study is conducted by Simulink™ (Matlab). Regarding system parameter setting, we assume that the lead times ratio between τ_{SA} and τ_{AS} is 1:2 (i.e. 4 and 8 for transportation and component manufacturing delay), to represent the long upstream supplier's manufacturing time and relatively short time for component acquisition delay between supplier and the OEM echelon.

$$\tau_{SA}=2\tau_{AS}=2\tau_{I}=8\tau_{DD}=8, \tau_{WIP}=16 \ \ \tau_{AINV}=8$$

5.2.2.4.1. Feedback and feedforward control policy

To test the impact of feedback and feedforward control loops $(\tau_{I}, \tau_{A}, \tau_{AINV})$ on bullwhip and CODP inventory variance analytically derived in Section 3.1, a unit step demand increase as the input is used due to its advantage of offering rich information for the dynamic behaviour of the system (John, Naim and Towill, 1994). It should be noted that all nonlinearities are assumed inactive during the simulation regarding the test of analytical results for feedback and feedforward control policies. The recommended settings of both VIOBPCS and APVIOBPCS will be used as the initial design as illustrated above in Section 5.2.2.4, although different control policies are varied to understand the impact of each control policy on dynamic performance in the nonlinear environment (i.e. capacity limit is set as 2). All results are shown in Figure 5.11.

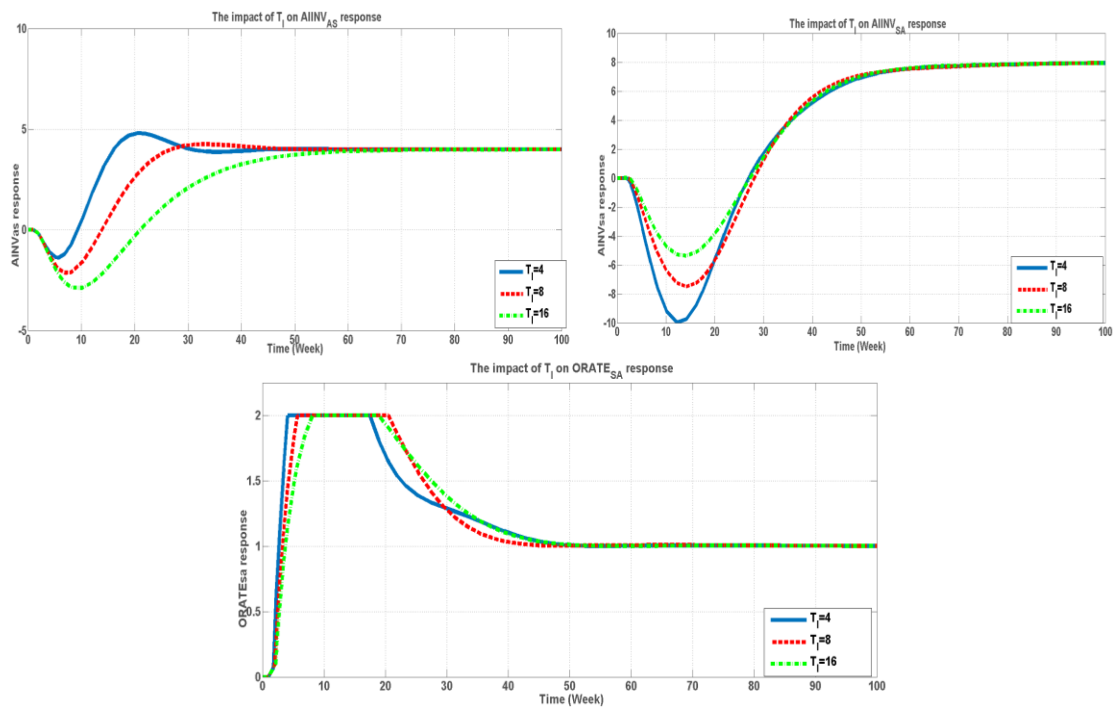


Figure 5.11a. The impact of τ_{I} on $\mathrm{AINV_{AS}}$, $\mathrm{AINV_{SA}}$ and $\mathrm{ORATE_{SA}}$ dynamic response.

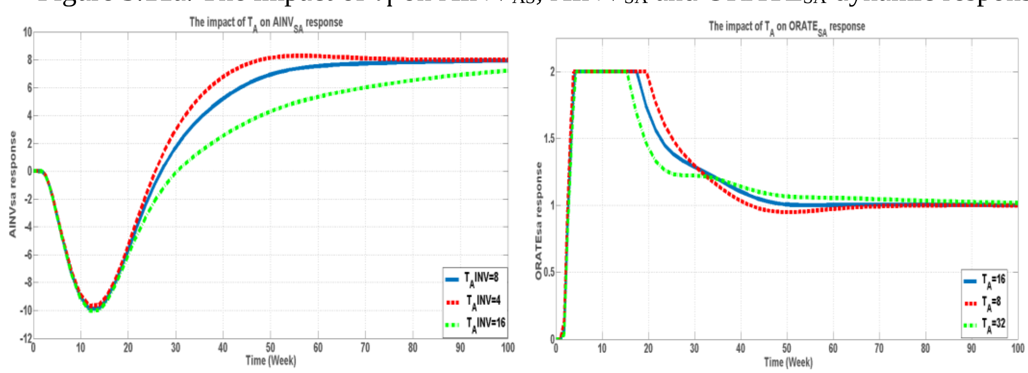


Figure 5.11b. The impact of τ_{A} on $\mathrm{AINV_{SA}}$ and $\mathrm{ORATE_{SA}}$ dynamic response.

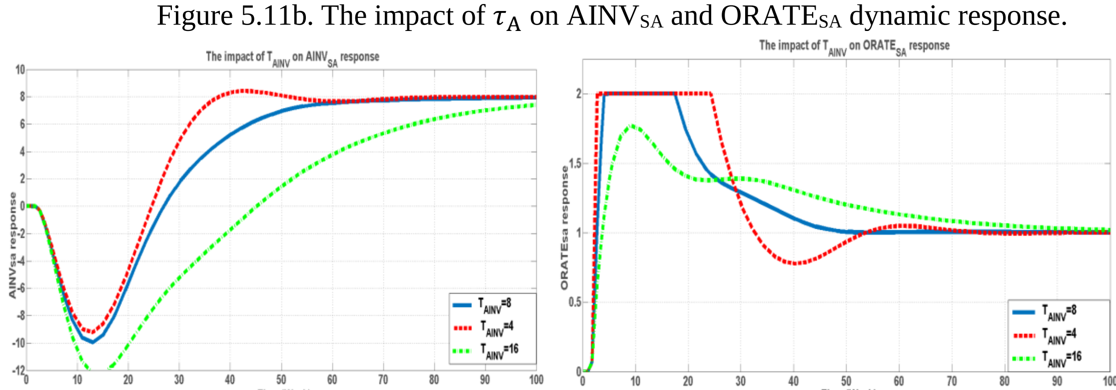


Figure 5. 1. The impact of τ_{AINV} on $\mathrm{AINV_{SA}}$ and $\mathrm{ORATE_{SA}}$ dynamic response.

In general, the simulation results support the analytical insights. The increase of τ_{I} led to less oscillatory system response due to the increase of ζ_1, at the expense of a slower response of the ATO system (e.g. slow recovery of $AINV_{AS}$, Figure 5.11a) driven by the decrease of ω_{n1}. As a result, τ_{I} should be carefully adjusted due to the availability of $AINV_{AS}$ that directly relate to the customer service level; i.e. whether all incoming customised orders can be immediately final-assembled and shipped out. Like the effect of τ_{I}, the increase of τ_{AINV} benefits the more 'damped' system compromised by slow system recovery due to the decrease of ω_{n2} and increase of ζ_2. Furthermore, the simulation result verifies the analytical result that τ_{AINV} significantly influences the dynamic behaviour of the ATO system, comparing the influence of τ_{I} and τ_{A} (compare Figures 5.11a, 5.11b and 5.11c). Quick adjustment of τ_{AINV} leads to high bullwhip and significant oscillations, while long-term adjustment causes slow system recovery to reach the steady state condition. Thus, the upstream subassembly echelon should carefully tune their inventory policy to benefit the maintenance of true ATO state and the cost of supply chain dynamics, such as bullwhip and inventory variance. Note that, compared to other control policies, forecasting policy (τ_{A}) has little impact on the dynamic property of the ATO system.

5.2.2.4.2. The impact of nonlinearities on ATO dynamic performance

To test whether the analytical results of nonlinearities derived from the linearised model (Section 5.2.2) hold under the non-linear model, the asymmetrical capacity and non-negative constraint zone is set as $[0, 1]$. i.e. the minimum value will not be less than 0 and the CL is 1. Specifically, the sinusoidal input amplitude directly influences the describing function gain, $N_{A(CA)}$ and $N_{B(CA)}$, of the sinusoidal output response at the sub-assembly plant under capacity and non-negative order constraints. Table 5.3 presents the comparison between analytical and simulation results of $N_{A(CA)}$. Sinusoidal input amplitudes ranging between 0.3 to 4 with 0.1rad/week frequency are used to examine the output amplitude gain change. Within reasonable error range, the simulation results support the analytical insights.

$N_{A(CA)}$ simulation (analytical) results	A=0.3	A=1	A=2	A=4
B=0.2	0.833 (0.890)	0.500 (0.574)	0.250 (0.311)	0.165 (0.158)
B=0.5	1 (1)	0.500 (0.608)	0.250 (0.314)	0.165 (0.158)
B=0.8	0.833 (0.890)	0.500 (0.574)	0.250 (0.311)	0.165 (0.158)

Table 5. 3. Comparison between simulation and analytical results.

Also, as highlighted by the analytical findings that the impact of input amplitude on mean gain ($N_{B(CA}$) depends on the relationship between the average of input and the half of capacity limit, numerical simulation is implemented to test the analytical result shown in Table 5.4. The mean value of input demand is set 0.2, 0.5 (half) and 0.8 units to represent the different nonlinear dominated zones (non-negative order or capacity constraints). Input amplitudes ranging between CL to 5CL with 0.1rad/week frequency are utilised to examine the output mean gain change. It can be concluded that the simulation results support the analytical insights.

Furthermore, simulation is conducted to test analytical insights derived by Root locus techniques (Spiegler et al., 2016a; Spiegler and Naim, 2017) regarding the prediction of the impact of nonlinearities on the system responses. Due to input, frequency does not impact on the output gains of nonlinearities (the property of single-value discontinuous nonlinearities), CL=3 and sinusoidal demand pattern with mean=1, frequency = 3 rad/week and amplitudes = 5 is implemented for a better visualisation. All results are shown in Figure 5.12. It should be noted that a mix of step increase, and sinusoidal demand patterns are adopted with zero initial condition, which has the advantage of visualising the impact of nonlinearities on ATO dynamic property in responding to both step and sinusoidal patterns

$N_{B(CA)}$ **simulation results**	**A=0.3**	**A=1**	**A=2**	**A=3**	**A=4**	**Summary**
B=0.2	1.08	1.660	1.770	1.845	1.590	$N_{B(CA)}$ is larger than 1 and is monotonically increasing in A
B=0.5	1.021	0.986	0.996	1.002	0.1004	$N_{B(CA)}$=1 within a reasonable error range
B=0.8	0.931	0.806	0.791	0.783	0.763	$N_{B(CA)}$ is monotonically decreasing in A and less than 1

Table 5. 4. Numerical simulation result for $N_{B(CA)}$ based on different input amplitude and mean.

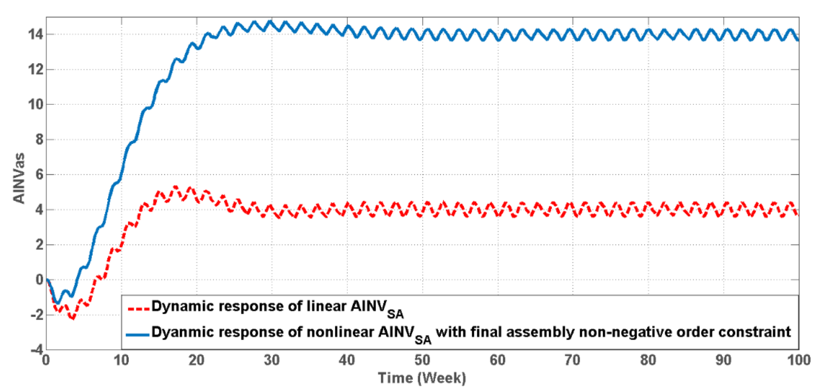


Figure 5.12a. Linear and nonlinear $AINV_{AS}$ response (the OEM non-negativity constraint only).

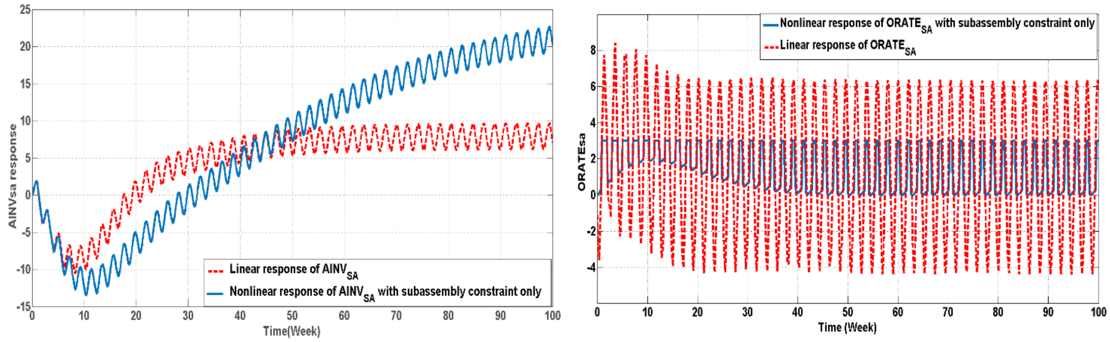
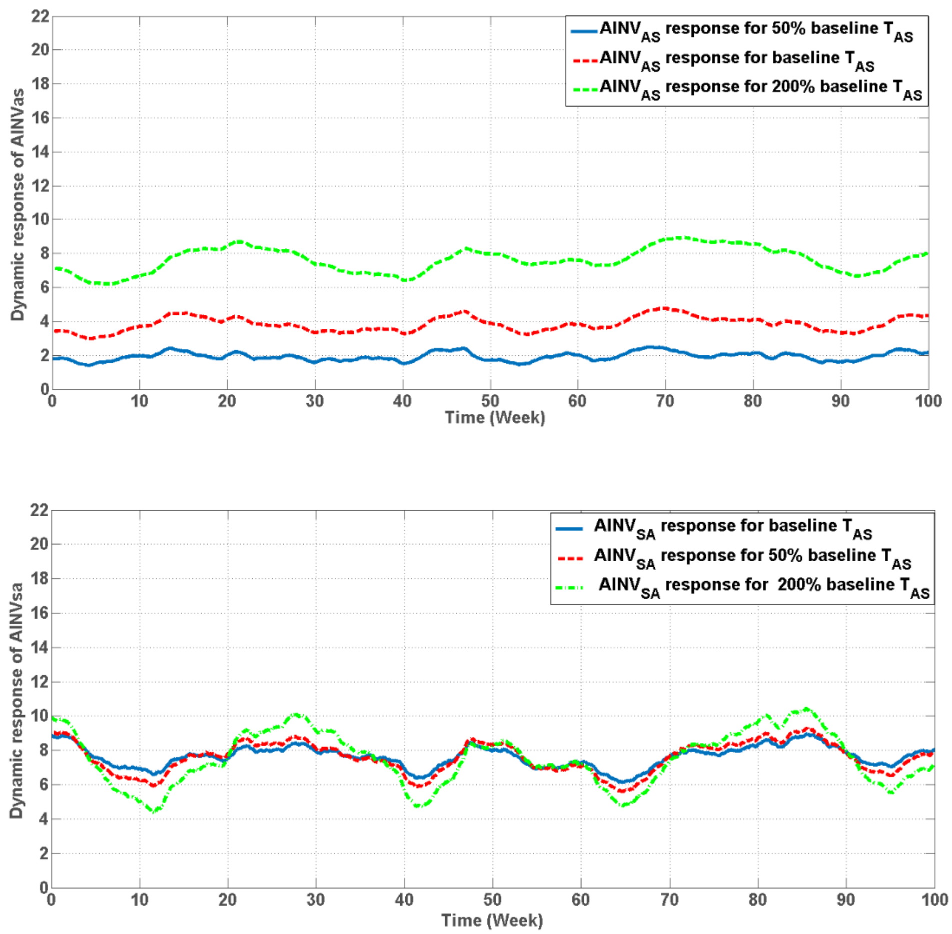


Figure 5. 2b. Linear and nonlinear AINV$_{SA}$ response (the supplier's nonlinearity only)

Overall, simulation results support the analytical findings. The incorporation of non-negative constraints at the final assemble echelon leads to fewer oscillations (the increase of ζ_1) but slow recovery speed (the decrease of ω_{1n}). Also, the incorporation of such nonlinearity increases the mean level of AINV$_{AS}$. This may improve the dynamic performance of the supplier internal system by reducing AINV$_{SA}$ but contradicts the OEM's general objective, i.e. minimise inventory to reduce the risk of technological redundancy with ever shorter product life cycles of products entering the market. The sub-assembler's constraints for both capacity and non-negative order, verified by simulation (Figure 5.12b), reduce the bullwhip (ORATE$_{SA}$), at the expense of slowing AINV$_{SA}$ recovery speed as well as increasing its mean level, driven by the decrease of $N_{A(NO)}$ and the increase of $N_{B(NO)}$. This finding is widely acknowledged in the literature, e.g. see Cannella, Ciancimino, and Marquez (2008); Nepal, Murat, and Chinnam (2012); Ponte et al. (2017).

5.2.2.4.3. Sensitivity analysis

Like the analysis of the semiconductor ATO system, the impact of physical lead times, as well as quality parameters (upstream supplier yield rate and final assembly line efficiency) on the dynamic performance are evaluated by using i.i.d. demand with mean =1 and variance =0.5. Figure 5.13 demonstrates the impact of two physical lead times, τ_{AS} and τ_{SA}, on dynamic performance of the hybrid ATO system under hybrid *Push-Pull-Pull* state. Note the capacity and non-negative order constraints are not considered during the sensitivity analysis to visualize the impact of physical lead times on bullwhip and inventory variance.



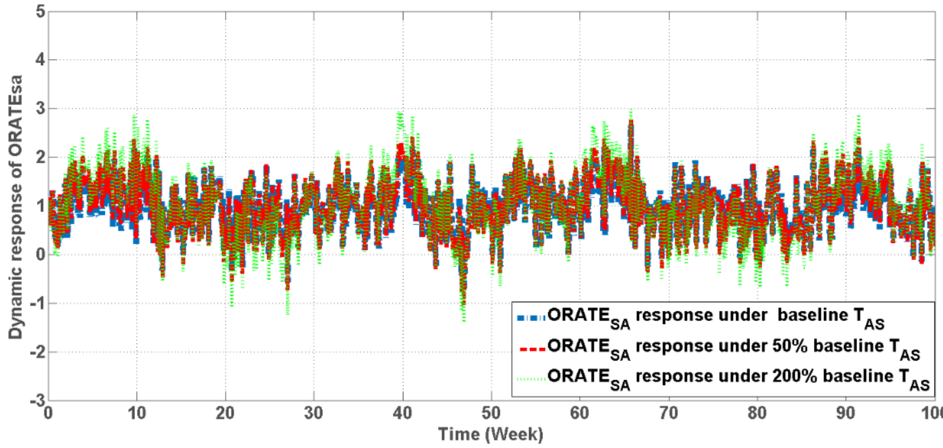


Figure 5.13a. The impact of τ_{AS} on the dynamic performance of the hybrid Push-Pull-Pull state.

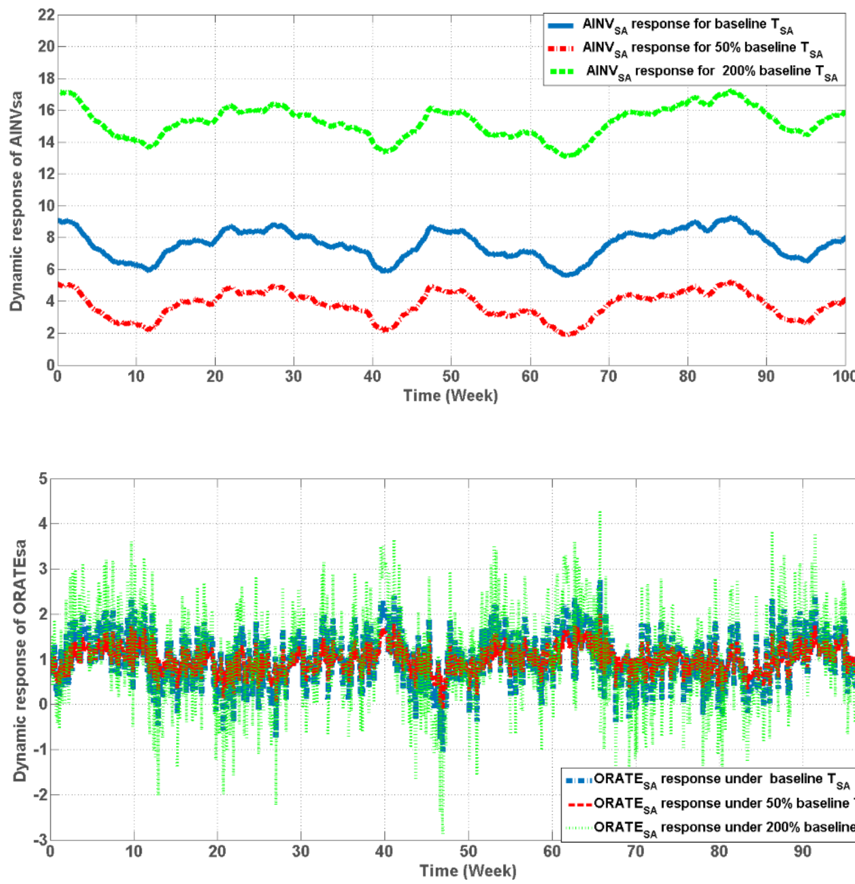


Figure 5. 3b. The impact of τ_{SA} on the dynamic performance of the hybrid Push-Pull-Pull state

As expected, the physical τ_{AS} is sensitive for the dynamic performance of the system, negatively impacting on the dynamic property of $ORATE_{SA}$, $AINV_{AS}$ and $AINV_{SA}$. i.e. the increase of τ_{AS} leads to the increase in bullwhip of $ORATE_{SA}$ and inventory variance of $AINV_{AS}$ and $AINV_{SA}$. Also, the long τ_{AS} leads to increased mean level of $AINV_{AS}$, indicating the fact that long transportation time may contribute to the high OEM inventory. Moreover, the large value of τ_{SA} yields unwanted dynamic performance of the push part of the hybrid system in terms of high bullwhip ($ORATE_{SA}$) and increased mean level of $AINV_{SA}$, although the latter is due to the safety stock setting as the function of physical production time. Furthermore, comparing τ_{AS}, τ_{SA} gives more impact on the dynamic performance of the hybrid system, the bullwhip level of $ORATE_{SA}$, for example. This indicates the long upstream production delay, comparing the downstream transportation and final assembly lead times, play a dominant role in influencing the dynamic performance of the hybrid ATO system.

Furthermore, in the dynamic analysis above, one of the fundamental assumptions is that there is no loss of product quality or assembly line efficiency, which is not realistic in real-world ATO system. To test the impact of quality and assembly line efficiency, we incorporate two general parameters related to quality and efficiency, Y_F (final assembly line efficiency, the percentage of shippable goods for each final assembly line) and Y_S (subassembly quality yield rate), into original the nonlinear hybrid *Push-Pull-Pull* state (Figure 5.3), as presented in Figure 5.14. The perfect quality and efficiency (Y_F= Y_S=1) are used as the baseline setting, although we vary two parameters between 0.8 and 1. A step demand input is introduced, and all nonlinearities are temporarily removed to visualize the key dynamic property such as peak level (bullwhip) and inventory variance. All results are presented in Figure 5.15.

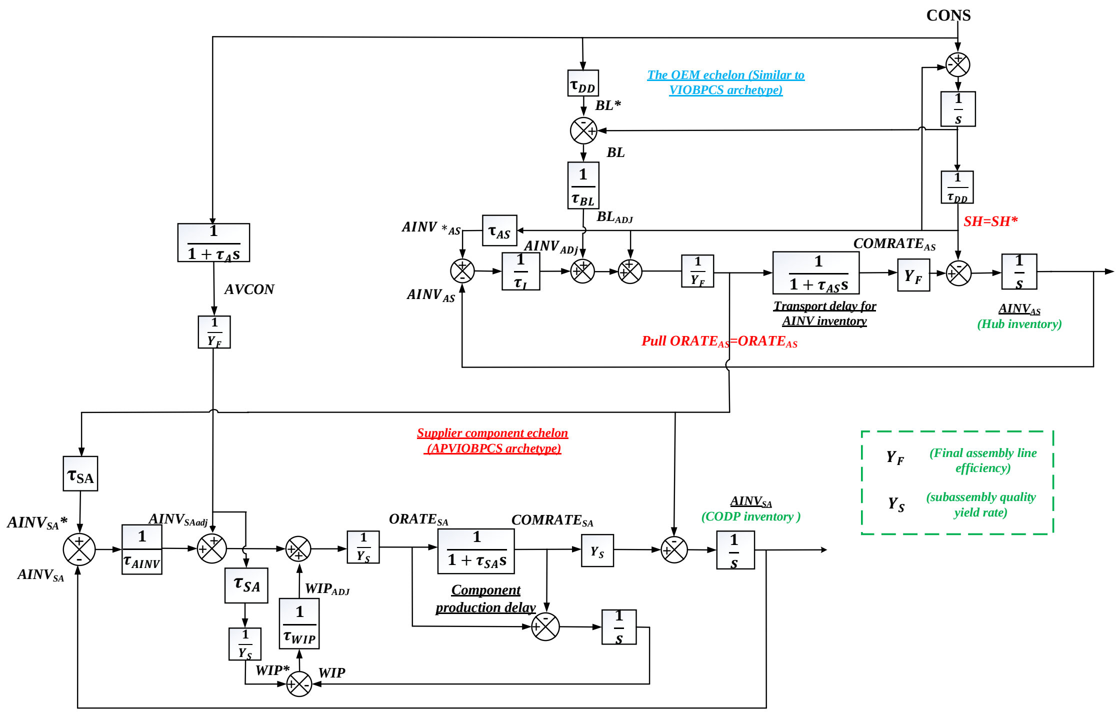
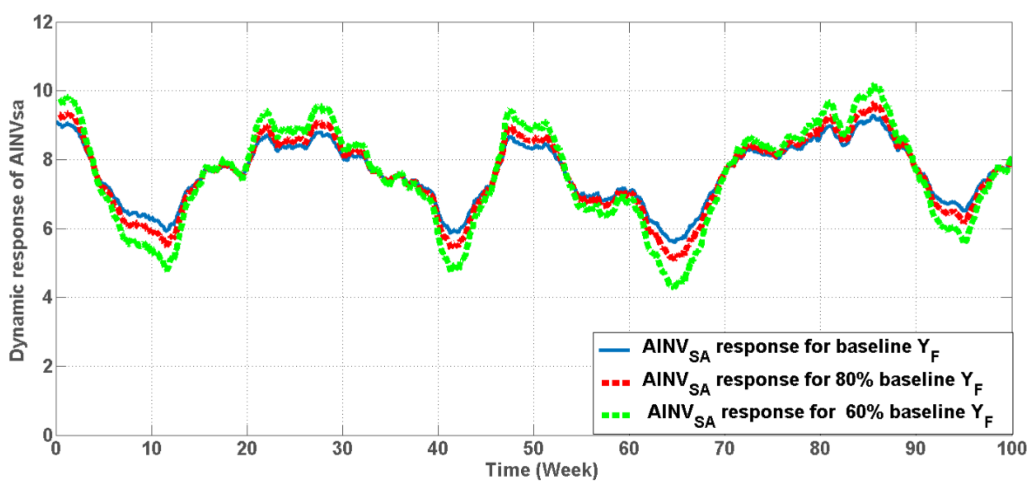


Figure 5. 4. The incorporation of quality and efficiency parameters in hybrid ATO state.



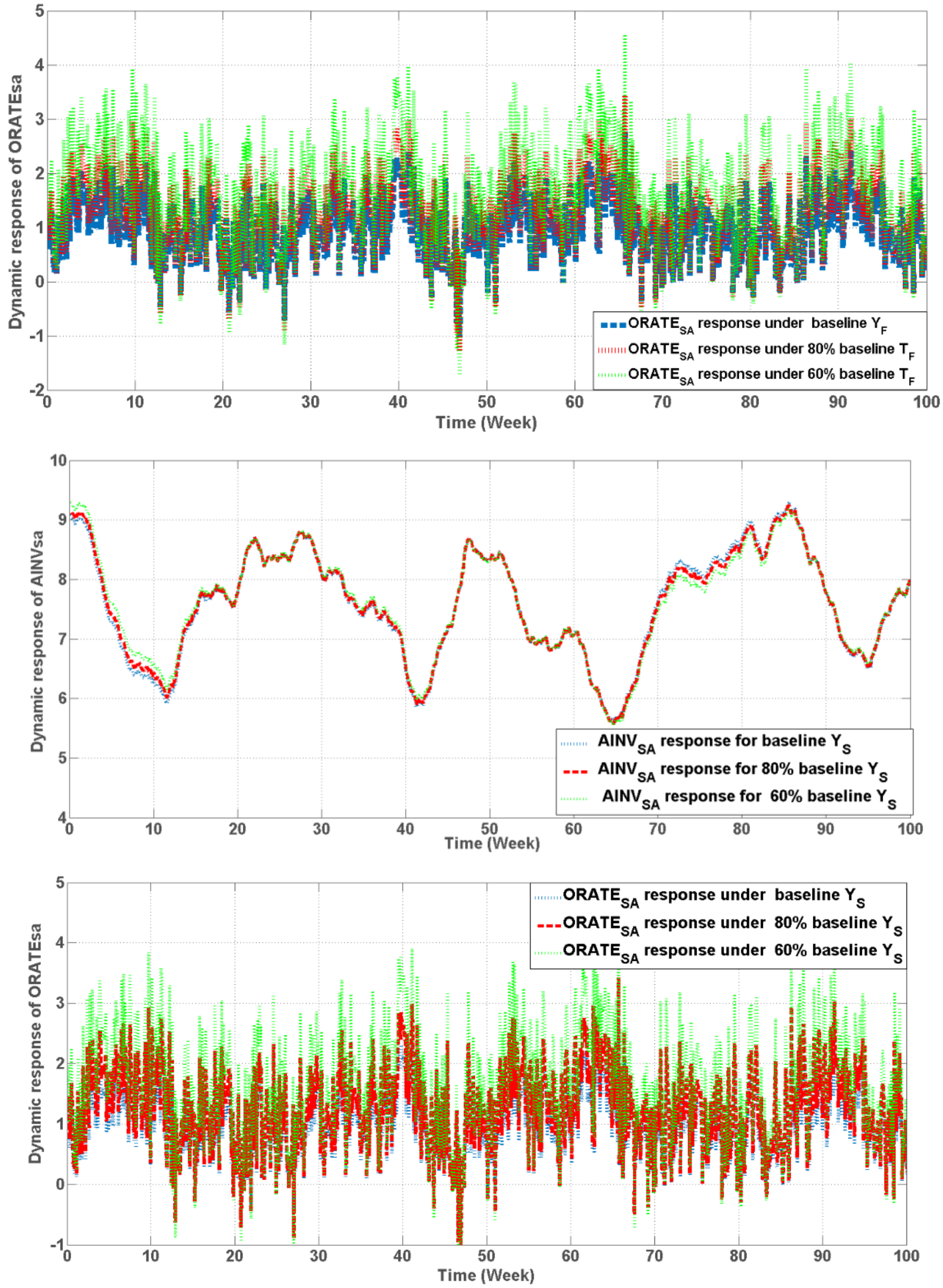


Figure 5. 5. The impact of Y_L and Y_F on dynamic property of the ATO system.

The simulation results show that the low-quality yield rate and line efficiency is sensitive for the ATO system, negatively impacting on its dynamic property. The decrease of Y_F and Y_S significantly increase the bullwhip of $ORATE_{SA}$, while, in comparing the significant impact of Y_F on inventory variance, Y_S has much less influence on $AINV_{SA}$, due to the safety stock setting of $AINV_{SA}$, i.e. $AINV^*_{SA}$ is only driven by the Y_F. To be more specific, the decrease of final assembly line efficiency, Y_F, indicates the requirement of a higher level of finished $AINV_{SA}$ to satisfy end customized orders in responding stochastics demand, which result in an increase of the safety stock needed in the subassembly site ($AINV^*_{SA}$). This implies the importance of maintaining high final assembly line efficiency to not only ensure the customer service level, but also improve the dynamic performance of the whole ATO system to reduce supply chain dynamics related cost. Furthermore, as expected, the decrease of quality yield and efficiency may lead to an increase in mean value of $ORATE_{SA}$ to ensure the same customer service level.

5.2.3. Frequency response design

Instead of developing the cost functions and minimising them, the concentration in this section is to design the ATO system to yield a ‘good’ dynamic performance from the frequency domain perspective. The rationale behind this is that cost control follows from good dynamic design, and we especially need to ensure high customer service level concurrently with small swings in capacity requirements (Towill et al., 2003; Towill et al., 2007). At the heart of decision-making in production-inventory system is the desire to ensure that the system correctly identifies and tracks genuine variations in demand at minimum bullwhip level, while simultaneously detecting and rejecting rogue variations in demand. Filter theory (Dejonckheere et al., 2002; Dejonckheere et al., 2003; Towill et al., 2003; Towill et al., 2007) can thereby be utilised to design such desirable systems based on frequency domain analysis as introduced in Section 3.2.1.3.

Based on analysis of the CEs of the hybrid *Push-Pull-Pull* operational process in Section 4.2.1, major control policies influencing system oscillation and bullwhip, $\tau_{\mathrm{I}}, \tau_{\mathrm{AINV}}$ and τ_{A}, are analysed in designing the ATO system's filter capability ($\mathrm{ORATE_{SA}}$ response) in response to a range of sinusoidal demand. For a certain type of PC product, the customer demand cycle is roughly half a year, which are, T=52 weeks, the crossover frequency (ω_{cr}) equals to

$$\omega_{cr} = \frac{2\pi}{T} \approx \frac{2 \times 3.142}{52} \approx 0.12\, rad/week \quad (5.48)$$

This is a realistic assumption given the observation of demand pattern in the electronics sector, i.e. winter holiday demand peak (e.g. Black Friday, Christmas shopping and Chinese New Year) and the following off-season demand (Zhou et al., 2017). As a result, for those parts required in assembling a final laptop (e.g. core processor, graphics, hardware, motherboard etc.), the demand frequencies equal or lower than $0.12\, rad/week$ should be treated as the true demand message and need to be traced at supplier plants.

Three types of model designation are presented (Fast, Medium and Slow speed design) and five filter designs, following Towill et al. (1997; 2003), as shown in Table 5.5. Physical delay for final assembly/distribution, PC parts acquisition delay and the supplier's production are set as 1, 4 and 8 units to represent quick downstream final assembly/distribution but relatively long material acquisition and the supplier production time.

Model designation	**Downstream final assembly echelon**	**Downstream final assembly echelon**	**Upstream supplier echelon**	**Upstream supplier echelon**
	$\tau_{\mathbf{I}}$	$\tau_{\mathbf{A}}$	$\tau_{\mathbf{AINV}}$	$\tau_{\mathbf{WIP}}$
Fast	2	8	8	8
Medium	4	16	16	16
Slow	8	24	24	24

Table 5.5a. Model designation based on major control policies in the hybrid ATO system.

ATO system design	**A**	**B**	**C**	**D**	**E**
Final assembly	*Fast*	*Medium*	*Slow*	*Fast*	*Medium*
Subassembly	*Fast*	*Medium*	*Slow*	*Slow*	*Slow*

Table 5. 5b. Dynamic filter design for the hybrid ATO system.

Figure 5.16 illustrates the Bode plot of $ORATE_{SA}$ response for a range of demand frequencies based on five types of filter designs. Clearly, fast or medium design including Designs A and B are not desirable, due to the significant bullwhip level at both low and high frequency ranges ($\omega_{cr} \approx 1rad/week\ and\ 4rad/week$). As a result, 'noise demand' (demand frequencies greater than 0.12 rad/week) cannot be filtered and orders can be significantly amplified at 'true' demand frequency, which leads to excess operational cost. Design D also cannot yield 'good' filter characteristics, due to the strong effect of two peak magnitudes driven by two natural frequencies. Therefore, although demand frequency range between around 0.08 rad/week to 0.24 rad/week can be filtered (magnitude is lower than 0 dB), the second peak frequency (about 5 dB) leads to further demand amplification between 0.24 rad/week to 0.7 rad/week. Design C seems to produce adequate dynamic filter performance regarding its appropriate crossover frequency (0.12 rad/week) for the product demand cycle and fewer unwanted demand amplification at low frequencies range, comparing Designs A and B. Furthermore, compared with Design C, Design E has a similar dynamic performance at lower frequency range (ω<0.12rad/week), but such design yields slightly more bullwhip (around 2dB at second peak frequency) between 0.18 rad/week and 0.32 rad/week due to the effect of two degrees of freedom system.

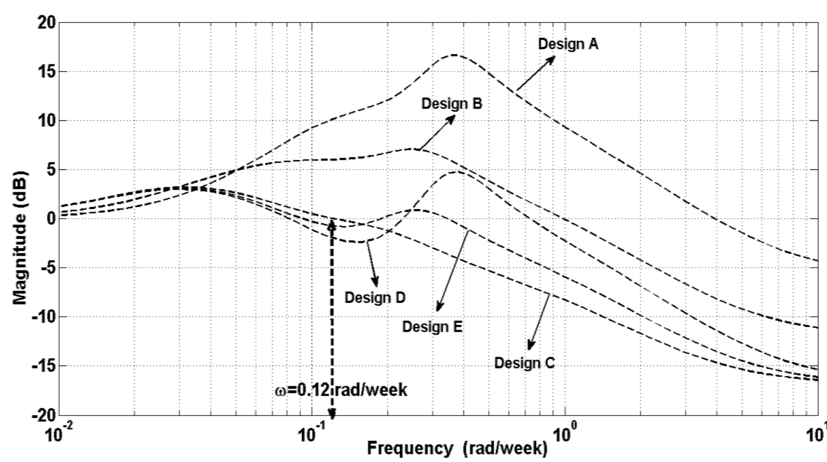
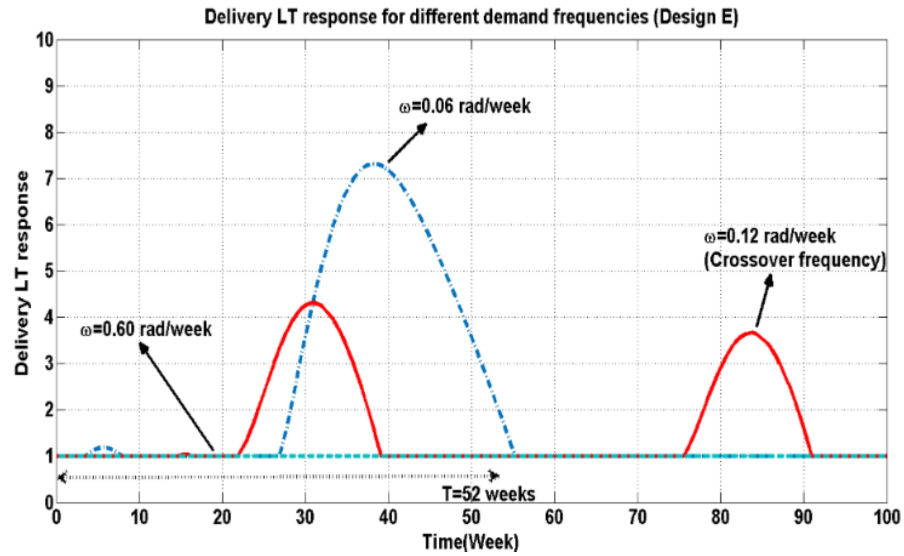


Figure 5. 6. Five basic designs for $ORATE_{SA}$ response under Push-Pull-Pull state

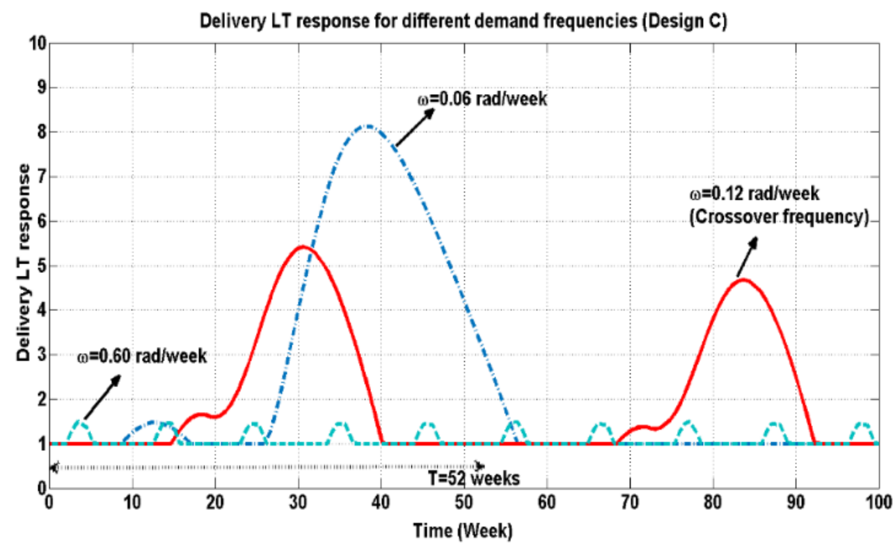
To verify and enhance the linear frequency response design, the system dynamic simulation is conducted for Design C and Design E in the nonlinear ATO system. Dynamic response of 'performance triangle' ($ORATE_{SA}$, $AINV_{SA}$ and delivery LT) for sinusoidal demand with amplitude=mean=1 are presented in Figure 5.17. Three different demand frequencies, which are, ω=0.06 rad/week, 0.12 rad/week and 0.60 rad/week, are chosen, based on crossover frequency derived before (ω=0.12 rad/week). The purpose is to test whether the low demand frequency (smaller than crossover frequency) can be traced, while the high demand frequency (larger than crossover frequency) can still be rejected in the nonlinear environment.

All nonlinearities are incorporated, except for the capacity constraint at the supplier production, as such a limit may prevent the insight of outcome, i.e. whether $ORATE_{SA}$ is successfully traced or filtered for different demand frequencies. In general, the linear frequency design result remains robust in the nonlinear environment. For Design C, for example, the $ORATE_{SA}$ response at crossover demand frequency (ω=0.12 rad/week) can be adequately traced (little demand amplification), although the peak level is slightly greater than 2 due to the effect of non-negative order nonlinearity. Similarly, at ω=0.06 rad/week, $ORATE_{SA}$ response has slightly more demand amplification (Magnitude $\approx$ 1.65) than linear prediction (Magnitude $\approx$ 3dB $\approx$ 1.41) because of the nonnegative order restriction. Moreover, as expected, $ORATE_{SA}$ response can be successfully rejected at high frequency demand. Furthermore, CODP inventory at the supplier site can be significantly amplified, adequately traced, or filtered when demand frequencies are lower (ω=0.06 rad/week), equal or higher (ω=0.60 rad/week) than crossover frequencies as predicted in the linear frequency response analysis.

However, by comparing Designs C and E, the better dynamic filter performance (C) in linear frequency analysis is no longer 'good' in the nonlinear ATO environment when delivery LT are considered. Although $ORATE_{SA}$ in both Design C and E can be roughly traced and rejected for low and high demand frequency range respectively, delivery LT dynamics is better for design E in terms of peak level and recovery time, although both designs explore delivery LT variance at crossover and low demand frequency ranges. However, Design E delivery LT dynamic performance is better for the Design E (e.g. ω=0.60 rad/week, green line), and this means the such production control designs can fulfil most 'noise' demand patterns by the quoted time. This is important for an ATO system due to the significant cost of maintaining promised delivery LT (i.e. high customer service level). Furthermore, dynamic performance of CODP inventory and $ORATE_{SA}$ for Design C is slightly better than Design E regarding amplification ratio at different frequency ranges, in which a natural trade-off design in the nonlinear ATO system between 'performance triangle' should be considered.



Delivery LT response for different demand frequencies (Design E)
ω=0.06 rad/week
ω=0.12 rad/week
(Crossover frequency)
ω=0.60 rad/week
T=52 weeks
Delivery LT response
Time(Week)



Delivery LT response for different demand frequencies (Design C)
ω=0.06 rad/week
ω=0.12 rad/week
(Crossover frequency)
ω=0.60 rad/week
T=52 weeks
Delivery LT response
Time (Week)

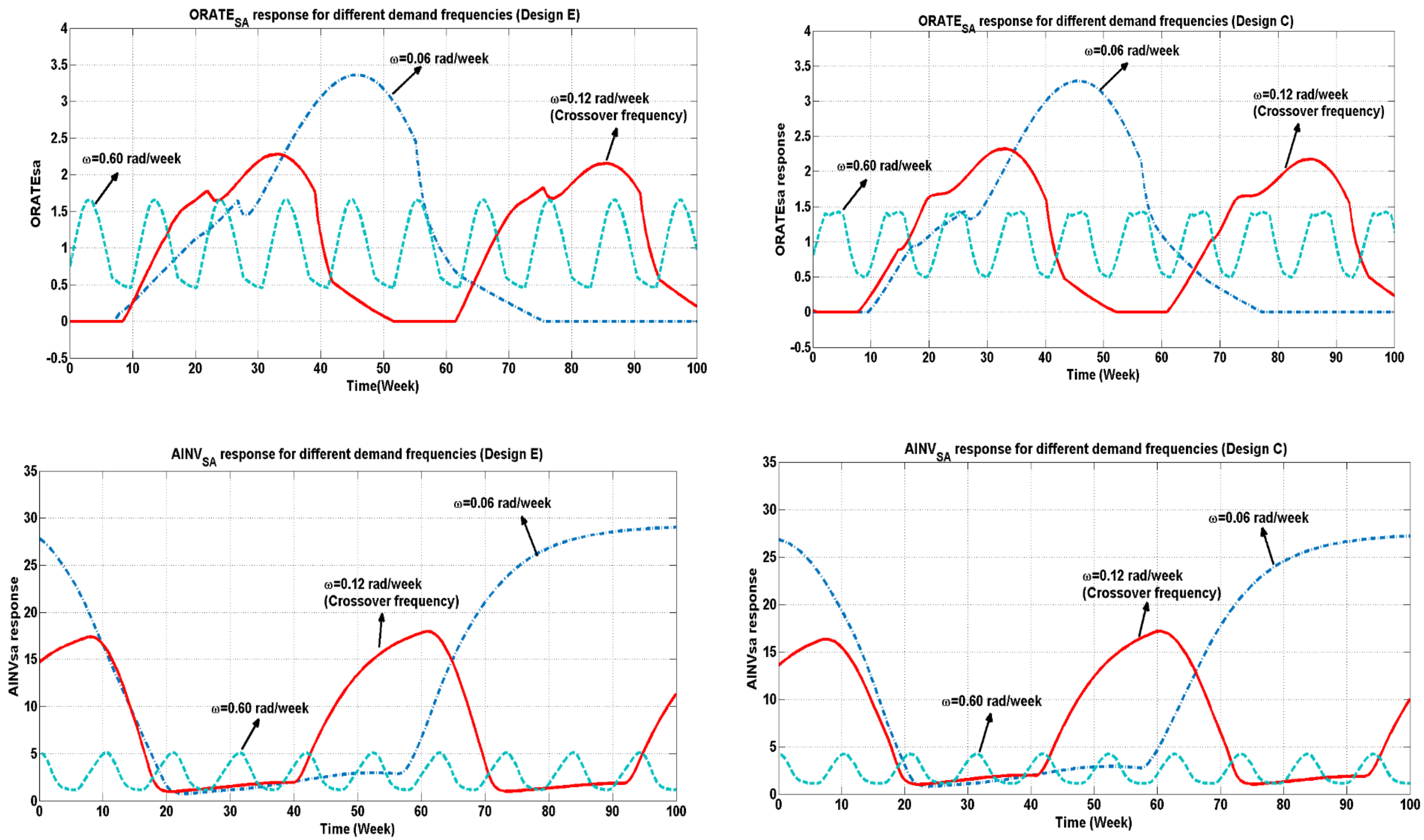


Figure 5. 7. Delivery LT, ORATE$_{SA}$ and AINV$_{SA}$ response for sinusoidal demand (Mean=Amplitude=1) with different frequencies (ω=0.06 rad/week, 0.12 rad/week and 0.60 rad/week) in the nonlinear ATO system

Overall, by presenting the example of designing the ATO system in the frequency domain, linear frequency analysis offers a traceable starting point for designing a ‘good’ dynamic system, by retaining a useful demand pattern while rejecting rogue demand information to appropriately allocate the resources at minimum operational cost. There are two major corresponding managerial implications. First, managers need to carefully consider their ATO system structures before designing control policies, including the *number of independent feedback loops* in their system and *the different kinds of nonlinearities*. As illustrated in Section 5.2.1, the two-degrees-of-freedom system has two natural frequencies, which gives two peak demand amplifications at both low and high demand frequency ranges and this is particularly the case if the downstream and upstream systems of CODP follow the opposite extreme design principle, i.e. quick adjustment of final assembly raw materials to fulfil customer orders as soon as possible, while long time adjustment for CODP inventory at subassembly plant. Thus, managers may successfully trace low frequencies demand but still yield high bullwhip level for rogue high demand frequencies.

Nonlinearity is another main factor in influencing the design philosophy. Nonnegativity order constraint prevents free return behaviour and thus leads to higher amplification ratio than the linear prediction. The switch between different operational processes due to the limitation of $AINV_{SA}$ and $AINV_{AS}$ can further increase the complexity of dynamic performance because of the change in fundamental system structure. The next section will give a detailed analysis of the impact of nonlinear switch on ‘performance triangle’ in the ATO system

5.3. Dynamic analysis of the Push-Pull-Push and pure Push states

In this section the impact of two multi-valued nonlinearities on dynamic performance of the nonlinear ATO system will be examined. As highlighted before, two multi-valued nonlinearities (i.e. Min functions), depending on the feasible $AINV_{AS}$ and $AINV_{SA}$, govern three operational states of the hybrid ATO system. The ATO system may, thereby, be switched to another state if $AINV_{AS}$ and $AINV_{SA}$ are insufficient. More importantly, the delivery LT can no longer be a constant level, and this means the average and variance of delivery LT may be increased for customers due to the shortage of CODP inventory. To understand how the switch of structure may influence the dynamic performance of the ATO system, especially the influence of 'performance triangle' in the ATO system, the author conducted detailed analysis in this section.

5.3.1. Linearisation of delivery LT

The continuous nonlinearity, delivery LT, as illustrated by Equation (5.18), can be linearised by using the Taylor series expansion technique. By temporarily removing all discontinuous nonlinearities, the whole system can be represented by a set of linear differential equations that do not need to be linearised. It should be noted that two multi-valued nonlinearities govern the three-different operational status of the system (Push or Pull), and, therefore, there are three sets of linear differential equations, depending on the specific operational state. e.g. the system will become *Push-Pull-Pull* state if $SH^{*}>SH_{MAX}$ and Pull $ORATE_{AS}$<Push $ORATE_{SA}$. The only nonlinearity now is the delivery LT, so the problem becomes the linearisation of a nonlinear, continuous function with *one state variable*

and *one input variable* only. Let the output delivery $LT = y$, input $BL = u$ and $SH = x$, we have

$$LT = \frac{BL}{SH} \rightarrow \; y = g(x, u) \qquad (5.49)$$

The delivery LT can be linearised about a nominal operating state space x* for a given input u*, by using small perturbation theory with Taylor series expansion. The first order Taylor series approximation of the nonlinear state derivatives leads to the following linearised function

$$y - y^* = \frac{\partial g}{\partial x} \; /_{x^*,u^*} (x - x^*) + \frac{\partial g}{\partial u} \; /_{x^*,u^*} (u - u^*) \qquad (5.50)$$

The equilibrium, or resting points (x*, u*), is determined by the final value theorem of a step input demand (D) with zero initial condition, $\frac{\partial g}{\partial x} \; /_{x^*,u^*}$ (final value of SH in responding to a step D) and $\frac{\partial g}{\partial u} \; /_{x^*,u^*}$ (final value of BL in responding to a step D) can be found through the partial derivatives of the output LT equations:

$$\frac{\partial g}{\partial x} \; /_{x^*,u^*} = -\frac{\tau_{DD}}{D} \,, \qquad \frac{\partial g}{\partial u} \; /_{x^*,u^*} = \frac{1}{D} \,, \qquad y^* = \tau_{DD} \qquad (5.51)$$

Thus, delivery LT can be linearised by

$$\mathrm{LT} - \tau_{DD} = \left(-\frac{\tau_{DD} D}{D^2} (SH - D) \right) + \frac{1}{D} (BL - \tau_{DD} D) = \frac{BL - \tau_{DD} SH}{D} \qquad (5.52)$$

So

$$\mathrm{LT} = \frac{BL - \tau_{DD} SH}{D} + \tau_{DD} \qquad (5.53)$$

Where SH depends on the minimum value of SH^* and SH_{MAX}, if SH^* can be always satisfied, i.e. $SH^* = SH$, so:

$$BL = SH^{*}\tau_{DD} = SH\tau_{DD} \tag{5.54}$$

and consequently, delivery LT will become constant:

$$\text{LT} = \frac{BL - \tau_{DD}SH}{D} + \tau_{DD} = \tau_{DD} \tag{5.55}$$

From a customer perspective, this means that their customised PC products can be received by promised τ_{DD} (100% customer service level). However, if there are insufficient $AINV_{AS}$ to meet SH^{*} ($SH^{*}<SH_{MAX}$):

$$SH = \frac{AINV_{AS}}{\tau_{DD}} \tag{5.56}$$

and therefore, LT is time varying so that

$$\text{LT} = \frac{BL - \tau_{DD}\frac{AINV_{AS}}{\tau_{DD}}}{D} + \tau_{DD} = \frac{BL - AINV_{AS}}{D} + \tau_{DD} \tag{5.57}$$

As a result, if Equation (5.56) holds, LT can be approximated by the summation of τ_{DD} and the difference between BL and $AINV_{AS}$ level. Since $BL - AINV_{AS} > 0$ under $SH^{*}<SH_{MAX}$, the averaged delivery LT now is larger than τ_{DD} and this means the time for end customer to wait is longer than the promised τ_{DD} and thus leads to a decrease in customer service level.

Moreover, $AINV_{AS}$ will be further determined by the CODP inventory constraint between downstream final assembly and supplier manufacturing, i.e. the minimum value of Pull $ORATE_{AS}$ and Push $ORATE_{SA}$. Numerical simulation in the system responding to a sinusoidal input with Mean =1, different frequency (ω) and amplitude (A) is conducted to verify the linearised LT results when $SH^{*}<SH_{MAX}$. The different operational states based on the discontinuous nonlinearity switch between Pull $ORATE_{AS}$ and Push $ORATE_{SA}$ are

deliberately cross-checked; that is, comparing the original and linearised lead time response for *Push-Pull-Push* and *pure Push* production scenarios. Note that two single-valued nonlinearities, capacity and non-negative constraints, are kept in the simulation verification to ensure system stability; as we will show in the next section, the linear system with *Push-Pull-Push* state is fundamentally unstable. Figure 5.17 shows the result of *Push-Pull-Push* and pure Push states. It can be seen that overall the linearised delivery LT response is accurate. Furthermore, linearisation accuracy is increased from Push-Pull-Push to pure Push state and the linearised LT response tends to be more accurate with the increase in demand frequency.

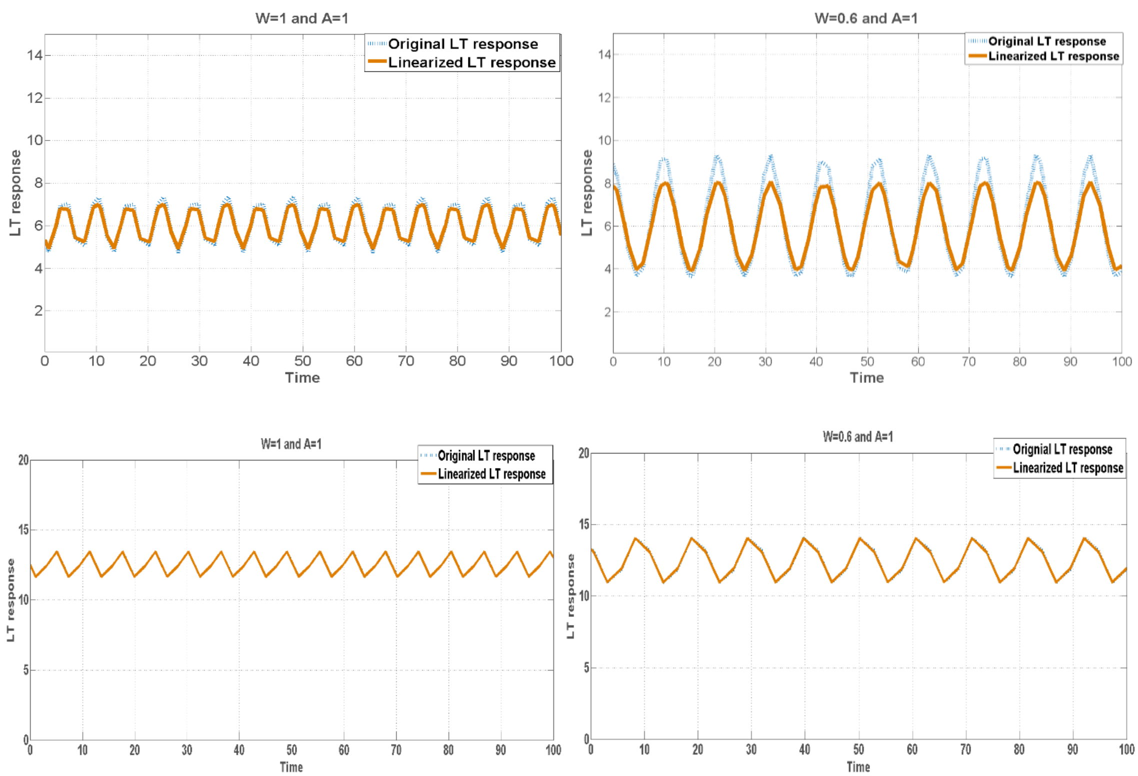


Figure 5. 8. Comparison between linearised and original LT response for Pull $ORATE_{AS}$> Push $ORATE_{SA}$ (Different scales in the y-axis).

5.3.2. The analysis of multi-valued nonlinearities

To understand the impact of such multi-valued nonlinearities on dynamic performance, that is, the 'performance triangle', we analyse the three operational states, *Push-Pull-Pull, Push-Pull-Push* and *pure Push* separately by assuming all discontinuous nonlinearities inactive and the whole system temporarily operates as a certain production state. Due to the *Push-Pull-Pull* state with single-valued discontinuous nonlinearities having been explored in Section 5.2, the author now exclusively investigates two other states: hybrid *Push-Pull-Pull* and *Pure Push* states.

5.3.2.1. The Push-Pull-Push operational state

If $AINV_{AS}$ continuously falls and is insufficient for satisfying SH*, the OEM can only start assembly and ship what they have on hand, S_{MAX}, to customers. As a result, the final assembly and distribution is switched from Pull to Push and if CODP inventory at the supplier site ($AINV_{SA}$) can still be pulled by replenishment of VMI, the system now operates as *Push-Pull-Push* state, that is:

$$SH(t) = SH_{MAX}(t) < SH^*(t) \tag{5.58}$$

$$ORATE_{AS}(t) = Pull\ ORATE_{AS}(t) < Push\ ORATE_{SA}(t)$$

The corresponding block diagram to represent such operational state can be derived, as illustrated in Figure 5.18. The only difference between hybrid *Push-Pull-Pull* and *Push-Pull-Push* states (compare Figures 5.18 and 5.2) is that SH now equals to SH_{MAX} due to the $AINV_{AS}$ constraint. The transfer function of 'performance triangle' is derived as follows:

$$\frac{LT}{CONS} = \frac{(s\tau_{\mathrm{DD}} - 1)\big(\tau_{\mathrm{DD}}(\tau_{\mathrm{BL}} + (s\tau_{\mathrm{BL}} - 1)\tau_i) + \tau_{\mathrm{AS}}\tau_{\mathrm{BL}}(s(1 + s\tau_{\mathrm{DD}})\tau_i - 1)\big)}{\begin{matrix} s^3\tau_i\tau_{\mathrm{AS}}\tau_{\mathrm{BL}}\tau_{\mathrm{DD}} + s^2(\tau_i\tau_{\mathrm{AS}}\tau_{\mathrm{BL}} + \tau_i\tau_{\mathrm{BL}}\tau_{\mathrm{DD}}) \\ -s(\tau_{\mathrm{AS}}\tau_{\mathrm{BL}} + \tau_{\mathrm{BL}}\tau_{\mathrm{DD}}) + \tau_i \end{matrix}} \quad (5.59)$$

$$\frac{ORATE_{SA}}{CONS} = \frac{\left((1 + s\tau_{\mathrm{SA}}) \left(\begin{matrix} s\tau_{\mathrm{AINV}}\left(\tau_i + s\tau_{\mathrm{BL}}\left(\begin{matrix} -\tau_{\mathrm{AS}} + \tau_{\mathrm{DD}} + \\ s\big(\tau_{\mathrm{DD}} + \tau_{\mathrm{AS}}(1 + s\tau_{\mathrm{DD}})\big)\tau_i \end{matrix}\right)\right) \\ (\tau_{\mathrm{SA}} + \tau_{\mathrm{WIP}}) \\ -(1 + s\tau_A)(1 + s\tau_{\mathrm{AS}}) \\ \big(-1 + s^2\tau_{\mathrm{DD}}^2\big)\tau_i(1 + s\tau_{\mathrm{SA}})\tau_{\mathrm{WIP}} \end{matrix} \right) \right)}{\begin{matrix} (1 + s\tau_A)\left(\begin{matrix} s^3\tau_i\tau_{\mathrm{AS}}\tau_{\mathrm{BL}}\tau_{\mathrm{DD}} + s^2(\tau_i\tau_{\mathrm{AS}}\tau_{\mathrm{BL}} + \tau_i\tau_{\mathrm{BL}}\tau_{\mathrm{DD}}) \\ -s(\tau_{\mathrm{AS}}\tau_{\mathrm{BL}} + \tau_{\mathrm{BL}}\tau_{\mathrm{DD}}) + \tau_i \end{matrix}\right) \\ \big(\tau_{\mathrm{WIP}} + s^2\tau_{\mathrm{AINV}}\tau_{\mathrm{SA}}\tau_{\mathrm{WIP}} + s(\tau_{\mathrm{AINV}}\tau_{\mathrm{SA}} + \tau_{\mathrm{AINV}}\tau_{\mathrm{WIP}})\big) \end{matrix}} \quad (5.60)$$

$$\frac{AINV_{SA}}{CONS} = \frac{\left(\begin{matrix} -(1 + s\tau_A)(1 + s\tau_{\mathrm{AS}})\big(-1 + s^2\tau_{\mathrm{DD}}^2\big)\tau_i\tau_{\mathrm{SA}}\tau_{\mathrm{WIP}} \\ +s\tau_{\mathrm{AINV}}\left(\begin{matrix} \tau_{\mathrm{BL}}\tau_{\mathrm{DD}}(1 + s\tau_i)(\tau_{\mathrm{SA}} + \tau_{\mathrm{WIP}}) + \\ \tau_i\left(\begin{matrix} -\tau_{\mathrm{SA}}\tau_{\mathrm{WIP}} + s\tau_{\mathrm{DD}}^2(\tau_{\mathrm{SA}} + \tau_{\mathrm{WIP}} + s\tau_{\mathrm{SA}}\tau_{\mathrm{WIP}}) \\ +\tau_A\big(-1 + s^2\tau_{\mathrm{DD}}^2\big)\big(\tau_{\mathrm{WIP}} + \tau_{\mathrm{SA}}(1 + s\tau_{\mathrm{WIP}})\big) \end{matrix}\right) \\ +\tau_{\mathrm{AS}}\left(\begin{matrix} \tau_{\mathrm{BL}}(-1 + s(1 + s\tau_{\mathrm{DD}})\tau_i)(\tau_{\mathrm{SA}} + \tau_{\mathrm{WIP}}) \\ +(1 + s\tau_A)\big(-1 + s^2\tau_{\mathrm{DD}}^2\big)\tau_i\big(\tau_{\mathrm{WIP}} + \tau_{\mathrm{SA}}(1 + s\tau_{\mathrm{WIP}})\big) \end{matrix}\right) \end{matrix} \right) \end{matrix} \right)}{\left(\begin{matrix} (1 + s\tau_A)\left(\begin{matrix} s^3\tau_i\tau_{\mathrm{AS}}\tau_{\mathrm{BL}}\tau_{\mathrm{DD}} + s^2(\tau_i\tau_{\mathrm{AS}}\tau_{\mathrm{BL}} + \tau_i\tau_{\mathrm{BL}}\tau_{\mathrm{DD}}) \\ -s(\tau_{\mathrm{AS}}\tau_{\mathrm{BL}} + \tau_{\mathrm{BL}}\tau_{\mathrm{DD}}) + \tau_i \end{matrix}\right) \\ \big(\tau_{\mathrm{WIP}} + s^2\tau_{\mathrm{AINV}}\tau_{\mathrm{SA}}\tau_{\mathrm{WIP}} + s(\tau_{\mathrm{AINV}}\tau_{\mathrm{SA}} + \tau_{\mathrm{AINV}}\tau_{\mathrm{WIP}})\big) \end{matrix} \right)} \quad (5.61)$$

The CEs for both final assembly and supplier manufacturing echelons can be obtained:

$$CE_{final\ assembly}:\ s^3\tau_i\tau_{\mathrm{AS}}\tau_{\mathrm{BL}}\tau_{\mathrm{DD}} + s^2(\tau_i\tau_{\mathrm{AS}}\tau_{\mathrm{BL}} + \tau_i\tau_{\mathrm{BL}}\tau_{\mathrm{DD}}) - s(\tau_{\mathrm{AS}}\tau_{\mathrm{BL}} + \tau_{\mathrm{BL}}\tau_{\mathrm{DD}}) + \tau_i \quad (5.62)$$

$$CE_{supplier\ manufacturing}: \begin{matrix} (1 + s\tau_A)\left(\begin{matrix} s^3\tau_i\tau_{\mathrm{AS}}\tau_{\mathrm{BL}}\tau_{\mathrm{DD}} + s^2(\tau_i\tau_{\mathrm{AS}}\tau_{\mathrm{BL}} + \tau_i\tau_{\mathrm{BL}}\tau_{\mathrm{DD}}) \\ -s(\tau_{\mathrm{AS}}\tau_{\mathrm{BL}} + \tau_{\mathrm{BL}}\tau_{\mathrm{DD}}) + \tau_i \end{matrix}\right) \\ (\tau_{\mathrm{WIP}} + (\tau_{\mathrm{AINV}}\tau_{\mathrm{SA}} + \tau_{\mathrm{AINV}}\tau_{\mathrm{WIP}})s + \tau_{\mathrm{AINV}}\tau_{\mathrm{SA}}\tau_{\mathrm{WIP}}s^2) \end{matrix} \quad (5.63)$$

Equations (5.62) and (5.63) illustrate the upstream part of the *Push-Pull-Push* state, $(\tau_{\mathrm{WIP}} + (\tau_{\mathrm{AINV}}\tau_{\mathrm{SA}} + \tau_{\mathrm{AINV}}\tau_{\mathrm{WIP}})s + \tau_{\mathrm{AINV}}\tau_{\mathrm{SA}}\tau_{\mathrm{WIP}}s^2)$, remain the same as the *Push-Pull-*

Pull state, due to the assumption that CODP inventory at the supplier site can still be pulled by customer orders. However, the structure of downstream final assembly and distribution echelon changes, due to the constraint of $AINV_{AS}$. Also, the delivery LT is no longer a constant level and its dynamic property can be characterised by a third order polynomial in non-factorised form including BL and $AINV_{AS}$ loops; that is, Equation (5.60). Furthermore, the non-factorised third order polynomial indicates that the independent feedforward BL→ SH*→BL loop in the desired Push-Pull-Pull state has now been transformed into part of the feedback loop, due to the SH_{MAX} constraint caused by insufficient $AINV_{AS}$, i.e. BL→ $ORATE_{AS}$→$AINV_{AS}$→BL. Thereby, $AINV_{AS}$ becomes work-in-process inventory and will be pushed out for final assembly, provided they have arrived in the VMI inventory hub.

To access the stability of the *Push-Pull-Push* state, that is, the stability of the non-factorised third-order polynomial, Equation (5.62), the Routh-Hurwitz stability criterion is utilised. As introduced in Section 3.2.1.3, substitute Equation (5.62) to (3.1) and (3.2) to yield (5.64):

$$\begin{array}{c|cc|} S^3 & \tau_i\tau_{AS}\tau_{BL}\tau_{DD} & -(\tau_{AS}\tau_{BL}+\tau_{BL}\tau_{DD}) \\ S^2 & \tau_i\tau_{AS}\tau_{BL}+\tau_i\tau_{BL}\tau_{DD} & \tau_i \\ S^1 & -(\tau_i+\tau_{AS}\tau_{BL}+\tau_{BL}\tau_{DD}) & 0 \\ S^0 & \tau_i & \end{array} \quad (5.64)$$

Given all physical and control parameters are positive, there are two sign changes in the first column and hence there are two complex roots with positive real parts. This means the system characterised by a third order polynomial is unstable. The switch, from desired *Push-Pull-Pull* to *Push-Pull-Push*, resulting by stock out of $AINV_{AS}$, not only decreases customer service levels due to the increase of delivery LT, but also yields unstable dynamic response (exponentially growing) of CODP inventory and $ORATE_{SA}$ and thus, such a state cannot be maintained for a long period of time.

5.3.2.2 The *pure Push* operational state.

If CODP inventory at the supplier site, $AINV_{SA}$, still constrains Pull $ORATE_{AS}$ required by VMI hub replenishment, the system state will switch to the pure Push and its block diagram representation is reported in Figure 5.19.

$$SH(t) = SH_{MAX}(t) < SH^{*}(t) \qquad (5.65)$$

$$ORATE_{AS}(t) = Push\ ORATE_{SA}(t) < Pull\ ORATE_{AS}(t) \quad (5.66)$$

Similar to the analysis of hybrid *Push-Pull-Pull* state, the transfer function of ‘performance triangle’ is derived as follows:

$$\frac{LT}{CONS} = \frac{\left(\left((1+s\tau_{\mathrm{DD}})\left(\begin{matrix}(1+s\tau_A)\begin{pmatrix}\tau_i\tau_{\mathrm{SA}}(\tau_{\mathrm{DD}}+(-1+s\tau_{\mathrm{DD}})\tau_{\mathrm{SA}})\\ +\tau_{\mathrm{BL}}\begin{pmatrix}(1+s\tau_{\mathrm{AS}})(1+s\tau_{\mathrm{DD}})\tau_i\\ -(\tau_{\mathrm{AS}}-\tau_{\mathrm{DD}}+\tau_i)\tau_{\mathrm{SA}}\end{pmatrix}\end{pmatrix}\tau_{\mathrm{WIP}}\\ +\tau_{\mathrm{AINV}}\tau_{\mathrm{BL}}\tau_i\\ \left(\begin{matrix}-\tau_{\mathrm{SA}}(1+s\tau_{\mathrm{SA}})+\\ \left(\begin{matrix}s+\tau_{\mathrm{SA}}+s(1+s)\\ \begin{pmatrix}\tau_{\mathrm{DD}}+(1+(1+s)\tau_{\mathrm{DD}})\tau_{\mathrm{SA}}+\\ \tau_{\mathrm{AS}}(1+s\tau_{\mathrm{DD}})(1+(1+s)\tau_{\mathrm{SA}})\\ +\tau_A(1+s\tau_{\mathrm{AS}})(1+s\tau_{\mathrm{DD}})(1+(1+s)\tau_{\mathrm{SA}})\end{pmatrix}\end{matrix}\right)\tau_{\mathrm{WIP}}\end{matrix}\right)\end{matrix}\right)\right)\right)}{(1+\tau_A s)\left(\begin{matrix}\left(\tau_i\tau_{\mathrm{SA}}+s\tau_{\mathrm{BL}}\left((1+s\tau_{\mathrm{AS}})(1+s\tau_{\mathrm{DD}})\tau_i-(\tau_{\mathrm{AS}}-\tau_{\mathrm{DD}}+\tau_i)\tau_{\mathrm{SA}}\right)\right)\\ \tau_{\mathrm{WIP}}+s(1+s)\tau_{\mathrm{AINV}}(1+s\tau_{\mathrm{AS}})\tau_{\mathrm{BL}}\\ (1+s\tau_{\mathrm{DD}})\tau_i\left(\tau_{\mathrm{WIP}}+\tau_{\mathrm{SA}}(1+s\tau_{\mathrm{WIP}})\right)\end{matrix}\right)} \quad (5.67)$$

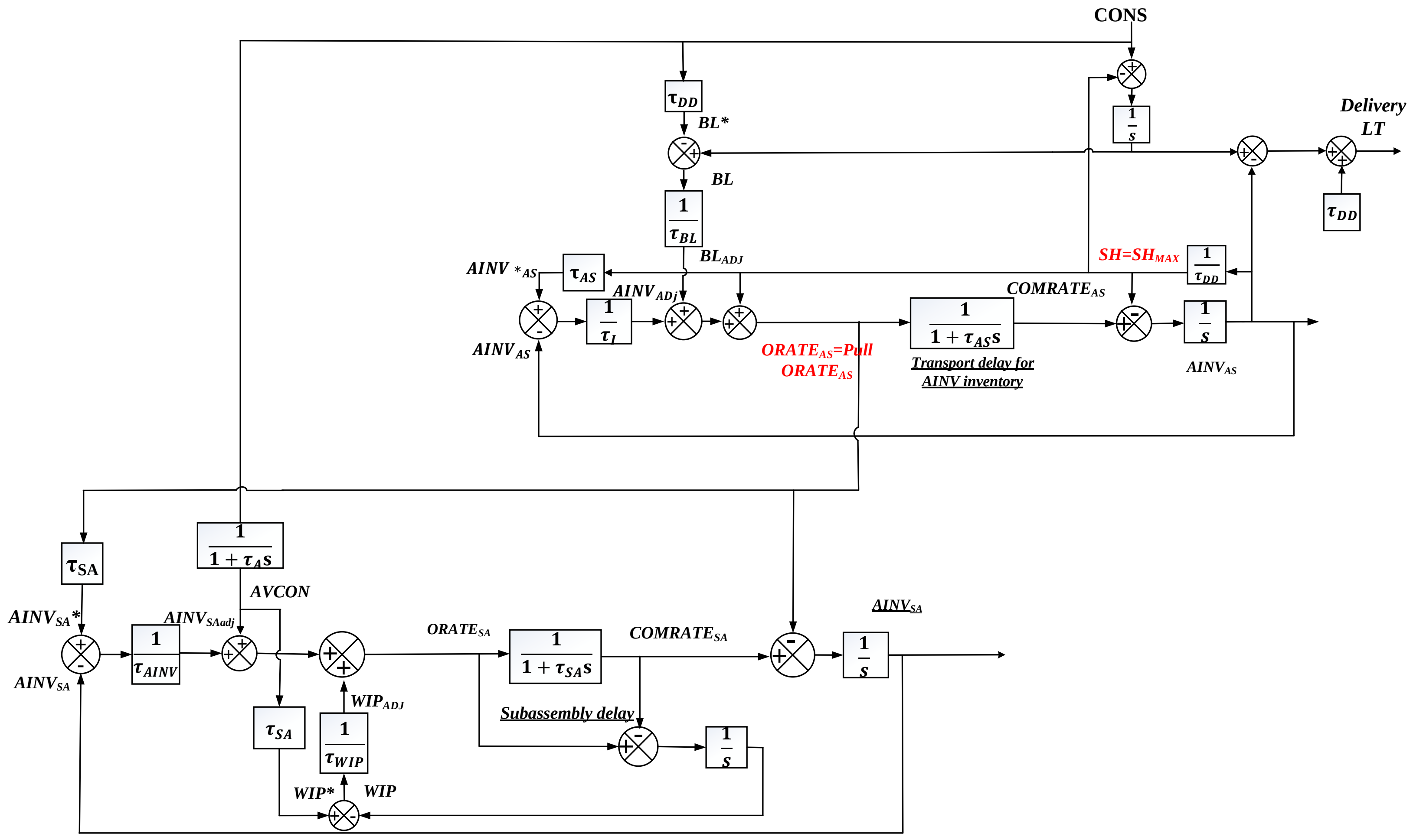


Figure 5. 9. The Push-Pull-Push operational state in the block diagram form.

$$\frac{ORATE_{SA}}{CONS} = \frac{\tau_i(1+s)(1+s\tau_{\mathrm{AS}})(1+s\tau_{\mathrm{DD}})(1+s\tau_{\mathrm{SA}})}{\begin{array}{c}\big((1+s\tau_A)(1-s\tau_{\mathrm{DD}})\tau_{\mathrm{SA}}\tau_{\mathrm{WIP}}+s\tau_{\mathrm{AINV}}\tau_{\mathrm{BL}}(\tau_{\mathrm{SA}}+\tau_{\mathrm{WIP}})\big) \\ \hline (1+\tau_A s)\left(\begin{array}{c}\left(\tau_i\tau_{\mathrm{SA}}+s\tau_{\mathrm{BL}}\begin{pmatrix}(1+s\tau_{\mathrm{AS}})(1+s\tau_{\mathrm{DD}})\tau_i \\ -(\tau_{\mathrm{AS}}-\tau_{\mathrm{DD}}+\tau_i)\tau_{\mathrm{SA}}\end{pmatrix}\right) \\ \tau_{\mathrm{WIP}}+s(1+s)\tau_{\mathrm{AINV}}(1+s\tau_{\mathrm{AS}})\tau_{\mathrm{BL}} \\ (1+s\tau_{\mathrm{DD}})\tau_i\big(\tau_{\mathrm{WIP}}+\tau_{\mathrm{SA}}(1+s\tau_{\mathrm{WIP}})\big)\end{array}\right)\end{array}} \quad (5.68)$$

$$\frac{AINV_{SA}}{CONS} = \frac{(1+s\tau_{\mathrm{AS}})(1+s\tau_{\mathrm{DD}})\tau_i(1+s\tau_{\mathrm{SA}})}{\begin{array}{c}\big(-(1+s\tau_A)(-1+s\tau_{\mathrm{DD}})\tau_{\mathrm{SA}}\tau_{\mathrm{WIP}}+s\tau_{\mathrm{AINV}}\tau_{\mathrm{BL}}(\tau_{\mathrm{SA}}+\tau_{\mathrm{WIP}})\big) \\ \hline (1+s\tau_A)\left(\begin{array}{c}\left(\tau_i\tau_{\mathrm{SA}}+s\tau_{\mathrm{BL}}\begin{pmatrix}(1+s\tau_{\mathrm{AS}})(1+s\tau_{\mathrm{DD}})\tau_i \\ -(\tau_{\mathrm{AS}}-\tau_{\mathrm{DD}}+\tau_i)\tau_{\mathrm{SA}}\end{pmatrix}\right) \\ \tau_{\mathrm{WIP}}+s(1+s)\tau_{\mathrm{AINV}}(1+s\tau_{\mathrm{AS}})\tau_{\mathrm{BL}} \\ (1+s\tau_{\mathrm{DD}})\tau_i\big(\tau_{\mathrm{WIP}}+\tau_{\mathrm{SA}}(1+s\tau_{\mathrm{WIP}})\big)\end{array}\right)\end{array}} \quad (5.69)$$

The corresponding CEs can be derived as follows:

$$CE_{final\ assembly} = CE_{supplier\ manufacturing}$$

$$(1+s\tau_A)\left(\begin{array}{c}\Big(\tau_i\tau_{\mathrm{SA}}+s\tau_{\mathrm{BL}}\big((1+s\tau_{\mathrm{AS}})(1+s\tau_{\mathrm{DD}})\tau_i-(\tau_{\mathrm{AS}}-\tau_{\mathrm{DD}}+\tau_i)\tau_{\mathrm{SA}}\big)\Big) \\ \tau_{\mathrm{WIP}}+s(1+s)\tau_{\mathrm{AINV}}(1+s\tau_{\mathrm{AS}})\tau_{\mathrm{BL}} \\ (1+s\tau_{\mathrm{DD}})\tau_i\big(\tau_{\mathrm{WIP}}+\tau_{\mathrm{SA}}(1+s\tau_{\mathrm{WIP}})\big)\end{array}\right) \quad (5.70)$$

Comparing the *Push-Pull-Push* and *Push-Pull-Pull* state, the *pure Push* state is characterised by a sixth-order polynomial including a first order forecasting loop, and a new fifth-order polynomial in the non-factorised form. This suggests that the final assembly structure, independent of the supplier manufacturing site in the former two states (i.e. BL→ $ORATE_{AS}$→$AINV_{AS}$→BL), is now incorporated into the supplier's $AINV_{SA}$→$ORATE_{SA}$→ $AINV_{SA}$ feedback loop, i.e. a fifth order production push loop (Figure 5.20). The reduction of independent feedback loops thus may reduce the oscillatory behaviour and contribute to the corresponding decrease of bullwhip and inventory variance.

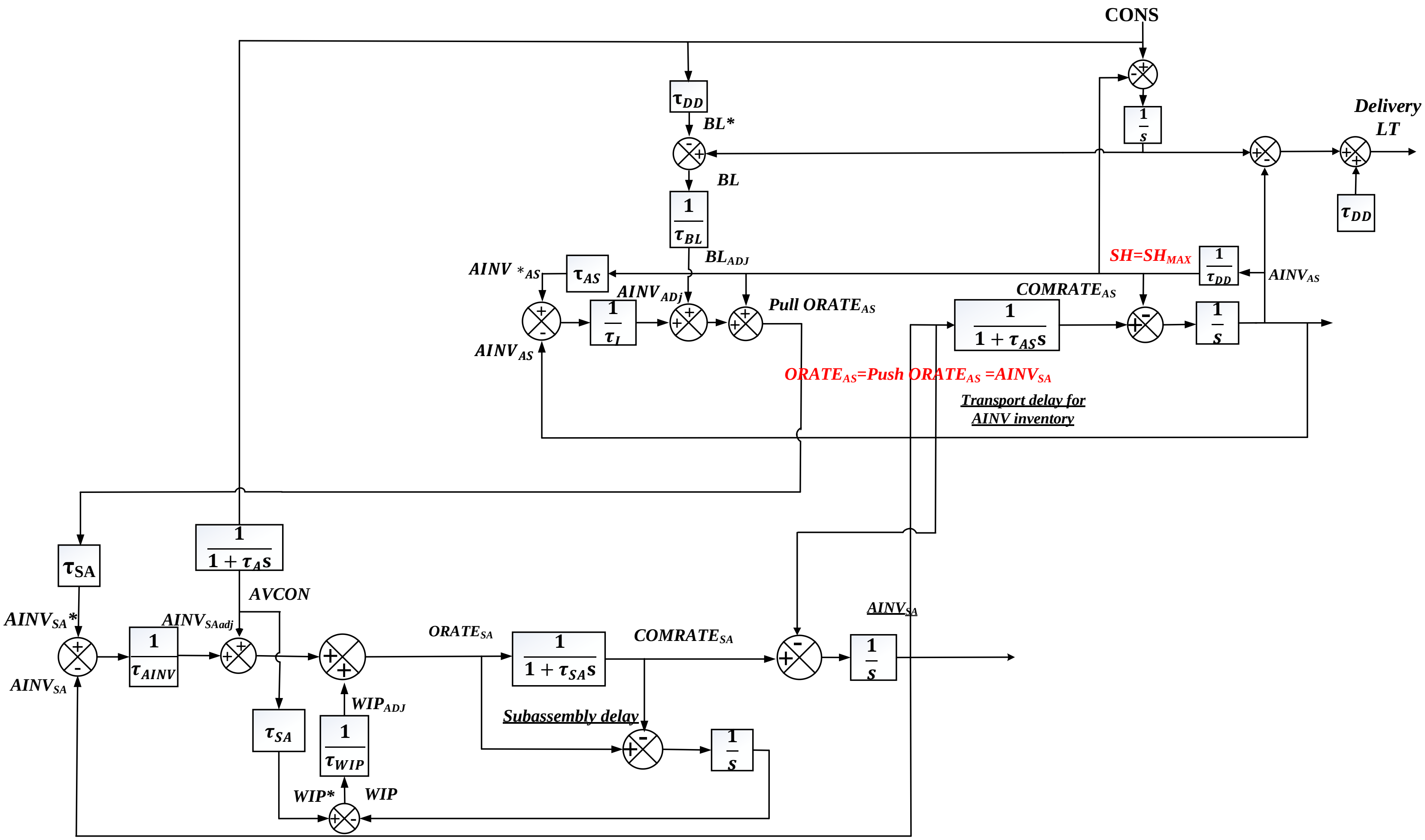


Figure 5. 20. The pure Push state in the block diagram for pure Push state.

The Routh-Hurwitz stability criterion is utilised to examine the stability of Pure Push operational state, i.e. the stability of Equation (5.70). Specifically, for a fifth order polynomial:

$$a_5 s^5 + a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s^1 + a_0 = 0 \quad (5.71)$$

The necessary and sufficient conditions for a stable system are:

$$a_2 \cdot a_5 - a_3 \cdot a_4 < 0\,, (a_0 \cdot a_3 - a_1 \cdot a_2)^2 - (a_3 \cdot a_4 - a_3 \cdot a_5) * (a_1 \cdot a_2 - a_0 \cdot a_3) < 0 \quad (5.72)$$

By inspecting the fifth-order polynomial, we yield the following necessary and sufficient conditions shown by Equations (5.73) and (5.74):

$$-\tau_{\mathrm{AINV}}\tau_{\mathrm{BL}}^2\tau_i^2\tau_{\mathrm{WIP}}\left(\tau_{\mathrm{AS}}^2\tau_{\mathrm{DD}}^2(1+\tau_{\mathrm{SA}})\tau_{\mathrm{WIP}} + \tau_{\mathrm{AINV}}\left(\tau_{\mathrm{DD}}\tau_{\mathrm{SA}}(\tau_{\mathrm{DD}} + (1+\tau_{\mathrm{DD}})\tau_{\mathrm{SA}})\tau_{\mathrm{WIP}} + \tau_{\mathrm{AS}}(\tau_{\mathrm{DD}} + (1+\tau_{\mathrm{DD}})\tau_{\mathrm{SA}})^2\tau_{\mathrm{WIP}} + \tau_{\mathrm{AS}}^2(1+\tau_{\mathrm{SA}})\big(\tau_{\mathrm{DD}}^2\tau_{\mathrm{SA}} + (1+\tau_{\mathrm{DD}})(\tau_{\mathrm{DD}}+\tau_{\mathrm{SA}})\tau_{\mathrm{WIP}}\big)\right)\right) < 0 \quad (5.73)$$

$$\tau_{\mathrm{BL}}^2\tau_i^2\left(\tau_{\mathrm{BL}}\big((-\tau_{\mathrm{AS}}+\tau_{\mathrm{DD}})\tau_{\mathrm{SA}} + \tau_i(1+\tau_{\mathrm{AINV}} + (-1+\tau_{\mathrm{AINV}})\tau_{\mathrm{SA}})\big)\big(\tau_{\mathrm{AS}} + \tau_{\mathrm{DD}} + \tau_{\mathrm{AINV}}(1 + \tau_{\mathrm{AS}} + \tau_{\mathrm{DD}} + (2+\tau_{\mathrm{AS}}+\tau_{\mathrm{DD}})\tau_{\mathrm{SA}})\big) - \tau_i\tau_{\mathrm{SA}}\left(\tau_{\mathrm{AS}}\tau_{\mathrm{DD}} + \tau_{\mathrm{AINV}}\big(\tau_{\mathrm{DD}} + \tau_{\mathrm{SA}} + 2\tau_{\mathrm{DD}}\tau_{\mathrm{SA}} + \tau_{\mathrm{AS}}(1 + \tau_{\mathrm{DD}} + (2+\tau_{\mathrm{DD}})\tau_{\mathrm{SA}})\big)\right)\right)\left(\tau_{\mathrm{BL}}\big((-\tau_{\mathrm{AS}}+\tau_{\mathrm{DD}})\tau_{\mathrm{SA}} + \tau_i(1+\tau_{\mathrm{AINV}} + (-1+\tau_{\mathrm{AINV}})\tau_{\mathrm{SA}})\big)\big(\tau_{\mathrm{AS}} + \tau_{\mathrm{DD}} + \tau_{\mathrm{AINV}}(1+\tau_{\mathrm{AS}}+\tau_{\mathrm{DD}} + (2+\tau_{\mathrm{AS}}+\tau_{\mathrm{DD}})\tau_{\mathrm{SA}})\big) - \tau_i\tau_{\mathrm{SA}}\left(\tau_{\mathrm{AS}}\tau_{\mathrm{DD}} + \tau_{\mathrm{AINV}}\big(\tau_{\mathrm{DD}} + \tau_{\mathrm{SA}} + 2\tau_{\mathrm{DD}}\tau_{\mathrm{SA}} + \tau_{\mathrm{AS}}(1+\tau_{\mathrm{DD}} + (2+\tau_{\mathrm{DD}})\tau_{\mathrm{SA}})\big)\right)\right) - \tau_{\mathrm{AINV}}\tau_{\mathrm{BL}}\tau_i\left(\tau_{\mathrm{DD}}\tau_{\mathrm{SA}} + \tau_{\mathrm{AS}}\big(\tau_{\mathrm{SA}} + \tau_{\mathrm{DD}}(1 + \tau_{\mathrm{SA}})\big)\right)\left(\tau_{\mathrm{AS}}\tau_{\mathrm{DD}} + \tau_{\mathrm{AINV}}\big(\tau_{\mathrm{DD}} + \tau_{\mathrm{SA}} + 2\tau_{\mathrm{DD}}\tau_{\mathrm{SA}} + \tau_{\mathrm{AS}}(1+\tau_{\mathrm{DD}} + (2+\tau_{\mathrm{DD}})\tau_{\mathrm{SA}})\big)\right) < 0 \quad (5.74)$$

Equation (5.73) can always be negative for all positive values of physical and control parameters, while regarding Equation (5.74), it may be positive or negative. Two examples of the stability region based on different values of two inventory stock adjustments (τ_{AINV} and τ_i) are plotted in Figure 5.21, although the combination of different physical and controllable parameters may yield different stability regions.

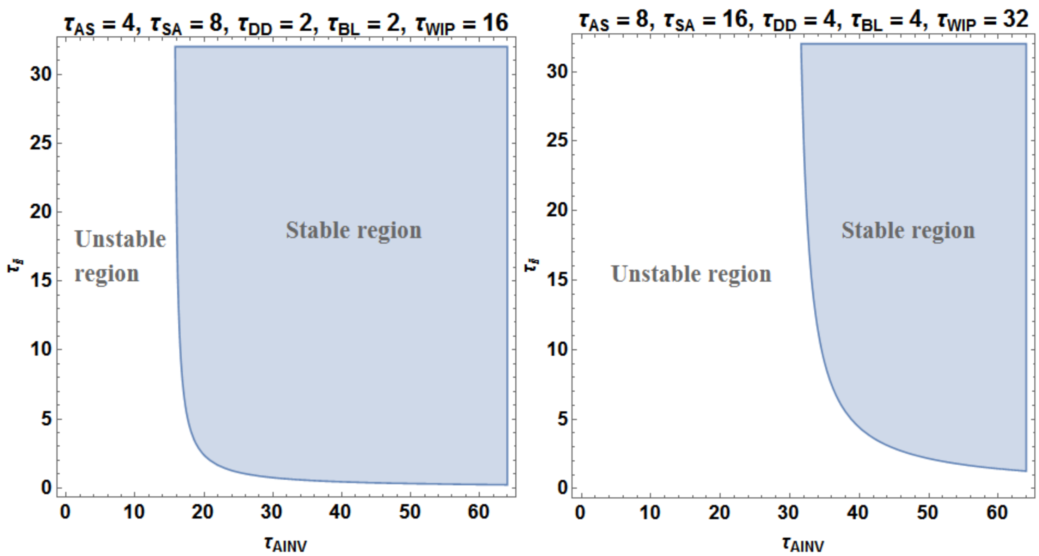


Figure 5. 10. Stability region based on range of τ_{AINV} and τ_i for different physical lead time.

It is apparent that the system can be stable for long-term adjustment of two inventory stocks (τ_{AINV} and τ_i), although τ_{AINV} has a more profound impact on the system stability condition. Also, the stability region is subject to other control policies and physical lead time in pure Push state, e.g. the increase of lead time leads to an increase of instability region. To summarise, depending on the physical delay, the system is partially stable for a certain choice of control policies. Specifically, the system can be stable for long time adjustment of two inventory stocks (τ_{AINV} and τ_i), although τ_{AINV} has a more profound impact on the system stability condition.

The initial value and final value of the performance triangle related variables can be obtained as follows:

$$\lim_{s\to\infty} s\frac{LT}{CONS} = 0 \qquad \lim_{s\to 0} s\frac{LT}{CONS} = \tau_A + \tau_{\mathrm{DD}} + \tau_{\mathrm{BL}}(\frac{\tau_{\mathrm{DD}} - \tau_{\mathrm{AS}}}{\tau_i} + \frac{1}{\tau_{\mathrm{SA}}} - 1)$$

$$\lim_{s\to\infty} s\frac{AINV_{SA}}{CONS} = 0 \qquad \lim_{s\to 0} s\frac{AINV_{SA}}{CONS} = 1$$

$$\lim_{s\to\infty} s\frac{ORATE_{SA}}{CONS} = 0 \qquad \lim_{s\to 0} s\frac{ORATE_{SA}}{CONS} = 1 \qquad (5.75)$$

The final value of $\mathrm{AINV_{SA}}$ is 1, due to the stock-out condition that $\mathrm{AINV_{SA}}$ become WIP inventory, which means all finished PC parts at the supplier manufacturing are pushed out as long as they are produced. As a result, the average of $\mathrm{AINV_{SA}}$ will equal the average of CONS. The final value of delivery LT, as expected, is greater than the desired constant τ_{DD} and depends on the combined control policies for the final assembly and manufacturing systems. This is due to the increased average of BL driven by insufficient $\mathrm{AINV_{AS}}$ and $\mathrm{AINV_{SA}}$, as well as long delay of transport and manufacturing delay (τ_{AS} and τ_{SA}), if the system switches to the pure Push state.

5.4. Simulation studies

To summarise, there are four different nonlinearities present in the ATO system. Particularly, two multi-valued nonlinearities govern the system states depending on the availability of two CODP inventories, which not only influence the dynamic behaviour of the system but may also change the system structure. This section uses repeated simulation approach to summarise and provide further insights of four nonlinearities in the ATO system.

5.4.1. The impact of single-valued nonlinearities

Two single-valued nonlinearities are found in the PC ATO system, including non-negative order constraint at the VMI hub near the OEM's final assembly factory and the supplier's manufacturing capacity constraint, although non-negative order constraint is also found in the supplier manufacturing site. To understand the difference between two single-valued nonlinearities, the non-negative order constraint is temporarily not considered in the supplier manufacturing site.

5.4.1.1. Non-negative order constraint at the VMI hub

In the linear system, order rate is permitted to take negative values. This means that all participants in a supply chain can return excess product freely. Practically, this may mean that the excess inventory is not moved from one location to another but instead is considered in the possession of the upstream member until being used as part of a future replenishment (Hosoda and Disney, 2009). In the PC supply chain model, it means that the VMI inventory can be freely returned to the supplier's site if desired $ORATE_{AS}$ is negative, which is an unrealistic assumption due to extensive geographical distance and export/import policies between the OEMs and their PC parts suppliers.

As a result, the non-negative order constraint, i.e. see Equation (5.8), should be put into the model to prevent the free inventory return from the VMI hub to the supplier site. Based on analytical findings in Section 5.2.2.2, the incorporation of non-negative order constraint at the OEM VMI site leads to the 'more damped' system with fewer oscillations at the expense of slow system recovery speed. Also, such nonlinearity leads to an increase in VMI inventory level (mean).

The simulation is conducted to verify and provide further insights regarding the impact of the VMI non-negative order constraint on both CODP inventory ($AINV_{AS}$ and $AINV_{SA}$) and $ORATE_{SA}$ at the supplier site. All difference equations utilised for simulation can be seen in Section 5.1 and will also be implemented in the following simulation study. Settings recommended by the original APVIOBPCS are utilised for simulation. The sinusoidal demand pattern with mean=1, amplitude=1 (make amplitude high enough to deliberately hit the negative order constraint) and w=0.12 rad/week is utilised as the input, since it represents the PC seasonal demand characteristics with peak demand periods (e.g. Christmas, Black Friday). It should be noted that all other nonlinearities are removed except for non-negative order constraint, which means the system always operates as *Push-Pull-Pull state* in which the SH and Desired $ORATE_{AS}$ can always be satisfied. As a result, the delivery LT is a constant value, i.e. all customers' order can be fulfilled by quoted τ_{DD}.

$$SH(t) = SH^{*}(t);\ ORATE_{AS}(t) = Desired\ ORATE_{AS}(t) \quad (5.76)$$

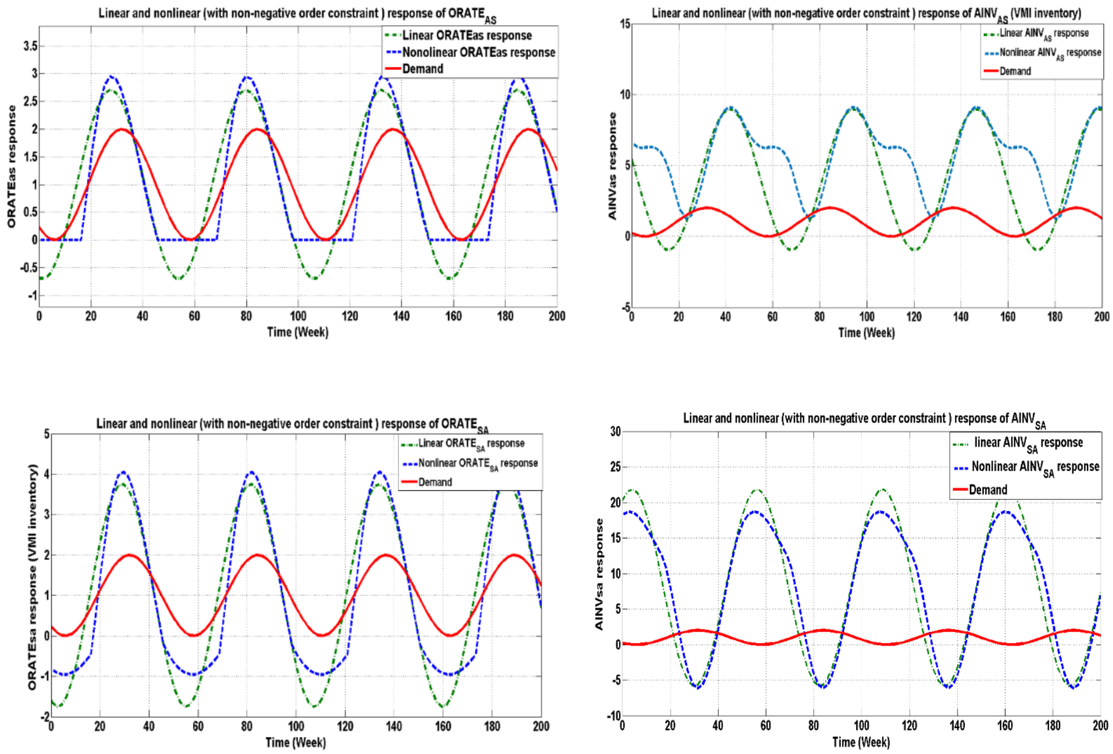


Figure 5. 11. The impact of non-negative order constraint nonlinearity on the dynamic performance of the OEM ($AINV_{AS}$ and $ORATE_{AS}$) and supplier manufacturing variables ($AINV_{SA}$ and $ORATE_{SA}$). Note: different scales in the y-axis. (Control parameter settings: $\tau_A = \tau_{WIP} = 2\tau_{SA} = 2\tau_{AINV} = 16$, $\tau_I = \tau_{AS} = 2\tau_{BL} = 4\ \tau_{DD} = 1$).

Figure 5.22 presents the dynamic response of order rate and inventory variables at both OEM and the supplier echelons. Specifically, the incorporation of non-negative order constraint decreases the variance of $ORATE_{AS}$ and $AINV_{AS}$, i.e. the decrease of bullwhip and inventory variance measured by the variance ratio between the variance of output and input (demand), at the expense of increasing the mean level of them. This is consistent with Spiegler and Naim's (2017) analytical results. In the linear system, as the customer demand decreases, the excess inventory level may lead to negative $ORATE_{AS}$. However, the non-negative nonlinearity prevents such free return scenario and thereby increases the mean inventory level at the VMI hub site. Although the non-negative order constraint improves the dynamic performance of final assembly system by reducing bullwhip and inventory variance, the increase of mean of VMI inventory may be against the OEM's general objective that minimises VMI inventory to reduce the risk of technological redundancy with ever shorter product life cycles of products entering the market.

On the other hand, according to Figure 5.22, comparing the linear system, the supplier echelon may benefit the nonnegative order constraint policy by decreasing the mean of $AINV_{SA}$ as well as the improvement of dynamic performance, i.e. the reduction of bullwhip ($ORATE_{SA}$) and inventory variance ($AINV_{SA}$). Note that the mean and variance of $AINV_{SA}$ are significantly higher than the $AINV_{AS}$, which indicates the fact that CODP at the supplier site takes major responsibility in absorbing end customer demand fluctuation in a hybrid ATO supply chain structure.

5.4.1.2. Capacity constraint at the supplier manufacturing site

In contrast to the nonnegative order constraint that has a low boundary limit, the capacity constraint, i.e. Equation (5.11), at the supplier site, due to resources limits such as people, machines, raw materials, has the upper boundary constraint in which excess orders cannot be entered into the production line. As in the analysis of nonnegative order constraint, system dynamic simulation is conducted to analyse the impact of capacity constraints on the supplier site's variables, $AINV_{SA}$ and $ORATE_{SA}$, under the *Push-Pull-Pull state*. The dynamic response of the supplier's variables, which are, $AINV_{SA}$ and $ORATE_{SA}$ in the linear and nonlinear environment, are reported in Figure 5.23.

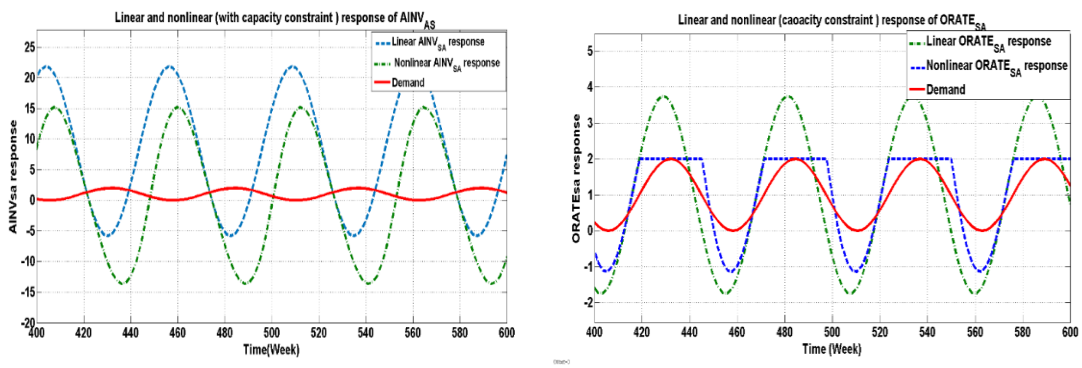
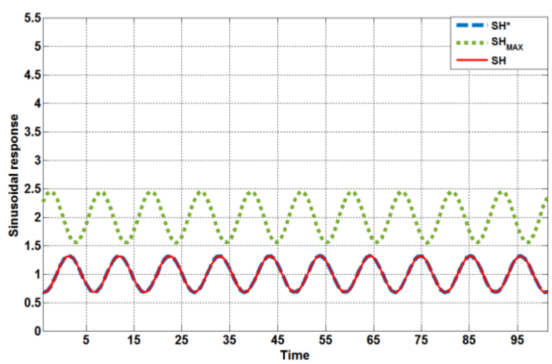


Figure 5. 12. The impact of PC parts supplier capacity constraint (Capacity limit =2) on $ORATE_{SA}$ and $AINV_{SA}$. Note: different scales in the y-axis and control parameter settings: $\tau_A = \tau_{WIP} = 2\tau_{SA} = 2\tau_{AINV} = 16$, $\tau_I = \tau_{AS} = \tau_{I=}\ 2\tau_{BL} = 4\ \tau_{DD} = 1$

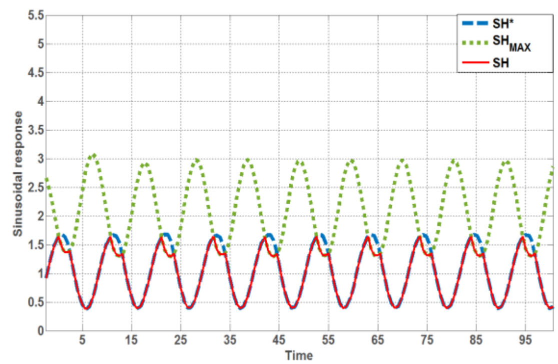
Consistent with the results of Spiegler et al. (2016) and Spiegler et al. (2017), the capacity constraint leads to a decrease of bullwhip effect ($ORATE_{SA}$) compromised by a decrease of average $AINV_{SA}$. The decrease of inventory average may increase the stock-out probability and thus influence customer service level by delaying the fulfilment time; the delivery LT, for example. As discussed in the next section, the decrease of stock out level may also cause the switch from desired *Push-Pull-Pull* state to the pure Push state, further damaging the dynamic performance of the ATO system.

5.4.2. The impact of multi-valued nonlinearities

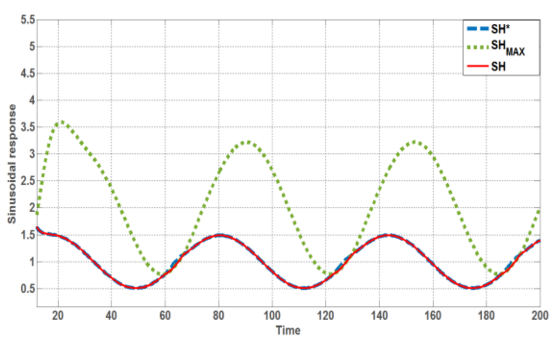
There are two multi-valued nonlinearities present in the PC supply chains illustrated by Equations (5.1) and (5.7): shipment constraints due to limited $AINV_{AS}$ and desired VMI replenishment constraint due to the limited $AINV_{SA}$. Their nature is fundamentally the same, which is the inventory constraint that avoids any final assembly made to the final customer or any shipment to the VMI hub if there are insufficient inventory available in two stock points. The shipment constraint nonlinearity is utilised as an example to illustrate its multi-valued characteristics. Figure 5.23 shows the SH dynamic performance in responding to sinusoidal demand (mean=1) with different amplitude and frequency. Note that other nonlinearities are assumed inactive when investigating the impact of the multi-valued nonlinearities on dynamic performance of the ATO system.



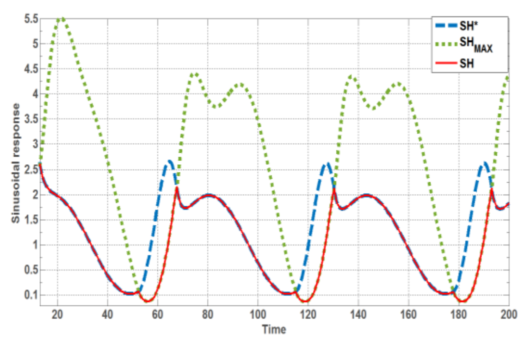
(a) ω=0.6rad/week, Input amplitude=0.5



(b) ω=0.6rad/week, Input amplitude=1



(c) ω=0.1rad/week, Input amplitude=0.5



(d) ω=0.1rad/week, Input amplitude=1

Figure 5. 13. The dynamic response of SH_{MAX}, SH* and SH for different frequencies and amplitudes

The dynamic response of SH (output) depends on the history of the input (SH*) due to SH_{MAX} being a time-varying constraint determined by the dynamic response of $AINV_{AS}$. The simulation results show that SH equals to SH* for low amplitude and high frequency (11a); however, the increase of amplitude or the decrease of frequency leads to the nonlinear behaviour of SH because of the constraint of SH_{MAX}. The simulation also indicates that the shipment constraint is the multi-valued nonlinearity in which a given SH* will result in different SH over time, depending on the past values of SH*. Figure (5.20d), for example, a given SH* value, 2, (blue line shown on y-axis), results in the different value of SH (red line, 2 or 0.1), depending on the past state of SH*. To further understand the impact of multi-valued nonlinearities on the dynamic performance in the ATO system, we analyse three distinct operational states separately, as categorised before; that is, assume the system operates as *Push-Pull-Pull*, *Push-Pull-Push* and Pure Push states temporarily based on the availability of $AINV_{AS}$ and $AINV_{SA}$.

Table 5.6 summarises the findings for the impact of two multi-value nonlinearities on the dynamic performance of the ATO system. Depending on the availability of $AINV_{AS}$ and $AINV_{SA}$, the ATO system may be switched between different states. By design, the system operates the desired *Push-Pull-Pull* state in which two inventory stocks are pulled by end customer orders. Thus, all customised orders can be fulfilled by quoted τ_{DD}. Such system state is permitted to be stable for positive value of control policies and there are two feedback inventory control loops that may characterise the oscillatory behaviour, although control policies in the supplier manufacturing system (e.g. τ_{AINV}) play a key role in determining the dynamic oscillations and recovery speed.

Operational state	**Structure**		**Initial insights for the dynamic properties**	**Stability**
Push-Pull-Pull	Final assembly part	Includes a first order BL and second order $\mathrm{AINV}_{\mathrm{AS}}$ adjustment loops	1. Delivery LT is a constant level, τ_{DD}. 2. the state is characterised by a two-degrees-of-freedom system with independent feedback adjustment loop at final assembly and the supplier manufacturing sites, which may lead to complex dynamic response, such as two-resonance peak frequencies	The system is stable for all positive values of control policies
	The supplier manufacturing part	Includes a first order forecasting and second order $\mathrm{AINV}_{\mathrm{SA}}$ adjustment loops		
Push-Pull-Push	Final assembly part	Characterised by a third order, non-factorized loop, due to the incorporation of BL adjustment loop into feedback $\mathrm{AINV}_{\mathrm{AS}}$ loop (i.e. stock out of $\mathrm{AINV}_{\mathrm{AS}}$)	Not applicable due to the state is unstable	The system is unstable for all control policies selection

	The supplier manufacturing part	Same structure for the Push-Pull-Pull state		
Pure Push	The whole system is characterised by a first order forecasting loop and a fifth order, non-factorised loop, due to the incorporation of final assembly structure into the supplier manufacturing loops		1. The average delivery LT is larger than τ_{DD} and its dynamic performance due to physical delay and system control policies at both final assembly (VMI) and the supplier manufacturing site. 2. $AINV_{SA}$ becomes WIP inventory and the average level equal to the mean of demand. 3. the variance of $ORATE_{SA}$ and $AINV_{SA}$ may be reduced due to the incorporation of final assembly structure.	The system is conditionally stable for positive value of control policies

Table 5. 6. Summary of three operational states based on two multi-valued nonlinearities.

As the level of $AINV_{AS}$ falls sufficiently, the OEM can no longer pull required PC parts from $AINV_{AS}$, instead, all feasible $AINV_{AS}$ at the VMI hub are pushed into the final assembly plant at the maximum shipment rate, i.e. SH_{MAX}. This leads to a switch from desired *Push-Pull-Pull* state to *Push-Pull-Push* state under the condition that $AIVN_{SA}$ are still sufficient to be pulled by the VMI hub replenishment. As a result, delivery LT is increased, driven by a new third-order feedback loop (one real root and two complex roots), which depends on all control and physical parameters in the final assembly echelon and leads to an increase in instability. Such an operational state is not stable and cannot be maintained for a long period of time due to the permanent $AINV_{AS}$ discrepancies.

If $AINV_{SA}$ still constrain the pull $ORATE_{AS}$, the whole system switches to the *pure Push* production state. Two inventory stock points, $AINV_{AS}$ and $AINV_{SA}$, become WIP inventory to be pushed out as soon as possible. As a result, LT is further increased due to the longer upstream supplier manufacturing delay. The whole system is characterised as a first order forecasting loop and a fifth-order push loop. The new non-factorised fifth-order loops may increase instability but reduce the complex dynamic property contributed by independent feedback loops in the *Push-Pull-Pull* state. The *pure Push* state is conditionally stable subject to the choice of control policies and actual physical lead time ratio, although it seems τ_{AINV} has a key impact on system stability.

To further analyse the dynamic performance of $ORATE_{SA}$, $AINV_{SA}$ and Delivery LT as the ‘performance triangle’ and to consider the hybrid ATO system switch from one state to another, Bode diagram and system dynamic simulation are utilised. A Bode Plot is a useful tool to show the gain response of a given linear, time-invariant system for different demand frequencies, which are, bullwhip, inventory and LT variance in the ATO context (Towill et al., 2003; Towill et al., 2007). For the Bode diagram, the dynamic performance of two different operational states are compared: the *Push-Pull-Pull* and *pure Push*. The control policies selected follow the recommended settings of APVIOBPCS (Wang et al., 2014) and VIOBPCS (Edghill and Towill, 1990) archetypes beside the different choices of τ_{AINV}, to deliberately maintain two different states. Regarding the simulation, we select sinusoidal demand, i.e. ω=0.12rad/week, mean=1 and amplitude=0.2, to represent the cyclical demand pattern evident in the real-world PC industry. All result and policy settings can be found in Figure 5.25. Note that there is no Bode plot of delivery LT for the *pure Push* state due to the constant value of LT (τ_{DD}); i.e. there is no dynamic oscillation (variance) of delivery LT but a constant value.

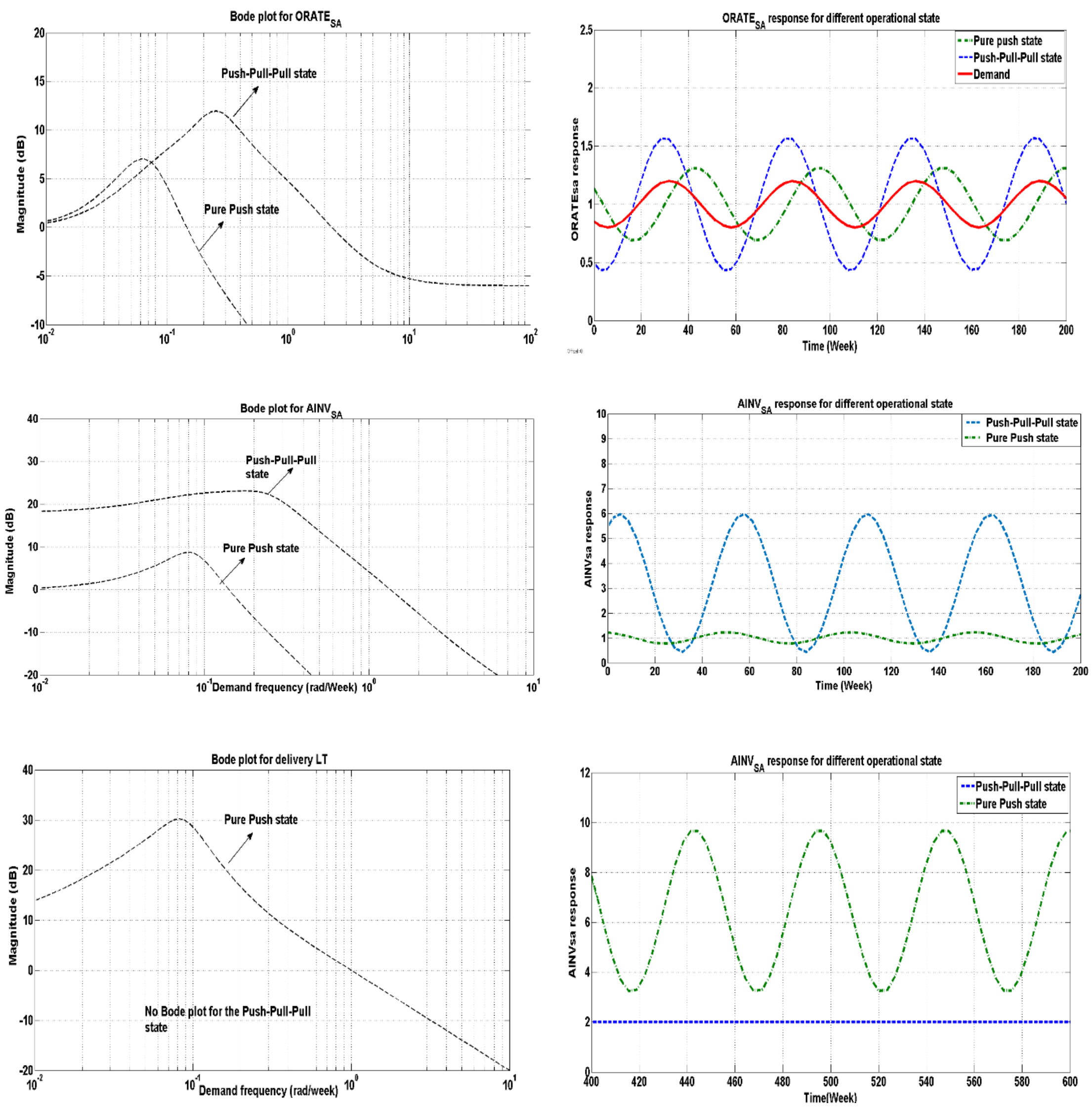


Figure 5. 14. Bode plot of $ORATE_{SA}$, $AINV_{SA}$ and linearised LT for different operational modes

($\tau_{SA}=2\tau_{AS}=2\tau_{I}=8\tau_{DD}=8, \tau_{WIP}=16\ \ \tau_{AINV}=8$ for the Push-Pull-Pull and $\tau_{AINV}=40$ for the Pure Push states)

Overall, the simulation results support the analytical insights. With the shift from *Push-Pull-Pull* to *pure Push* state due to the stock-out of $AINV_{SA}$ and $AINV_{AS}$, the speed of $ORATE_{SA}$ response becomes slow (the decrease of the cross-over frequency) and the unwanted demand amplification (bullwhip) is significantly decreased for a range of frequencies due to the change from the demand pull to the production push; that is, the shift from two-degrees-of-freedom state with two independent feedback loops to one-degree *Push* state. Although the corresponding bullwhip related cost will be decreased, e.g. ramping up / down machines, hiring and firing staff, the mean and variance of delivery LT is significantly increased as the move from desired hybrid state to *pure Push* state. For the desired *Push-Pull-Pull* state, the delivery LT is a constant value and thus there is no Bode plot, i.e. the amplification ratio is zero (infinitely small) for all demand frequencies, so that consistent customer service levels can be guaranteed, even for highly volatile demand patterns. However, if the desirable state cannot be maintained, the peak magnification and bandwidth of LT response are dramatically increased for low frequencies demand range, which means both the variance and mean of LT are significantly increased due to the influence of CODP inventory shortage and long manufacturing and transport delay. Hence, high customer service level cannot be maintained with the increase of demand fulfilment uncertainty.

The frequency response performance of $AINV_{SA}$, as expected, is significantly improved from the desired *Push-Pull-Pull* to the *pure Push* state. This is because $AINV_{SA}$ becomes WIP inventory with the change of system structure, i.e. $AINV_{SA}$ will be pushed out immediately, for as long as they are produced in the supplier plant. Note that $AINV_{SA}$ exhibits significant oscillatory behaviour for the desired hybrid state for demand with low frequencies (e.g. between 0.01 rad/week - 0.1 rad/week), suggesting CODP inventory utilised as the buffer will unavoidably experience high variance for maintaining 'Leagile' balance (Naylor et al., 1999).

5.5. Summary

In this chapter, a nonlinear system dynamic model, representing the typical PC ATO supply chain including a PC component supplier and OEM echelons, has been developed. Main nonlinearities present in the PC ATO system have been identified and analytically explored by utilising nonlinear control engineering, as well as simplification methods gained.

Specifically, based on two 'switches' nonlinearities, three operational states have been identified: *hybrid Push-Pull-Pull*, *Push-Pull-Push*, and *pure Push* states. Due to the importance of maintaining truly hybrid *Push-Pull-Pull* state in practice, for the first part of the analysis the author has solely focused on such state by assuming it is always operated via ensuring sufficient two CODP inventories. Linear control techniques and the 'Filter' lens approach are adopted to explore the impact of major control loops, including feedback inventory and feedforward forecasting control. Also, main single-valued discontinuous nonlinearities present in the desired hybrid *Push-Pull-Pull* state are identified and the corresponding nonlinear control engineering approaches are conducted to give further analytical insights. The system dynamic simulation is utilised for verification and providing some further insights into the ATO dynamic property.

The theoretical result indicated that the hybrid *Push-Pull-Pull* state is always desired, as it is stable, and the customer delivery lead time can be guaranteed. Also, being aware of the impact of the system's nonlinearities and constraints is very important for both the PC component suppliers and the OEM. Depending on the demand amplitude, the non-negative order constraint at the OEM VMI site may occur and this may lead to a significant increase of averaged VMI inventory level and a decrease of the recovery speed of VMI inventory. Furthermore, the amplitude of customer demand (variance) is also important for the supplier to manager CODP inventory at their site, due to the possible occurrence of capacity and non-negative order constraints for PC component production.

In terms of the second part of analysis, the author has mainly explored dynamic performance of the nonlinear ATO system based on 'performance triangle' driven by multi-valued nonlinearities, i.e. capacity and the CODP inventory at the supplier measured by $ORATE_{SA}$ $AINV_{SA}$ and the delivery LT at the final assembly echelon measured by LT. Delivery LT dynamics is incorporated into the ATO system dynamics model and nonlinear control engineering approach is utilised to linearise the delivery LT dynamics measurement, in which analytical techniques, such as transfer function, can be applied to assess dynamic performance.

The analysis indicates that the hybrid *Push-Pull-Pull* state can only be maintained if there are sufficient $AINV_{AS}$ and $AINV_{SA}$. In such circumstances, delivery LT is a constant level in which all customer orders can be fulfilled within the scheduled time. As a result, the trade-off of capacity and CODP inventory as the buffer (i.e. inventory or responsive capacity buffer) should be considered, based on the cost assignment for capacity and inventory related parameter, such as inventory holding cost and machine/labour adjustment cost. The system will fail to operate as the desired state with a decrease in the CODP inventory at final assembly (VMI hub) and the supplier manufacturing site, leading to a shift from *Push-Pull-Pull* to *pure Push* state. Although the variance of CODP inventory and the bullwhip (the corresponding capacity adjustment) will be significantly decreased, the mean and variance of the delivery LT are dramatically increased, due to the stock out issues, as well as long physical delay (τ_{SA} and τ_{AS}). This is an undesirable condition because of the significant decrease in customer service level. In the real PC supply chain, upstream suppliers, such as semiconductor manufacturers, may design long-time inventory adjustment to retain 'Lean' production and avoid expensive capacity fluctuation (Lin et al., 2017). On the other hand, from the entire ATO supply chain perspective, this may cause operational shift from the desired hybrid structure to the *pure Push* state driven by the frequent stock out issue, which significantly influences the downstream OEMs' customer service level; i.e. the long and unreliable delivery LT. Such findings also support the importance of adopting collaborative design and planning strategy between supplier and OEMs to reduce operational cost driven by poor supply chain dynamics. Also, the theoretical analysis supports the practical rationale as to why PC OEMs make every effort, exploiting such approaches as supplier qualifying programmes and VMI to ensure CODP inventory availability for immediate final assembly.

Chapter 6. Insights gained from the system dynamics of the ATO systems.

This chapter summarises the insights gained from the research process. More specifically, the main gaps identified in Chapter 2 highlighted the system dynamics modelling of the ATO structure, as well as the need for evaluation of the performance triangle (bullwhip, inventory and lead times) and nonlinearities present in the ATO system. Also, major insights are illustrated in detail and synthesised regarding the design, modelling and analysis of the ATO system within the context of semiconductor and PC supply chains as given in Chapters 5 and 6. Finally, based on all main findings, a framework, adapted from Naim and Towill (1994), is proposed to design, model and analyse the dynamic performance of the ATO system.

6.1. Insights gained from the conceptual literature review

In summary, a conceptual literature review was used to critically examine the existing literature and to map knowledge in the area of ATO and system dynamics in order to conceptualise a framework. Many insights were gained when using this approach:

- The concept of CODP and DIDP related to the material and information decoupling points is critically reviewed. Since the customer order flow is based on actual customer orders, it is necessary to position the DIDP upstream of the CODP, or possibly at the CODP. If DIDP is positioned upstream of the CODP the forecast used for the forecast driven flow can be improved, as it may be based on more up to date point of sales data.
- Based on supply chain performance (Table 2.1), many performance metrics were examined in the ATO stochastic modelling and analysis literature. Among these performance metrics, time (CODP and end customer delivery LT), production capacity (e.g. component capacity, final assembly capacity), and CODP inventory are well-recognised as the most important metrics (Sections 2.1.1 to 2.1.4);
- Within the system dynamics and IOBPCS family literature, bullwhip and inventory are the two main dynamics indicators. Very few studies have assessed time-based ATO dynamics performance, although some works have given implications for the dynamic behaviour of orderbook/backlog order in the MTO system. Based on findings gained from the stochastic analysis and literature gaps identified in the system dynamics literature, the so-called ‘performance triangle’ performance

assessment metrics, which are: capacity availability and CODP inventory at the supplier; delivery LT at the final assembler, are developed (Sections 2.1 to 2.3):

- Despite the importance of the impact of nonlinearities on system dynamics performance, only simulation methods have been exploited to analyse complex, high-order, nonlinear supply chain models. Although an emerging number of analytical studies (e.g. Wang et al., 2012; 2014; Spiegler et al., 2016a) have explored the impact of nonlinearities on dynamics performance, all of them focus on the MTS-based system by considering inventory and order variability as main performance indicators (Section 2.2.3). As the result, a review of linear and nonlinear control engineering approaches establishes the main analytical methods utilised in this study: 'Shock' lens and 'Filter' lens analysis techniques, describing function and Taylor series expansion linearisation approaches. Also, a combined system dynamics and control engineering analysis strategy is implemented in assessing the dynamics property of the ATO system to offer robust and traceable dynamics insights (Section 3.2).

6.2. Insights gained from the semiconductor ATO supply chains (RQ2a and 2b)

In Chapter 4, the existing Intel system dynamics model, originally developed by Gonçalves et al. (2005), is utilised as an illustration of a typical ATO system. The complete dynamic picture can be visualised, including main entities (e.g. balancing, reinforcing loops, delays and nonlinearities) and their interconnections. Thus, such a system dynamics model is referred to as ***Target model***, i.e. the observed or current situation/problem to be addressed is identified, documented and modelled.

The Intel supply chain is highly nonlinear and complex (a ninth-order system), including various feedback balancing loops, delays and control policies monitoring the system states. Also, there are two nonlinear 'switches', defined by the Min functions (Figure 4.1), governing the minimum value of two inputs as the output. The relative complexity of the block diagram suggests that it will be difficult to derive the transfer function and any quantitative analysis would have to rely on simulation alone. The simulation has the main drawback of lacking analytical guidance, due to its nature of a trial-and-error approach that may hinder the system improvement process (Sarimveis et al. 2008, Lin et al. 2017). As a result, instead of directly considering the 'surface similarities' (i.e. based on the mere appearance between two objects), the adoption of 'behavioural similarity' (based on the function, matching relations, and final goal of the problems, even when they do not appear to be similar) by source model(s)/candidate solutions should be considered.

As analysed in Chapter 4, the IOBPCS family, enabled by control engineering, is utilised as the benchmark model for gaining analytical insights into the ATO system dynamics model. The insights of a high-order, nonlinear ATO system, as personified by the Intel system dynamics model, can be gained by adapting analogical reasoning (Gavetti and Rivkin, 2005; Naim et al., 2017) including the following three-step design and analysis method:

Linearisation and/or simplification: several simplification procedures are conducted in the study of the Intel system dynamics model. Specifically, the nonlinearities are assumed temporarily inactive and thus, the capacity and non-negative order constraints in the original

Intel system dynamic model can be removed. Also, removing the system physical variables that do not influence dynamics behaviour, such as die yield rate, line yield rate, although their associated impact of quality issues (e.g. different yield rate) on dynamics performance are analysed in the sensitivity analysis Section 5.2.2.4.3. Furthermore, as the distribution delay in the semiconductor industry is much shorter than upstream assembly and fabrication, the corresponding echelon and redundancies can be temporarily eliminated;

Search source model(s)**:** after simplifying and linearising the original system dynamics model, the direct analogues with the IOBPCS family can be observed. That is, the simplified semiconductor ATO system consists of a VIOBPCS (Edghill et al., 1990) without lead time, as well as similar APVIOBPCS (Wang et al, 2014) archetypes.

Candidate solutions: As a result, the corresponding recommended settings can now be utilised to assess the dynamics property of the simplified semiconductor ATO system, to explore the underlying mechanisms of bullwhip and inventory variance. The linear control engineering approaches, including transfer function, stability analysis, characteristics equations analysis, can be implemented to provide further analytical insights into the simplified system.

Furthermore, the simulation is again utilised to verify the semiconductor ATO model by re-installing nonlinearities, which give more robust and traceable analytical results. Based on these procedures, the summarised findings and corresponding managerial implications are presented in Table 6.1.

Systems		Findings	Corresponding managerial implications
Linear Pull part of hybrid ATO system	ω_n *and* ζ	1. T_{sAdj} and T_{FGI} inversely proportional to ω_n. 2. $\zeta \geq 1$ for all positive value of T_{sAdj} and T_{FGI}.	1. Quick forecasting smoothing and inventory error correction lead to rapid system recovery to the steady state condition. 2. The Pull part system always produces over-damped behaviour without oscillations.
	Stability	The real roots are always negative for positive value of T_{sAdj} and T_{FGI}.	The Pull part system is permitted to be stable and robust for any forecasting methods and a positive value of inventory correction policy.
	Dynamic response	T_{sAdj} plays a major role in the A_N response, while T_{FGI} has a major impact on the FGI dynamic behaviour.	Bullwhip is mainly caused by the feedforward compensation in the semiconductor Pull supply chains: A careful compromise between advance stock availability and bullwhip effect should be considered.
Nonlinear Pull system	Dynamic response	The same insights from the linear MTO system are confirmed.	The same managerial implications indicated by linear analysis are obtained.
Linear Push part of hybrid ATO system	ω_n *and* ζ	1. T_{AWIP} and T_{FWIP} inversely proportional to ω_n. 2.T_{AWIP} has a major influence on ζ.	1. Quick CODP (AWIP) and FWIP inventory error correction leads to the system's rapid recovery to steady state conditions. 2. The CODP (AWIP) inventory policy plays a major role in the system's dynamic behaviour.
	Stability	The real roots are always negative for positive value of T_{FWIP} and T_{AWIP}.	The Push system is guaranteed to be stable for any positive choice of the AWIP and FWIP inventory correction policies.
	Dynamic response	1. T_{sAdj}, T_{FGI}, T_{AWIP} and T_{FWIP} influence the bullwhip effect. However, T_{sAdj} and T_{AWIP} play a major role for bullwhip level. 2. T_{AWIP} is the key factor for system oscillations.	1. The CODP inventory error correction and forecasting smoothing policy should be carefully tuned, due to their major influence on bullwhip level in the Push system. 2. The trade-off between the cost of bullwhip (e.g. capacity ramp up/down, labour hiring and firing) and the benefit of implementing CODP strategy should be considered, due to the system's oscillations being sensitive to the CODP policy settings.

Systems (Continued)		**Findings**	**Corresponding managerial implications**
Nonlinear Push part	Dynamic response	The same results regarding the impact of control policies on the dynamic behaviour can be confirmed in the nonlinear MTS system. However, the introduction of nonlinearities can reduce the bullwhip effect at the expense of increasing CODP inventory variability.	Additional to the managerial insights gained from the linear analysis, the impact of capacity constraint should be considered for trade-offs design between the CODP inventory and capacity utilisation when the hybrid ATO production strategy is adopted.
Comparison for the semiconductor Push (MRP) and the APVIOPBPCS system	ω_n	Semiconductor MRP system is always larger than the APVIOBPCS system for all positive control policy.	The dynamic recovery speed of semiconductor MRP system is faster than the APVIOBPCS system, which may benefit higher customer service level by increasing the inventory recovery speed in responding to customer demand
	ζ	On the other hand, re-order APVIOBPCS always has larger ζ than MRP-based system for all positive value.	MRP system will produce more oscillations under the same policies settings and its associated production activities and cost, such as ramp up and ramp down machines, hiring and firing staff, have to be considered in designing such production control systems.
The impact of lead times and quality		1. The increase of T_F leads to high variance of WS and AWIP 2.1. The decrease of T_U, T_L and T_D leads to high variance of WS and AWIP	The upstream wafer yield rate and downstream final assembly line efficiency should be monitored, since it is not only directly related to the customer service level (i.e. whether the customised orders can be delivered within quoted time), but also significantly drives the supply chain dynamics cost driven by the high bullwhip and inventory variance.

Table 6. 1. Summary of the findings and managerial implications.

In summary, the analysis offers robust and traceable insights for the effect of fundamental system structures (feedback, feedforward) and the corresponding control policies on the dynamic behaviour of the hybrid ATO system, which contribute to the analytical guidance of supply chain system design in the context of the semiconductor industry. The analytical stability region map proides a basic framework for examining stability conditions in both a linear and nonlinear environment. The well-established results derived from the linear system, bullwhip level, fill rate and the corresponding economic implications, for example, can also be used as indicators to compare the nonlinear dynamic results. A good example is Ponte et al.'s (2017) method to set optimal capacity based on the benchmark of well-established linear analysis results in a capacitated production environment.

6.3. Insights gained from the theoretical PC ATO system

The thesis conducts extensive study on dynamic modelling and analysis of a stylised ATO system within the context of PC supply chains, to provide valuable insights regarding the scientific visualisation and assessment of system dynamic property of an ATO system structure from a system dynamics perspective. All main findings and corresponding managerial implications are summarised in Table 6.2.

6.3.1. Modelling the ATO system

Specifically, based on the literature review of the IOBPCS family model, as well as the insights gained from the Intel system dynamics model, the author developed a two-echelon, non-linear ATO system dynamic model to represent the main dynamics characteristics of the ATO system structure:

Pull loops**:** there are two pull loops in a typical PC downstream supply chain if two CODP inventory are sufficient, including 1) end customers' customised orders pull PC CODP component inventory from the VMI inventory hub near the final assembly site, and 2) the VMI inventory replenishment pull PC CODP inventory at the supplier site. To model the first pull loop, as illustrated in Figure 6.1, the first order modelling approach can be utilised. The cumulative difference between inflow (CONS) and outflow (actual SH) can be obtained as a measure of backlog. i.e. a work-in-progress orders, WIP (Wikner, 2003).

	Findings/Outcomes		**Managerial implications**
The analysis of hybrid Push-Pull-Pull state	Control loops	1. The ATO is stable for any positive value of $\tau_{\mathrm{A}}, \tau_{\mathrm{AINV}}, \tau_{\mathrm{WIP}}$ and τ_{I}. 2. ω_{n1} and ζ_1 are inversely proportional to τ_I. 3. ω_{n2} and ζ_2 are inversely proportional to τ_{AINV}. 4. τ_{AINV} plays a dominant role in influencing the whole state's oscillatory behaviour.	1. There is a need to consider the inventory policy of the downstream echelon to avoid excessive bullwhip and inventory variance. Managers need to avoid too quick an inventory adjustment, defined by τ_I. 2. There is a trade-off in the sub-assembler between capacity and CODP inventory variance defined by τ_{AINV}. This policy parameter needs to be carefully selected due to its dominant influence on the dynamic behavior of the ATO system. 3. The forecasting policy plays a substantively smaller role in influencing the dynamic performance of the ATO system in comparison to the other policies in the system, contrasting to previous studies that assumed linearity (Dejonckheere et al. 2002; Li, et al., 2014).
		An increase in τ_{A} leads to a reduction in bullwhip ($ORATE_{SA}$ variance) at the expense of increasing $AINV_{SA}$ variance, although the effect of τ_{A} is limited comparing feedback control loops.	
	Non-negative order constraint at the VMI site	1. The occurrence of non-negative order constraints at the OEM VMI site lead to the change of $N_{A(NO)}$ ranging between 0.5 and 1, which depends on the amplitude of input demand. 2. $N_{\mathrm{B(NO)}}$ increases with the increase in input demand amplitude	1.Being aware of the impact of the system's nonlinearities and constraints is very important for final assemblers. Depending on the demand amplitude, the non-negative order constraint at the final assembly plant may occur, such that $N_{\mathrm{B(NO)}}$ will increase with demand amplitude, and this could lead to a significant increase in average inventory level, which increases total costs.

	Capacity and nonnegative order constraint at the supplier site	1. $N_{A(CA)}$ decreases and can approach 0 as the increase of input demand amplitude triggered by the occurrence of capacity and non-negative order constraints at the supplier site. 2. The change of $N_{B(CA)}$, however, depends on the relationship between mean of input (B) and half the capacity limit (CL). $N_{B(CA)}$ equals to 1 irrelevant to input amplitude A if B=CL/2. if $B < \frac{1}{2}CL$, the increase of A leads to the increase of $N_{B(CA)}$. Furthermore, N_B monotonically decreases in A if $B > \frac{1}{2}CL$.		2. Production managers at the subassembly site should carefully consider capacity utilization, i.e. should the mean of the orders received from the downstream final assembly exceed half of the maximum capacity, then the dominant impact on CODP inventory dynamics will be the capacity constraint rather than the non-negative order low boundary. Under such condition, $N_{B(CA)}$ will increase with demand amplitude, leading to the decrease in average inventory level. 3. In contrast, if the mean of the orders received is less than half of the maximum capacity then the non-negative order boundary dominates. This leads to the increase in average CODP inventory level at sub-assemblers. Alternatively, if the mean of the orders received equals half of the maximum capacity then nonlinearities do not have impact on the averaged inventory level.
	Impact of VMI non-negative order	The impact of $N_{A(NO)}$ and $N_{B(NO)}$	As the decrease of $N_{A(NO)}$, will result the decrease of ω_{n1} but the increase of ζ_1.	1. An increase in demand amplitude, which influences $N_{A(NO)}$, will yield a system with lower bullwhip and inventory variance, although at the expense of a slower inventory recovery speed at the final assembly. The

	constraint gains		the $N_{B(NO)}$ will be also increased as the increase of input demand amplitude.	latter suggests a decrease in customer service level due to the increased probability of stock-out, in particular when the system's steady state condition is disturbed by a sudden but a sustained demand increase. 2. An increase in demand amplitude (influences $N_{A(CA)}$) will decrease CODP inventory recovery speed at the subassembly, which also directly increases the stock-out probability of CODP inventory at the final assembly site. Final assembler should aware their final assembly line efficiency, defined by Y_F, and the sub-assembler needs to consider yield losses, given by Y_S, since they not only directly relate to the customer service level, i.e. whether the total orders can be delivered within the quoted lead times, but also increase supply chain dynamics costs of the upstream supplier in the ATO system.
	Impact of supplier capacity and non-negative order constraints	The impact of $N_{A(CA)}$ and $N_{B(CA)}$	The decrease of output amplitude gain, $N_{A(CA)}$, resulting from the capacity and non-negative order constraints at the supplier site, will lead to the decrease of ω_{n2} and ζ_2.	
			Depending on the relationship between mean of input demand and the half of capacity constraint, the increase of demand amplitude may lead to the increase of decrease of $N_{B(NO)}$.	
Delivery LT linearization	Based on Taylor series expansion with small perturbation theory, delivery LT can be linearised by the following equations: $LT = \tau_{DD} \quad if\ SH_{MAX} > SH^*$ $LT = \tau_{DD} + BL - AINV_{AS} \quad if\ SH_{MAX} < SH^*$			Managers may simply calculate the estimated delivery LT by considering the difference between current backlog and raw materials inventory level at final assembly plant (VMI hub), under the condition that desired shipment rate cannot be fully satisfied.

The analysis of hybrid Push-Pull-Push state	The final OEM assembly echelon is characterised by a third order, non-factorised loop, due to the incorporation of BL adjustment loop into feedback $AINV_{AS}$ loop (i.e. stock out of $AINV_{AS}$), while the structure of upstream supplier is same for the *Push-Pull-Pull* state.	Not applicable due to the state being unstable.
The analysis of pure Push state	1. The average delivery LT is larger than, τ_{DD} and its dynamic performance due to physical delay and system control policies at both final assembly (VMI) and the supplier manufacturing site. 2. The variance of $ORATE_{SA}$ and $AINV_{SA}$ may be reduced due to the incorporation of final assembly structure.	Although both downstream and upstream players benefit from the reduction of supply chain dynamics cost driven by the decrease of inventory variance and bullwhip, the mean and variance of delivery LT is significantly increased and this directly influences the customer service level.
The summary of performance triangle	As the switch from true hybrid *Push-Pull-Pull* to *pure Push* state, the mean and variance of delivery LT can be significantly increased, although $ORATE_{SA}$ and $AINV_{SA}$ variance can be mitigated due to independent inventory feedback loops at both final assembly and supplier manufacturing sites has been integrated as a fifth-order production push feedback loop.	Due to nonlinear switch between different operational processes, maintaining the 'true' hybrid ATO operational state is always desirable to ensure customer service level; that is, the reliable LT.
	Two peak frequencies can be observed in the Bode plot diagram of $ORATE_{SA}$ due to the effect of two natural frequencies driven by two independent feedback loops (two-degrees-of-freedom system).	It is important for managers to consider the adoption of collaborative control policy design with their supply chain partners to reduce the influence of supply chain dynamics.

Table 6. 2. Main results and managerial insights based on modelling and analysis of the stylised PC ATO system dynamic model.

The output SH is the result of the fraction of WIP ($1/\tau_{DD}$) depending on the minimum between SH* and SH_{MAX}, i.e. the availability of VMI inventory ($AINV_{AS}$). τ_{DD} is the average delay of the production unit.

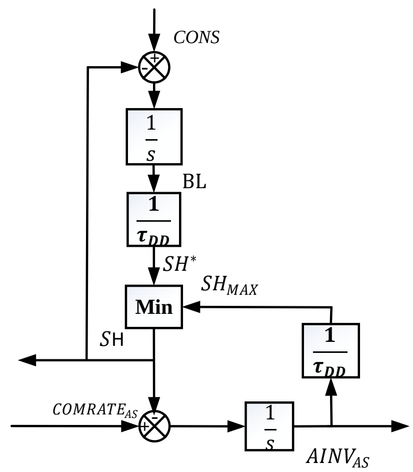


Figure 6. 1. The first order modelling approach for the first pull loop.

The second pull loop (Figure 6.2) representing the VMI hub inventory replenishment, based on Darwish and Odah (2010) and Katariya and Tekin (2014), is determined by three factors: 1) the VMI inventory adjustment, which is a feedback loop well-recognised in the IOBPCS family literature, 2) the feedforward shipment compensation loops utilised as a reliable proxy to replenish the VMI inventory and 3) feedforward backlog adjustment based on desired backlog and actual backlog level.

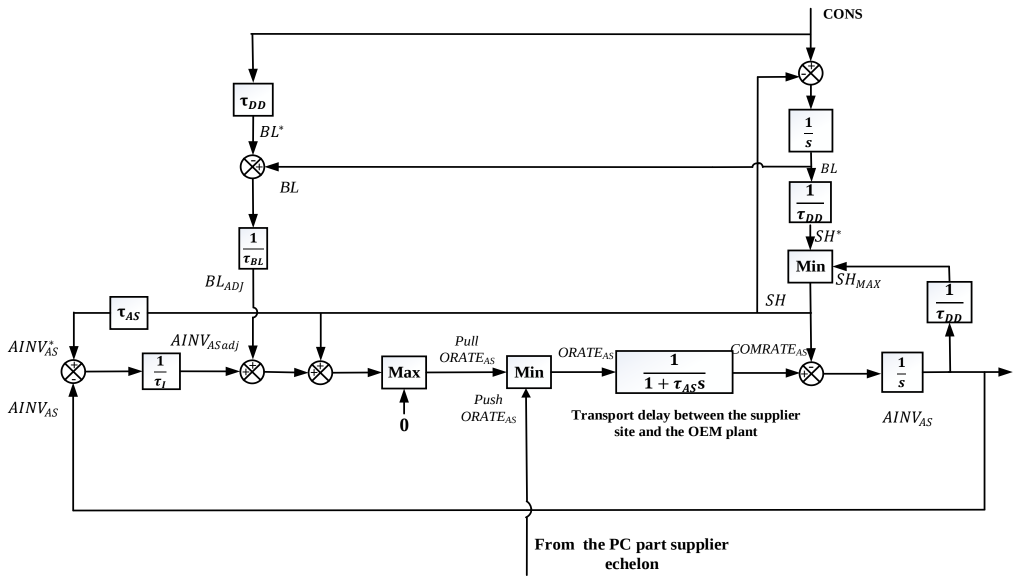


Figure 6. 2. The second pull loop modelling approach.

Push loop: as the upstream PC component supplier is a typical MTS with information sharing (forecasting sharing by the downstream OEM; in other words, the DIDP is positioned in the upstream supplier site), the well recognised APVIOBPCS archetype can be utilised for directly modelling such a system. Specifically, for each ordering cycle, the replenishment decision is based on three variables of the system: feedforward forecasting adjustment, feedback inventory adjustment and feedback work-in-process inventory adjustment.

Thereby, two echelons stylised system dynamic model, representing main ATO characteristics, including pull and push loops, information (forecasting sharing) and material CODP positions, can be developed.

6.3.2. Dynamic analysis of the truly ATO state (hybrid Push-Pull-Pull state)

Based on the system dynamic model developed in Section 5.1, four discontinuous nonlinearities are found in the ATO system, although continuous nonlinear lead times measurement as the output measurement does not influence the dynamic property of the ATO system. Two multi-valued nonlinearities, i.e. two CODP inventory constraints, may govern the system states, depending on the availability of two CODP inventory, which not only influences the dynamic behaviour of the system, but may also change the ATO system structure. Due to the importance of maintaining a truly hybrid ATO state, the impact of such a structure on the dynamic behaviour was analysed, including main feedback and feedforward loops, and nonlinearities present in such a state. The three steps design method (Figure 6.1) gained from the analysis of Intel ATO supply chains can be implemented to extract and analyse the truly hybrid ATO state. From the 'Filter' lens perspective, the describing function method, as reviewed in Section 3.2.1.3 and analysed in Section 5.2.2, is utilized to linearise the single-valued nonlinearities including capacity and non-negative order constraints at the supplier site, as well as the non-negative order constraint at the VMI inventory hub site. Then, the linear control engineering approach, including transfer function, characteristics equations analysis can be further applied to gain further dynamic property of the truly hybrid ATO state.

To summarise, similar insights, by comparing the Intel supply chains, are gained regarding the impact of feedback and feedforward loops on the dynamic behaviour of the ATO system. That is, the CODP inventory adjustment policy at the supplier site should be fine-tuned to balance the cost of supply chain dynamics and the benefit of maintaining a hybrid ATO state, as such policy plays a key role for oscillation. Furthermore, two single-valued nonlinearities can influence the recovery speed and oscillations of the ATO system, depending on the amplitude of input demand from the 'filter' lens perspective.

6.3.3. Dynamic analysis of multi-valued nonlinearities

If two multi-valued CODP constraints are re-installed in the ATO system, the dynamic behaviour become complex due to the introduction of delivery LT dynamics as the third important performance measurement in the ATO system. To summarise, based on different operational states governed by the two multi-valued nonlinearities, there are three distinctive states due to the existence of two stock points:

1) A 'desired' ATO state in which both stock points are available for immediate VMI replenishment shipment, and final assembly,

2) A 'hybrid push-pull-*push state', where the PC parts are available for VMI replenishment shipment but not for immediate final assembly, and*

3) The 'pure push' state, where both stock points run out of inventory.

The analysis of two stock constraints nonlinearities suggests the "hybrid" ATO structure can switch to the pure push structure triggered by insufficient CODP inventory. This state is undesirable, not only due to the high probability of stock-out itself, but also because it leads to increased bullwhip and higher delivery LT variance, which further damages supply chain performance. By maintaining the desired ATO state, the trade-off between capacity and

CODP inventory as the buffer should be considered. The theoretical modelling also supports the practical rationale as to why PC OEMs make every effort, exploiting such approaches as supplier qualifying programmes and VMI to ensure CODP inventory availability for immediate final assembly.

6.4. A framework for designing, modelling and analysing the dynamic ATO system

Based on insights gained above and by adapting the widely recognised framework developed by Naim and Towill (1994), the author develops a holistic framework to design, model and analyse the impact of ATO structure on dynamic performance, as illustrated in Figure 6.3.

Specifically, there are two distinct but overlapping phases of analyses: qualitative and quantitative stages. The qualitative phase focuses on the exploration of a specific supply chain system (i.e. the ATO based systems) and defining its boundaries and interfaces. Naim and Towill (1994) suggested that four main business objectives can be evaluated using their framework. These are: inventory reduction target, controlled service levels, minimum variance in material flow, and minimum total cost of operations and procurement. In the ATO system, the end customer delivery LT dynamics is incorporated as the fifth objective. Moreover, organisations should be aware that there are trade-offs between these objectives and different weighting may be given to each of them.

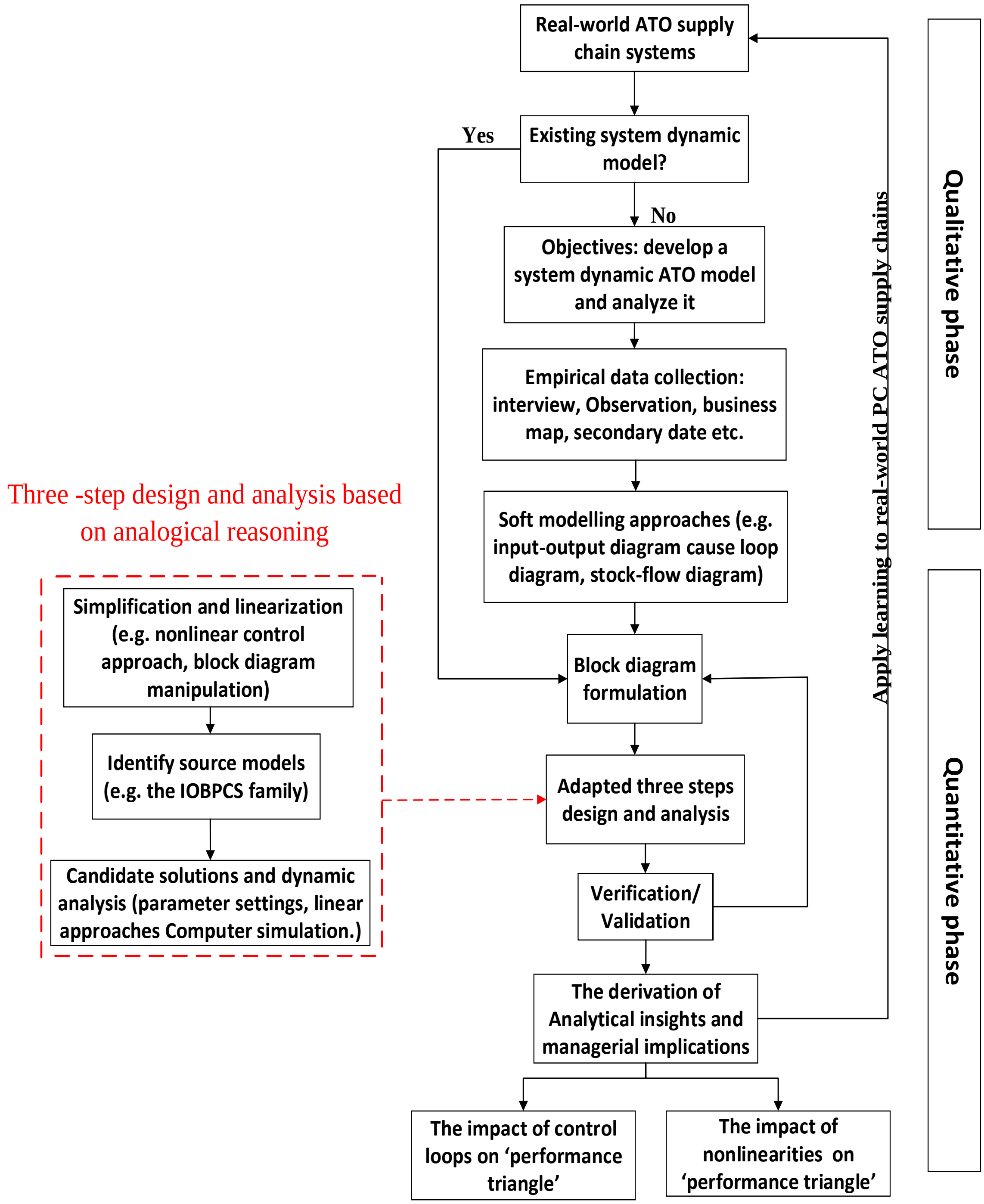


Figure 6. 3. A holistic framework for system dynamic analysis of an ATO system, adapted from Naim and Towill (1994) and Naim et al. (2017)

More specifically, if the system dynamics model of the ATO has been created and verified, *a three-step design* (see the source models/candidate solutions illustrated in Section 6.2), can be implemented to gain deep insights into its dynamic property, especially the underlying causes of supply chain dynamics; bullwhip effect, for example. In this thesis, the existing Intel system dynamic model, developed by Gonçalves et al. (2005), is chosen and analyzed.

If the system dynamic model of ATO is not available, qualitative modelling procedures need to be followed before quantitative modelling and analysis. This thesis focuses on the development of a generic two-echelon PC ATO system. Soft modelling techniques, including cause loop diagram and/or stock-flow diagram, can be applied to develop a conceptual model to map and visualise main entities and their relationship within the system, e.g. feedback, feedforward, delay, nonlinearities. These illustrative diagrams are also reported to help in communicating with the relevant people in the supply chain and extracting more information to refine the model (Naim and Towill, 1994). Other methods, as illustrated in Table 5.1, such as extremities test, boundary and structure validation, and family members and parameters reproduction are applied to verify the system dynamic model. The conceptual model can then be formulated by *the block diagram* to describe the overall concept of a complex system without concerning the details of implementation, as well as allowing for both a visual and an analytical representation within a single entity.

During the quantitative analysis stage, the author synthesises the original framework (Naim and Towill, 1994), i.e. chooses one or more of three possible techniques for analysing the supply chain, including control theory, computer simulation and statistical analysis, as well as three-stage analogical reasoning design based on insights gained from analysis of the Intel semiconductor ATO system, i.e. the three-step design and analysis. It should be noted that, unlike the Intel supply chains, only simplification is conducted; ***the linearisation***, enabled by the non-linear control engineering approaches, is also adopted in the study of the nonlinear PC ATO system.

Specifically, based on the findings of this thesis, the describing function method is appropriate for linearising discontinuous nonlinearities, including capacity and non-negative order constraints, as well as CODP inventory constraints. Furthermore, Taylor series expansion with small perturbation theory can be applied for continuous nonlinearities, i.e. the delivery LT dynamics as the output measurement. The validation procedure is involved to compare the simplified and linearised models with the original ones. For each step taken in the simplification and linearisation process, frequency and/or step output responses have been used for comparison and validation.

After simplifying and linearising the original nonlinear, complex system dynamics model of the ATO system, the direct analogues with the benchmark models (e.g. the IOBPCS family) can be observed. Like the Intel supply chain design and analysis, the benchmark models' recommended system settings now can be utilised for assessing the dynamic property of the ATO system, to explore the underlying mechanisms of bullwhip and inventory variance. The linear control engineering approaches and computer simulation approaches give further analytical insights into the system, which can be summarised as follows (Naim and Towill, 1994):

- Tuning existing parameters: supply chains can be redesigned by maintaining the original supply chain structure but varying the control parameters to improve performance.
- Structural re-design: this involves altering the model's structure, such as removing an echelon or including feedback information in the control system. Moreover, re-engineering processes, such as the inclusion of new feedback control systems, were beyond the scope of this research.
- 'What if?' business scenarios: this involves testing how the supply chain would perform for alternative business propositions or unexpected changes in the business scenario. This thesis has tested the impact of both expected changes in control parameters, such as forecasting and inventory control policies, and physical parameters, including physical lead times and production yield, on the dynamic performance of the ATO system.

The analytical insights based on the procedures above can be obtained regarding the impact of major control loops and nonlinearities on the ATO system dynamic performance. Finally, managerial implication derived can contribute feedback to the real-world scenario to guide practitioners in designing and analysing their ATO ordering system structure. Note that the real-world data or further analytical tools (optimisation, for example) can be applied to conduct trade-off design and analysis, although this is outside the scope of this thesis.

6.5. Summary

This chapter synthesises insights gained from the thesis. Regarding the literature review and method chapters, the author critically assesses two branches of research directions: the CODP and ATO systems, as well as system dynamics with the IOBPCS family models. The author has identified that the ATO system remains unexplored within the context of supply chain dynamics, although ATO topics are well-researched in stochastic modelling and analysis literature. A so-called 'performance triangle' assessment framework is developed to evaluate the dynamic performance of the ATO system; that is, the capacity variation and CODP inventory variance at the supplier and end customer delivery LT at the final assembly site. A series of linear and nonlinear control methods are reviewed and selected as main approaches to investigate the research questions.

The author utilises existing system dynamics model of Intel, as the starting point, and develops the corresponding simplification/linearisation method to gain insights into the impact of control loops on dynamic performance in the present ATO structure. Then, a generic two-echelon system dynamic model, based on PC sector supply chains, is developed, which includes the main characteristics of the ATO system, including CODP, hybrid Push-Pull and 'performance triangle'. The author also contributes to the linearisation methodology development regarding main nonlinearities present in the PC ATO system dynamics model, so that analytical tools can be implemented to explore its impact on system dynamics.

Furthermore, the theoretical analysis of the PC ATO system structure supports the practical rationale as to why PC OEMs make every effort, exploiting such approaches as supplier qualifying programmes and VMI, to ensure CODP inventory availability for immediate final assembly. Finally, a framework for the design, modelling and analysis of the ATO system is proposed based on Naim and Towill (1994), which contributes to the guidance to explore the impact of the ATO system structure on dynamics performance.

Chapter 7. Conclusion

This chapter will relate the findings back to the research questions that emerged from the preliminary investigation for this research and from the literature review process. In addition, the contributions of this research to theory, methodology and practice will be summarised. Finally, the limitations and potential areas for further investigation will be discussed.

7.1 Theoretical contributions

7.1.1 Answer RQs related to the research objective 1 (RQ1a, RQ1b)

The ATO system is well-adopted in the PC and semiconductor industries, and academic communities have extensively explored such a system from the stochastic modelling and analysis perspective. e.g. Hsu et al., 2006; 2007; Fu et al.. 2006; Benjaafar and Elhafsi, 2006; Feng et al., 2008; Lu et al., 2010; Cheng et al., 2011; Kebils and Feng, 2012; Lu et al., 2015).

However, the ATO system’s dynamic property remains unexplored, especially given that adopting industries suffer severally from poor supply chain dynamics (Gonçalves et al., 2005; Hofmann, 2017; Li and Disney, 2017; Lin et al., 2017). System dynamics and control policies have been pointed to as a central activity in the management of material and information flow (Mason-Jones and Towill, 1998) and as major sources of supply chain disruption (Colicchia et al., 2010). System dynamics can be studied by utilising the well-known IOBPCS family as a base framework to model the new ATO systems and benchmark to existing system dynamics models of ATO. Therefore, the answers to RQ1 and RQ2 contribute to supply chain theory development, i.e. the complement of exploring the IOBPCS family model in studying supply chain dynamics and, specifically, for the ATO system.

RQ1a. How may the IOBPCS family be utilised to study ATO system dynamics?

Based on Lin et al.'s (2017) systematic citations review of Towill (1982) and John et al. (1994) from 1982 to 2016, as well as the updated citations review to May 2018 in Chapter 2, Figure 2.6 reported the synthesis of the adoption of IOBPCS family in studying supply chain dynamics. Although details can be found in Section 2.2.2 and Figure 2.4, the author summarises the review result as follows:

- The IOBPCS family models are extensively studied in the context of MTS production-inventory, as well as supply chain systems based on four inherent policies, including 1) forecasting policy, 2) inventory adjustment policy, 3) lead time policy and 4) work-in-process inventory policy;
- Adopting the IOBPCS family as an entire system to study supply chain dynamics. For these articles, a framework of dynamic system control was adopted in order to categorise contributions into the *sensing*, *assessing*, *selecting and acting* clusters.
- The extension of the IOBPCS family into different supply chain contexts, including remanufacturing, supply chain resilience, order-based system, e.g. MTO and ATO), and nonlinearities.
- The modelling and analysis of order-driven systems by utilising the IOBPCS family models remains very rare; only two studies are found, i.e. Wikner et al. (2007) and Wikner et al. (2017). Most research studies utilise bullwhip and inventory variance as the two main performance indicators for assessing MTS supply chain dynamics. Furthermore, most studies assume the system is completely linear and thus ignore

common nonlinearities present in the system, such as physical constraints (e.g. capacity, shipment) and policy constraints (e.g. forbidden return) (Lin et al., 2017).

RQ1b. What kind of criteria can be utilised to assess the performance of the ATO system dynamics?

Based on cost-related supply chain performance, the author reviews the study of the ATO system from an analytical modelling and analysis perspective as the starting point to capture the main performance metrics utilised for assessing ATO systems in Chapter 2. To conclude, four major metrics are utilised for performance evaluation in the ATO system, including delivery LT, component (CODP) inventory, production/final assembly capacity and pricing. Within the system dynamics and IOBPCS family literature, bullwhip and inventory are the two main dynamics indicators, while limited study has explored time-related metrics, such as delivery time dynamics performance.

Based on findings and literature gaps identified in the system dynamics literature in Chapter 2, performance assessment metrics are developed, known as a *'performance triangle'* comprising **capacity availability (bullwhip)** and **CODP inventory** at the supplier, with **delivery lead times** at the final assembler.

7.1.2. Answer RQs related to the research objective 2 (RQ2a and 2b)

Facing complex, non-linear high order dynamics systems, only simulation is recommended (Forrester, 1961; Wikner et al., 1991; Naim and Towill, 1994; Shukla et al., 2009). Although system dynamics simulations contribute to a representation of a real system by incorporating nonlinear components and complex structures, it is a trial-and-error approach that may hinder the system improvement process (Towill, 1982; Sarimveis et al., 2008). This is also true in the semiconductor industry in which simulation is the primary choice when investigating system dynamics (Gonçalves, et al., 2005; Orcun et al., 2006; Orcun and Uzsoy, 2011).

For this reason, the author utilises the Intel supply chains introduced in Section 3.3.2, as an example of an existing complex ATO system, and develop a simplification method to analytically explore its dynamic property. The underlying causes of supply chain dynamics in the ATO system are analytically explored and the corresponding mitigation strategies can be proposed to reduce unwanted poor supply chain dynamics.

RQ2a. How to design the nonlinear, high-order ATO supply chain to gain insight into its dynamic properties as personified by the Intel system dynamics model?

***Simplification**:* simplification techniques were applied first in Section 4.1 to decrease the number of equations and variables in the model. The purpose is to allow the investigator to understand the underlying causes of bullwhip among many feedback, feedforward and delay loops. The system dynamic simulation will be conducted by re-installing the nonlinearities after analysing the dynamic property of linearized ATO system.

Benchmark to the IOBPCS family: the IOBPCS family now can be utilised to benchmark with the stylised ATO semiconductor model. The rationale is that the well-understood family model with recommended system parameter setting can be used to test the dynamic behaviour of such stylised ATO systems, to see whether the system dynamic performance is still ‘good’ enough (Sections 4.2.1, 4.2.4, and 4.2.6). Also, since the ATO system is now completely linear, the linear control engineering approaches such as transfer function, characteristics equation analysis, and stability analysis can be applied to gain deep insights into such a stylised ATO dynamic property.

RQ2b. What are the underlying mechanisms of the dynamic behaviour in a semiconductor ATO supply chain and how can these dynamics be mitigated?

Based on Sections 4.2.2 and 4.2.5, the author found feedforward forecasting compensation and the CODP inventory correction policy play a major role in the bullwhip effect in the semiconductor hybrid ATO system, instead of the production delay/feedback loop usually claimed in practice. Also, semiconductor managers may need to cautiously consider the balance between the cost of keeping an adequate CODP inventory to maintain the mode of ATO and the cost of supply chain dynamics, due to the policies’ settings in the CODP point being significantly sensitive to inventory variance and bullwhip level.

7.1.3. Answer RQs related to the research objective 3 (RQ3a, 3b, 3c and 3d).

RQ3a. How to develop an ATO system dynamics model within the context of PC sector?

The PC system can be modelled as a two-echelon ATO system, consisting of a downstream OEM echelon and the upstream supplier echelons. From an information flow perspective, as discussed in Section 3.3.2.2, the hybrid ATO production strategy implements the CODP in the OEMs’ final assembly plants. The downstream production of the CODP (final assembly) essentially operates as an MTO (pull) in which end customers’ orders pull the available CODP inventory based on their specific PC configurations. However, upstream production of the CODP, i.e. the PC components manufacturing, is characterised by MTS (push): long-term demand forecasting is shared by the OEM and the CODP inventory to determine production rates. In other words, similar to the Intel supply chain, the DIDP is located in the upstream PC supply chain to share end customer demand with PC components suppliers.

Thus, the generic ATO system dynamic model can be developed by modelling the ***pull*** and ***push*** parts separately. Section 5.1 illustrates the detailed mathematical modelling process of push and pull loops in the PC ATO system. The distribution pull part can be modelled by utilising the first order delay approach, by which the desired shipment rate can be interpreted as ratio between the work-in-process orders and estimated physical delay. On the other hand, the similar VIOBPCS archetype can be utilised for modelling the VMI inventory pull loop, while the APVIOBPCS archetype, as reviewed and analysed in Section 4.3, is used for modelling the upstream supplier production-inventory system.

RQ3b. How to measure delivery LT dynamics and how to analytically assess delivery LT dynamics?

Based on Little's law, the delivery LT can be measured as the ratio between current backlog order level (BL) and current shipment rate (SH). However, it is a continuous nonlinearity and thus needed to be linearised in order to analytically assess its dynamic behaviour. By reviewing and categorising different types of nonlinearities present in the supply chain system in Section 3.2.1, Small perturbation theory can be applied to investigate the continuous nonlinearities. Then, the Taylor series expansion is used because the delivery LT nonlinearities are single-valued (Section 5.3.1). The result shows that the estimated delivery LT can be calculated by considering the difference between current backlog and raw materials inventory level at final assembly plant (VMI hub), if the desired shipment rate cannot be fully satisfied.

RQ3c. What are nonlinearities present in the PC ATO system and how do nonlinearities influence the dynamic performance of the ATO system?

By reviewing the categorisation of different types of nonlinearities present in the supply chain system in Section 3.2.1, the results (Section 5.1) show that there are usually four inherent nonlinearities present in PC supply chains. Note that, in addition to four nonlinearities, the delivery lead time dynamics is a kind of continuous nonlinearity in which such variables do not impact on the dynamic performance of the ATO system itself, but the kind of performance metrics needs to be evaluated.

These four nonlinearities are discontinuous nonlinearities in which sharp changes in output values or gradients occur in relation to input (e.g. piecewise linear function). There are two single-valued nonlinearities, namely non-negative order constraint at the VMI hub near the OEM’s final assembly factory, and supplier’s manufacturing capacity constraint. Single-valued nonlinearities are also called memory-less, which means that the output value does not depend on the history of the input (Spiegler et al., 2016a).

Also, there are two multi-valued nonlinearities in the PC ATO system, i.e. two inventory stock point constraints at the VMI hub and supplier site. In contrast to the single-value nonlinearity, the output value of multi-valued discontinuous nonlinearity depends on the history of the input. For example, the output shipment depends on the history of input demand, i.e. the variable shipment constraints (dynamic response) are driven by the history of demand.

Two multi-valued nonlinearities, the two CODP inventory constraints, can categorise the nonlinear ATO system as three interchangeable states: *Push-Pull-Pull*, *Push-Pull-Push* and *Pure Push* states. Due to the importance of maintaining a true ATO system state, the author begins to analyse the linear and nonlinear hybrid Push-Pull-Pull state with capacity and non-negative order constraints by assuming two multi-valued nonlinearities are inactive (Section 5.2). Under the *Push-Pull-Pull* state the delivery LT for end customer can be guaranteed but the trade-off design between CODP inventory and capacity variation needs to be considered, which is significantly influenced by the CODP inventory control policy (Section 5.2.1).

Under true hybrid ATO state (*Push-Pull-Pull* state), there are only single-value discontinuous nonlinearities, including non-negative order and capacity constraints. The describing function method can be applied to linearise them so that the analytical tools, such as root causes analysis, can be utilised to gain further insights (Section 5.2.2). The results show that, depending on the demand amplitude, the non-negative order constraint at the final assembler site may occur, and this may lead to a significant increase of average inventory levels and a decrease in speed to recovery. Also, an increase in demand amplitude will decrease CODP inventory recovery speed at the upstream supplier, due to the capacity and non-negative order constraints simultaneously present at the supplier site. This also directly increases the stock-out probability of inventory at the final assembly site. Furthermore, driven by the capacity and non-negative order constraints, the change of average inventory level at the supplier site will depend on the relationship between incoming orders from downstream assembler and half of the maximum capacity level.

If two CODP inventory constraints are considered, the ATO system may switch between different states driven by the insufficient CODP inventory, and thereby customer delivery LT dynamics may be created, which is analysed specifically in Section 5.3. Based on the 'performance triangle' developed in Chapter 2, the system may fail to operate as the desired state with the decrease in the CODP inventory at final assembly (VMI hub) and the supplier manufacturing site, leading to a shift from Push-Pull-Pull to pure Push state. Although the variance of CODP inventory and the bullwhip (the corresponding capacity adjustment) will be significantly decreased, mean and variance of the delivery LT, however, are dramatically increased due to the stock out issues, as well as long physical delay (τ_{SA} and τ_{AS}). This is an undesirable condition because of the significant decrease of customer service level. In a real PC supply chain, the upstream suppliers, such as semiconductor manufacturers, may design long-time inventory adjustment to retain 'Lean' production and avoid expensive capacity fluctuation (Lin et al., 2017). On the other hand, from the entire ATO supply chain perspective, this may cause operational shift from the desired hybrid structure to pure Push state driven by the frequent stock out issue, which significantly influences the downstream OEMs' customer service level, i.e. long and unreliable delivery lead times. Such findings also support the importance of adopting collaborative design and planning strategy between supplier and OEMs to reduce operational cost driven by poor supply chain dynamics.

7.1.4. Summary of theoretical contributions

- A *'performance triangle'* of performance assessment metrics, comprising **<u>capacity availability (bullwhip)</u>** and **<u>CODP inventory</u>** at the supplier, **<u>delivery lead times</u>** at the final assembler, are developed, which contribute to the extension of a traditional assessment of studying supply chain dynamics from Push-driven systems to the time- and/or order-oriented Pull systems.
- Nonlinearities play an important role in influencing system dynamics behaviour of the ATO supply chain and are comprehensively assessed based on the generic PC ATO system. The non-negative order constraint at the downstream final assembler site (OEM) leads to an increase in averaged inventory level and a decrease in its recovery speed. The *capacity and non-negative order constraints* at the upstream supplier site also play a crucial role for dynamic performance. When these two nonlinearities occur simultaneously, the mean of demand received from the downstream final assembly is an important indicator in influencing the dynamic

performance due to the nonlinearities with capacity upper and non-negative order low boundary may have a different impact on the level of CODP inventory.

- The two inventory constraints nonlinearities (i.e. see Figure 4.1 for Intel ATO and Figure 5.1 for the PC ATO supply chains), on the other hand, lead to the structure of the ATO supply chains as three interchangeable operational states depending on two stock points (CODP at the supplier site and finished goods inventory at the final assembly site): *hybrid Push-Pull-Pull, hybrid Push-Pull-Push and pure Push states*. Regarding the desired *hybrid Push-Pull-Pull* state, that is, all customised orders are fulfilled within a quoted time, the trade-off between CODP and capacity utilisation as the buffer are found in both Intel and PC ATO systems. The CODP inventory control policy significantly influences such trade-off design and thereby should be fine-tuned. Furthermore, if two inventory constraints nonlinearities occur, the trade-off between delivery lead times, CODP inventory and capacity utilisation (bullwhip) are found as the switch between different states. Specifically, due to the insufficient inventory (CODP or finished goods inventory), the mean and variance of delivery lead times is significantly increased, although upstream supplier may benefit from the reduction of CODP inventory and bullwhip reduction. This theoretical analysis supports the practical rationale as to why PC OEMs make every effort, exploiting such approaches as supplier qualifying programmes and VMI to ensure CODP inventory availability for immediate final assembly

- The IOBPCS family models (Towill, 1982; John et al., 1994; Lin et al., 2017), traditionally used in representing the Push/MTS based system, are extended to model the ATO system, including both Pull and Push part connected by the CODP inventory point. The Pull part can be modelled by a similar VIOBPCS (Edghill et al., 1990) with a first order backlog order control, while the Push part of the ATO can be represented by the well-established APVIOBPCS archetype (Wang et al., 2014).
- A three-step design and analysis method, enabled by the linear and/or nonlinear control engineering approach, is developed in order to analytically explore the impact of the ordering structure (feedback/feedforward, delay and nonlinearities) on the system dynamics performance. This includes 1) simplification and/or linearisation, 2) Search source model(s) (i.e. the IOPBPCS family) and 3) the Candidate solution.
- The linearisation methods based on Taylor series expansion with Small perturbation theory, is developed to allow for the analytical dynamic analysis of delivery lead times present in the ATO system. If there is sufficient inventory at the downstream final assembler (e.g. VMI hub near the OEM site), delivery lead times are a constant level determined by the estimated physical delay, including final assembly and transport. If insufficient inventory constrains the desired incoming orders, the delivery lead times can be approximated by the difference between current backlog orders and inventory level, plus constant physical delay (final assembly and transport).

- Synthesising all findings and insights gained from the previous chapters, a holistic framework, adapted from Naim and Towill (1994) and based on the idea of analogical reasoning (Gavetti and Rivkin, 2005; Naim et al., 2017), is developed to assess ATO system dynamics (Section 6.4).
- The linearization methods, including describing function method as well as Taylor series expansion can be used for analysing other type of nonlinearities present in real-world supply chain systems. Specifically, the describing function method, utilized in this thesis for analysing fixed capacity and non-negative order constraints, can be also applied to the various capacity constraint and shipment constraints environment. Note that these two nonlinearities are multi-valued in which its output not only depend on the current state of the system, but also is determined by the history of the system. Also, the Taylor series expansion based on perturbation theory can be also used for assessing time-varying parameters in supply chain dynamics model. e.g. Shipment rate and production completion rate (nonlinear time delay rate).
- Although the semiconductor ATO model is considerably simple comparing the original Intel ATO system, the simplified base ATO framework can be used for other industries who adopted the similar ATO system. Also, the insights gained from the analytical results can be generalized to other high-volume and low-variety supply chains.

- The PC ATO system dynamics model developed in Chapter 5 is a very general ATO framework and can be extended to study other ATO-based system under different industries or products. Furthermore, the modelling concept, i.e. the Pull part and Push part separated by the CODP stock point, can be exploited for modelling other types of hybrid systems with different location of the CODP, as in Figure 2.2. For example, in the case of the engineering-to-order system where the CODP is located fully upstream in the design process. (see Gosling et al., 2018). Details how to implement CODP into ETO can be found in Gosling et al. (2018). Another example is the Make-to-Stock system where the CODP is located further downstream in the distribution process.

7.2. Contributions for practice

The managerial implications can be summarised as follows:

The true ATO structure (Semiconductor supply chains)

- Feedforward forecasting compensation and the CODP inventory correction policy play a major role in the bullwhip effect in the semiconductor hybrid ATO system, instead of the production delay/feedback loop usually claimed in practice. Also, semiconductor managers may need to cautiously consider the balance between the cost of keeping an adequate CODP inventory to maintain the state of ATO and the cost of supply chain dynamics, due to the policies' settings in the CODP point being significantly sensitive to inventory variance and bullwhip level.
- Targeted pipeline inventory setting is important due to its significant impact on dynamic performance. The utilisation of summation of feedback inventory correction

and feedforward forecasted demand as targeted pipeline inventory may benefit from high customer service level increasing the inventory recovery speed at the expense of higher supply chain dynamics cost driven by high bullwhip.

- The upstream wafer yield rate and downstream final assembly line efficiency should be monitored, since they are not only directly related to the customer service level (i.e. whether the customised orders can be delivered within the quoted time), but also significantly drive the supply chain dynamics cost, driven by the high bullwhip and inventory variance.

The true ATO structure (PC supply chains).

- Being aware of the impact of the system's capacity and non-negative order constraints is very important for both the PC component suppliers and the final assemblers. Depending on the demand amplitude, non-negative order constraint at the final assembler site may occur, and this may lead to a significant increase in average inventory levels and a decrease in speed to recovery. While this may improve the dynamic performance of the upstream supplier internal system, it enhances OEM's risk of technological redundancy with ever shorter product life cycles of products entering the market;
- The amplitude of cyclic customer demand is also important for the supplier to manage CODP inventory at their site, due to the possible occurrence of capacity and non-negative order constraints. Although the bullwhip level may be decreased, the recovery speed for CODP inventory is slow if such nonlinearity occurs, which also

directly increases the stock-out probability and further influences the end customer service levels.

- Production managers at the supplier site need to carefully consider capacity utilisation, i.e. whether the mean of orders received from the final assemblers exceeds half of the available capacity, as nonlinearities with capacity upper limits and non-negative order boundary may differentially impact on the mean level of CODP inventory.

Nonlinear ATO systems and the 'performance triangle'

- Managers may simply calculate the estimated delivery LT by considering the difference between current backlog and raw materials inventory level at final assembly plant (VMI hub), under the condition that desired shipment rate cannot be fully satisfied.
- Due to nonlinear switch between different operational processes, maintaining the 'true' hybrid ATO operational state by ensuring sufficient CODP stock is always desirable to ensure customer service level; that is, the reliable delivery LT. However, by maintaining the desired ATO state, the trade-off between capacity and CODP inventory as the buffer should be considered. The theoretical modelling and analysis support the practical rationale as to why PC OEMs make every effort, exploiting such approaches as supplier qualifying programmes and VMI to ensure CODP inventory availability for immediate final assembly.

- Two independent negative feedback loops are present in the ATO system, which may lead to superposition or separation of dynamic oscillations, e.g. separate two-resonant peak frequencies (that is, the dynamic system can generate peak oscillations with greater amplitude, e.g. high bullwhip, at two different demand frequencies). As a result, it is beneficial for different companies to collaboratively design the replenishment policy to reduce the influence of two-resonance peak frequencies, which support the practical adoption of collaborative planning, forecasting and replenishment (CPFR) from the system dynamics perspective.

7.3. Limitations and future research agenda

This thesis systematically assesses the impact of ATO ordering structures on dynamic performance. However, several limitations should be highlighted and a corresponding future research agenda can be illustrated as follows:

- The IOBPCS-based production control frameworks (linear or nonlinear representations) may not be capable of capturing the nonlinear increase of cycle time in the semiconductor fab production *at high resources utilisation condition* (Orcun et al., 2006) due to the lead time modelling approaches, i.e. first order/third order delay under the fixed mean lead time assumption. To be more specific, with the increase of WIP level, longer time is required for the semiconductor fab system to transform releases into output, resulting from the nonlinear increase of cycle time in both mean and variability, which may lead to different dynamic behaviour under high capacity utilisation level compared with the corresponding response of the IOBPCS family. Although a similar behaviour can be obtained from IOBPCS-based and non IOBPCS-based systems (e.g. the adoption of the clearing functions) *at low utilisation level*, the exploration of alternative lead time/capacity modelling approaches in the IOBPCS family, e.g. Clearing Function based capacity models that expected output of a production resource over a given planning period is related to the WIP level during that period (Orcun et al., 2006), in representing a more realistic semiconductor fab WIP congestion condition is strongly recommended for future study.

- Due to the importance of maintaining ATO structures to ensure customer service level, further control policy optimal design between capacity and CODP inventory should be considered to minimise the corresponding operational cost within the context of the PC sector.
- Researchers should consider the adoption of empirical methodologies, such as survey or interview/case studies, to validate and generalise the theoretical findings in industries where the hybrid ATO supply chain strategy is adopted, such as the steel industry (Denton et al., 2003; Kerkkanen, 2007; Perona et al., 2009), food production and processing organisations (van Donk, 2001; Soman et al., 2004) and the automobile industry (Choi et al., 2012).
- Two kinds of demand input are evaluated: cyclic and step demand increase. Although these two inputs are commonly-observed in semiconductor and PC real-world supply chains, other important demand patterns, such as the stochastics demand (‘variance lens’) following different probability distributions, step demand decrease, saw-tooth

and impulse, can be explored. In particular, real stochastic data can be utilised to assess the dynamic property of the ATO ordering system and propose corresponding control design.

- The study for dynamic performance of multiple ATO systems in the PC industry connected to each other can be another extension for future research. The PC industry, including the upstream semiconductor and downstream sub-assembler and OEM, contains multiple ATO systems. An interesting scenario thereby observed is that the upstream semiconductor's order-driven system (i.e. the pull part of the ATO system) may receive the downstream players' order (e.g. sub-assemblers or OEMs) that is the forecasted data based on end customer demand, i.e. the push part of the downstream players' ATO system. As a result, the two ATO systems, for example, can be connected as Push-Pull-Push-Pull and its dynamic performance should be further explored.

7.4. Summary

This chapter has sought to draw the thesis to a close, highlighting the overall conclusions, as well as the contributions that these make to the literature and industrial practice. The author contributes to the modelling, design and analysis of the ATO system from a system dynamics perspective. Specifically, the author contributes to the synthesis of the well-established IOBPCS family as the foundations for modelling and analysing the ATO system.

The author uses the Intel supply chains as an example of an existing complex ATO system and proposes a simplification method to analytically explore its dynamic property, especially for the underlying mechanisms of bullwhip that are usually investigated only by simulation when facing complex, non-linear system dynamics model.

Furthermore, a generic PC ATO system dynamic model is developed and analysed. A ‘performance triangle’, i.e. capacity at the supplier, CODP inventory and the delivery lead-time for the end customer, is developed and its dynamic property is formally assessed. The author contributes to methodological developments by proposing a linearisation method to allow for rigorous synthesis of customer delivery lead-time dynamics, often neglected in the existing literature that generally focuses on bullwhip and inventory variance.

The limitations brought about as a result of the methods adopted are also recognised, together with potential lines of further enquiry, including the nonlinear modelling and analysis of lead time variance, the assessment of different demand patterns, optimisation of the CODP inventory and bullwhip under the desired hybrid ATO state, and the exploration of multiple ATO systems connected to each other in the PC sector.

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Appendix 1. Mathematical modelling of the Intel ATO system

The author gives a brief introduction to the supply chain operational design, while full details can be found in Gonçalves et al. (2005). Specifically, there are three stages in the Intel supply chain including two production stages (wafer manufacturing and die assembly) and one distribution process.

Distribution pull (with possibly switch to push)

Customer demand ultimately drives production activities. Current demand determines the replenishment of FGI and assembly, while long-term demand forecast drives wafer production. To model the distribution process, the relationship between customer demand and replenishment of FGI need to be captured. By design, S is determined by the minimum of S^* and S_{MAX}:

$$\mathrm{S(t)} = \mathrm{Min}\left(S^*(t), S_{MAX}(t)\right) \quad (1.1)$$

S^* is determined by the ratio of B and DD^*, and S_{MAX} is the ratio of FGI and order processing time, T_{op}:

$$S^*(t) = \frac{B(t)}{DD^*(t)} \quad (1.2)$$

$$S_{MAX} = \frac{FGI(t)}{T_{op}} \quad (1.3)$$

B is the cumulative level for the difference between D and S and FGI depends on the accumulation between the replenishment from A_N(t) and the depletion of S:

$$B(t) = B(t-1) + D(t) - S(t) \quad (1.4)$$

$$\text{FGI(t)} = \text{FGI(t)} + A_N(t) - S(t) \quad (1.5)$$

So, the switch between pull and push in the distribution process is ultimately determined by customer demand and feasible FGI. The distribution mode operates in 'pull' mode if there is enough FGI to meet customer orders immediately, otherwise the system will 'push' all feasible FGI and the backlog orders will directly 'pull' from assembly die inventory, ADI

Assembly pull (with possibly switch to push)

While shipment deplete the FGI, assembly complete rate A_N replenish it. The A_N is determined by the product of A_G and Y_U, i.e. the percentage of good chips for each assembly die:

$$A_N(t) = A_G(t) * Y_U (1.6)$$

Where A_G is resulted of the minimum of 'pull' gross signal from downstream distribution and the feasible 'push' gross assembly complete signal:

$$A_G(t) = Min\left(Pull\ A_G(t), Push\ A_G(t)\right) (1.7)$$

By design, the intel assembly operates as 'pull' mode adjusted by the ratio of A_N^* and Y_U, where desired net assembly aims to eliminate any gaps for FGI and remove any excess for Backlog. More reliable ES as a proxy is also utilized for deciding A_N^*. However, if there is no enough AWIP to meet desired pull signal, the assembly process will automatically switch to 'push' mode in which AWIP and average T_A decide the push A_G. For simplicity, a first order delay is utilized:

$$Pull\ A_G(t) = Max\left(0, \frac{A_N^*(t)}{Y_u}\right) = Max\big(0, FGI_{ADJ}(t) + B_{ADJ}(t) + ES(t)\big) \quad (1.8)$$

$$Push\ A_G(t) = \frac{AWIP(t)}{T_A} \quad (1.9)$$

$$FGI_{ADJ}(t) = \frac{1}{T_{FGI}}\big(FGI^*(t) - FGI(t)\big), \qquad FGI^*(t) = ES(t) \cdot WOI \quad (1.10)$$

$$B_{ADJ}(t) = \frac{1}{T_B}\big(B^*(t) - B(t)\big), \qquad B^*(t) = D(t) \cdot DD \quad (1.11)$$

$$ES(t) = ES(t-1) + a \cdot (D(t) - ES(t-1),$$

$$and \quad a = \frac{1}{1 + \frac{T_A}{\triangle T}} \quad (Towill\ 1970) \quad (1.12)$$

Where T_{FGI} and T_B are the adjustment time for eliminating FGI and Backlog errors, WOI is the desired weeks of safety FGI, recent shipment is determined by smoothed demand in which the relationship between smoothing level a and T_A is justified by Towill (1970).

Wafer production push

While A_N depletes the AWIP, D_I in upstream fabrication production replenishes it:

$$\mathrm{AWIP(t)} = \mathrm{AWIP(t)} + D_I(t) - F_G(t) \quad (1.13)$$

Where D_I is measured by die/month and is given by gross fabrication rate (F_G, wafers/month) and adjusted by the number of DPW, D_L and Y_L, i.e. the percentage of good fabricated wafers:

$$D_I(t) = F_G(t) \cdot DPW \cdot D_L \cdot Y_L \quad (1.14)$$

The F_G is given by the ratio of available FWIP and T_F:

$$F_G(t) = \frac{FWIP(t)}{T_F} \quad (1.15)$$

Where the accumulation of difference between WS and F_G determine the FWIP:

$$FWIP(t) = FWIP(t-1) + WS(t) - F_G(t) \qquad (1.16)$$

Production wafer starts perform the 'push' mode in which WS is the result of FWIP adjustment to reflect managers' desired for adjusting the local FWIP level and the D^*_I requested by assembly plant. Non-negativity constraint prevents negative wafer start rate

$$WS(t) = Max\left(0, FWIP_{ADJ} + D_I^*\right) \quad (1.17)$$

FGI_{ADJ} aims to eliminate the gaps between desired FWIP ($FWIP^*$, determined by desired die inflow and fabrication time) and actual FWIP

$$FWIP_{ADJ}(t) = \frac{FWIP^*(t) - FWIP(t)}{T_{FWIP}} \quad (1.18)$$

Where D^*_I depend on the long-term forecasting (ED) and the adjustment from AWIP ($AWIP_{ADJ}$). For simplicity, a first order lag is used for long-term forecasting. The AWIP adjustment reflect the managers' desired time (T_{AWIP}) to correct the assembly inventory error between targeted AWIP and actual AWIP. Non-negativity constraint prevents negative die inflow rate

$$D_I^*(t) = Max\left(0, \frac{ED(t)}{Y_U} + AWIP_{ADJ}(t)\right) \quad (1.19)$$

$$ED(t) = ED(t-1) + a \cdot \big(D(t) - ED(t-1)\big) \quad and \quad a = \frac{1}{1 + \frac{T_{sAdj}}{\triangle T}} \quad (1.20)$$

$$AWIP_{ADJ}(t) = \frac{1}{T_{FWIP}} \cdot \big(AWIP^*(t) - AWIP(t)\big) \ (1.21)$$

Appendix 2. An introduction of the (AP)IOBPCS archetypes

1) *Demand Policy:*

$$AVCON_t = a \cdot (CON_t - AVCON_{t-1}) + AVCON_{t-1} \qquad (2.1)$$

Where

$$a = \frac{1}{1 + \frac{Ta}{\triangle T}} \qquad (2.2)$$

2) *WIP policy:*

$$WIP_t = \frac{1}{T_w} \cdot (DWIP_t - AWIP_t) = \frac{1}{T_w} \cdot (AVCON_t \times T_P - AWIP_t) \qquad (2.3)$$

3) *Lead time policy:*

$$\frac{1}{1 + T_p \, \mathrm{S}} \qquad (2.4)$$

As we are interested in the relationship between CONS and AINV/COMRATE/WIP, the transfer function of APIOBPCS archetype are shown as follow:

$$\frac{AINV}{CONS} = -T_i \cdot \left[\frac{\frac{T_p - T_{p'}}{T_w} + \left(T_a + T_p + \frac{T_a T_p}{T_w}\right) s + T_a T_p S^2}{(1 + T_a s)\left(1 + \left(1 + \frac{T_p}{T_w}\right) T_i s + T_p T_i s^2\right)} \right] \qquad (2.5)$$

$$\frac{COMRATE}{CONS} = \frac{1 + \left(T_a + T_i + \frac{T_{p'} T_i}{T_w}\right) s}{(1 + T_a s)\left(1 + \left(1 + \frac{T_p}{T_w}\right) T_i s + T_p T_i s^2\right)} \qquad (2.6)$$

$$\frac{WIP}{CONS} = T_p \cdot \left| \frac{1 + \left(T_a + T_p + \frac{T_a T_p T_{p'}}{T_w}\right)s}{(1 + T_a s)\left(1 + \left(1 + \frac{T_p}{T_w}\right)T_i s + T_p T_i s^2\right)} \right| \qquad (2.7)$$

It should be noted that equations above can represent the original IOBPCS by setting $T_w = \infty$. The Initial/final value theorem can be applied to the equation (2.5)

$$\frac{AINV}{CONS_{IVT}} = 0; \qquad \frac{AINV}{CONS_{FVT}} = \frac{T_i\left(T_{p'} - T_p\right)}{T_w} \qquad (2.8)$$

The *noise bandwidth* can be represented as follow:

$$W_N = \int_0^{\infty} \left| \frac{COMRATE}{CONS}(jw) \right|^2 dw \qquad (2.9)$$